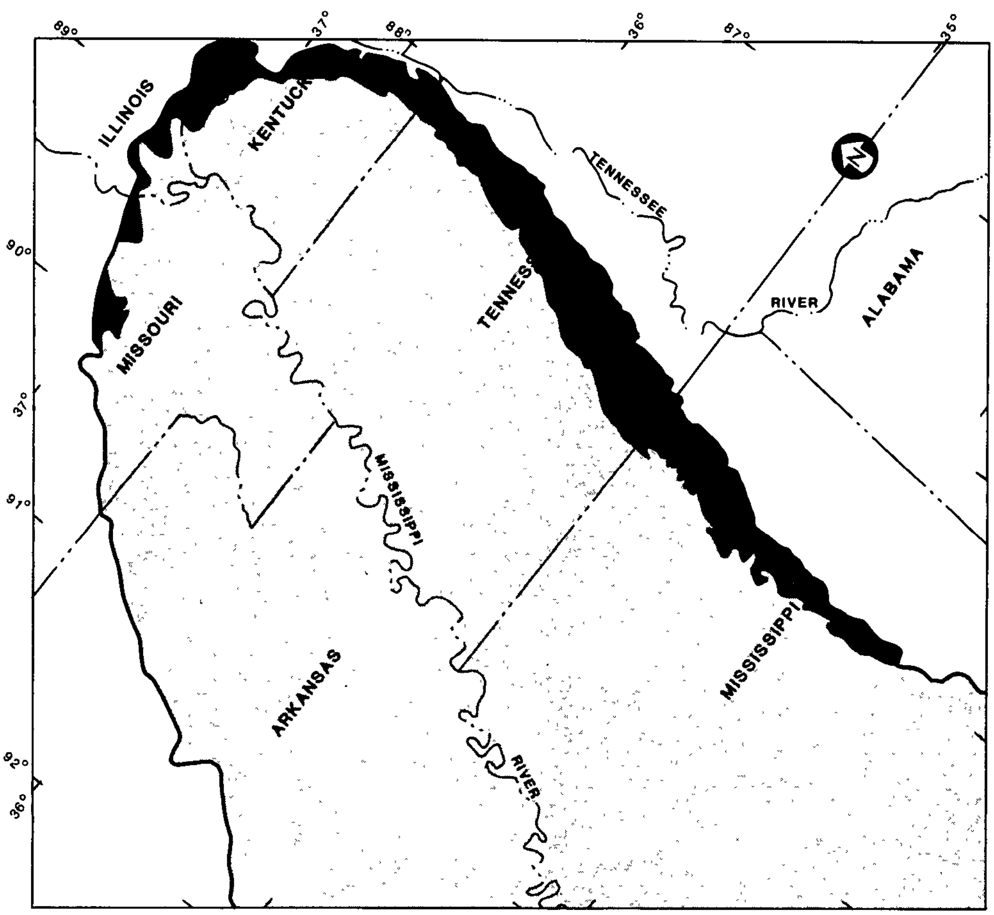
Water-Resources Investigations Report 87-4000

HYDROGEOLOGY AND PRELIMINARY ASSESSMENT OF REGIONAL FLOW IN THE UPPER CRETACEOUS AND ADJACENT AQUIFERS IN THE NORTHERN MISSISSIPPI EMBAYMENT



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HYDROGEOLOGY AND PRELIMINARY ASSESSMENT OF REGIONAL FLOW IN THE UPPER CRETACEOUS AND ADJACENT AQUIFERS IN THE NORTHERN MISSISSIPPI EMBAYMENT

by J.V. Brahana and T.O. Mesko

U.S. GEOLOGICAL SURVEY

Water Resources Investigations Report 87-4000

Nashville, Tennessee
1988

DEPARTMENT OF THE INTERIOR

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U.S. GEOLOGICAL SURVEY

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CONVERSION FACTORS

For those readers who may prefer to use metric (International System) units rather than inch-pound units, conversion factors for the terms used in this report are listed below:

Multiply	By	To obtain
	Length	
inch (in.)	25.40	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
	3.785×10^{-3}	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow	
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	6.309×10^{-5}	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
inch per year (in/yr)	25.40	millimeter per year (mm/a)
cubic foot per second (ft^3/s)	2.832×10^{-2}	cubic meter per second (m^3/s)
[(ft^3/s)/mi^2]		[(m^3/s)/km^2]
foot per year (ft/yr)	0.3048	meter per year (m/yr)
gallon per day (gal/d)	3.785	liter per day (L/d)
	Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Leakance	
foot per second per foot [(ft/s)/ft]	1.000	meter per second per meter [(m/s)/m]

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

$$°F = 1.8\,°C + 32.$$

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.

HYDROGEOLOGY AND PRELIMINARY ASSESSMENT OF REGIONAL FLOW IN THE UPPER CRETACEOUS AND ADJACENT AQUIFERS IN THE NORTHERN MISSISSIPPI EMBAYMENT

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ABSTRACT

On a regional scale, the ground-water system of the northern Mississippi embayment is composed of a series of nonindurated clastic sediments that overlie a thick sequence of Paleozoic carbonates, sandstones, and shales. Precambrian crystalline rocks form both the structural and the hydrogeologic basement throughout the northern embayment. The units that comprise the hydrogeologic framework of this study are the alluvium-lower Wilcox aquifer, the Midway confining unit, the Upper Cretaceous aquifer, the Cretaceous-Paleozoic confining unit, and the Ozark-St. Francois aquifer. The Upper Cretaceous aquifer of Late Cretaceous age is the primary focus of this investigation; the study is part of the Gulf Coast Regional Aquifer-System Analysis.

A ground-water flow model was developed as the main tool to refine the concepts of deep regional flow in the northern Mississippi embayment. This four layer finite-difference model enabled testing of alternative boundary concepts and provided a refined definition of the hydrologic budget of the deep aquifers.

The alluvium-lower Wilcox aquifer, the Upper Cretaceous aquifer, and the Ozark-St.Francois aquifer form layers 2 through 4, respectively. Layer 1 is an inactive layer of constant heads representing shallow water levels, which are a major control on recharge to and discharge from the regional system. A matrix of leakance values simulates each confining unit, allowing vertical interchange of water between different aquifers. The model was calibrated to 1980 conditions by using the assumption that 1980 was near steady-state conditions; it was calibrated to simulate observed heads within acceptable limits. For this preliminary model, calculated heads were found to be most sensitive to pumping, and least sensitive to the leakance.

By using all available water-quality and water-level data, alternative boundary conditions were tested by comparing model simulated heads to observed heads. Simulation indicated that the major discharge zone for the Upper Cretaceous aquifer occurred along a narrow area coincident with the boundary of a buried rift.

The results of the early modeling effort also contribute to a better understanding of the regional hydrologic budget, indicating that upward leakage from the Ozark-St. Francois aquifer to the Upper Cretaceous aquifer is about 43 cubic feet per second, with about 30 cubic feet per second occuring west of the western margin of the embayment. Calculations suggest upward recharge of about 68 cubic feet per second occurs to the lower Wilcox-alluvium aquifer from the Upper Cretaceous aquifer. Simulation results also indicate that the Midway is an effective regional confining unit.

INTRODUCTION

The Upper Cretaceous aquifer of Cretaceous age is a regionally extensive but relatively little-used aquifer in the northern Mississippi embayment. Throughout much of its area of occurrence, this aquifer is the deepest freshwater source available. Because it is commonly overlain by high-yielding, shallower aquifers that supply most of the water needs of the region, the Upper Cretaceous aquifer has been the focus of few studies. Data are relatively sparse, and details about the hydrogeology and regional flow in this aquifer are poorly defined.

The Upper Cretaceous aquifer, as discussed in this report, includes the McNairy Sand in Missouri, Tennessee, and Kentucky; the Nacatoch Sand in Arkansas; and the Ripley Formation (including the McNairy Sand Member) in Tennessee and Mississippi. Hydrologic units adjacent to the Upper Cretaceous aquifer that are described in this report include the Ozark-St. Francois, the lower Wilcox and the alluvial aquifers, and the undifferentiated Cretaceous-Paleozoic, the Midway, and the undifferentiated Claiborne-upper Wilcox confining units (table 1).

Table 1.--*Summary of the relation of selected regional hydrologic units to the geology of the study area, including a summary of aquifer characteristics*

[ft, foot; ft/d, foot per day; ft^2/d, foot squared per day; E, Estimated from geophysical logs; modified from Grubb, 1984]

Hydrogeologic unit	Reference	Aquifer characteristics				Remarks
		Maximum mapped thickness (ft)	Hydraulic conductivity (ft/d)	Transmissivity (ft^2/d)	Storage coefficient	
Alluvium	Boswell and others (1968) Newcome (1971) Broom and Lyford (1981) Luckey (1985)	250	60-450	8,000-80.000	0 0003-0.14	Area west of subcrop with lower Wilcox aquifer considered in this report.
Undifferentiated Claiborne and upper Wilcox confining unit	Hosman and others (1968)					Not evaluated quantitatively in this report.
Lower Wilcox aquifer	Hosman and others (1968) Boswell (1976) Arthur and Taylor (1988)		25-470	670-85.000	0.0002-0.015	Current simulation of this aquifer limited only to head as it affects vertical leakage with Upper Cretaceous aquifer.
Midway confining unit	Grubb (1984)	1,200E				Simulated throughout area of occurrence. Coastal Uplands confining system of GC RASA (Grubb, 1984).
Upper Cretaceous aquifer	Boswell and others (1965) Newcome (1971) Boswell (1978)	500	10-75	270-4,300	0.0001-0.0008	Simulated throughout area of occurrence.
Paleozoic-Cretaceous confining unit	Boswell and others (1965) Schwalb (1982); M.J. Mallory, U.S. Geological Survey, written commun., (1986)	11,500E				This layer has not been completely defined in the study area. Many Cretaceous formations in this interval serve as aquifers in the southeastern part of study area (Boswell and others, 1965). It is an important confining layer in part of the embayment.
Ozark-St. Francois aquifer	Imes (1988a. 1988b)	5,000	0.9 (Ozark)	50-2,600		This aquifer contains the Ozark aquifer, the St. Francois confining bed, and the St. Francois aquifer of Imes (1988a, 1988b, 1988c. 1988d). It contains saline water throughout most of study area, and is evaluated only in its outcrop area (fig. 9) and east of the area of outcrop.
Precambrian confining unit	Imes (1988a)					Dense crystalline basement. Regionally serves as lower limit to ground-water flow.

The Upper Cretaceous aquifer study area is irregularly shaped and slightly larger than the physical boundaries of the northern Mississippi embayment. The 52,000 square mile area, with maximum dimensions of 240 miles by 260 miles, includes parts of eastern Arkansas, southeastern Missouri, southern Illinois, western Kentucky, western Tennessee, and northern Mississippi (fig. 1). Boundaries of the area are aligned at approximately 50° east of north and 40° west of north.

The Upper Cretaceous aquifer study is a subproject of the larger, regional Gulf Coast Regional Aquifer-Systems Analysis (GC RASA) study. The GC RASA study, one of several RASA studies being conducted by the U.S. Geological Survey on major regional aquifers, is designed to define the hydrogeology of Tertiary and younger age units in the Mississippi embayment and Gulf Coastal area, and of Upper Cretaceous sedimentary rocks where these are used for ground-water supplies in the northern Mississippi embayment.

OBJECTIVES

The objectives of this report are (1) to describe the hydrogeology of the Upper Cretaceous and adjacent aquifers; (2) to document the development and calibration of a preliminary multilayer model used to simulate flow within this system of aquifers; and (3) to evaluate quantitatively the contributions of the various aquifer-system components to the regional hydrologic budget.

The three-dimensional finite-difference flow model (McDonald and Harbaugh, 1984) is one of several tools that will be used in later studies to develop a more complete understanding of ground-water flow in the northern Mississippi embayment. Final results of the Gulf Coastal Plain RASA study and its subprojects will be documented in chapters of a report in the U.S. Geological Survey Professional Paper series.

PREVIOUS INVESTIGATIONS

Although the hydrogeology of the northern Mississippi embayment has been documented in a variety of reports, details of the deep aquifers (Paleozoic and Upper Cretaceous rocks) are not well understood. These formations are not used as widely as shallower formations for sources of water, and consequently few data exist.

Geologic studies describing lithologic, stratigraphic, and structural aspects of the area include papers by Caplan (1954), Groshkopf (1955), Stearns and Armstrong (1955), Pryor (1960), Marcher and Stearns (1962), Cushing and others (1964), Schwalb (1969, 1982), McCracken (1971), Howe and others (1972), and Crone and Russ (1979). Ervin and McGinnis (1975) described the regional tectonics of the northern embayment, and McKeown and Pakiser (1982) edited a collection of papers that examined both the regional tectonics and geophysical studies of the New Madrid, Missouri, earthquake region in detail. Other significant studies include Stauder and others (1976), Mitchell and others (1977), Hildenbrand and others (1977), Zoback and others (1980), Crone and Brockman (1982), Hildenbrand and others (1982), Swanberg and others (1982), and Crone and others (1985).

The hydrogeology of the area, including the areal extent of the geologic units, has been compiled from a variety of sources. The generalized geology (fig. 2) is based on geologic maps published by Arkansas (Haley, 1976), Missouri (Anderson and others, 1979), Illinois (Willman and others, 1967), Kentucky (Olive, 1980), Tennessee (Hardeman and others, 1966; Parks and Russell, 1975), and Mississippi (Mississippi Geological Survey, 1979). The basis for current understanding of the hydrogeology of the Cretaceous and younger sediments is a series of interpretive reports by Boswell and others (1965), Boswell and others (1968), Hosman and others (1968), Cushing and others (1970), and Davis and others (1973).

Modeling studies that have been conducted in the area on aquifers related to this study include work on the Cretaceous aquifers in northern Missisissippi by Kernodle (1981), on the regional aquifer system of Cretaceous age in Mississippi by Mallory (M.J. Mallory, U.S. Geological Survey, written commun., 1985) and on the Ozark Plateaus aquifer system of Cambrian and Ordovician age in southeastern Missouri and northeastern Arkansas by Imes (1988a, 1988b, 1988c).

In addition to interpretive reports, reports by Boswell (1963, 1978), Hines and others (1972), Davis and others (1973), Newcome (1974), Luckey and Fuller (1980), Wasson (1980), Edds (1982), and Luckey (1985) contain valuable water-level and water-quality data.

HYDROGEOLOGY

Occurrence and movement of ground water in the study area are controlled by (1) the distribution of recharge to and discharge from the aquifers, (2) the hydraulic gradients established between recharge and discharge locations, (3) the hydraulic characteristics, stratigraphic position, and thickness of aquifers and confining units, and (4) the tectonic setting and structural discontinuites that may serve as hydrogeologic boundaries.

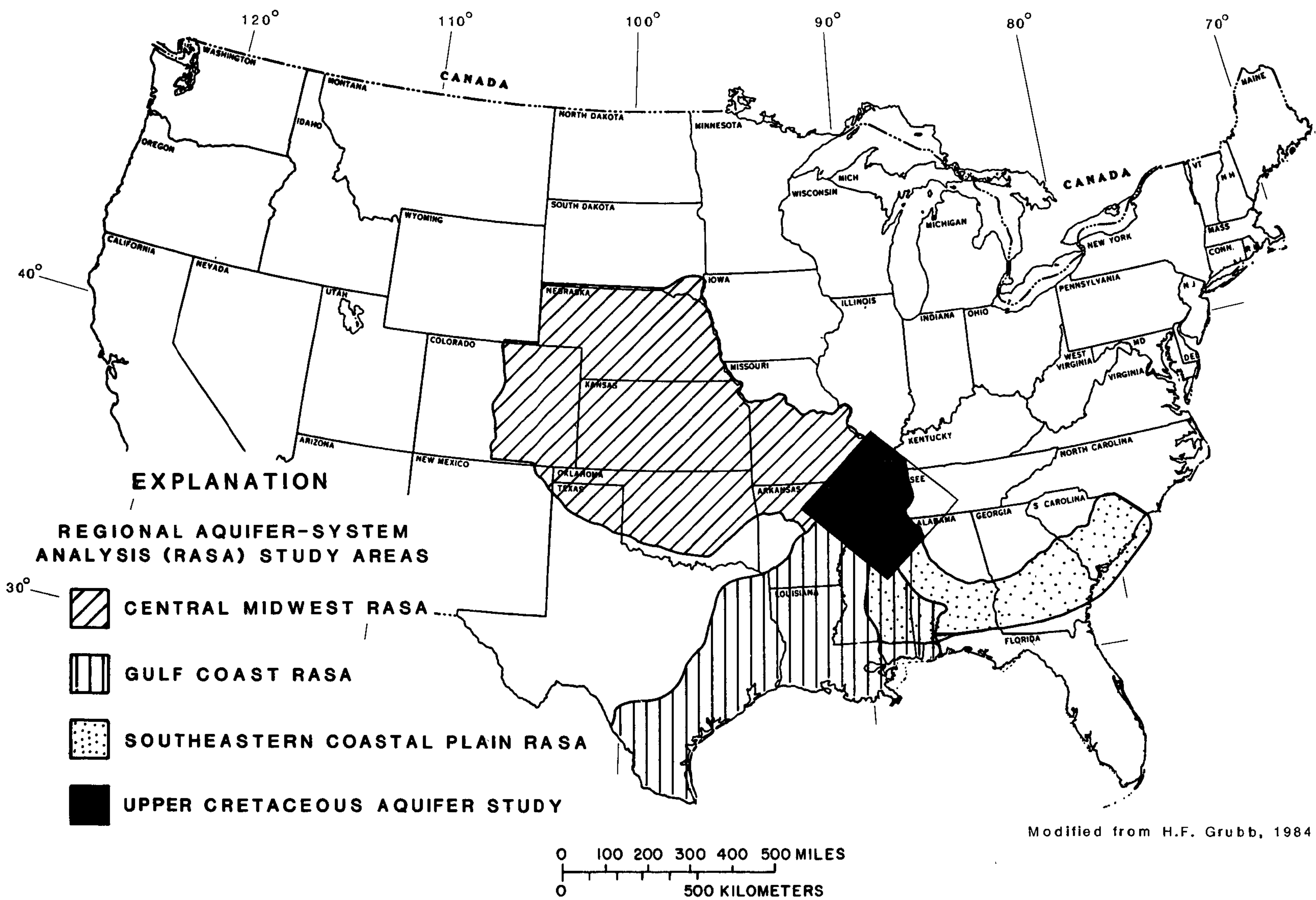


Figure 1.--Location of the Upper Cretaceous aquifer study with respect to the boundaries of the Gulf Coast, the Central Midwest, and the Southeastern Coastal Plain Regional Aquifer-System Analysis Study Areas.

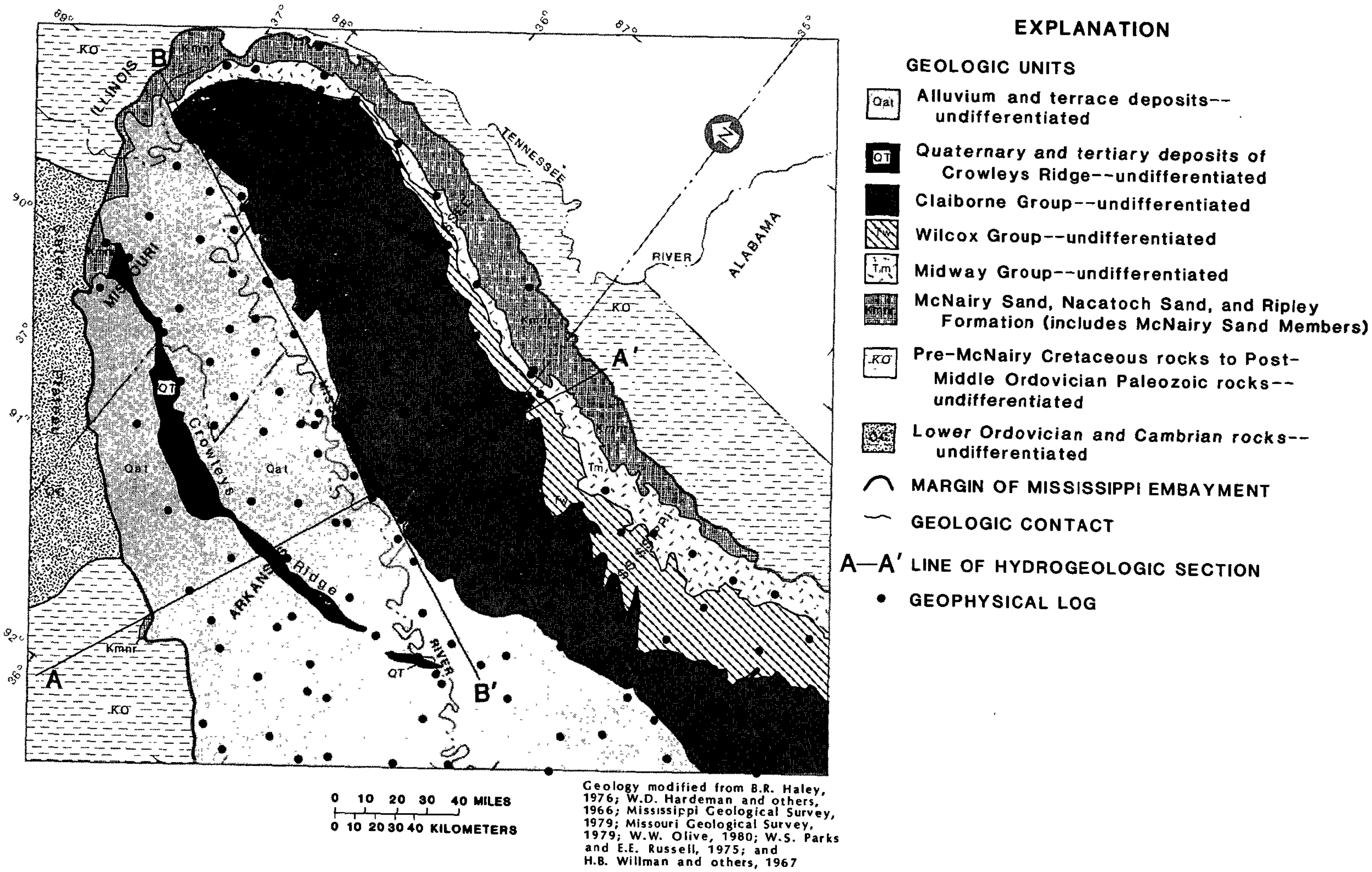


Figure 2.--Generalized geology of the study area, including distribution of geophysical logs, location of hydrogeologic sections A-A' and B-B', and selected physiographic features.

Recharge to the aquifers is provided mostly by precipitation. Mean annual precipitation in the study area ranges from less than 46 inches in southern Illinois to more than 56 inches in northeastern Mississippi (Cushing and others, 1964; U.S. Geological Survey, 1970). Except in areas of intense pumping, more water is available for recharge than the deeper, confined flow systems can accept. Consequently, almost all the water that enters the shallow parts of the aquifer in the outcrop area is discharged locally to streams.

Physiography and altitude of the land surface (fig. 3) influence ground-water levels significantly. In this study, land-surface altitude has been used to estimate the altitude of the water table, based on a multiple linear regression of depth-to-water as a function of land-surface altitude and well depth. Setting well depth equal to the depth-to-water and solving the regression equation for water-table altitude yielded the equation:

Water-table altitude, in feet = (land-surface altitude, in feet x 0.9585)-3 feet

(A.K. Williamson, U.S. Geological Survey, written commun., 1985). This equation was used to generate a water-table map with a calculated average water level for each 5-mile square block. The blocks are defined by the GC RASA model grid (A.K. Williamson, U.S. Geological Survey, written commun., 1985).

HYDROGEOLOGIC FRAMEWORK

The sediments of Cretaceous and Tertiary age that comprise the aquifers and confining units within the area are exposed at land surface in narrow bands that roughly parallel the eastern and northern margins of the embayment (fig. 2). Alluvium occurs at the surface throughout most of the western half of the embayment. Carbonate rocks of Cambrian and Early Ordovician age crop out in the western part of the study area as part of the Salem Plateau.

Maps of thickness, sand percentage, and structure of hydrogeologic units described in this report were based primarily on geophysical well logs and secondarily on previous studies. Geophysical logs, which are part of a common data base of all GC RASA regional and subproject studies, were selected to give the most regionally representative three-dimensional definition of the system (R.L. Hosman, written commun., 1985).

Hydrogeologic sections A-A′ (fig. 4) and B-B′ (fig. 5) illustrate the vertical framework of the system with reference to the Upper Cretaceous aquifer, and table 1 lists generalized hydraulic characteristics of this framework. Section A-A′ is transverse to and section B-B′ is parallel to the axis of the embayment (fig. 2). These sections illustrate the southward plunging synclinal structure of the embayment, show the relatively flat relief of the land surface, and indicate the relative thickness of the units.

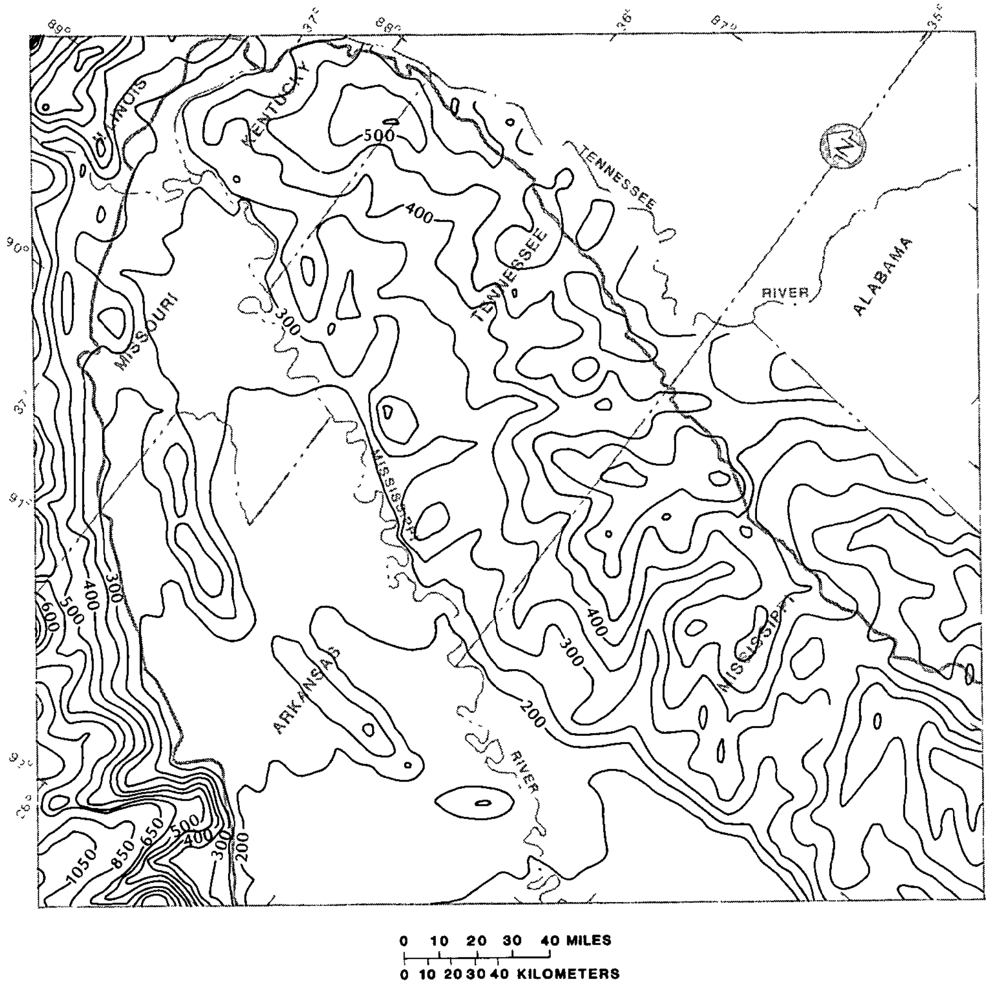
The Mississippi embayment rift is one of the dominant tectonic features in the northern Mississippi embayment (fig. 6) (McKeown and Pakiser, 1982). This deep zone of faulting in Precambrian basement rocks has been reactivated periodically by crustal stresses. As a zone of crustal weakness, the rift is thought to be a potential propagator of faults into the overlying younger rocks and sediments (Brahana and others, 1982). Geologic and hydrologic discontinuities occur close to the western margin of the rift, suggesting that this feature, or effects associated with this feature, is important to the regional hydrogeologic framework of the study area.

On a regional scale, the ground-water system of the northern Mississippi embayment is composed of a series of nonindurated granular sediments that overlie a thick sequence of Paleozoic carbonate rocks, sandstones, and shales. Precambrian crystalline rocks form both the structural and the hydrogeologic basement throughout the northern embayment.

Precambrian rocks consist of felsitic volcanic rocks ranging from rhyolite to andesite, granites and granite porphyries, and basic intrusives of gabbroic composition, which locally may be fractured (Howe and Koenig, 1961). The Precambrian rocks are dense and commonly have exceedingly low porosity and permeability. These rocks crop out in the St. Francois Mountains northwest of the study area and slope steeply toward the axis of the Mississippi embayment. Depth to Precambrian basement generally ranges from less than 2,000 to more than 10,000 feet within the study area, but is greater than 15,000 feet at the southern margin of the study area (T.C. Buschbach, written commun., 1981; Schwalb, 1982).

Several thousand feet of Cambrian and Lower Ordovician rocks, primarily dolomite, sandstone, and shale overlie the Precambrian basement. This sequence has been separated (Imes, 1988a) into three hydrogeologic units, the St. Francois aquifer, the St. Francois confining bed, and the Ozark aquifer.

The basal LaMotte Sandstone and overlying Bonneterre Formation, consisting of dolomite and limestone of Cambrian age, have been defined as the St. Francois aquifer by Imes (1988b). This aquifer is about 500 to 600 feet thick in the northwestern part of the study area. The LaMotte and Bonneterre are equivalent to the lower part of the



EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

—200— TOPOGRAPHIC CONTOUR--Shows approximate altitude of land surface. Contour interval 50, 150, and 200 feet. National Geodetic Vertical Datum of 1929

Figure 3.--Generalized topography of the study area.

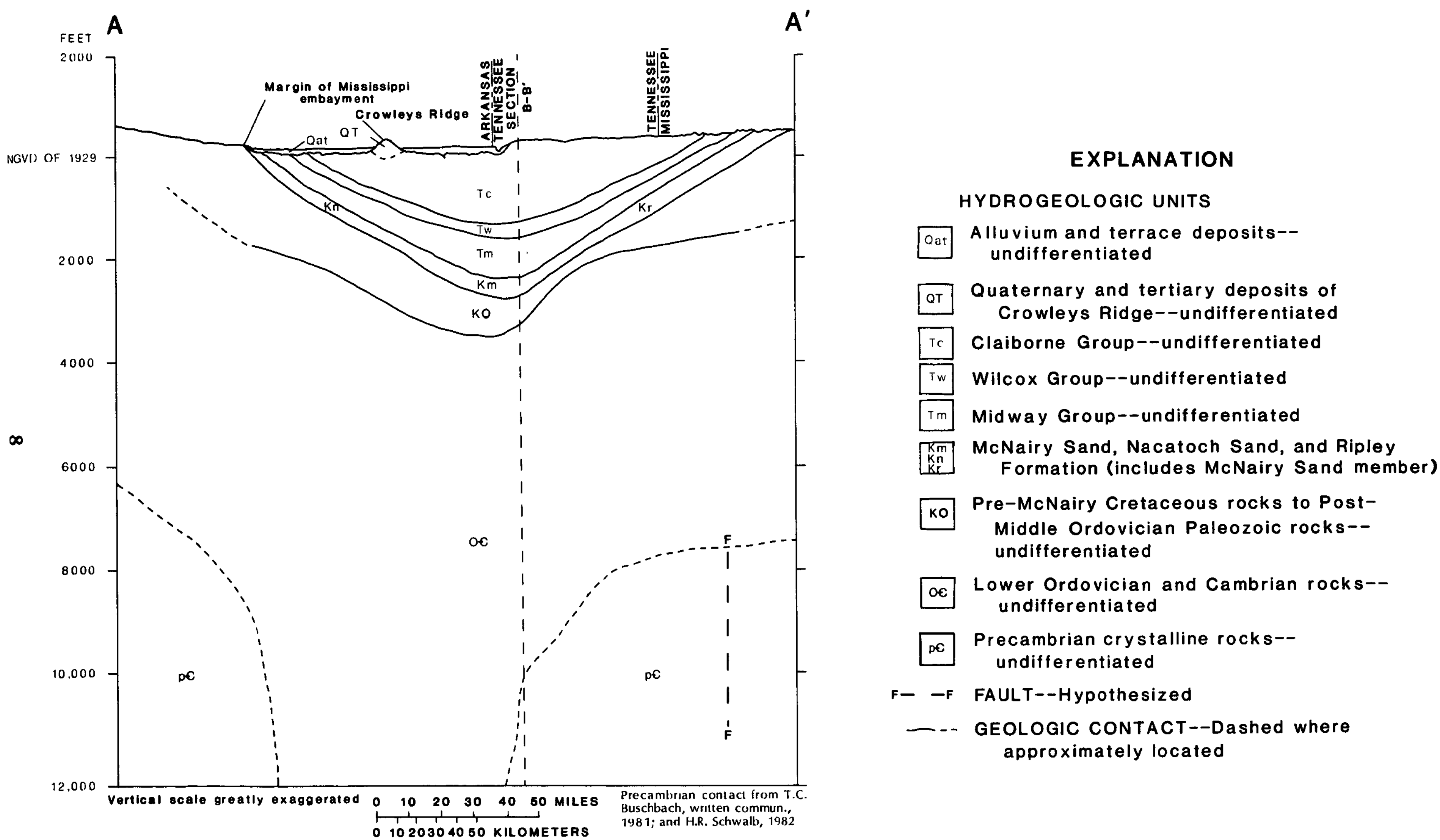


Figure 4.--Hydrogeologic section A-A' from northwest to southeast across the axis of the Mississippi embayment.

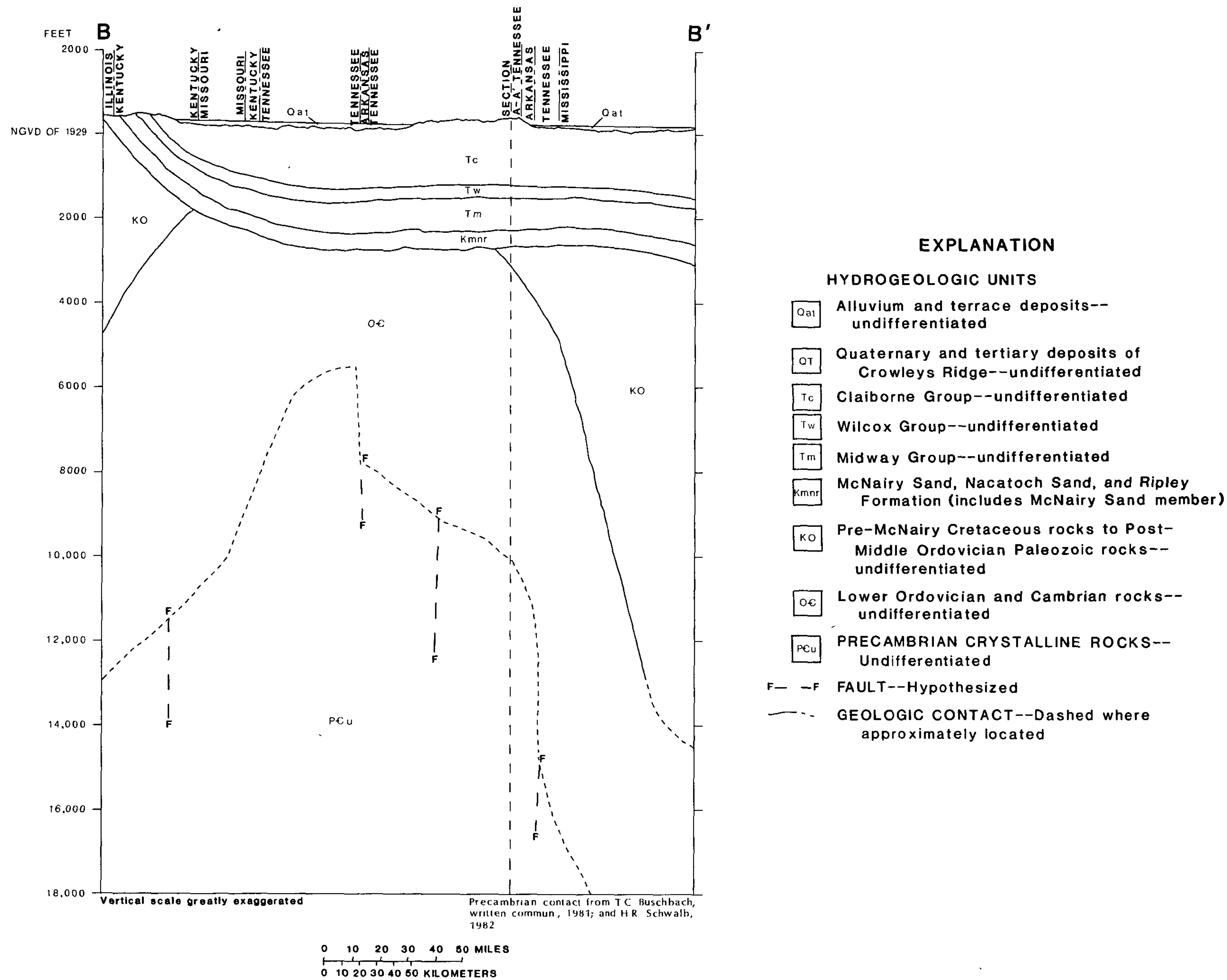


Figure 5.--Hydrogeologic section B-B′ from northeast to southwest along the axis of the Mississippi embayment.

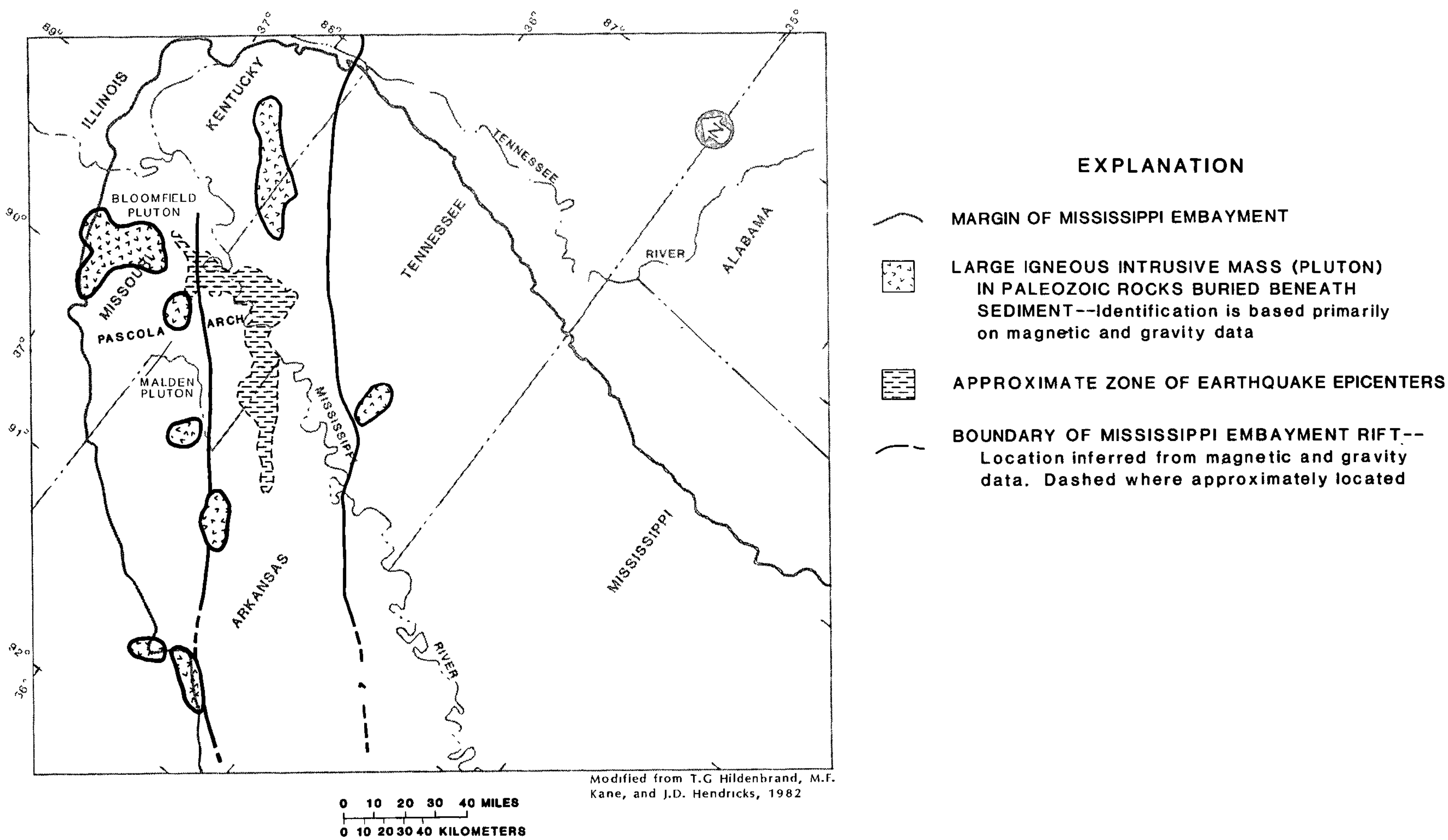


Figure 6.--Major tectonic features of the northern Mississippi embayment.

Copper Ridge Dolomite, which is part of the Knox Group in the eastern part of the study area (Schwalb, 1982).

The St. Francois aquifer is confined by the overlying St. Francois confining bed (Imes, 1988c), which consists of shale, siltstone, fine-grained sandstone, dolomite, and limestone conglomerate. These units total about 500 feet in thickness and include the Davis, Derby and Doe Run Formations of Late Cambrian age (Howe and Koenig, 1961). In the eastern part of the study area, these formations are equivalent to the middle part of the Copper Ridge Dolomite (Schwalb, 1982).

The Ozark aquifer consists of eight formations that overlie the St. Francois confining bed (Imes, 1988d). These formations, in ascending order, are the Potosi Formation and Eminence Dolomite of Cambrian age, and the Gasconade Dolomite, Roubidoux Formation, Jefferson City and Cotter Dolomites, Smithville Formation, and Powell Dolomite of Early Ordovician age, (Howe and Koenig, 1961). They are primarily siliceous dolomites, with some beds of sandstone and minor shale. The dolomites have well-developed zones of secondary porosity and permeability throughout the area of this study, including the area beneath the embayment.

A highly diverse sequence of rocks ranging in age from Middle Ordovician to Late Cretaceous may overlie the Ozark-St. Francois aquifer, depending on its location (Howe and Koenig, 1961; Boswell and others, 1965; Davis and others, 1973; Schwalb, 1982). In this report, these rocks are named the undifferentiated Cretaceous-Paleozoic confining unit. Data describing the hydrology of these rocks where they occur more than several hundred feet deep are scarce. Based on geologic data from the few deep oil-exploration wells in the embayment, the undifferentiated Paleozoic and Cretaceous rocks are believed to form a regional confining layer in the subsurface. Some formations of Cretaceous age within this sequence are known to function as aquifers at shallow depths around the margins of the embayment and as regional aquifers in the southeastern part of the study area (Boswell and others, 1965; Davis and others, 1973; M.J. Mallory, written commun., 1986). In the southern part of the study area, Middle Ordovician to Upper Cretaceous rocks have an aggregate thickness of more than 11,000 feet (fig. 5). Thickness decreases to the north, and this sequence of rocks is absent in the central part of the study area (fig. 5).

The Upper Cretaceous aquifer, consisting of the McNairy and Nacatoch Sands and the Ripley Formation (including the McNairy Sand Member), is composed of glauconitic, clayey sand interbedded with clay and chalk. Coarse sediments are common in the north, and clay and chalk predominate in the south (Boswell and others, 1965). The aquifer underlies most of the study area and crops out at the north end of Crowleys Ridge in Missouri and along the eastern edge of the embayment in Kentucky, Tennessee, and northern Mississippi.

Total thickness of the Upper Cretaceous aquifer ranges from 0 to about 500 feet, with the thickest zones occurring in the north central part of the study area in western Tennessee and southeastern Missouri. Cumulative sand thickness in the Upper Cretaceous aquifer (fig. 7), ranges from 0 to about 440 feet.

The Midway confining unit (Midway Group consisting of the Clayton Formation and Porters Creek Clay) consists primarily of fine-grained sediments and overlies the Upper Cretaceous aquifer throughout most of its area of occurrence in the northern embayment. The confining unit ranges in thickness from a few feet along its subcrop to about 1,200 feet in the south central part of the study area (fig. 8).

The lower Wilcox aquifer (composed of sands and clay of the lower part of the Wilcox Group) overlies the Midway confining unit. The Wilcox Group is undifferentiated in Arkansas and Kentucky, but has been subdivided and correlated in Missouri and Tennessee (Hosman and others, 1968). Throughout much of the area, sands of the lower Wilcox aquifer are separated from sands in the upper part of the Wilcox Group by clays in the middle and upper part of the Wilcox Group (Hosman and others, 1968). In the northern part of the study area where it subcrops, the Wilcox may be in direct contact with the alluvium (fig. 4). Sand thickness of the lower Wilcox Group may exceed 600 feet near the center of the embayment in northwestern Mississippi.

Upper sands in the Wilcox and younger Eocene formations, are referred to in this report as the undifferentiated Claiborne-upper Wilcox confining unit. These upper Wilcox and younger Eocene aquifers are described in a separate GC RASA study of the Mississippi embayment aquifer system (Arthur and Taylor, 1988).

The Mississippi River Valley alluvial aquifer (alluvium) consists of sand, gravel, silt, and clay, and is the surficial aquifer throughout the western part of the embayment. The extent and thickness (a few to 250 feet) of this alluvial aquifer have been mapped by Fisk (1944), Krinitzsky and Wiré (1964), Boswell and others (1968), and Luckey (1985). The alluvial aquifer directly overlies parts of the lower Wilcox, Upper Cretaceous, and Ozark-St. Francois aquifers in a subcrop relation (fig. 4).

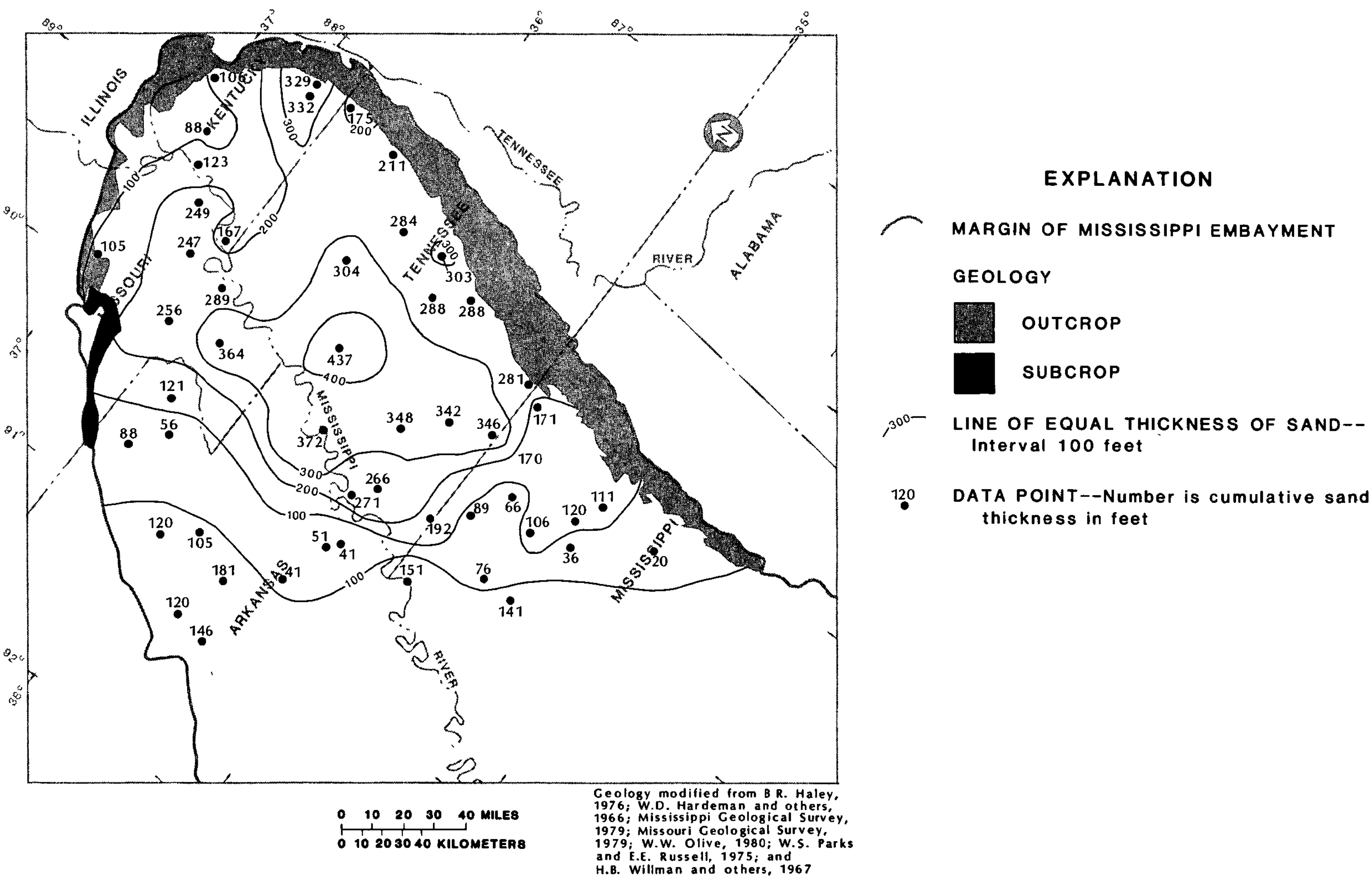
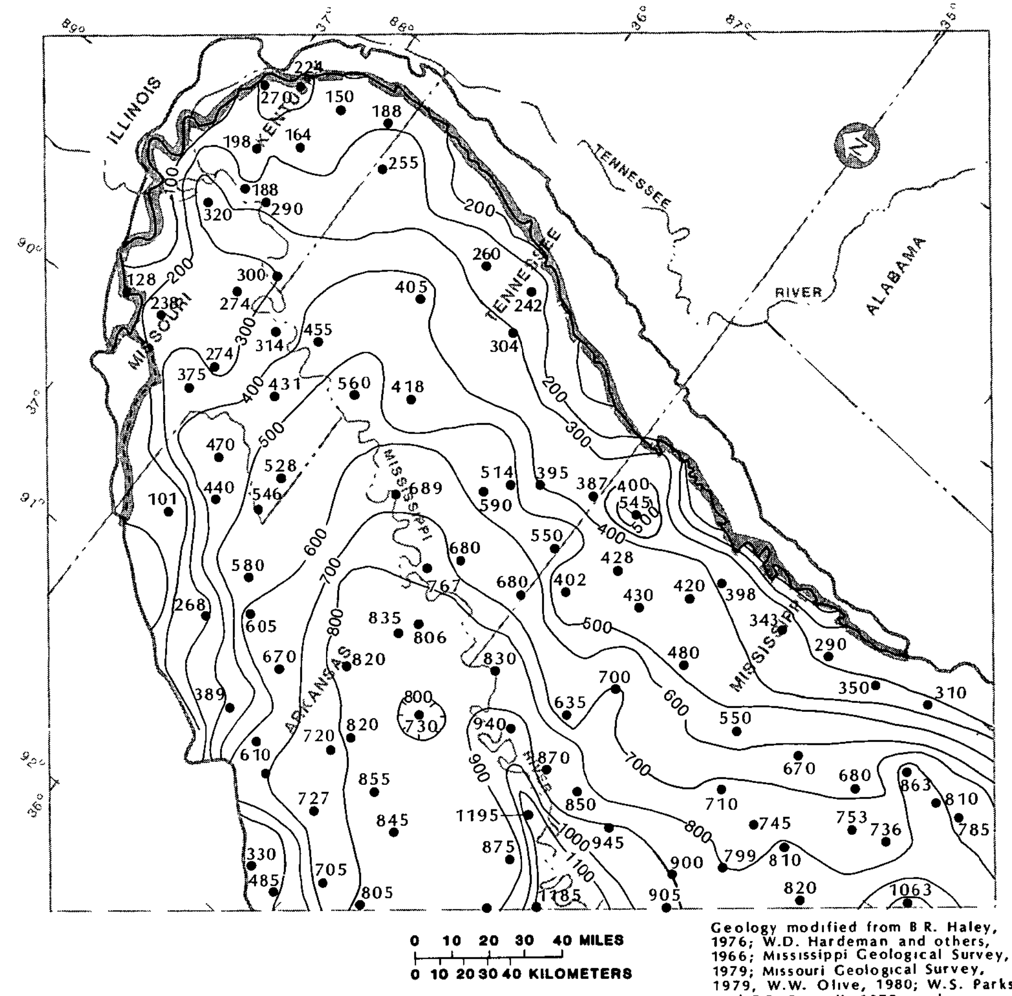


Figure 7.--Extent and cumulative thickness of sand in the McNairy and Nacatoch Sands and Ripley Formation.



EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

EXTENT OF MIDWAY GROUP--Dashed for subcrop

—100— LINE OF EQUAL THICKNESS OF CONFINING UNIT--Hachures indicate depression. Interval 100 feet

545 • DATA POINT--Number is thickness in feet

Geology modified from B R. Haley, 1976; W.D. Hardeman and others, 1966; Mississippi Geological Survey, 1979; Missouri Geological Survey, 1979, W.W. Olive, 1980; W.S. Parks and E.E Russell, 1975; and H.B. Willman and others, 1967

Figure 3.--Extent and thickness of the Midway Group.

REGIONAL FLOW

Estimates of the regional flow in the Upper Cretaceous aquifer were based primarily on water levels. Because this aquifer is relatively deep and ground-water supplies are readily available from shallower aquifers, extensive areas exist where no water wells tap the Upper Cretaceous or deeper aquifers. For those areas, information from oil test wells was used to estimate regional ground-water flow.

Water Levels

Water levels within the outcrop area of the Ozark-St. Francois aquifer (fig. 9) are based on data and interpretations provided by Imes (1988a; 1988b; 1988c; J.L. Imes, U.S. Geological Survey, written commun., 1986). Water-level gradients are relatively steep in the outcrop area and slope toward the margin of the embayment. These data indicate that streams are major discharge outlets for this aquifer in the Salem Plateau. Additionally, the presence of 12 springs with flows greater than 100 cubic feet per second (ft^3/s) along major stream valleys is consistent with this observation (Beckman and Hinchey, 1944; Vineyard and Feder, 1974).

It is believed that beneath the embayment, the gradients become much flatter, but few water-level data are available for the Ozark-St. Francois aquifer where it occurs within the embayment. Therefore, determinations of the direction of ground-water flow in this part of the aquifer can only be generalized. In southeastern Missouri, southward flow is indicated (fig. 9); in western Tennessee, eastward flow toward the Tennessee River is indicated (Brahana and Bradley, 1985).

The potentiometric surface of the Upper Cretaceous aquifer in 1980 (fig. 10) indicates that regional flow in this aquifer is from the outcrop area westward across the embayment to a major discharge area on the extreme western edge of the Missouri "bootheel" near the Arkansas boundary. Previous studies in Kentucky indicate that the aquifer discharges to the Ohio River and its tributaries and that streams draining the outcrop receive significant recharge from the aquifer, ranging from 7 to 10 inches per year (in/yr) (Davis and others, 1973; Zurawski, 1978). In the outcrop areas in Kentucky and Tennessee, flow locally may be eastward. In Missouri and Arkansas, flow toward the south also is indicated (fig. 10). The discharge zone, identified by a low in the potentiometric surface (fig. 10), is coincident with the approximate area of major use. The discharge zone is also nearly coincident with the western margin of the Mississippi embayment rift (fig. 6), but does not coincide with surface-drainage features.

The potentiometric surface of the lower Wilcox aquifer in 1980 (fig. 11) indicates that regional flow is west and southwest from the outcrop areas of Kentucky, Tennessee, and Mississippi, and south from subcrop areas in Missouri. West of the Mississippi River, flow in the aquifer is predominantly southward. In southeastern Missouri, western Tennessee, eastern Arkansas, and northwestern Mississippi, intensive pumping [greater than 1 million gallons per day (Mgal/d)] has caused localized depressions in the potentiometric surface.

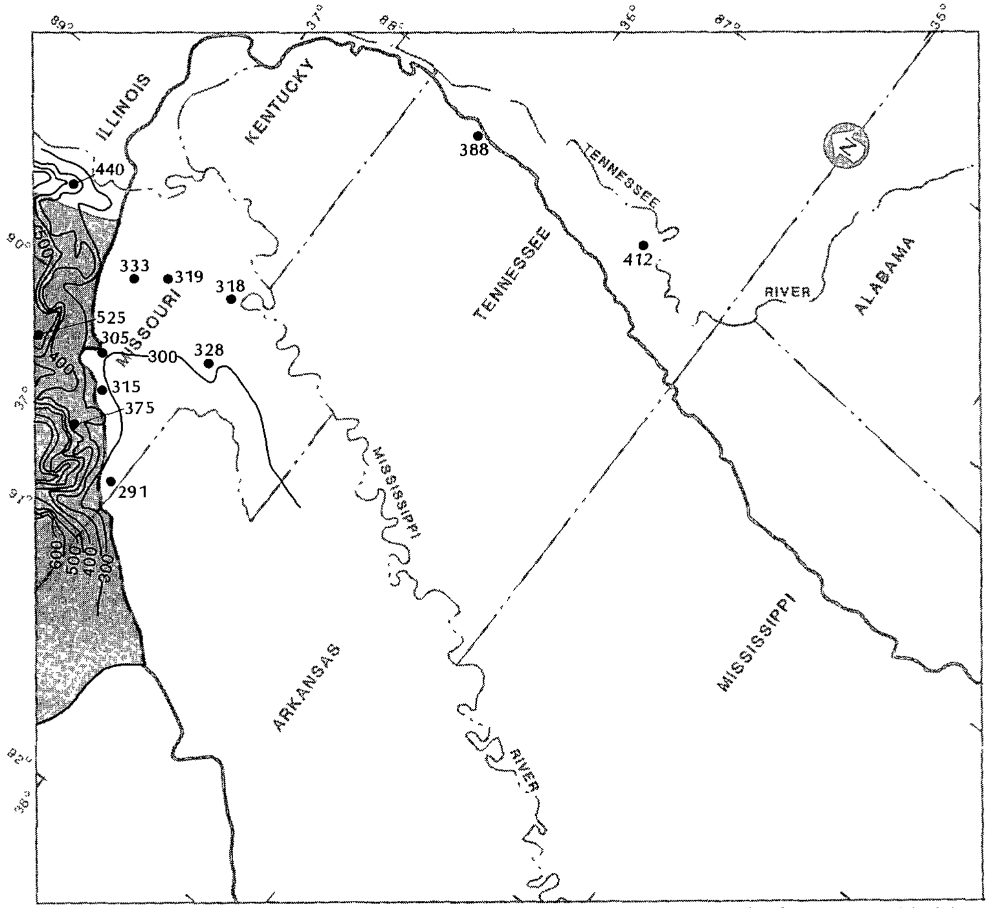
In the outcrop area of the Wilcox Group, the rivers act as drains and ground-water flow is toward the rivers (Wasson, 1980). Water levels near the area of subcrop of the lower Wilcox beneath the alluvium are not defined (fig. 11).

Water levels in the alluvial aquifer west of the subcrop of the lower Wilcox aquifer have been mapped by Broom and Lyford (1981) and Luckey (1985) (fig. 12). Water levels in the alluvium indicate a regional flow southward, with the rivers acting as major drains to the ground-water flow system.

In all aquifers of this study, water levels vary seasonally in response to natural variations in recharge and discharge, and in response to pumping. Hydrographs for selected wells in the Upper Cretaceous, lower Wilcox, and in the alluvial aquifers show long-term water-level trends (fig. 13). No hydrographs are available for the Ozark-St. Francois aquifer. In the outcrop areas (Murray, Paris, Malden, and Peach Orchard on fig. 13), mean yearly water levels appear to be at steady state. In contrast, a long-term water-level decline has occurred in the Fisher well, which is open to the alluvial aquifer west of Crowleys Ridge (figs. 2, 4, and 13), and which is located in an area intensively pumped for rice irrigation. This decline is also thought to affect water levels in the deeper aquifers, because of the high hydraulic conductivity along the subcrop areas. Hydrographs of wells in the confined aquifers in the western part of the study area (Campbell, Paragould, Delta Farms, and Walls) show small (about 1 foot/year) but continuing water-level declines.

Water Quality

The Ozark-St. Francois aquifer is characterized by two water types. According to Hollyday and others (1981), freshwater [dissolved-solids concentration less than 1,000 milligrams per liter (mg/L)] occurs throughout the aquifer in the Salem Plateau area (fig. 2), the approximate area of outcrop (Harvey, 1980). Water from the aquifer in this area is a calcium magnesium bicarbonate type with dissolved-solids concentrations generally less than 250 mg/L (table 2). In the Mississippi embayment where the aquifer



0 10 20 30 40 MILES
0 10 20 30 40 KILOMETERS

Water level contours modified from J.L. Imes, U.S. Geological Survey, written commun., 1986

EXPLANATION

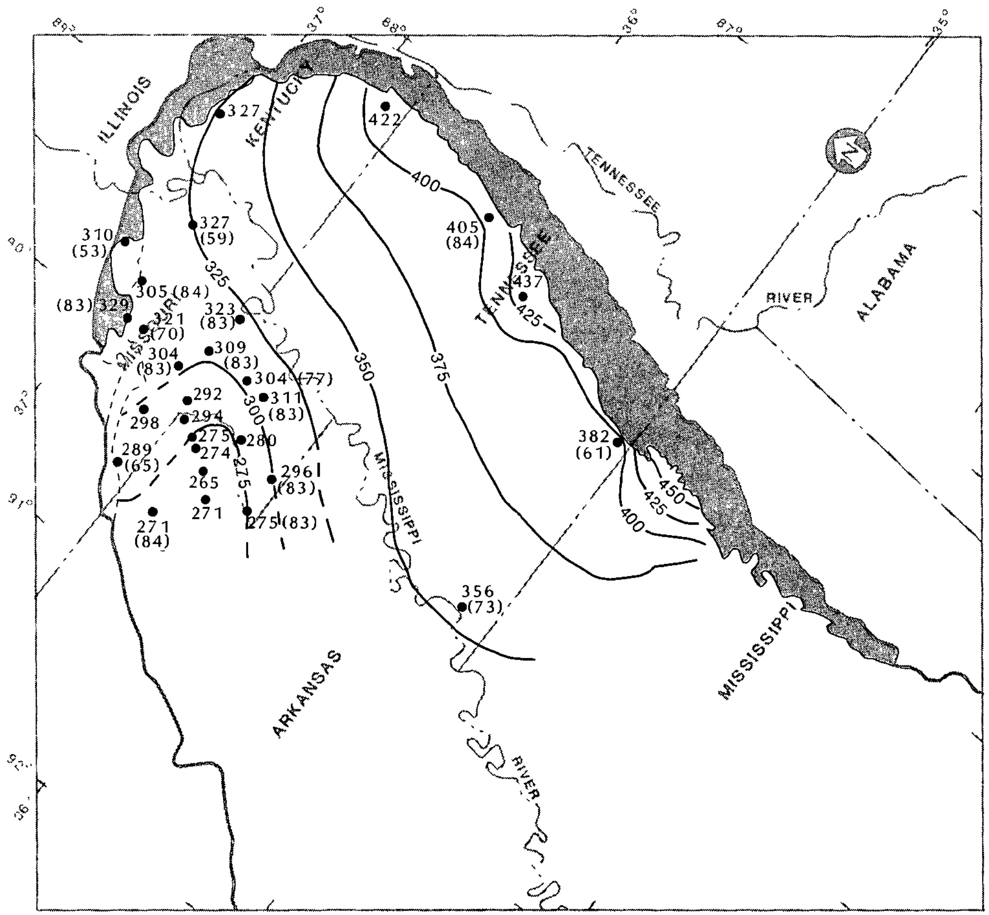
MARGIN OF MISSISSIPPI EMBAYMENT

OUTCROP OF OZARK-ST. FRANCOIS AQUIFER

—600— WATER-LEVEL CONTOUR--Shows altitude of water level in wells. Dashed where approximately located. Contour interval 50 feet National Geodetic Vertical Datum of 1929

319 ● DATA POINT--Number is altitude in feet of water level above National Geodetic Vertical Datum of 1929

Figure 9.--Water-level surface of the Ozark-St. Francois aquifer, 1980.



EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

OUTCROP OF UPPER CRETACEOUS AQUIFER

SUBCROP OF UPPER CRETACEOUS AQUIFER BENEATH ALLUVIUM

-325- POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Dashed where approximately located. Contour interval 25 feet. National Geodetic Vertical Datum of 1929

382 (61) DATA POINT--Number is altitude of water level in feet above National Geodetic Vertical Datum of 1929. Data are for 1980 unless year is shown in parentheses

0 10 20 30 40 MILES

0 10 20 30 40 KILOMETERS

Geology modified from B R. Haley, 1976; W.D. Hardeman and others, 1966; Mississippi Geological Survey, 1979; Missouri Geological Survey, 1979, W.W. Olive, 1980, W.S. Parks and E E. Russell, 1975; and H.B. Willman and others, 1967

Figure 10.--Potentiometric surface of the Upper Cretaceous aquifer, 1980.

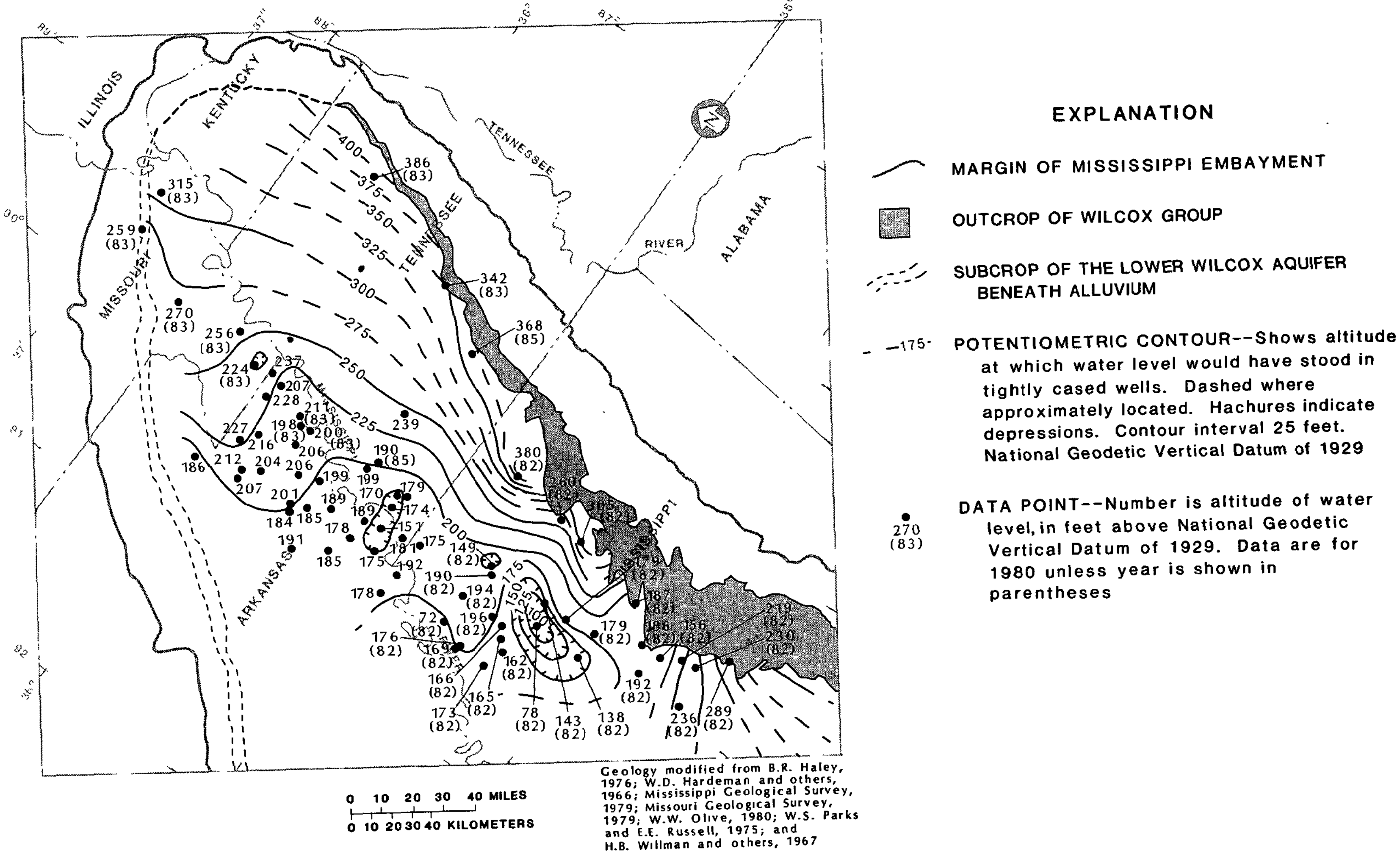


Figure 11.--Potentiometric surface of the lower Wilcox aquifer, 1980.

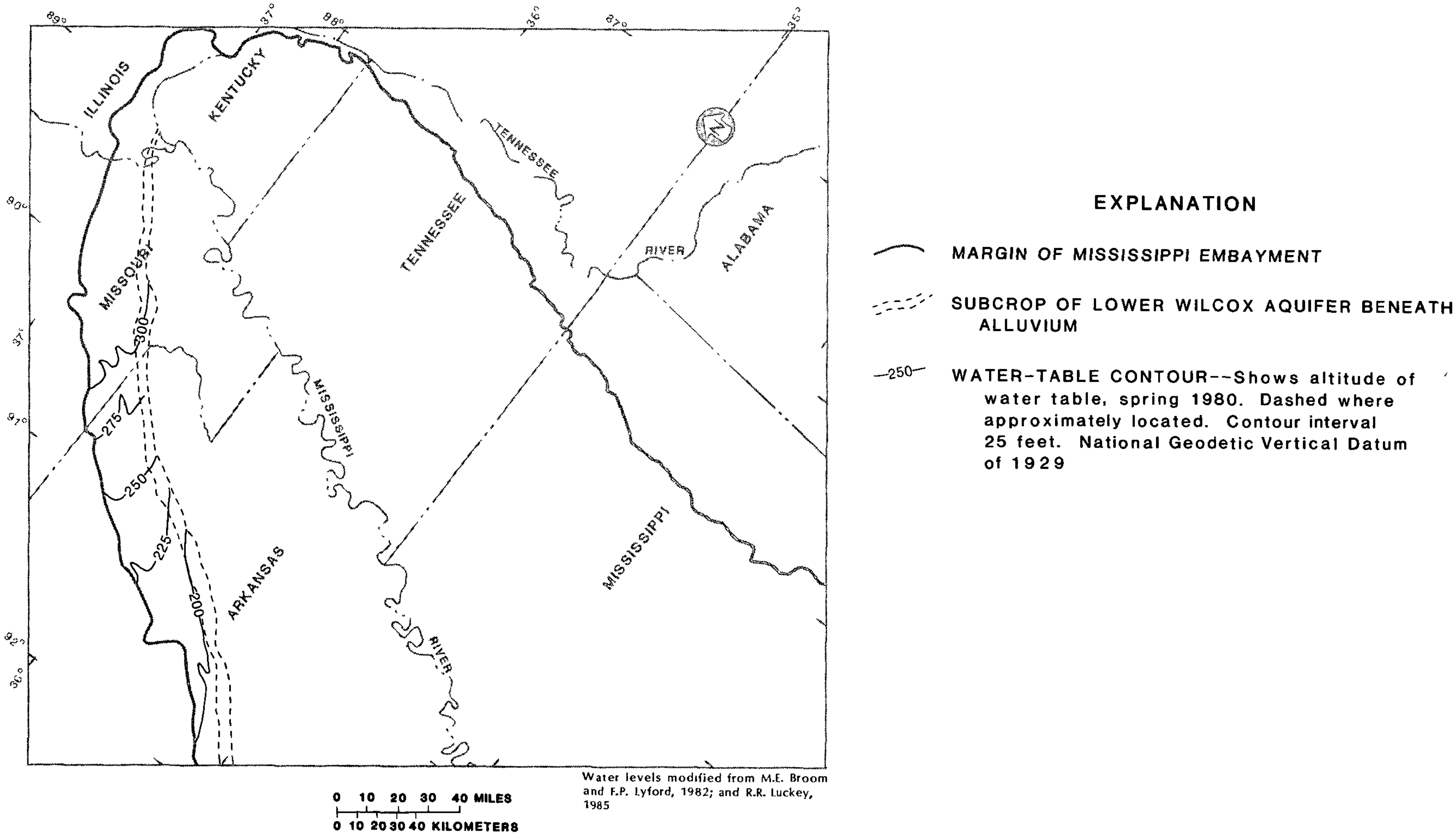


Figure 12.--Water levels in the alluvial aquifer west of the subcrop with the lower Wilcox aquifer, spring 1980.

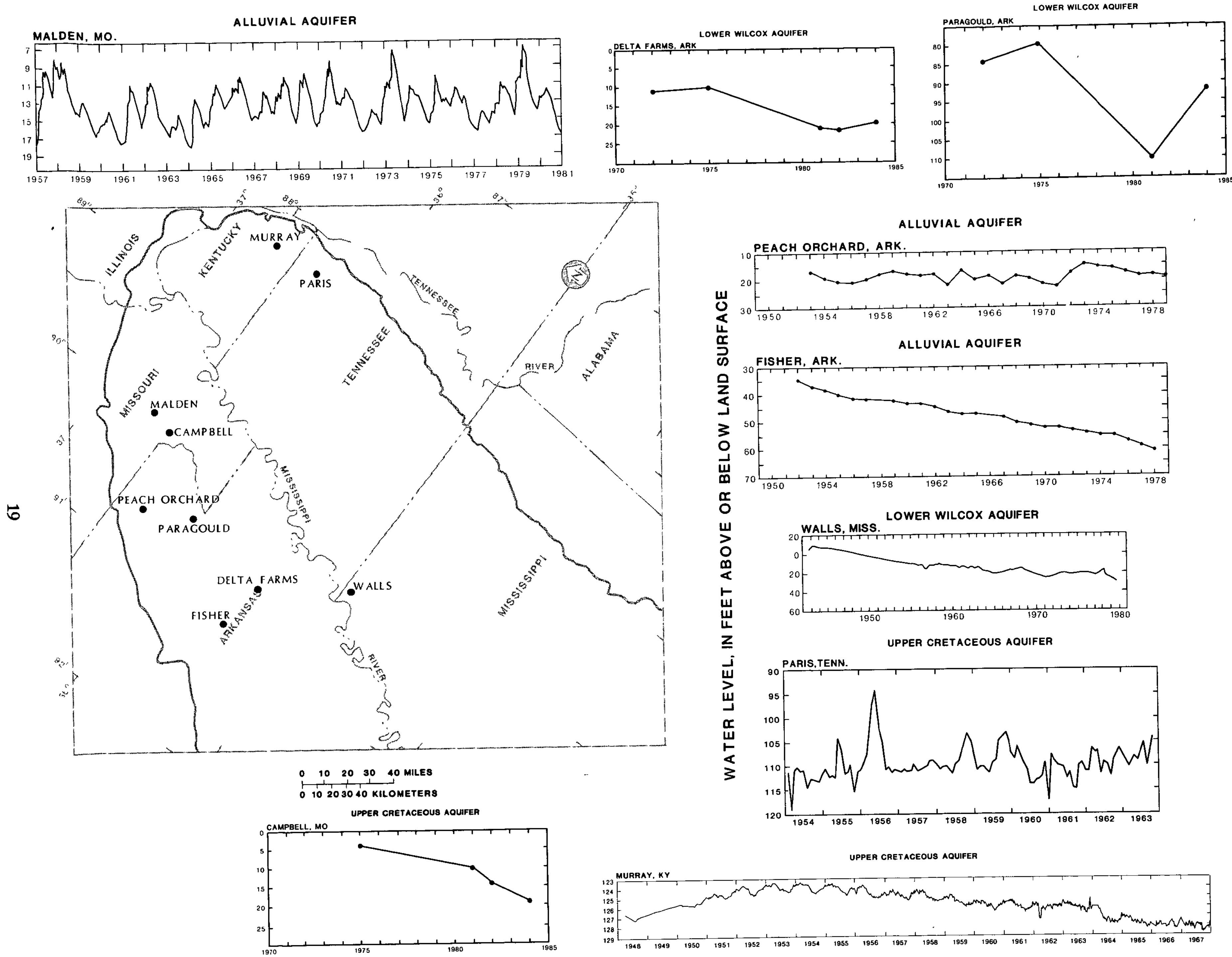


Figure 13.--Hydrographs of wells in the Upper Cretaceous, lower Wilcox, and the alluvial aquifers.

Table 2.--*Comparison of characteristic water types and representative water-quality characteristics for each major aquifer system*

[mg/L, million gallons per day; <, less than; >, greater than]

Aquifer	Setting	Characteristic water types(s)	Dissolved solids concentrations (mg/L)	Hardness (Durfor and Becker, 1964)	Water-quality characteristics
Alluvium	Outcrop	Calcium magnesium bicarbonate.	200-600	Hard to very hard.	Hard water-low chloride except near discharge zones from deeper sources.
Lower Wilcox	Outcrop-subcrop	Calcium magnesium bicarbonate.	< 250	Moderately hard to hard.	
	Embayment-confined	Sodium bicarbonate	< 250	Soft	Low chloride except near discharge areas and downdip (south) areas of sluggish flow that have not been completely flushed.
	Embayment-confined near western margin of rift in vicinity of southwest Poinsett Co., Ark.; also southern part of the study area where aquifer is deep and flow is stagnant.	Sodium chloride	> 1,000	Hard	
Upper Cretaceous	Outcrop	Calcium magnesium bicarbonate.	< 250	Soft to hard	
	Embayment-confined	Sodium bicarbonate	< 1,000	Soft	Anomalously hot water near western margin of rift near subcrop of Ozark-St. Francois; hydrothermal water distribution does not coincide with high chloride; water in confined part of aquifer is very soft.
	Embayment-confined near western margin of rift along a trend of Pascola arch-Bloomfield pluton; also southern part of the study area where aquifer is deep and flow is stagnant.	Sodium chloride	> 1,000	Hard	
Ozark-St. Francois	Outcrop	Calcium magnesium bicarbonate.	< 250	Hard to very hard.	Freshwater in outcrop. Sodium chloride type beneath embayment with increasing salinity down-dip and with depth.
	Embayment-confined	Sodium chloride	> 1,000		

is covered by younger sediments, the water is a sodium chloride type. Dissolved-solids concentrations generally exceed 1,000 mg/L, increasing gradually toward the south and generally with depth. Although few water-quality data are available, dissolved-solids concentrations greater than 10,000 mg/L are indicated in water from the upper part of the Ozark-St. Francois aquifer near the Missouri-Arkansas-Tennessee border (Grohskopf, 1955).

Three distinct types of water occur in the Upper Cretaceous aquifer. Within and fairly close to the outcrop areas, a calcium magnesium bicarbonate type with dissolved-solids concentrations less than 250 mg/L is typical (fig. 14 and table 2). Within the zone of confined flow, the water is generally either a sodium chloride or a sodium bicarbonate type. Sodium chloride type water is found in southeastern Missouri (fig. 15) near the western margin of the rift in the vicinity of the Pascola arch and Bloomfield pluton (fig. 6); and in the area (fig. 15) extending from northeastern Arkansas to north central Mississippi (Hines and others, 1972; Boswell, 1978). Elsewhere, water from the Upper Cretaceous aquifer is a soft, sodium bicarbonate type; dissolved-solids concentrations range from 200 to 700 mg/L, generally increasing from east to west and from north to south.

Water at a temperature of 5 °C or more above the mean annual temperature of the surrounding environment is termed "hydrothermal" (White, 1957). In this report, water that is cooler than hydrothermal but warmer than the geothermal gradient is called "anomalously warm." Zones of hydrothermal and anomalously warm water occur in the Upper Cretaceous aquifer on the western side and eastern sides, respectively, of the western rift boundary in southeastern Missouri (fig. 16). This water is thought to be recharging the Upper Cretaceous from a deeper aquifer.

The areal distribution of water types in the lower Wilcox aquifer is similar to that in the Upper Cretaceous. However, in southeastern Missouri, the zones of warm water and salty water found in the McNairy-Nacatoch have not been observed in the lower Wilcox (Brahana and others, 1982). Also, freshwater occurs about 10 miles further south in Arkansas in the lower Wilcox than in the Upper Cretaceous (Hines and others, 1972).

Throughout the area of freshwater occurrence in the lower Wilcox aquifer, dissolved-solids concentrations are generally less than 250 mg/L. The water is either a sodium bicarbonate type in the confined part of aquifer or a calcium magnesium bicarbonate type in the outcrop (Hosman and others, 1968).

Water from the alluvium is characterized as a hard, calcium magnesium bicarbonate type with dissolved-solids concentrations generally ranging from 200 to 600 mg/L (Boswell and others, 1968). Chloride concentrations less than 10 mg/L are common in water from this aquifer, but concentrations greater than 200 mg/L have been determined at several locations (fig. 15) (Broom and Lyford, 1981).

HYDRAULIC CHARACTERISTICS

Aquifer tests have been used in this study to define the range of transmissivity, hydraulic conductivity, and storage coefficients for the Upper Cretaceous, lower Wilcox, and alluvial aquifers. Results of tests selected to show representative values are presented in table 3, and locations are shown in fig. 17.

No aquifer tests have been conducted in the Ozark-St. Francois aquifer within the study area, but based on results of the few tests made at other locations (Imes, 1988a; 1988b), average hydraulic conductivity is assumed to be about 0.9 feet per day (ft/d) and transmissivity is believed to range from 50 to 2,600 feet squared per day (ft^2/d). No storage coefficients have been reported.

The Upper Cretaceous aquifer is reported to have a range of hydraulic conductivity from 10 to 75 ft/d, a range of transmissivity from 270 to 4,300 ft^2/d, and a range of storage coefficients from 0.0001 to 0.0008 (Boswell and others, 1965; Newcome, 1971; Boswell, 1978). Three representative aquifer tests of the Upper Cretaceous aquifer show a transmissivity range from 1800 to 4,300 ft^2/d, a hydraulic conductivity range from 16 to 45 ft/d, and a storage coefficient range from 0.007 to 0.0008 (table 3).

The lower Wilcox aquifer is reported to have a range of hydraulic conductivity from 25 to 470 ft/d, a range of transmissivity from 670 to 85,000 ft^2/d, and a range of storage coefficients from 0.0002 to 0.015 (Hosman and others, 1968; Boswell, 1976). Data from three representative tests in the lower Wilcox aquifer in table 3 show transmissivity ranges from 10,000 to 21,000 ft^2/d, hydraulic conductivity ranges from about 50 to 110 ft/d, and storage coefficients are about 0.002.

Reported aquifer tests of the alluvium indicate that the hydraulic conductivity ranges from 60 to 450 ft/d, transmissivity ranges from 8,000 to 54,000 ft^2/d, and storage coefficients range from 0.0001 to 0.04 (Newcome, 1972; Broom and Lyford, 1981; Luckey, 1985). Representative values of reliable tests from the alluvium (table 3) show transmissivity ranges from 8,500 to 50,000 ft^2/d, hydraulic conductivity ranges from 100 to 390 ft/d, and storage coefficients range from 0.0001 to 0.04.

No empirical data exist that can be used to calculate vertical hydraulic conductivity (K_z) of confining layers in

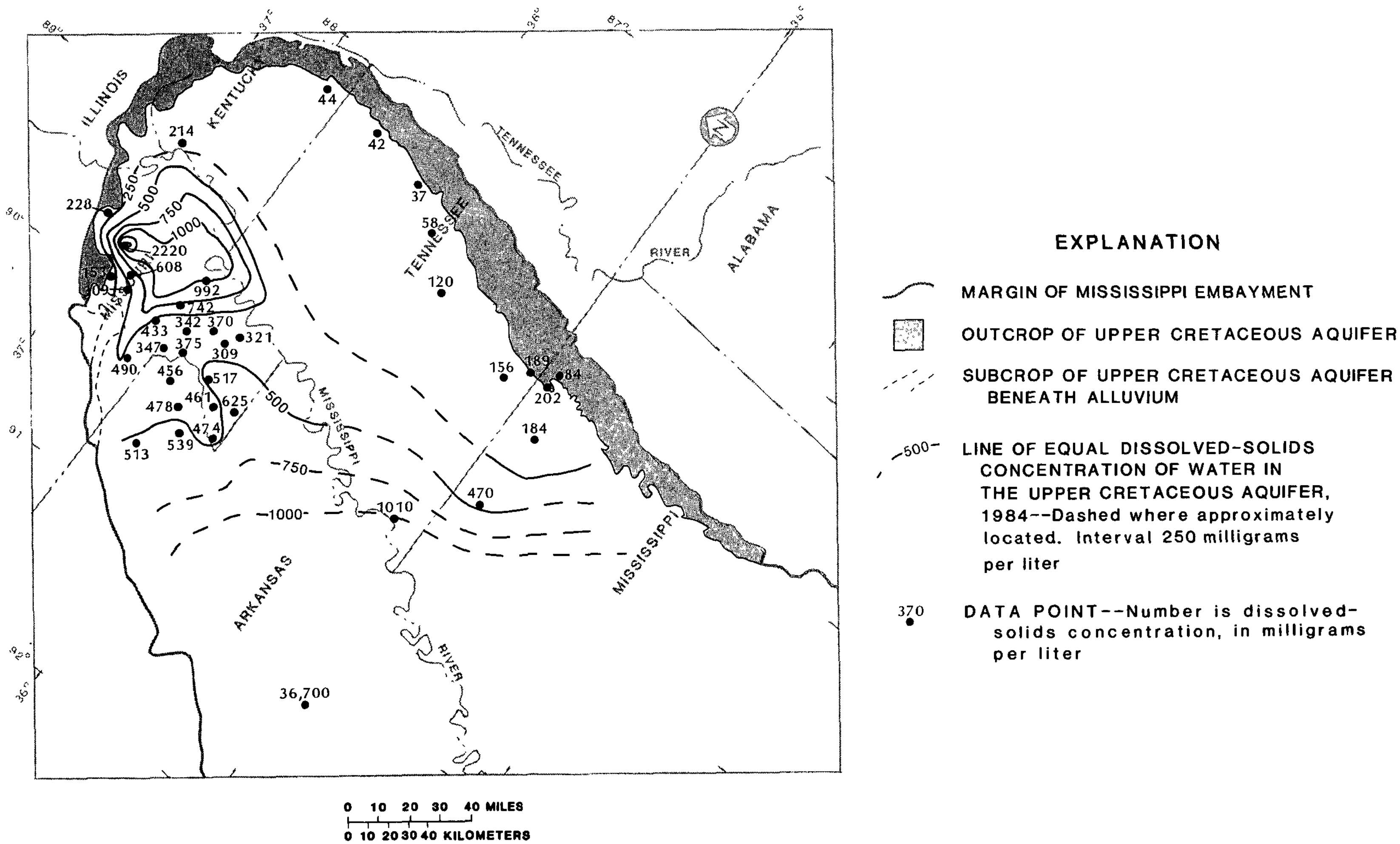


Figure 14.--Areal distribution of dissolved-solids concentrations in water from the Upper Cretaceous aquifer.

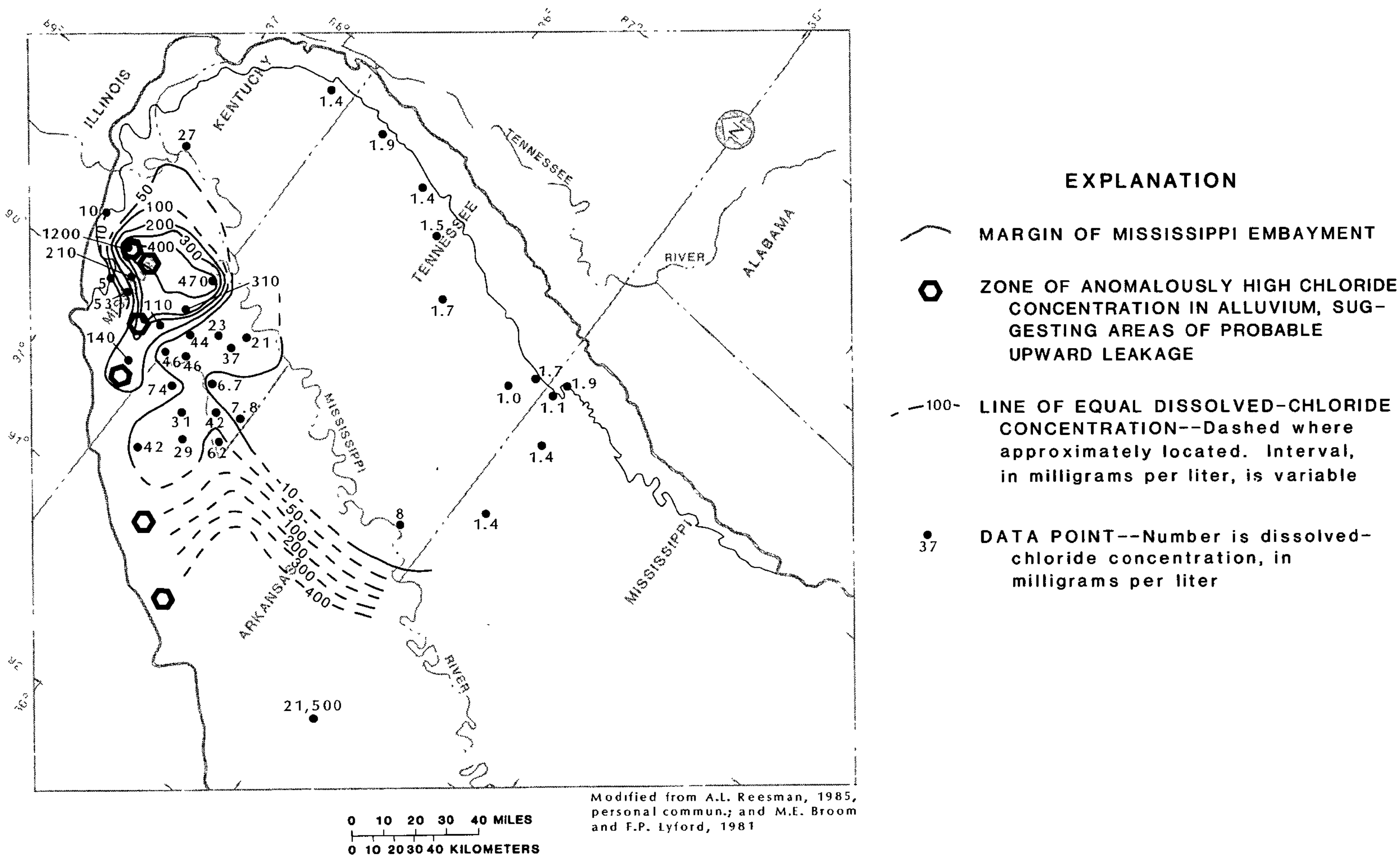


Figure 15.--Areal distribution of dissolved-chloride concentrations in the Upper Cretaceous aquifer, including areas of probable upward leakage into the alluvium.

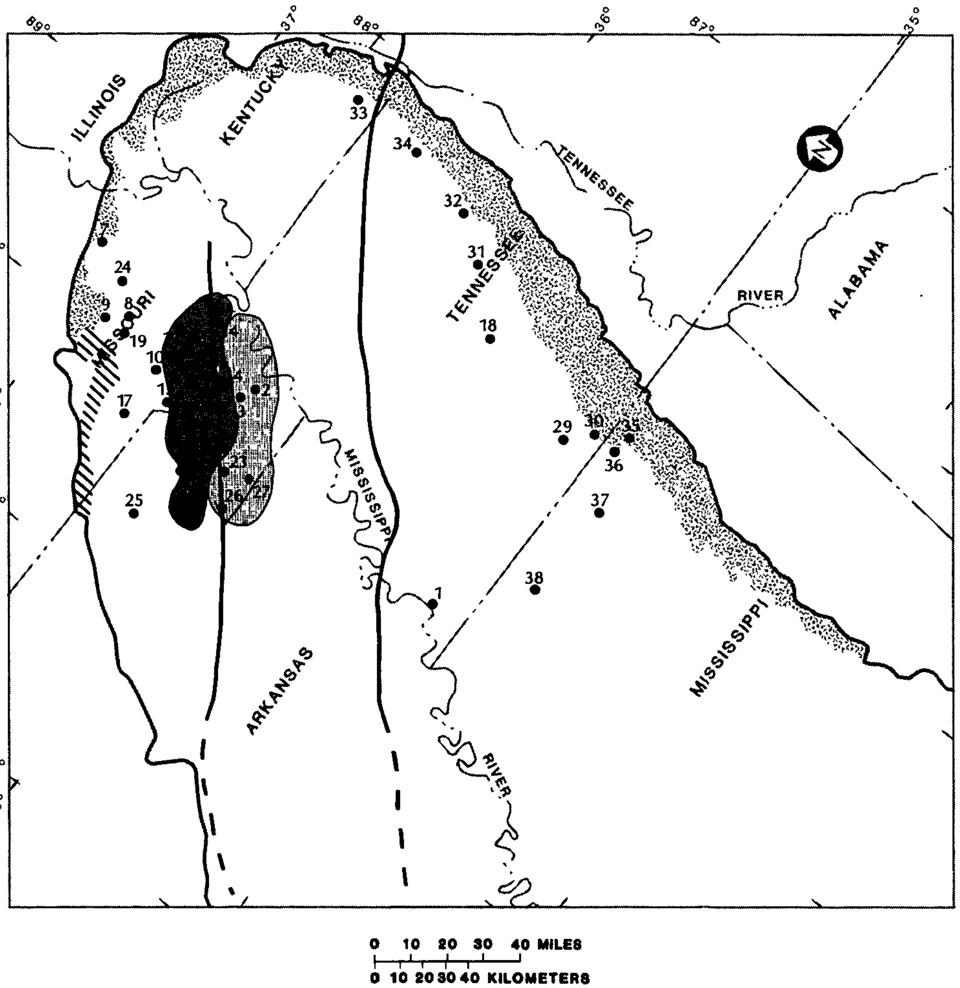
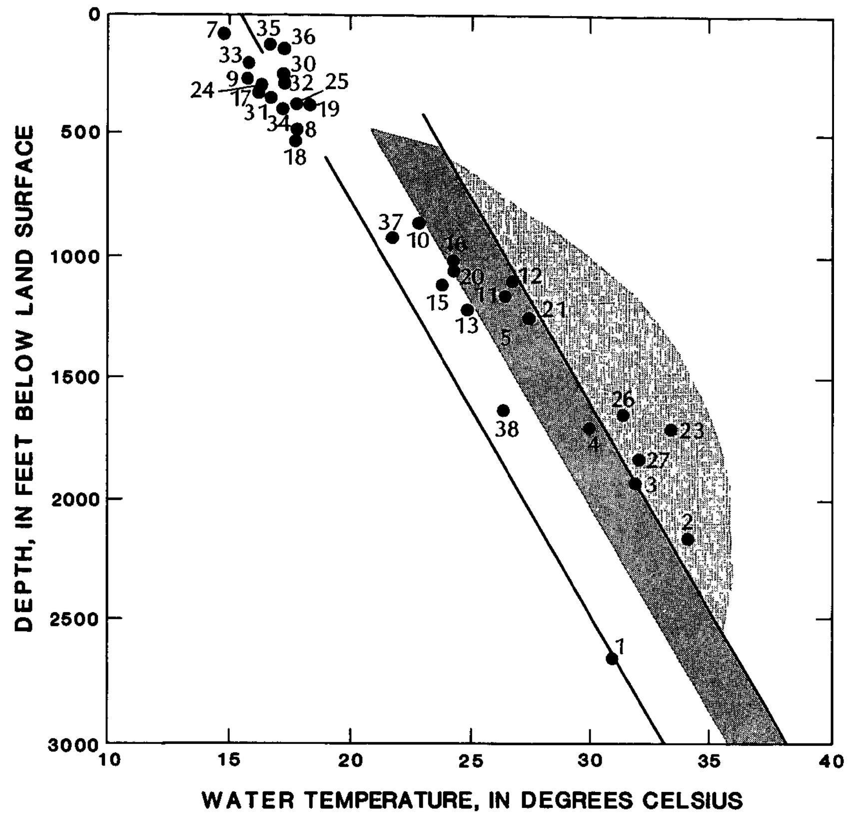


Figure 16.--Location of wells where ground-water temperature data were collected from the Upper Cretaceous aquifer, and the relation of water temperature to well depth.



EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

OUTCROP

SUBCROP

ANOMALOUSLY WARM WATER, IN DEGREES CELSIUS ABOVE GEOTHERMAL GRADIENT

2.5 to 5.0

Greater than 5.0 (hydrothermal)

GENERALIZED GEOTHERMAL GRADIENT FOR WATER IN THE UPPER CRETACEOUS AQUIFER IN THE NORTHERN MISSISSIPPI EMBAYMENT--Based on bottomhole temperature from geophysical log of well 1

BOUNDARY OF MISSISSIPPI EMBAYMENT RIFT--Location inferred from magnetic and gravity data. Dashed where approximately located

10 DATA POINT--Number is site identification

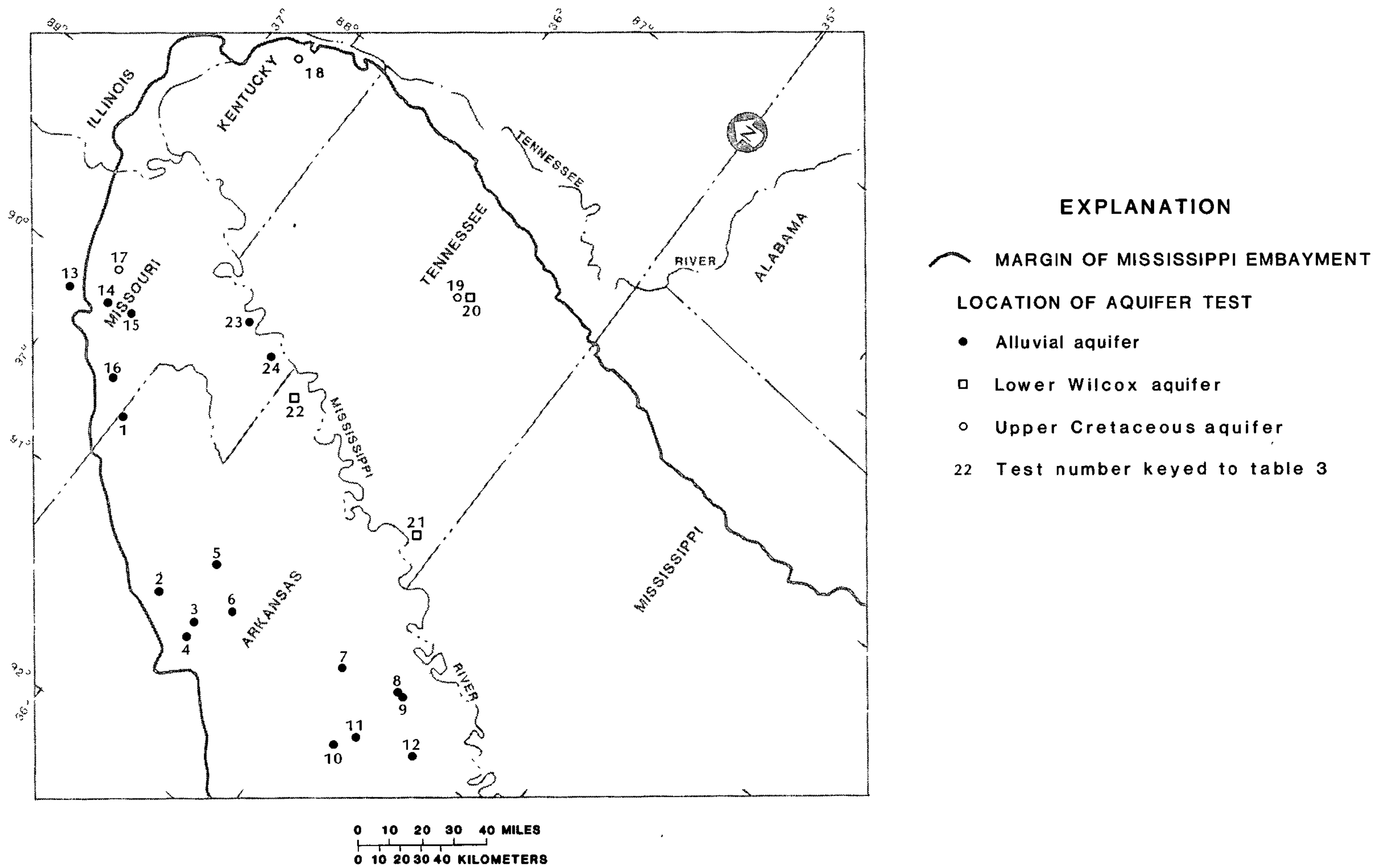


Figure 17.--Location of selected aquifer tests.

Table 3.--*Results of aquifer tests selected to show representative values*

[ft^2/d, foot squared per day; ft/d, foot per day; c, hydraulic conductivity calculated for this report; not given in original reference]

Test No. (fig. 17)	County/State	Well number	Date	Trans-missivity (T) (ft^2/d)	Hydraulic conduc-tivity (K) (ft/d)	Storage coeffi-cient (S)	Water-bearing unit	Reference
1	Clay Co., Ark.	21N05E02CCC	2/25/71	30,000	360	1.1×10^{-3}	Alluvium	Broom and Lyford (1981)
2	Jackson Co., Ark.	14N02W23BBB	2/12/70	39,000	320	2.2×10^{-2}	Alluvium	Albin and others (1967)
3	Jackson Co., Ark.	12N02W28DDC	12/ 7/64	10,000	100	7×10^{-3}	Alluvium	Broom and Lyford (1981)
4	Jackson Co., Ark.	11N03W11ABD	5/27/61	8,500	--	--	Alluvium	Broom and Lyford (1981)
5	Craighead Co., Ark.	13N02E35DAD	1/25/71	37,000	380	2.2×10^{-2}	Alluvium	Broom and Lyford (1981)
6	Poinsett Co., Ark.	10N01E06CBB	6/19/71	48,000	390	1×10^{-3}	Alluvium	Broom and Lyford (1981)
7	St. Francis Co., Ark.	04N02E03DDD	4/10/61	43,000	330	4×10^{-2}	Alluvium	Halberg and Reed (1964)
8	Lee Co., Ark.	02N03E35CCA	5/19/50	19,000	--	--	Alluvium	Broom and Lyford (1981)
9	Lee Co., Ark.	01N03E02BBC	11/18/69	13,000	130	7.3×10^{-4}	Alluvium	Broom and Lyford (1981)
10	Monroe Co., Ark.	02N02W01DDA	4/11/69	24,000	--	--	Alluvium	Broom and Lyford (1981)
11	Monroe Co., Ark.	02N01W28DDD	10/ 4/67	32,000	290	4×10^{-4}	Alluvium	Broom and Lyford (1981)
12	Phillips Co., Ark.	02S01E28CCB	2/23/72	34,000	247	1×10^{-4}	Alluvium	Broom and Lyford (1981)
13	Wayne Co., Mo.	28N08E36BCD1	9/15/77	47,000	--	9×10^{-4}	Alluvium	Luckey (1985)
14	Stoddard Co., Mo.	26N09E33ACC1	6/21/77	15,000	--	2×10^{-3}	Alluvium	Luckey (1985)
15	Stoddard Co.. Mo	24N09E11ACB1	7/16/76	20,000	--	1×10^{-3}	Alluvium	Luckey (1985)
16	Butler Co., Mo	23N06E22ABB1	6/ 9/76	50,000	--	1×10^{-3}	Alluvium	Luckey (1985)
17	Stoddard Co., Mo.	23N06E22ABB1	6/17/85	1,800	35^c	7×10^{-3}	McNairy	Unpublished USGS, Missouri District (1985)
18	Marshall Co., Ky.			4,300	45^c	1×10^{-4}	McNairy	Davis and others (1973)
19	Madison Co., Tenn.			3,300	16^c	8×10^{-4}	McNairy	Boswell and others (1965)
20	Madison Co., Tenn.			10,000	52^c	1.5×10^{-3}	Lower Wilcox	Hosman and others (1968)
21	Shelby Co., Tenn.			13,000	70^c	2×10^{-3}	Lower Wilcox	Hosman and others (1968)
22	Mississippi Co., Ark.			21,000	110^c	2×10^{-3}	Lower Wilcox	Hosman and others (1968)
23	Pemiscot Co., Mo.	20N13E02DAA1	8/23-24/77	32,000	--	1×10^{-4}	Alluvium	Unpublished USGS, Missouri District (1977)
24	Pemiscot Co., Mo.	19N12E18ACA1	6/22/77	50,000	--	2×10^{-3}	Alluvium	Unpublished USGS, Missouri District (1977)

the study area. Typical hydraulic conductivity values for clays reported in the literature range from 10^{-3} to 10^{-6} ft/d (Freeze and Cherry, 1979). The hydraulic conductivity for the Midway confining layer was assumed to be 10^{-6} ft/d, based on drilling records of the Midway that indicate it is a tight, low permeable unit throughout the northern embayment. Typical hydraulic conductivity values for limestone and dolomite range from 10^{4} to 10^{-4} ft/d, and for shale range from 10^{-3} to 10^{-7} ft/d. The hydraulic conductivity for the Cretaceous-Paleozoic confining bed was assumed to be 10^{-4} ft/d where the dominant lithology was limestone or dolomite, and 10^{-5} ft/d where the dominant lithology was shale.

STRESSES

Pumpage from each aquifer has been defined for the entire Gulf Coast RASA Regional Project area (D.J. Ackerman, personal commun., 1986). Individual wells that pump more than 10,000 gal/d for municipal, public supply, or industrial users have been identified. Pumpage from these wells represents about 75 percent of the total for the area (table 4). The remaining 25 percent of the pumpage is from rural, domestic, stock, irrigation, and other wells generally not identified in existing water-use studies. Pumpage, where not otherwise available, was estimated from population and per capita use data. Individual pumping sites reported by aquifer are shown in figure 18.

MODELING THE GROUND-WATER FLOW SYSTEM

The physical system, described in the previous section of ground-water hydrology, is the basis for a ground-water flow model. A model that simulates actual aquifer behavior provides a powerful tool with which to test understanding about the flow system. Although simplified from the physical system, a model should be consistent with all known hydrogeologic observations.

CONCEPTUALIZATION OF THE SYSTEM

Most of the flow in the Ozark-St. Francois aquifer occurs in the Salem Plateau, the area where the Lower Ordovician rocks that comprise the upper part of this aquifer outcrop (figs. 2 and 19). Precipitation directly recharges the aquifer in this area, and flow is transmitted through well-developed zones of secondary permeability to major springs and streams (Beckman and Hinchey, 1944; Harvey, 1980). Major springs in the outcrop area have components of both local and regional flow, suggesting that deeper flow paths are an important, dynamic part of the flow system (Feder, 1973). Deep flow is also consistent with the observation that in the Salem Plateau the aquifer contains freshwater throughout its entire thickness. Flow within or from the Ozark-St. Francois is believed to be more restricted in the embayment because the overlying sediments have low permeability and restrict vertical movement of water into or out of the aquifer.

Although most of the water in the Ozark-St. Francois aquifer is discharged to springs and streams in the outcrop area, a small amount is believed to flow southeast beneath the western margin of the embayment to discharge into overlying aquifers (fig. 19). The discharge occurs commonly along faults (Stearns and Zurawski, 1976; Schwalb, 1982; Stauder, 1982; Crone and others, 1985), and zones where the Midway confining layer has been removed or thinned by erosion (fig. 20) (Schwalb, 1982). Areas where relatively high dissolved-solids concentrations occur in water from the Upper Cretaceous aquifer and the alluvium are believed to coincide with discharge from the

Table 4.--*Water use from the Ozark-St. Francois and Upper Cretaceous aquifers for 1980, by state*

[All units are in thousand gallons per day]

State	Ozark-St. Francois aquifer		Upper Cretaceous aquifer		Total reported and simulated
	Rural domestic	Public supply and industrial	Rural domestic	Public supply and industrial	
Arkansas	300*	800*	600	900	2,600
Missouri	500*	1,600	500*	4,200	6,800
Illinois	0	0	0	0	0
Kentucky	0	0	1,100*	3,400	4.500
Tennessee	0	0	2,000*	6,800	8,800
Mississippi	0	0	500	500	1,000
Total	800	2,400	4,700	15,800	23,700

*Estimated.
All other values are reported (D.J. Ackerman, U.S. Geological Survey, written commun., 1986)

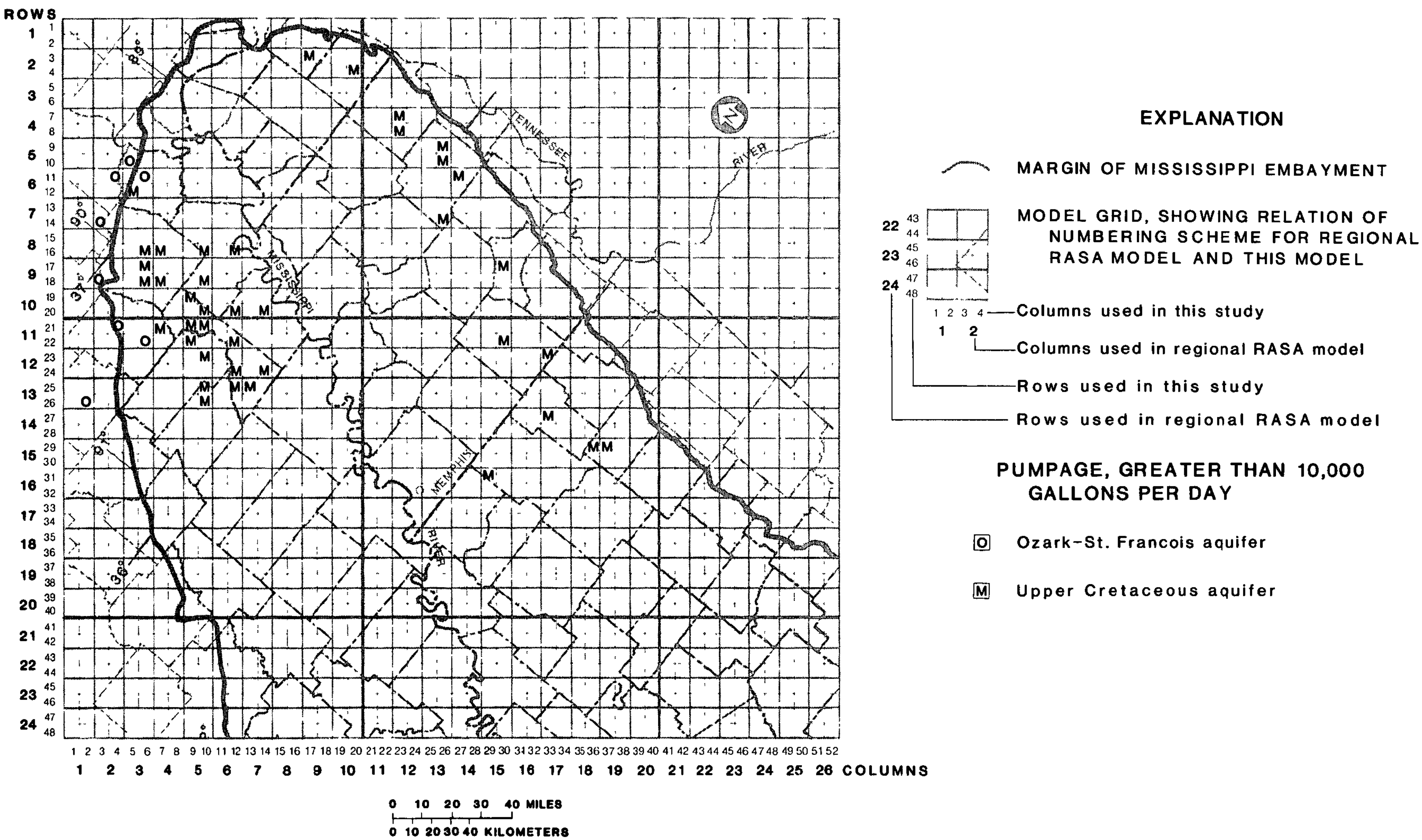


Figure 18.--Distribution of ground-water withdrawals exceeding 10,000 gallons per day from GC RASA model grid blocks for the Upper Cretaceous aquifer and the Ozark-St. Francois aquifer in the study area for 1980.

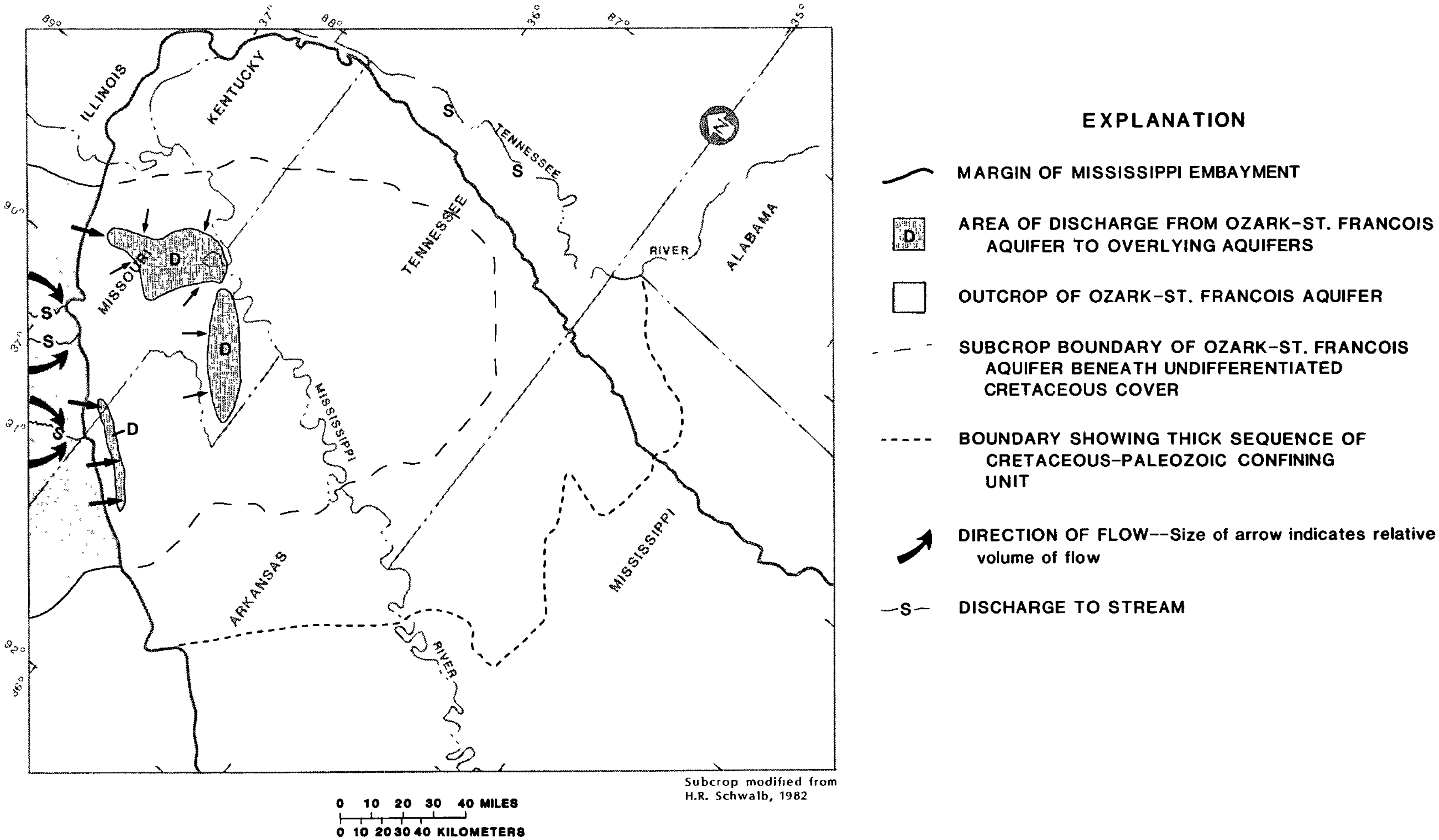
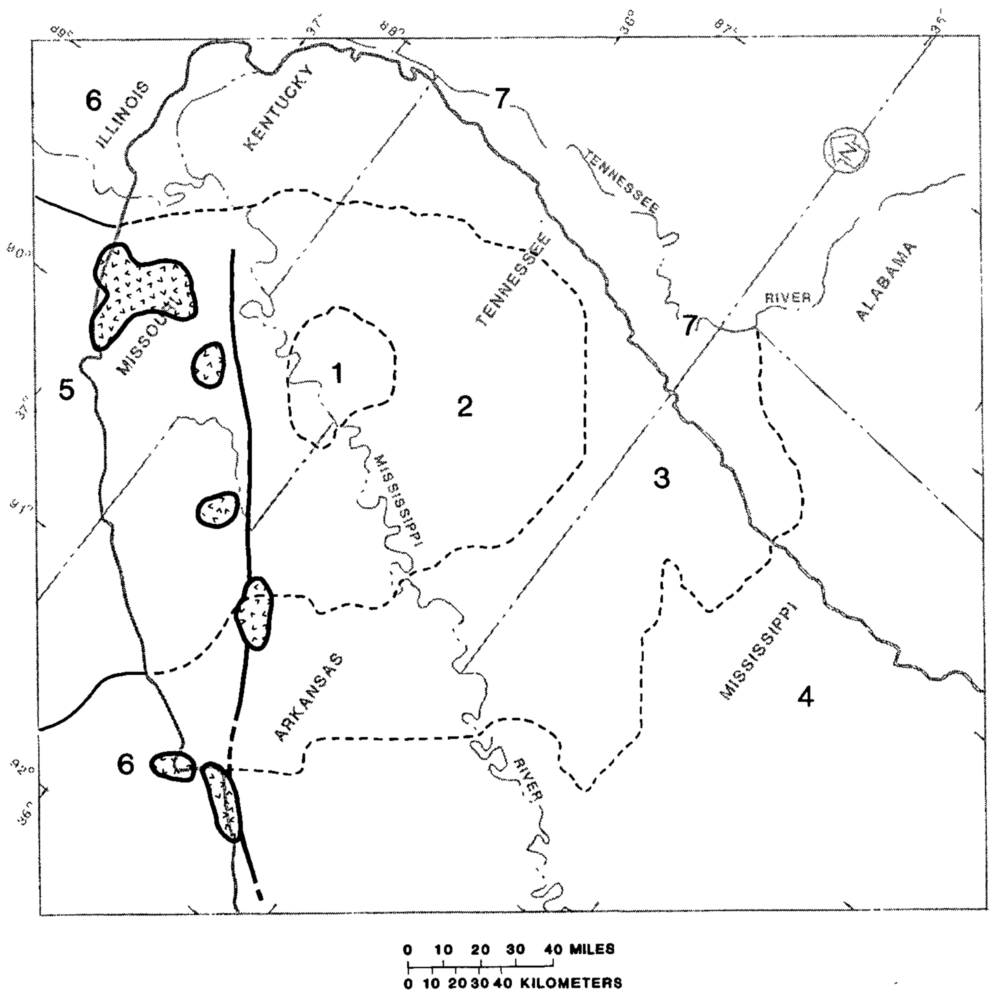


Figure 19.--Conceptual model of the major hydrogeologic features of the Ozark-St. Francois aquifer.



EXPLANATION

- MARGIN OF MISSISSIPPI EMBAYMENT
- LARGE IGNEOUS INTRUSIVE MASS (PLUTON) IN PALEOZOIC ROCKS BURIED BENEATH SEDIMENT. Identification is based primarily on magnetic and gravity data
- WESTERN BOUNDARY OF MISSISSIPPI EMBAYMENT RIFT-- Location inferred from magnetic and gravity data, Dashed where approximately located
- GEOLOGIC BOUNDARY-- Dashed where approximately located

1. OZARK-ST. FRANCOIS ERODED, FAULTING ON SOUTHERN BOUNDARY PASCOLA ARCH-- Probable moderate leakage
2. OZARK-ST. FRANCOIS DIRECTLY OVERLAIN BY CRETACEOUS SEDIMENTS -- Probable high leakage in this zone west of Mississippi River
3. THICK PALEOZOIC SECTION -- Low Leakage
4. THICK SEQUENCE OF CRETACEOUS AND PALEOZOIC ROCKS SEPARATE THE AQUIFERS -- Leakage probably very low
5. **OUTCROP OF OZARK-ST. FRANCOIS AQUIFER-- High leakage**
6. OUTCROP OF THICK PALEOZOIC SECTION -- Low leakage
7. LEAKAGE SUSPECTED -- Associated with hypothesized faulting

Figure 20.-- Conceptual model of the major hydrogeologic features of the Cretaceous-Paleozoic confining unit.

underlying, more mineralized Ozark-St. Francois aquifer. With the exception of a zone of flow between the outcrop area and the discharge areas within the western part of the embayment, flow in the Ozark-St. Francois aquifer is believed to be small.

Water-quality and water-level data from wells in the upper few hundred feet of the Ozark-St. Francois aquifer in central Tennessee indicate that flow from the aquifer east of the study area is discharged to the Tennessee River. The Ozark-St. Francois aquifer is within several hundred feet of land surface east of the Tennessee River and receives significant recharge by downward leakage (Brahana and Bradley, 1985). A freshwater zone occurs in the upper part of the aquifer in that area. West of the Tennessee River, dissolved-solids concentrations, ranging from 4,000 to 5,000 mg/L in water from the few wells sampled, indicate little freshwater recharge or circulation. The Tennessee River in western Tennessee is thought to be a regional discharge area and thus serves as a constant-head boundary.

Toward the south, the Ozark-St. Francois aquifer deepens rapidly and is overlain by a thickening wedge of undifferentiated Paleozoic and Cretaceous rocks (fig. 5). The southern part of the Ozark-St. Francois aquifer is probably a zone of very restricted ground-water flow. This assumption is based on the depth of the top of the aquifer, the thickness of the overlying confining layer, and the salinity of water in the aquifer. No head data exist from this part of the aquifer.

The undifferentiated Cretaceous-Paleozoic confining unit thins from the margins of the study area toward the center of the northern part of the embayment (fig. 20). Consequently, the potential for leakage through the confining unit is less near the southern and northern boundaries and is higher in the center of the study area. Leakage potential through the confining unit may also be relatively higher near the western margin of the rift and the Pascola arch-Bloomfield pluton (fig. 20).

Deep regional freshwater flow in the Upper Cretaceous aquifer occurs north of a line from the eastern boundary of the embayment near latitude 34° N. to the western boundary of the embayment at latitude 36° N. (fig. 21). Flow is from topographically high recharge areas at the northern and eastern margins of the embayment to topographically low discharge areas where Cretaceous sediments subcrop beneath the alluvium (fig. 2). Water level in the alluvium is thought to control aquifer discharge or recharge at the subcrop.

In addition to recharge at the outcrop, the Upper Cretaceous aquifer is thought to be recharged in two distinct areas in southeastern Missouri by upward leakage from the Ozark-St. Francois aquifer. An area of recharge overlying the Pascola arch (figs. 6, 20, and 21), has been delineated by differences in water-quality parameters. These differences include variations in water type, and in dissolved-solids, chloride, and trace-constituent concentrations (Brahana and others, 1985). Based on carbon isotope (^{14}C) data, water in the Upper Cretaceous aquifer in the area of the Pascola arch-Bloomfield pluton is younger than water elsewhere in the confined part of the aquifer (Brahana and others, 1985).

The second area of recharge is slightly east of the western margin of the rift and is defined by the zone of hydrothermal water in the Upper Cretaceous aquifer (fig. 16). Recharge to the Upper Cretaceous aquifer east of the rift area is less mineralized than in the area of the Pascola arch, more hydrothermal, and is relatively older based on ^{14}C isotope age interpretations (Brahana and others, 1985).

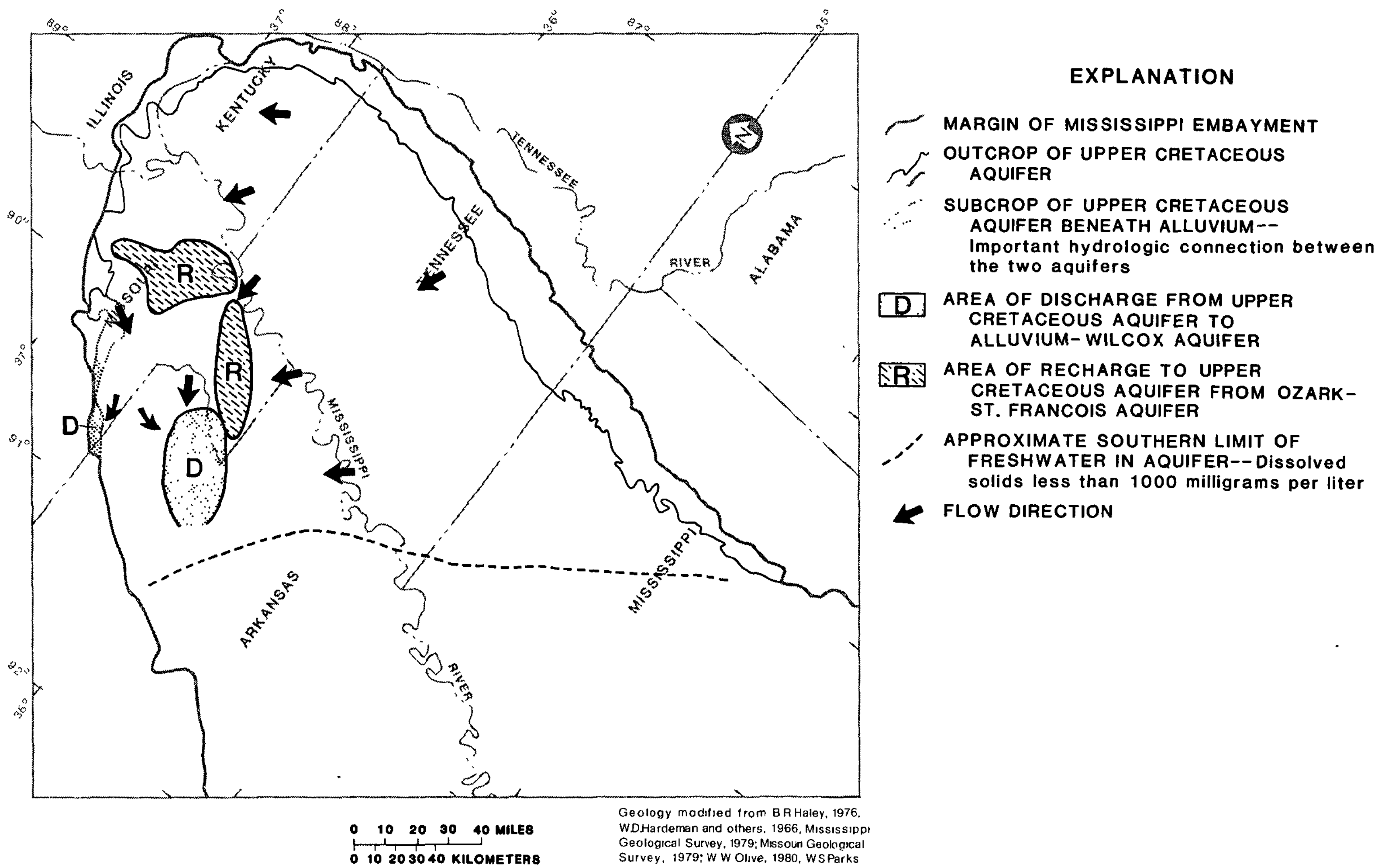
Unpublished radium isotope ratio data indicate that much of the Upper Cretaceous aquifer in southeastern Missouri is receiving recharge from the deep Ozark-St. Francois aquifer (Tom Kraemer, written commun., 1986).

Regional flow south of the line delineating freshwater in the Upper Cretaceous aquifer is assumed to be small (fig. 21). This assumption is based on (1) the higher dissolved-solids concentrations of the water toward the south, and (2) the decreasing permeability, caused by increasing amounts of clay, marl, and chalk in the Upper Cretaceous aquifer toward the south (Boswell and others, 1965).

Water levels in the Upper Cretaceous and the lower Wilcox aquifers (separated by the Midway confining unit), indicate an upward gradient from the Upper Cretaceous aquifer to the lower Wilcox aquifer for most of the area (figs. 10 and 11). Head differences of as much as 100 feet have been documented at Memphis (Graham and Parks, 1985).

A linear zone above the western margin of the rift (fig. 22) coincides with a low in the potentiometric surface of the Upper Cretaceous aquifer (fig. 10). This zone is an hypothesized area of higher leakance, possibly related to faulting overlying the rift. The occurrence of a hydrothermal anomaly in the lower Wilcox aquifer is also consistent with the hypothesis of greater upward leakage near the rift. Dissolved chloride and dissolved-solids concentrations, however, suggest that leakage across the Midway confining unit is minor in the vicinity of the rift.

Regional flow in the lower Wilcox is from the outcrop areas in the east and from the subcrop area in the north (fig. 23). Flow is confined throughout the area shown, except in the outcrop. Discharge from the aquifer occurs at three major pumping centers, along parts of the subcrop in



Geology modified from B R Haley, 1976, W.D.Hardeman and others, 1966, Mississippi Geological Survey, 1979; Missouri Geological Survey, 1979; W W Olive, 1980, W S Parks and E E Russell, 1975, and H B Willman and others, 1967

Figure 21.--Conceptual model of the major hydrogeologic features of the Upper Cretaceous aquifer.

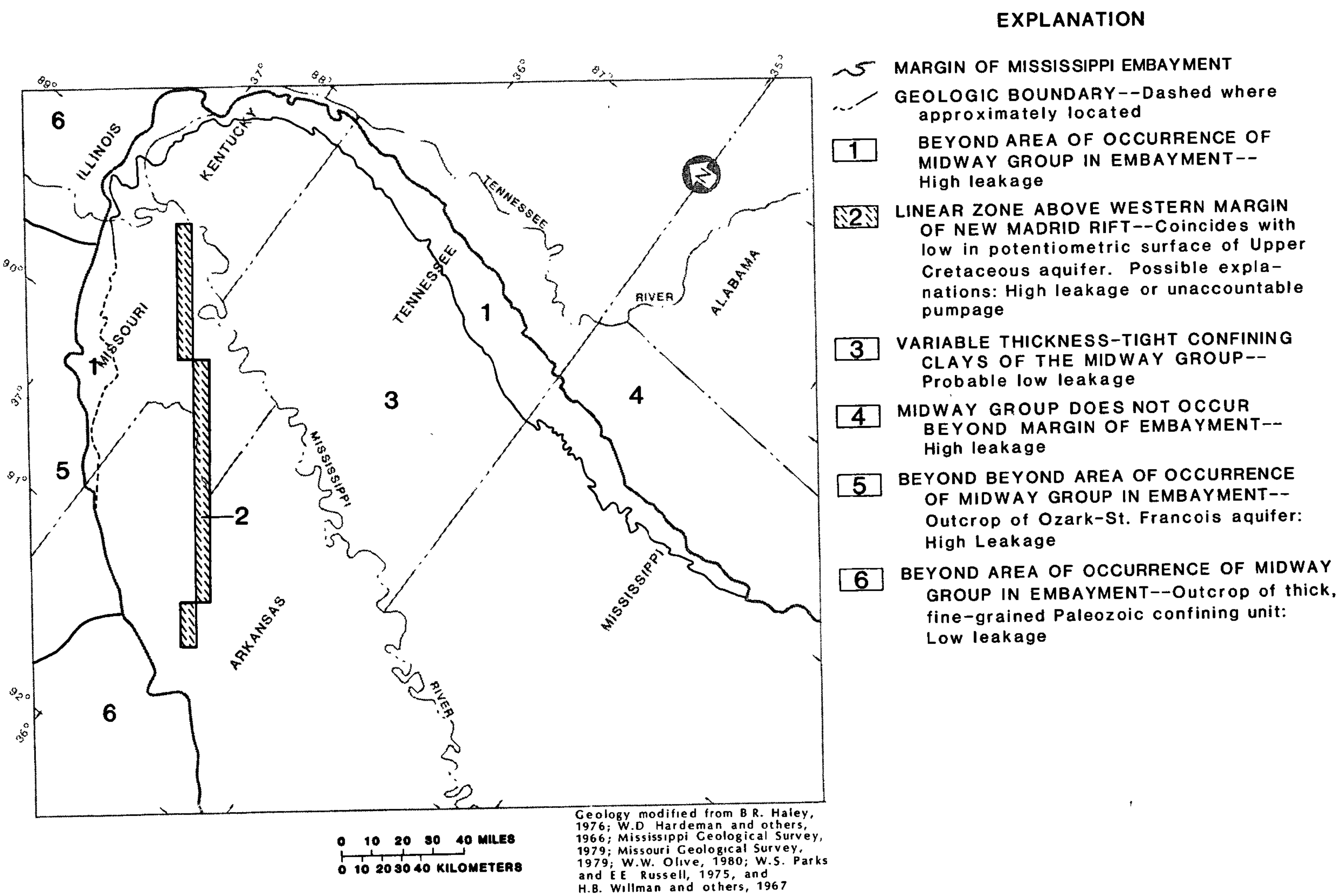
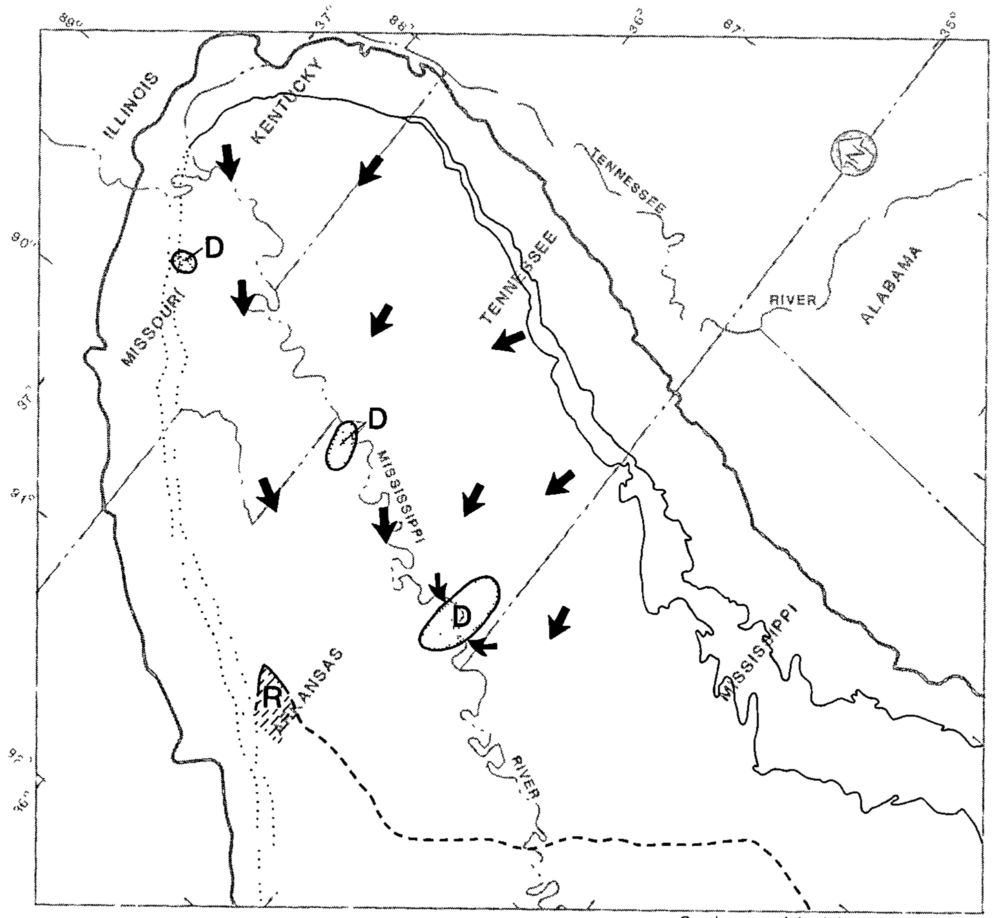


Figure 22.--Conceptual model of the major hydrogeologic features of the Midway confining unit.



EXPLANATION

- MARGIN OF MISSISSIPPI EMBAYMENT
- OUTCROP OF LOWER WILCOX AQUIFER
- SUBCROP OF LOWER WILCOX AQUIFER BENEATH ALLUVIUM--Important hydrologic connection between the two aquifers
- D — AREA OF DISCHARGE FROM LOWER WILCOX--Including pumping and possible upward leakage
- R — AREA OF RECHARGE TO LOWER WILCOX FROM DEEPER AQUIFERS--(Based on geometry of distribution of sodium chloride type water in aquifer- modified from M.S. Hines and others, 1968)
- APPROXIMATE SOUTHERN LIMIT OF FRESHWATER IN AQUIFER--North of this limit, dissolved solids are generally less than 1000 milligrams per liter. (Modified from M.S. Hines and others, 1972; R.L. Hosman and others, 1968; and E.H. Boswell, 1975)
- FLOW DIRECTION

Geology modified from B.R. Haley, 1976; W.D. Hardeman and others, 1966; Mississippi Geological Survey, 1979, Missouri Geological Survey, 1979, W.W. Olive, 1980, W.S. Parks and E.E Russell, 1975; and H.B. Willman and others, 1967

Figure 23.--Conceptual model of the major hydrogeologic features of the lower Wilcox aquifer.

Missouri and Arkansas, and upward to shallower aquifers beneath the alluvial plain of the Mississippi River. The occurrence of a sodium chloride type water in east central Arkansas at about latitude 36° N. and longitude 91° W. (Hines and others, 1972) suggests vertical upward leakage of salty water from deeper aquifers, including the Upper Cretaceous and the Ozark-St. Francois aquifers. Faults in the Midway confining unit near the western margin of the rift or deep wells drilled through the Midway and later abandoned are two possible explanations of the upward leakage. To the south in Mississippi, the approximate southern limit of freshwater in the aquifer is thought to represent an abrupt change in flow conditions. South and west of this freshwater limit, flow is very sluggish, because of restricted discharge upward through a thick sequence of confining clays. North and east of this boundary, the existence of freshwater documents that a deep regional dynamic flow system is active.

Flow within the alluvial aquifer is generally from north to south and locally from ground-water highs toward streams that drain the area (fig. 24) (Broom and Lyford, 1981; Luckey, 1985). In the southwestern part of the area, flow in the aquifer is toward the southeast. Throughout most of the area, water levels in the alluvium have remained relatively stable. An exception is the area west of Crowleys Ridge (fig. 2), where declines in alluvial water levels have been observed for more than 30 years (figs. 13 and 24) (Broom and Lyford, 1981).

Upward leakage from deeper aquifers is suspected of causing anomalously high chloride concentrations in water from the alluvium (fig. 15), but is thought to represent a small percentage of the total flux in the alluvium. An evaluation of a water budget of the alluvium indicates that surface-water and shallow ground-water contributions are probably several orders of magnitude greater than water contributed by confined aquifers (Luckey, 1985).

MODEL ATTRIBUTES

The ground-water flow model used in this study was developed by McDonald and Harbaugh (1984) and has the following attributes:

- flow in a sequence of layered aquifers separated by confining units can be simulated
- simulation of hydrologic features by several alternative methods is facilitated because of the modular design of the model
- documentation and testing of the model in hydrogeologic settings similiar to the study area has been conducted.

In this model, the differential equations of ground-water flow are simulated by an iterative numerical technique known as the strongly implicit procedure using the development and notation of Weinstein and others (1969). The theory and use of the model is documented thoroughly by McDonald and Harbaugh (1984), and no additional description of the general aspects of their work is included here.

A four layer model (three aquifers and one source bed) was constructed to represent the regional flow system in the Upper Cretaceous aquifer and adjacent hydrogeologic units. The relation between geologic units of the natural system, hydrogeologic units of the conceptual model, and equivalent units in the ground-water flow model is shown in figure 25.

Layer 1, the top layer of the model, represents a hydrologic boundary in the form of a source-sink term that allows movement and evaluation of recharge or discharge across the upper surface of the active model. Layers 2, 3, and 4 are simulated with a matrix that represents the hydraulic properties of the geologic units modeled.

Aquifer layers of the model are separated by matrices called confining units in this report. Geologically, the confining units are not present at all locations throughout the area of the model; they are absent in the western part of the model area, where the Ozark-St. Francois aquifer outcrops, and where the Ozark-St. Francois and Upper Cretaceous aquifers subcrop beneath the alluvium. Nodes in the model representing areas where the confining units are absent are modeled as high leakance, with aquifer directly overlying aquifer. The quantitative value used for these high leakance nodes is approximated as an average vertical hydraulic conductivity of the aquifers divided by an average distance between the centers of the aquifers.

At locations where the confining units exist, the conductance between aquifer layers represents the leakance of the confining units. The leakance matrix for the Midway confining unit (confining unit B) was determined by dividing an areally uniform vertical hydraulic conductivity for the layer by the average thickness of the unit within each grid block (a 25 mi^2 area). The leakance matrices for the upper confining unit (confining unit A) and the Cretaceous-Paleozoic confining unit (confining unit C) were determined by separating the confining units into zones based on hydrogeologic characteristics to be discussed later. Each zone was assigned a specific leakance. Horizontal flow in confining units is not calculated.

Because of the complex relation of geologic boundaries to model boundaries and because of fluxes near potential discharge areas in the western part of the study

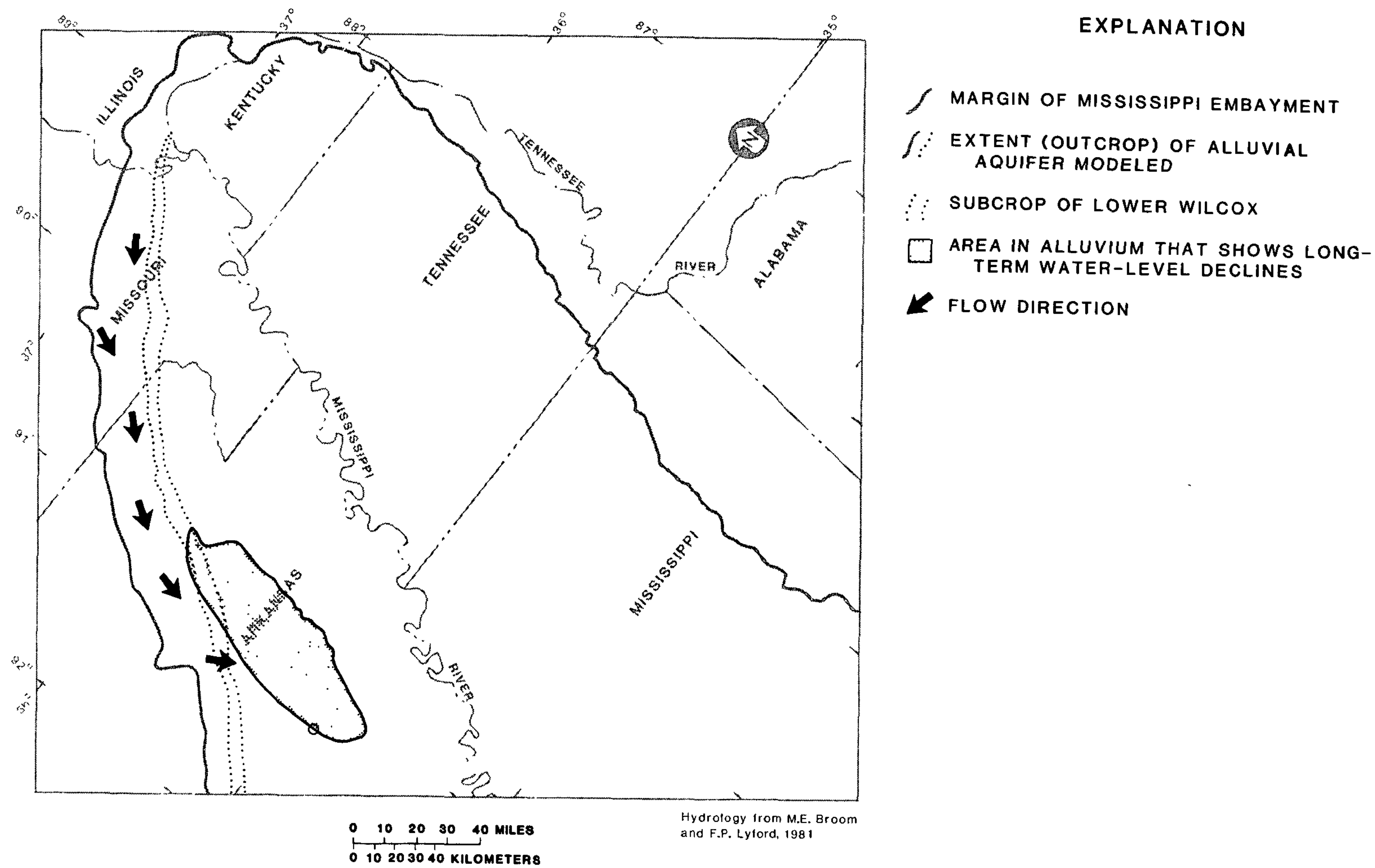


Figure 24.--Conceptual model of the major hydrogeologic features of the alluvial aquifer west of the subcrop of the lower Wilcox aquifer.

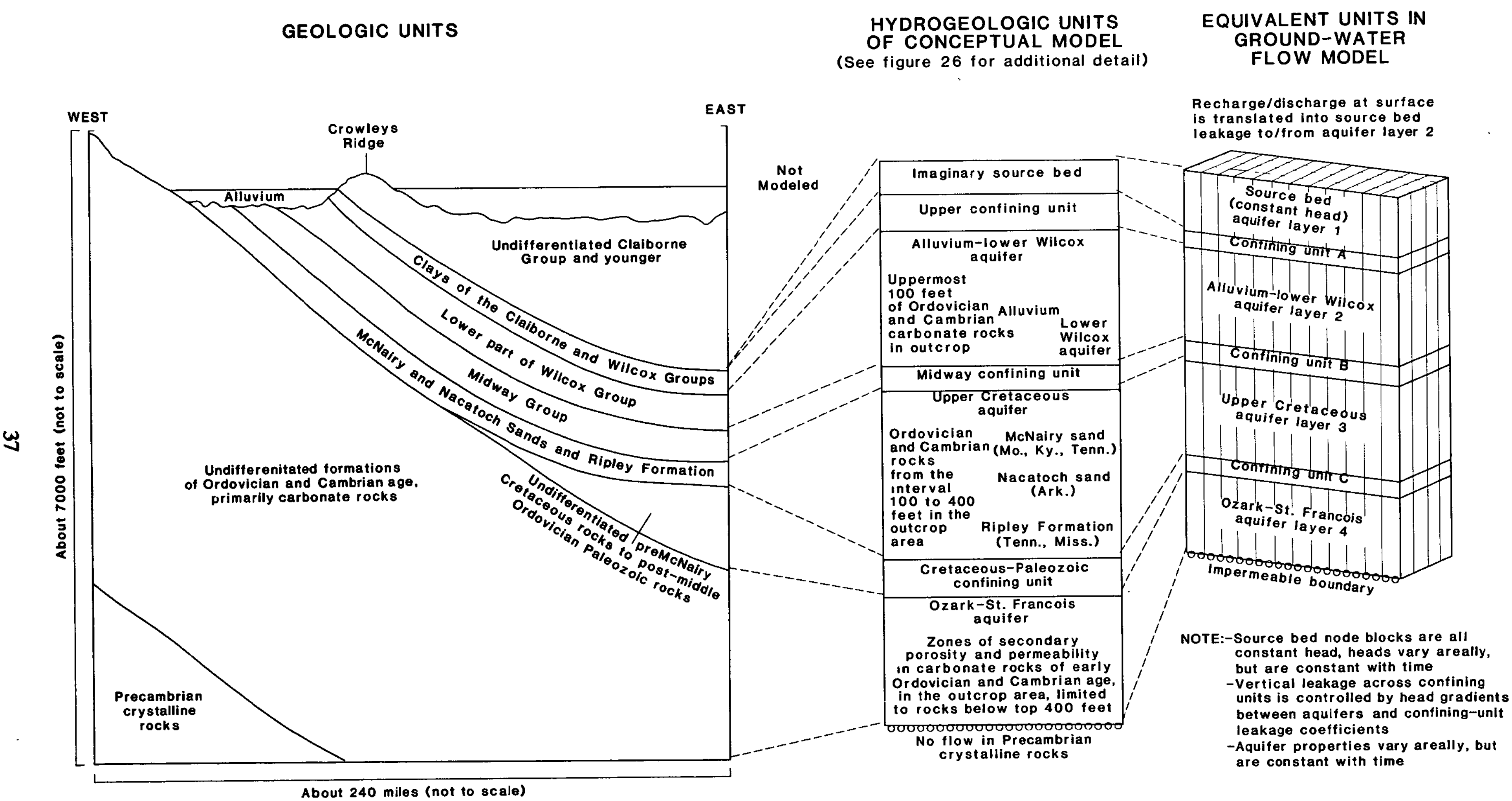


Figure 25.--Geologic units of the natural system, hydrogeologic units of the conceptual model, and equivalent model units in the ground-water flow model.

area, a more detailed section view is given in figure 26. In addition to showing the horizontal and vertical boundaries across which flux is evaluated, the section view shows the multi-unit geologic makeup of model layers 2 and 3. Layer 2 consists of the top 100 feet of the Cambrian and Ordovician carbonate rocks in the Salem Plateau, the alluvium west of the subcrop of the lower Wilcox aquifer, and the lower Wilcox aquifer. Layer 3 consists of the Upper Cretaceous aquifer and of Cambrian and Ordovician carbonate rocks that occur from 100 to 400 feet below land surface in the Salem Plateau area.

Aquifer layer 4 represents most of the Cambrian and Ordovician carbonate rock section (table 1; figs. 25 and 26). Aquifer layer 4 includes the St. Francois aquifer, the St. Francois confining layer, and the Ozark aquifer, except for the top 400 feet which is included in layers 3 and 2 (Imes, 1988b, 1988c). The two aquifers and one confining unit have been combined into one model layer, because under the Mississippi embayment these rocks are thought to function as a single aquifer (J.L. Imes, written commun., 1985).

MODEL REQUIREMENTS

The digital model requires that the studied area be divided into discrete subareas (blocks), and that a finite-difference approximation of the continuous differential equation be solved for each block for specified boundary conditions, aquifer hydraulic properties, and pumping stresses. An orthogonal grid defines the discretization and arrangement of blocks in the model.

Finite-Difference Grid

A 48 row by 52 column grid was used to divide the study area (fig. 18). Grid spacing is equidemensional, resulting in blocks 5 miles on a side. The grid is coincident with the regional Gulf Coast RASA grid, and with all Gulf Coast RASA subproject grids. This coincidence facilitates interchange of fluxes and heads at common boundaries between the various models. Because the blocks in the regional RASA grid spacing are 10 miles on each side, each regional grid block corresponds to four model grid blocks in the Upper Cretaceous model (fig. 18).

Alignment of the regional grid, which was oriented to minimize the number of inactive nodes, originally dictated the alignment of the model grid of the Upper Cretaceous aquifer. Transmissivity was not used to determine grid alignment, because on a regional scale there was no evidence of anisotropic transmissivity (Hayes Grubb, U.S. Geological Survey, oral commun., 1986). An evaluation of an aquifer test of the Eocene Memphis Sand of the Claiborne Group at Memphis using tensor analysis (Randolph and others, 1985) was conducted after the grid was aligned. This evaluation indicated a slight anisotropy (2.3 to 1) with principal axes oriented within 10° of the grid of the Upper Cretaceous aquifer model (Morris Maslia, U.S. Geological Survey, written commun., 1985).

Boundary Conditions and Discretized Hydrogeology

The lowest boundary of the model (base of aquifer layer 4) consists of impermeable Precambrian crystalline rocks (fig. 25) and is simulated as a no-flow boundary throughout the study area. The northwestern boundary of aquifer layer 4 was initially modeled using a constant-head source to simulate recharge from the outcrop areas near the St. Francois Mountains. Water levels in the westernmost blocks where the Paleozoic rocks outcrop were set at constant values to simulate pre-development (prior to any pumping) of the aquifer layer (fig. 27). This boundary representation was later modified to allow input of specified recharge provided by calculations from the Central Midwest RASA model (J.L. Imes, written commun., 1985). Figure 27 shows the no-flow and constant head boundaries.

The eastern boundary of aquifer layer 4 was simulated as a constant-head boundary representing the Tennessee River. An alternative representation of this boundary was tested, using vertical leakage through the confining beds to a constant head boundary in layer 1. Preliminary results were inconclusive because of few data with which to check. The southern one third of the western boundary, the entire southern boundary, the northern boundary, and the southern one-half of the eastern boundary are simulated as no-flow boundaries (fig. 27). Calculated heads within 50 miles of these boundaries are not used in model interpretation.

Confining unit C represents the Cretaceous-Paleozoic confining unit, the upper boundary to aquifer layer 4. Geologically, confining unit C is not present in the western part of the study area. The area where the confining unit is absent is simulated in the model as a zone of high leakance, representing aquifers in direct contact with one another. Model representation of confining unit C (fig. 28) is based primarily on the geologic interpretations of Schwalb (1982). The confining unit was separated into zones of similar geology. A single leakance value was calculated for each zone, based on dividing the average vertical hydraulic conductivity of the dominant lithology (Freeze and Cherry, 1979) by the average thickness of the confining unit within the zone (Schwalb, 1982). Variations from the geology of Schwalb (1982) occur in zones 8 and 9. These high leakance zones represent fracturing in the con-

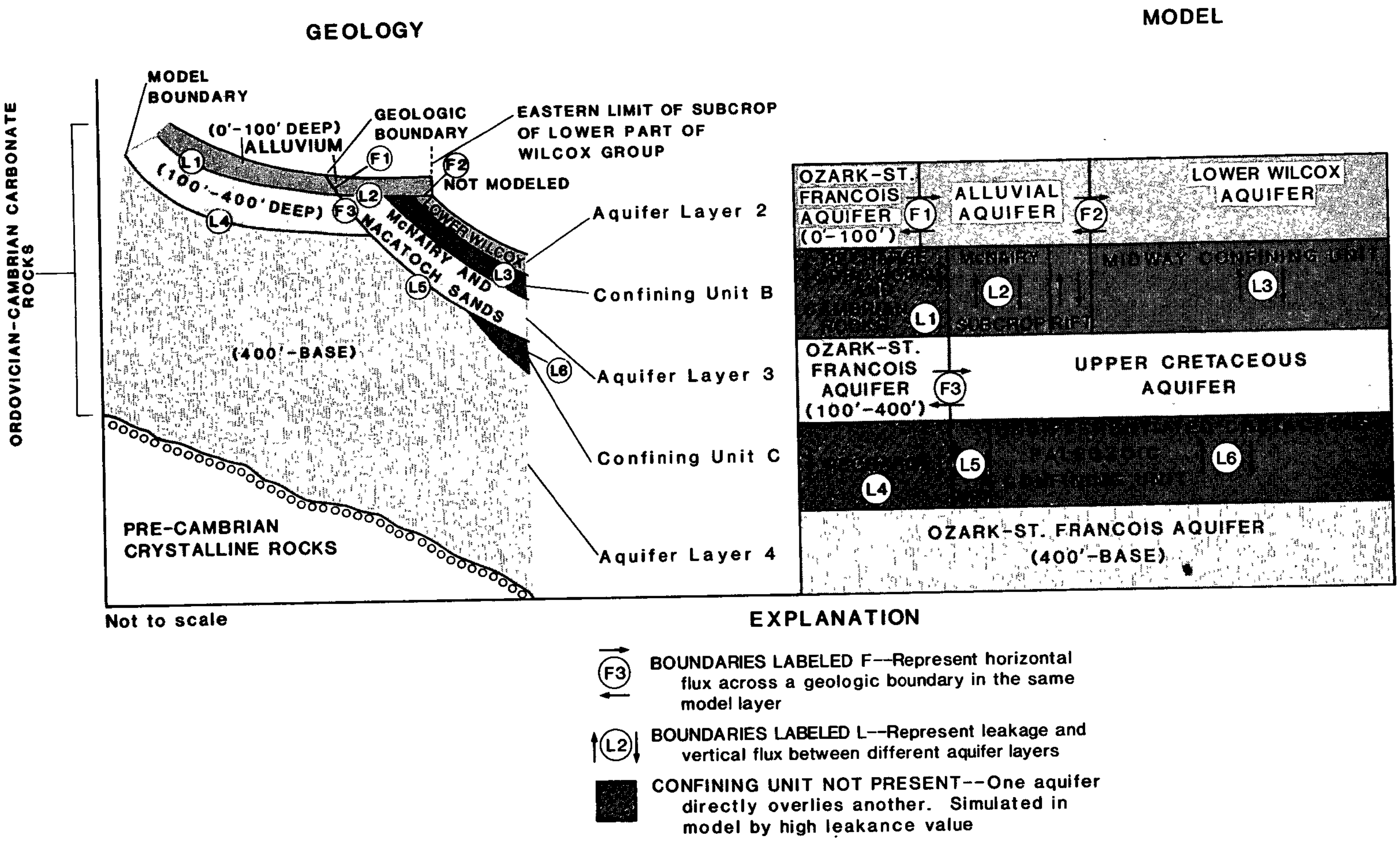


Figure 26.--Relation of geologic boundaries to model boundaries and fluxes near potential discharge areas in the western part of the study area.

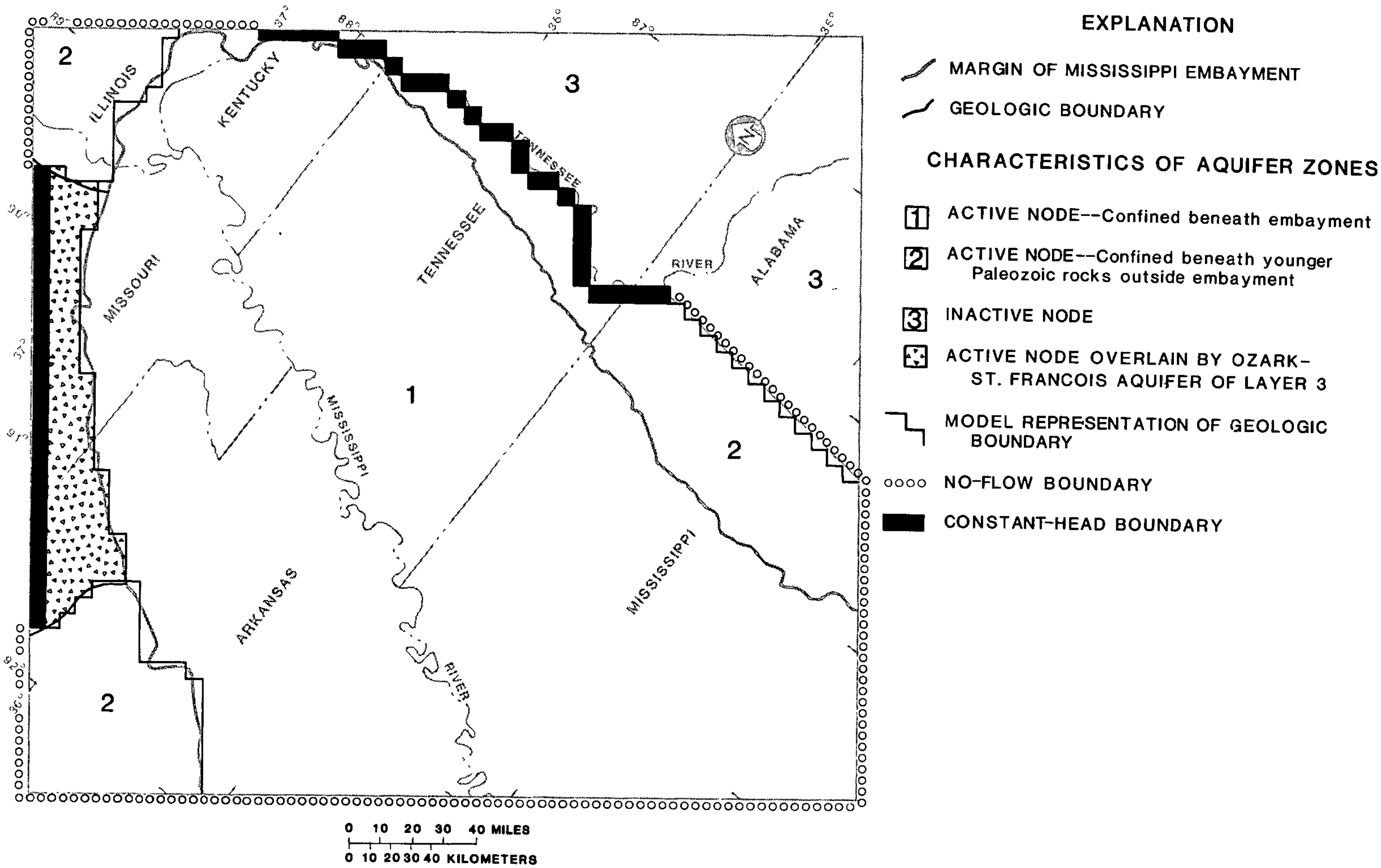


Figure 27.--Digital model representation of aquifer layer 4, Ozark-St. Francois aquifer.

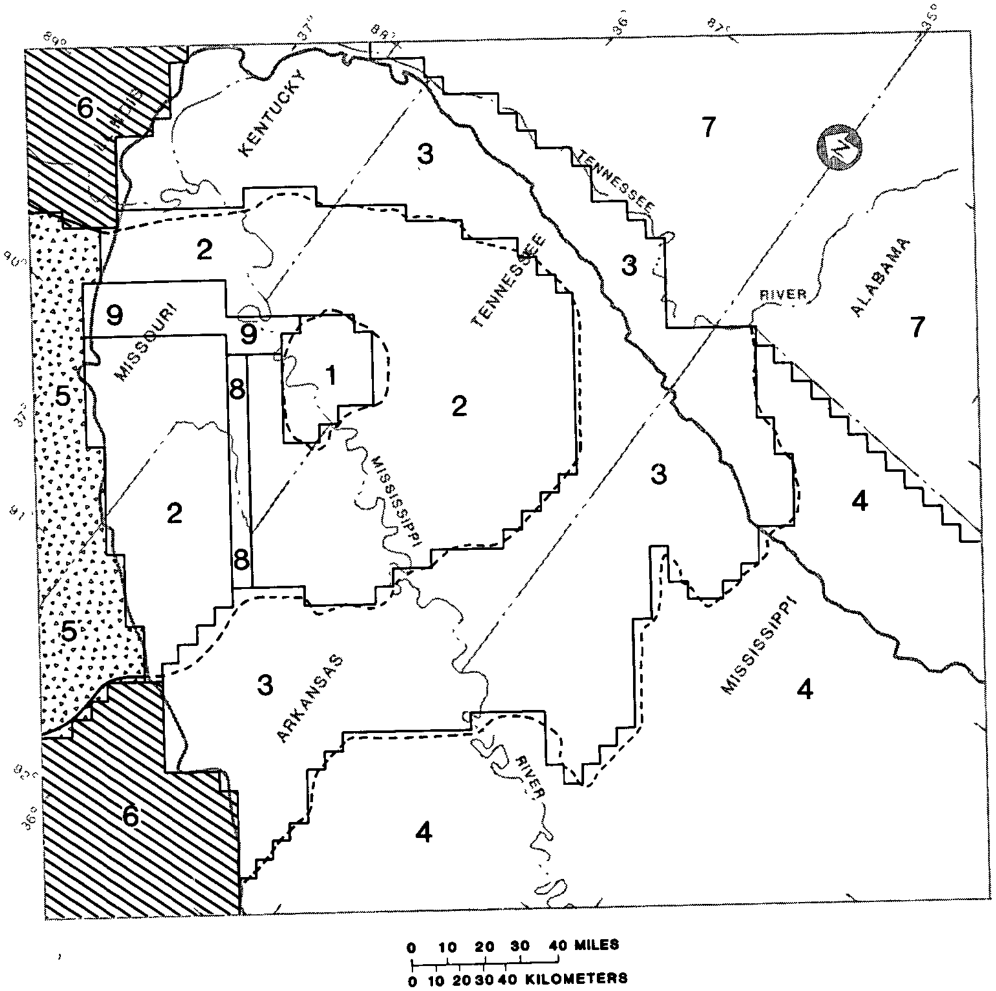


Figure 28.--Digital model representation of confining unit C, Cretaceous-Paleozoic confining unit.

EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

SUBCROP PATTERN OF PALEOZOIC ROCKS BENEATH CRETACEOUS COVER

CHARACTERISTICS OF CONFINING UNIT ZONES

1 LIMESTONE-DOLOMITE CONFINING BED--Thin or faulted; erosion has removed permeable part of underlying aquifer. [1×10^{-10} (foot/second)/foot] moderate leakance

2 LIMESTONE-DOLOMITE CONFINING BED--Thickness highly variable, faulting suspected. [1×10^{-9} (foot/second)/foot] high leakance

3 MIXED SHALE AND LIMESTONE-DOLOMITE LITHOLOGY--Thickness much greater than zone 2. [1×10^{-12} (foot/second)/foot], low leakance

4 SHALE--Thickness greater than 10,000 feet. [1×10^{-14} (foot/second)/foot], very low leakance

5 LIMESTONE-DOLOMITE OUTCROP OF OZARK-ST. FRANCOIS AQUIFER IN LAYER 2--[1×10^{-8} (foot/second)/foot]: high leakance simulates absence of confining unit

6 SHALE--Outcrop of thick fine-grained confining unit. [1×10^{-11} (foot/second)/foot], low leakance

7 INACTIVE

8 LIMESTONE-DOLOMITE--With suspected faulting over western margin of rift. [1×10^{-8} (foot/second)/foot], high leakance

9 LIMESTONE-DOLOMITE--With suspected faulting over Pascola Arch-Bloomfield Pluton. [1×10^{-8} (foot/second)/foot], high leakance

BOUNDARY OF CONFINING UNIT ZONES

fining unit above the western margin of the rift and fracturing in the confining unit above the Pascola arch-Bloomfield pluton.

Zone 1 (fig. 28) is modeled as a probable moderate leakance area corresponding to an eroded structural high. In zone 1, the Ozark-St. Francois aquifer is eroded, and less permeable units of the St. Francois confining layer (Imes, 1988c) are directly overlain by the Upper Cretaceous aquifer. Zone 2 is modeled as a zone with high to moderate leakance potential. Rocks of the Ozark-St. Francois aquifer are directly overlain by the Upper Cretaceous aquifer. Zone 3 is a low leakance zone representing a thick sequence of Ordovician through Devonian and possibly pre-McNairy Cretaceous sedimentary rocks that separate the Ozark-St. Francois aquifer from the Upper Cretaceous aquifer. Zone 4 has very low leakance and includes the units of zone 3, as well as thick fine-grained sedimentary rocks of Mississippian and Pennsylvanian age. The outcrop area of the Ozark-St. Francois aquifer (zone 5) is modeled as a zone of high leakance to simulate hydrologic interaction between the aquifer and the water table. The outcrop of post-Middle Ordovician rocks north and south of the Salem Plateau (zone 6) is characterized by a thick sequence of fine-grained rocks; these are simulated as having low leakance.

Aquifer layer 3 contains the Upper Cretaceous aquifer (fig. 29) and a thin part of the Ordovician and Cambrian rocks (fig. 26). A no-flow boundary is simulated around aquifer layer 3, except for constant heads that simulate recharge along the western margin (zone 6). The outcrop area of the Upper Cretaceous aquifer along the eastern and northern margins of the embayment is simulated as zone 4; subcrop is zone 5. Active nodes representing the confined Upper Cretaceous aquifer are zone 1. Nodes with zero transmissivity are zone 2, where vertical flux passes between deeper and shallower layers, but does not move laterally. Zone 3 is inactive.

Confining unit B, the Midway confining unit, is of major concern in this study. Major zones in confining unit B (fig. 30) and how each is simulated in the model include the following: the area of the Ozark-St. Francois aquifer outcrop (zone 1), where no confining bed separates different parts of the Ozark-St. Francois aquifer is modeled as a high leakance zone; the outcrop of the post Middle Ordovician Paleozoic formations (zone 2), modeled as a low leakance zone that has zero transmissivity in the underlying Upper Cretaceous aquifer; the subcrop of the Upper Cretaceous aquifer (zone 3), modeled as high leakance to represent direct hydraulic contact with the overlying alluvium; the outcrop of the Upper Cretaceous aquifer (zone 4), modeled as high leakance to represent recharge; the zone overlying the western margin of the rift in Missouri and Arkansas (zone 5), modeled as variable leakance; the zone of thick clays of the Midway Group (zone 6), modeled as very low leakance; and a zone beyond the extent of the Midway Group (zone 7), modeled as high leakance in this confining layer to pass recharge to deeper formations. Zones 1, 3, 4, and 7 simulate a geologic condition where the confining bed is actually absent. The large conductance of these nodes connects nodes in lower layers to constant head nodes in layer 1.

Aquifer layer 2 contains parts of three formations, the top 100 feet of the outcropping Cambrian and Ordovician carbonate rocks, the alluvium west of the subcrop with the lower part of the Wilcox Group, and the lower Wilcox aquifer throughout its area of occurrence (fig. 26). Aquifer layer 2 is not an active layer in the sense of aquifer layers 3 and 4. Heads in this aquifer are specified as initial conditions in response to 1980 pumping, and they are identical to heads in layer 1. The boundaries simulated in aquifer layer 2 are identical to those of aquifer layer 3, except for constant head along the southern boundary (fig. 31). Specific zones in aquifer layer 2 include the outcrop area of the Ozark-St. Francois aquifer (zone 6), the outcrop area of the alluvium (zone 4), a subcrop zone that has average properties of the alluvium over the Wilcox Group (zone 2), a zone of confined flow for the lower Wilcox aquifer (zone 3), the outcrop area of the Wilcox Group (zone 1), and a fairly wide zone of inactive nodes around the northern and eastern margins of the model (zone 5).

Confining unit A (not shown) has uniformly high leakance except for the area represented as confined in the lower Wilcox aquifer in figure 31. For the confined lower Wilcox aquifer, leakance varies from moderate to low.

Aquifer layer 1 (not shown) is represented by a layer of constant head nodes throughout the area modeled. The heads include confined heads in the lower Wilcox aquifer (1980), showing pumping effects, and water-table heads (1980) for the alluvium, the Ozark-St. Francois, Upper Cretaceous, and the lower Wilcox aquifers where these aquifers crop out (fig. 31). The heads represent a source layer which affects recharge to and discharge from all deep layers; without aquifer layer 1, recharge and discharge flux in aquifer layer 2 could not be evaluated.

Aquifer Hydraulic Properties

Preliminary model calibration was accomplished using transmissivity calculated from one uniform value of hydraulic conductivity for each of the various aquifers (fig. 32). Where thickness data from the GC RASA geophysical log file were available, the hydraulic conductivity value for each aquifer was multiplied by aquifer

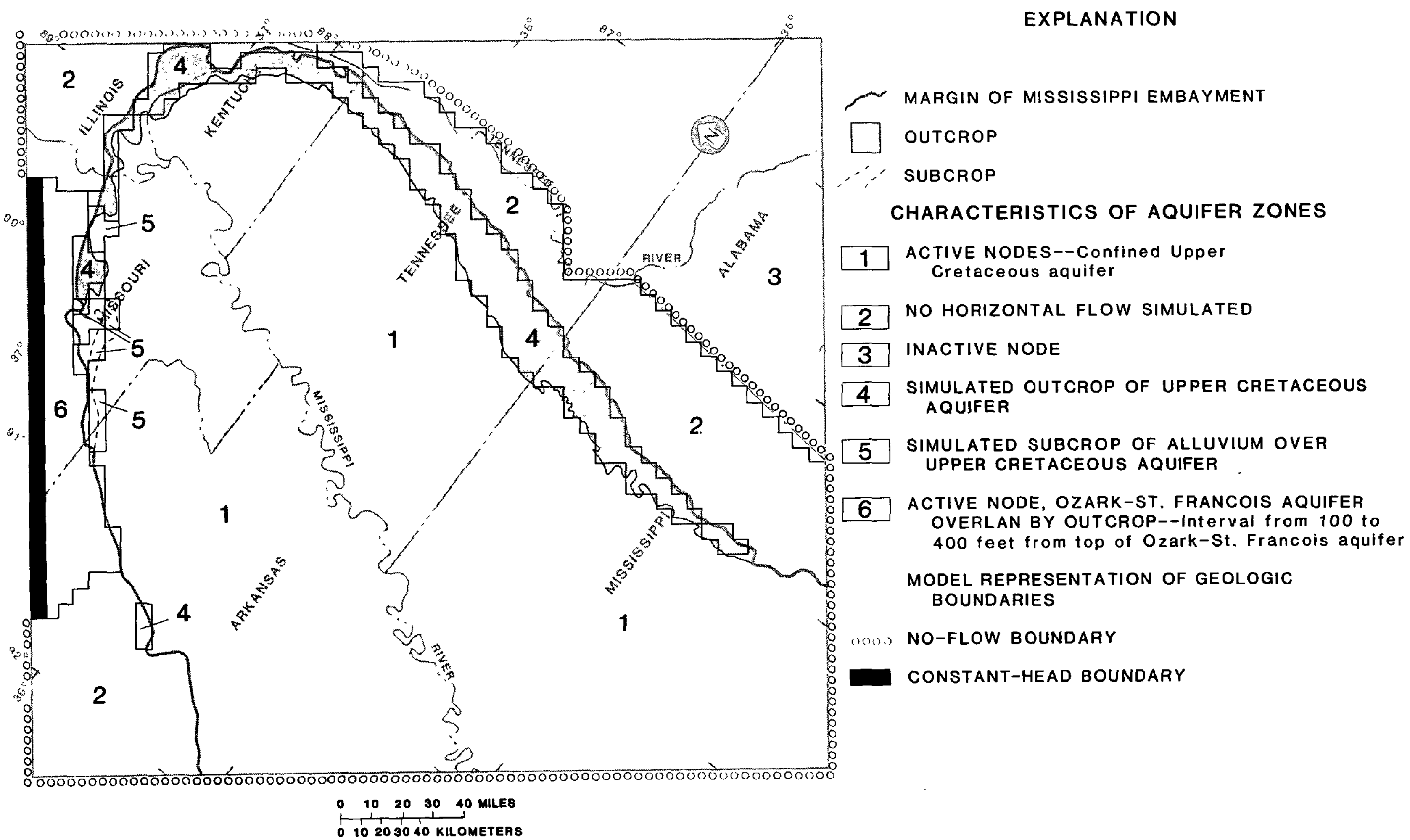
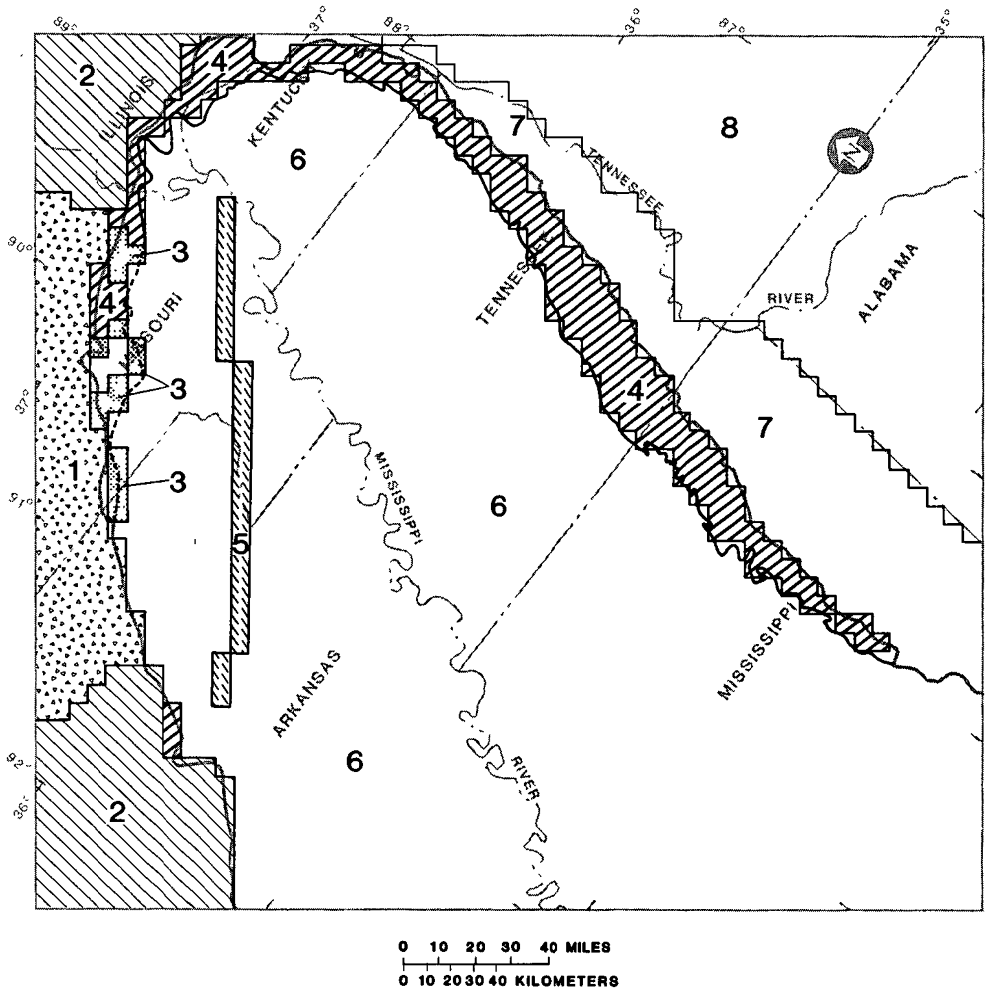


Figure 29.--Digital model representation of aquifer layer 3, Upper Cretaceous aquifer.



EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

BOUNDARY OF MIDWAY CONFINING UNIT--Dashed where approximately located

CHARACTERISTICS OF CONFINING UNIT ZONES

1 LIMESTONE-DOLOMITE OUTCROP OF OZARK-ST. FRANCOIS AQUIFER--[1×10^{-8} (foot/second)/foot]: high leakance, confining unit not present

2 SHALE--Outcrop of thick fine-grained confining unit. [1×10^{-11} (foot/second)/foot]: low leakance

3 SAND SUBCROP OF UPPER CRETACEOUS AQUIFER BENEATH ALLUVIUM--[1×10^{-8} (foot/second)/foot]: high leakance, confining unit not present

4 SAND OUTCROP OF UPPER CRETACEOUS AQUIFER--[1×10^{-8} (foot/second)/foot]: high leakance, confining unit not present

5 BOUNDARY OF RIFT--1×10^{-8} (foot/second) Divided by thickness of the Midway Group in feet (see figure 8)

6 CLAY CONFINED BY MIDWAY--1×10^{-11} (foot/second) Divided by thickness of the Midway Group in feet (see figure 8): low leakance

7 BEYOND LIMIT OF EXTENT OF MIDWAY GROUP--[1×10^{-8} (foot/second)/foot]: high leakance, confining unit not present

8 INACTIVE NODE

BOUNDARY OF CONFINING UNIT ZONES

Figure 30.--Digital model representation of confining unit B, Midway confining unit.

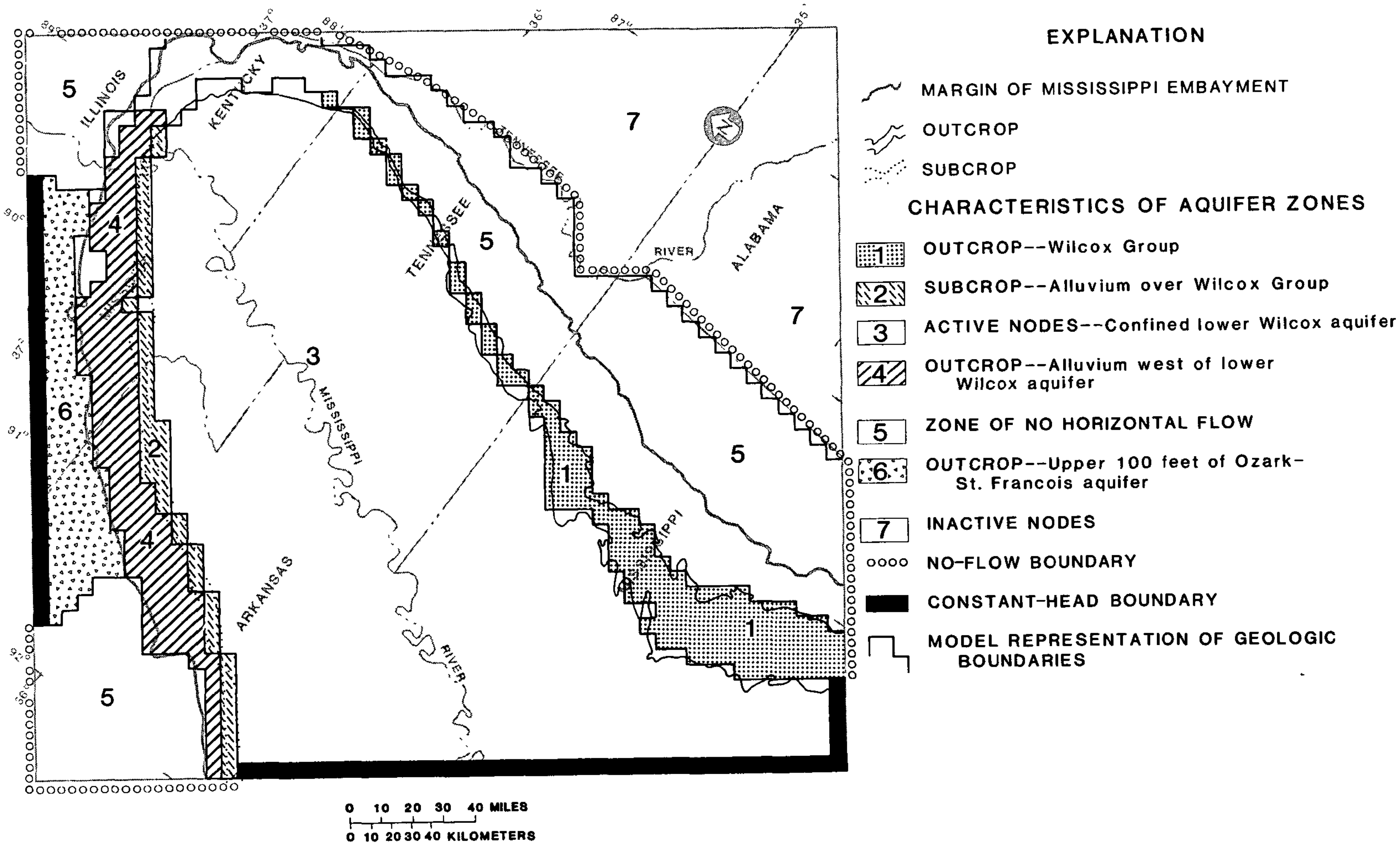


Figure 31.--Digital model representation of aquifer layer 2, alluvium-lower Wilcox aquifer.

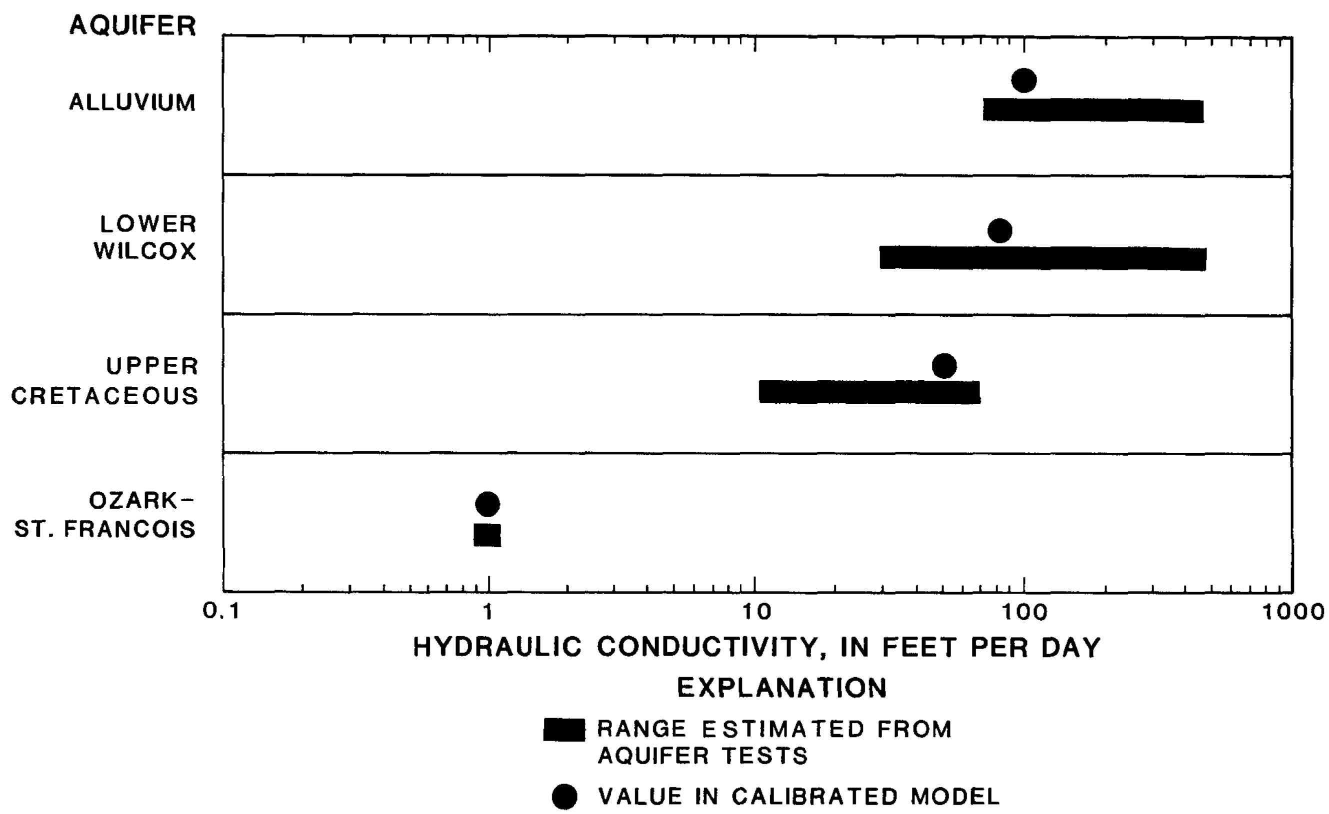


Figure 32.--Range of hydraulic conductivity estimated from aquifer tests and geologic considerations, and the hydraulic conductivity used in the calibrated model for each aquifer.

thickness to define transmissivity. Transmissivity for aquifer layers 2 (alluvium and lower Wilcox) and 3 (Upper Cretaceous) was calculated using this method. Because few thickness data were available, transmissivity for aquifer layer 4 was input as a single uniform value.

Hydraulic conductivities were initially selected based on the results of aquifer tests (tables 1 and 3 and fig. 32). These conductivities were adjusted during calibration, and the following values of hydraulic conductivity provided the best match of simulated and observed heads:

Alluvium aquifer	100 ft/d
Lower Wilcox aquifer	80 ft/d
McNairy-Nacatoch aquifer	50 ft/d
Ozark-St. Francois aquifer	0.9 ft/d

Ranges of values of these input parameters are shown for the model of the Upper Cretaceous aquifer, for the Central Midwest (CM) RASA model, the Southeast Coastal Plain (SE) RASA model, and the Mississippi embayment aquifer-system RASA model, the Mississippi River alluvial aquifer RASA model, and the Gulf Coast Regional RASA model (table 5).

Stresses

Model development involved evaluating both unstressed (prepumping) and stressed (pumping) conditions. Pumping stresses for point source and estimated domestic and stock use of water were located by grid block for the Ozark-St. Francois aquifer and the Upper Cretaceous aquifer (fig. 18). About 37 ft^3/s (24 Mgal/d) were pumped from these aquifers in the study area in 1980. This pumpage, most of which was concentrated in southeastern Missouri, was assigned to appropriate grid blocks (D.J. Ackerman, written commun., 1986). Inasmuch as observed 1980 heads from the lower Wilcox aquifer were input as starting heads, the effect of pumpage was included, and no pumpage was simulated from this layer.

PRELIMINARY MODEL DEVELOPMENT

Model development requires that model simulations be tested against actual hydrogeologic conditions. The testing provides a statistical level of confidence and documentation for the simulated results, and it can provide additional understanding of the natural system.

Calibration

Calibration involved matching observed heads with calculated heads for 1980 conditions. Calibration was accomplished by modifying (1) a sequence of selected boundary configurations, (2) areally uniform hydraulic conductivity for each individual aquifer layer and confining unit, and (3) pumping configurations.

The conditions in 1980 are assumed to approximate steady-state. This assumption is valid for all areas of the aquifer except the limited area of major pumping from the Upper Cretaceous aquifer (fig. 18), where sparse data suggest there may be a 10 to 30 year decline in water levels of less than a foot per year. The effect of the assumption that 1980 conditions represent steady state was tested by including storage as a component of the model, and the resulting heads in the area of interest generally showed less than 5 feet of change.

As a preliminary approximation, 1980 conditions represent the best available data. Testing of transient conditions will be part of the modeling effort to be described in later reports.

Difference between simulated and actual heads varied considerably as changes were made in boundary conditions. For example, by changing the northwestern boundary of the Ozark-St. Francois aquifer from constant head to constant flux and using a broad range of flux estimates from the CM RASA (J.L. Imes, written commun., 1986), head differences of greater than 100 feet from the best simulation were observed. The final boundary representations shown (figs. 27 to 31) match the known hydrogeologic boundaries as defined by the GC RASA geophysical log data base.

A second method of calibration involved adjusting the hydraulic conductivity. A representative value was tested for each zone of similar geology within a layer. Depending on whether the layer was an aquifer or a confining unit, the hydraulic conductivity was either multiplied or divided by the known thickness of the layer. This calibration method allows the effects of known variations to be assessed with a minimum of modeler bias in parameter selection.

A further constraint of the calibration was that the fluxes between different model layers be "hydrologically reasonable." Fluxes between units in this regional study cannot be measured directly; however, order of magnitude interaquifer exchanges can be approximated based on literature values from similar geologic settings and calculations from other models. These flux estimates were used as a basis for comparison, and large differences between model calculated fluxes or from fluxes calculated by other RASA models (table 6), may require justification or reevaluation of the conceptual model.

Heads calculated by the calibrated model are compared to measured heads for the northwestern part of the Ozark-St. Francois aquifer and for the Upper Cretaceous aquifer in figures 33 and 34. The observed heads are

Table 5.--*Comparison of input values of RASA models in the northern Mississippi embayment*

[K_h, hydraulic conductivity in the horizontal direction; K_v, hydraulic conductivity in the vertical direction; b, thickness; ft/d, foot per day; ft, foot]

Model reference model layer	Upper Cretaceous aquifer Brahana and Mesko (1988)			Mississippi embayment aquifer system Arthur and Taylor (1988)			Alluvial aquifer, D.J. Ackerman, USGS, written commun. (1986)			GC RASA Regional A.K. Williamson, USGS, written commun. (1986)			Central Midwest RASA Imes (1988a, 1988b, 1988c, 1988d)			Southeastern Coastal Plain RASA M.J. Mallory, USGS, written commun. (1986)		
	K_h (ft/d)	K_v (ft/d)	b (ft)	K_h (ft/d)	K_v (ft/d)	b (ft)	K_h (ft/d)	K_v (ft/d)	b (ft)	K_h (ft/d)	K_v (ft/d)	b (ft)	K_h (ft/d)	K_v (ft/d)	b (ft)	K_h (ft/d)	K_v (ft/d)	b (ft)
Alluvial aquifer	100	--	10 to 250	170	--	10 to 250	300	--	10 to 250	170	--	10 to 250						
Lower Wilcox aquifer	80	--		85	--		85	--		85	--							
Midway confining unit	--	0.9×10^{-6}	10 to 610	--	0	10 to 610	--	1×10^{-5}	10 to 610	--	1×10^{-5}	10 to 610						
Upper Cretaceous aquifer	50	--	20 to 1,200	--	0	--	50	--	20 to 1,200	50	--	20 to 1,200				[c]2,000 to 6,000	--	[c]--
Cretaceous-Paleozoic confining unit		[a]0.9×10^{-3} to 0.9×10^{-9}	40 to 470						40									
Ozark St. Francois aquifer	0.9	--	[a]--										0.1 to 1.0					

[a]Values are K_v/b for each geologic zone.
[b]Value is K_hb for the entire layer.
[c]Values are K_hb based on average thickness for aquifer.

Table 6.--*Comparison of simulated results of RASA models in the northern Mississippi embayment*

[RMSE, Root mean square error; H_o-Hs, observed head minus simulated head; NA, Not applicable, heads held constant; NS, Not simulated; NVA, No values available at this time; ft, feet; ft^3/s, cubic foot per second; in/yr, inch per year]

Model reference model layer	Upper Cretaceous aquifer Brahana and Mesko (1988)			Mississippi embayment aquifer system Arthur and Taylor (1988)			Alluvial aquifer, D.J. Ackerman, USGS, written commun. (1986)			GC RASA Regional A.K. Williamson, USGS, written commun. (1986)			Central Midwest RASA Imes (1988a, 1988b, 1988c, 1988d)			Southeastern Coastal Plain RASA M.J. Mallory, USGS, written commun. (1986)		
	Common boundary flux (ft^3/s)	RMSE (H_o-Hs) (ft)	Recharge (in/yr)	Common boundary flux (ft^3/s)	RMSE (H_o-Hs) (ft)	Recharge (in/yr)	Common boundary flux (ft^3/s)	RMSE (H_o-Hs) (ft)	Recharge (in/yr)	Common boundary flux (ft^3/s)	RMSE (H_o-Hs) (ft)	Recharge (in/yr)	Common boundary flux (ft^3/s)	RMSE (H_o-Hs) (ft)	Recharge (in/yr)	Common boundary flux (ft^3/s)	RMSE (H_o-Hs) (ft)	Recharge (in/yr)
Alluvial aquifer	125.8	NA	NS				766	9.4	0.4							NS	NS	NS
Lower Wilcox aquifer	10.7	NA	0.32	1.2	NVA	<0.1												
Midway confining unit	3.0	NS	NS							0.0	NS	NS						
Upper Cretaceous aquifer	40.4	9.7	.24													NA	NS	NVA
Cretaceous-Paleozoic confining unit	NS	NS	NS															
Ozark-St. Francois aquifer	40.4	25	6.5										100	NVA	7			

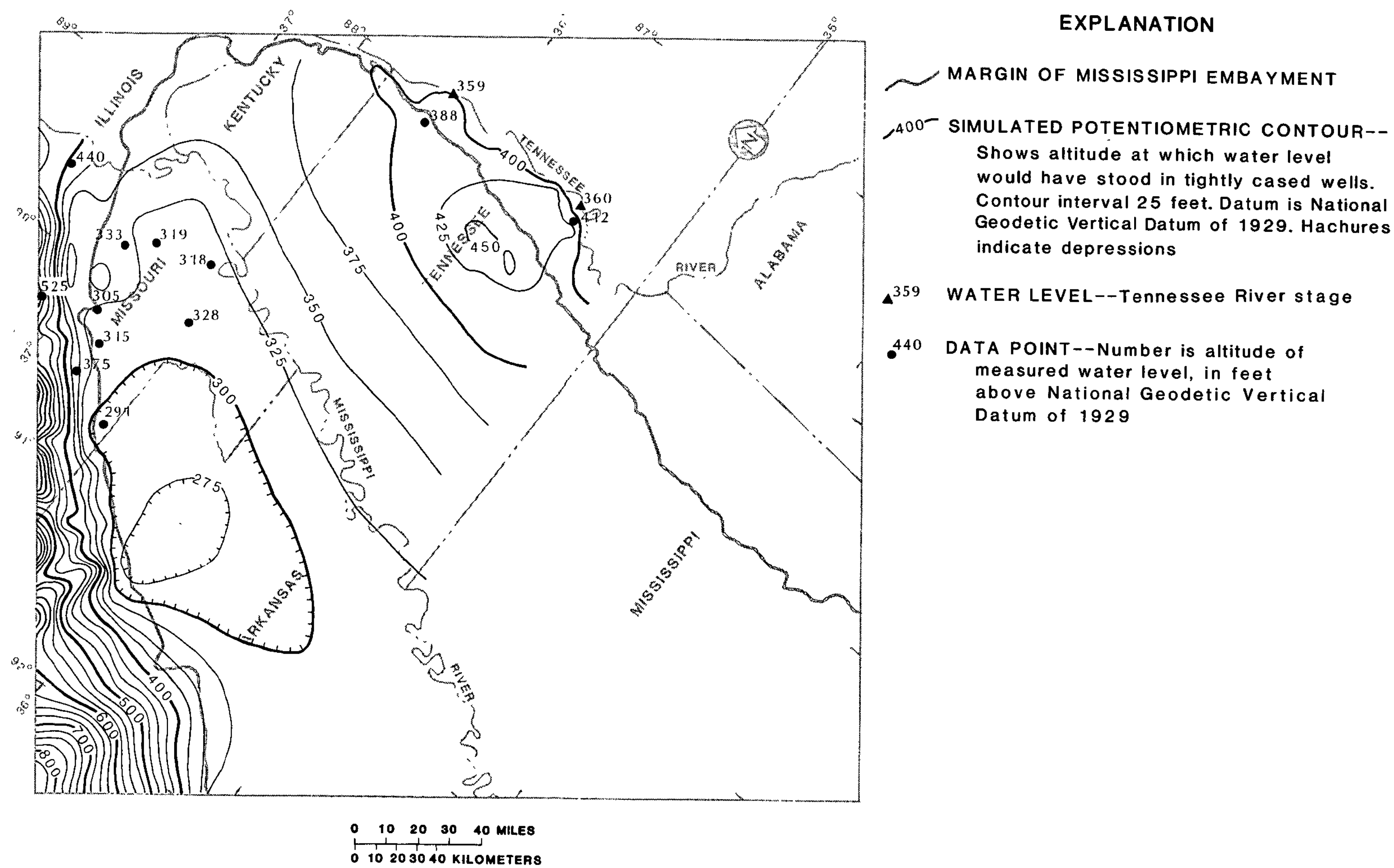
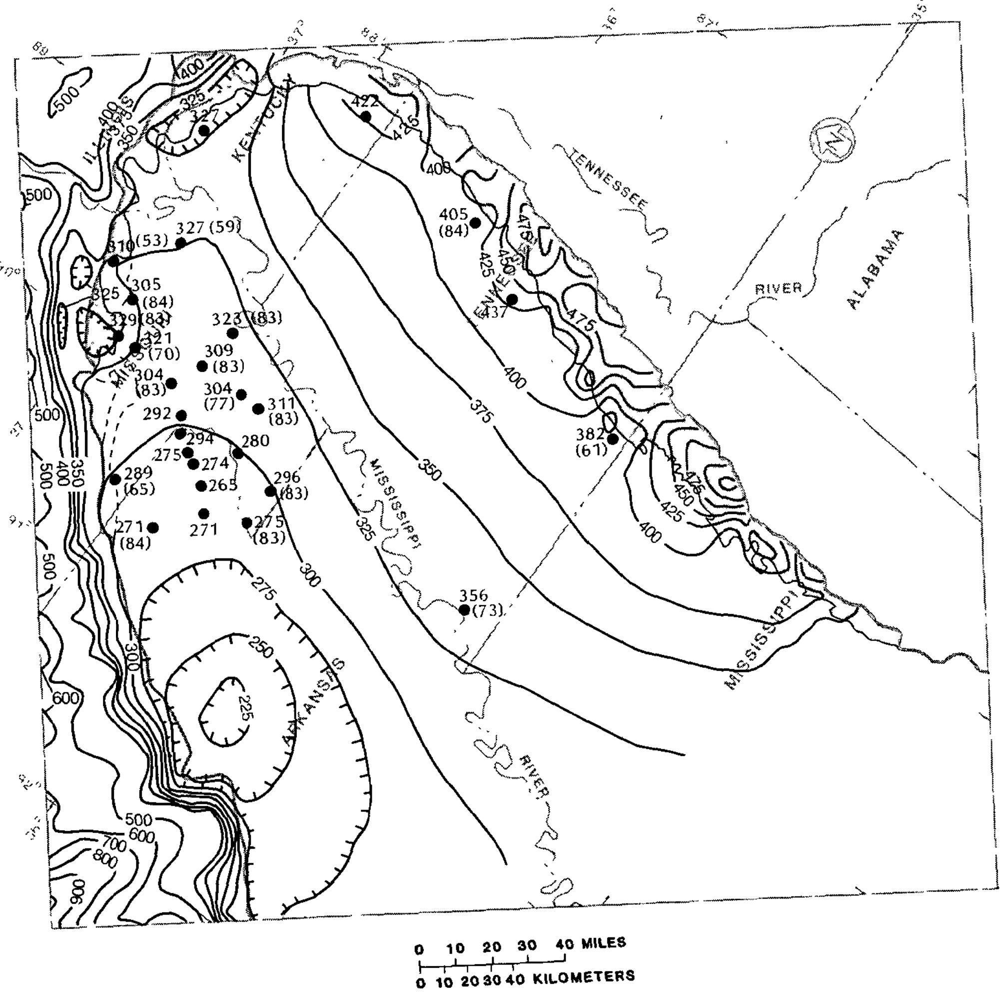


Figure 33. --Comparison of observed and model-calculated heads for the northwestern part of the Ozark-St. Francois aquifer in the study area, calibration to 1980 as steady state.



EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

OUTCROP OF UPPER CRETACEOUS AQUIFER

SUBCROP OF UPPER CRETACEOUS AQUIFER BENEATH ALLUVIUM

—300— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 25 feet. Hachures indicate depressions. National Geodetic Vertical Datum of 1929

305 ●(84) DATA POINT--Number is altitude of measured water level, in feet above National Geodetic Vertical Datum of 1929. Data are for 1980 unless year is shown in parentheses

Figure 34.--Comparison of observed and model-calculated heads for the Upper Cretaceous aquifer in the northern Mississippi embayment, calibration to 1980 as steady state.

reasonably matched by calibrated preliminary model calculations. For the Ozark-St. Francois aquifer, the root mean square error (described in the following section on Sensitivity Analysis) was 25 feet for 14 comparison points having both calculated and observed heads. Eight of 14 of the comparison points had calculated heads within 20 feet of observed. The maximum variation between calculated and observed heads was 53 feet. These values are within an acceptable limit considering the steep gradients in the western part of the area, the large area of the grid blocks compared with the point location of observed wells, and the use of extrapolated data. Water-level data for years other than 1980 were used for some observed match points because water-level data in the Ozark-St. Francois aquifer were sparse. For the Upper Cretaceous aquifer, the root-mean square error was 9.7 feet for the 29 comparison points having both model calculated and observed heads. Twenty-one of 29 of the comparison points had calculated heads within 10 feet of observed. The maximum variation between calculated and observed heads in the Upper Cretaceous aquifer was 26 feet. These values are also considered to be within acceptible limits based on the same rationale as given for the Ozark-St. Francois aquifer.

Sensitivity Analysis

The response of the model to adjustments in (1) pumping from aquifer layer 4 (Ozark-St. Francois aquifer); (2) transmissivity of aquifer layer 4; (3) leakance of confining unit C (Cretaceous-Paleozoic confining unit); (4) pumping from aquifer layer 3 (Upper Cretaceous aquifer); (5) transmissivity of aquifer layer 3; and (6) leakance of confining unit B (Midway confining unit) was evaluated by sensitivity analysis. The sensitivity of layer 2 was not evaluated because heads representing 1980 conditions in layer 2 were input as initial conditions in layers 2 and 1; the heads in layer 2 were maintained by high conductance in confining unit A. Heads in aquifer layer 1 were held constant. The adjustment of each variable (items 1 through 6 above) was uniform over the entire model area while all other variables were held constant. The adjustment of each variable was 2, 5, and 10 times larger, and $^1/_2$, $^1/_5$, and $^1/_{10}$ smaller than values used in the calibrated model.

The root mean square error (RMSE) was calculated as a measure of the difference between model calculated heads and observed heads. The root mean square error is described by the equation:

$$RMSE = \sqrt{\sum_{i=1}^{n} (H^c_i - H^o_i)}$$

where

RMSE is the root mean square error;
H^c is calculated head, in feet, at a model node;
H^o is observed head, in feet;
n is the number of comparison points;
i is a subscript that defines any specific comparison point, varying between 1 and n.

RMSE was plotted for each adjustment in a variable to display the range of sensitivity.

The results of the sensitivity analysis for aquifer layer 4 (Ozark-St. Francois aquifer) and aquifer layer 3 (Upper Cretaceous aquifer) are shown in figures 35 and 36, respectively. RMSE for all values in the original model was 25 feet for the Ozark-St. Francois aquifer, and 9.7 feet for the Upper Cretaceous aquifer. The RMSE was considered sensitive to changes in variable values when the RMSE of sensitivity tests exceeded the RMSE of the original model by 5 or more feet. For the Ozark-St. Francois aquifer, a RMSE greater than 30 feet was considered sensitive; for the Upper Cretaceous aquifer, a RMSE greater than about 15 feet was considered sensitive. Simulated ground-water flow to streams was not used as an indicator of sensitivity because the amount of ground-water seepage to streams is unknown in the study area.

Heads in aquifer layer 4 (Ozark-St. Francois aquifer) are relatively insensitive to the transmissivity of aquifer layer 4 and the leakance of confining unit C (Cretaceous-Paleozoic confining unit) (fig.35). The model was sensitive to pumping from aquifer layer 4 at rates about 5 times greater than the value used in the calibrated model. Lack of sensitivity of transmissivity is probably due to the model design, which incorporates constant heads around the margins. Such a representation rigidly defines a regional gradient and, in the case of slight to moderate pumping, which characterizes the Ozark-St. Francois aquifer, the effect of transmissivity on heads in the system is relatively insignificant.

For this preliminary model, calculated heads in aquifer layer 3 were found to be most sensitive to pumping (figure 36). An order-of-magnitude increase in pumping from the input of the calibrated model resulted in RMSE increases of more than 40 feet. Calculated heads, however, were relatively insensitive to decreases in pumping. Reduction in original pumping stresses by as much as 0.1 resulted in increased RMSE values of only 2 feet. The model was sensitive to transmissivity of aquifer layer 3 and leakance of confining unit B (Midway confining unit) at parameter values less than $^1/_3$ and greater than 3 times the calibrated values.

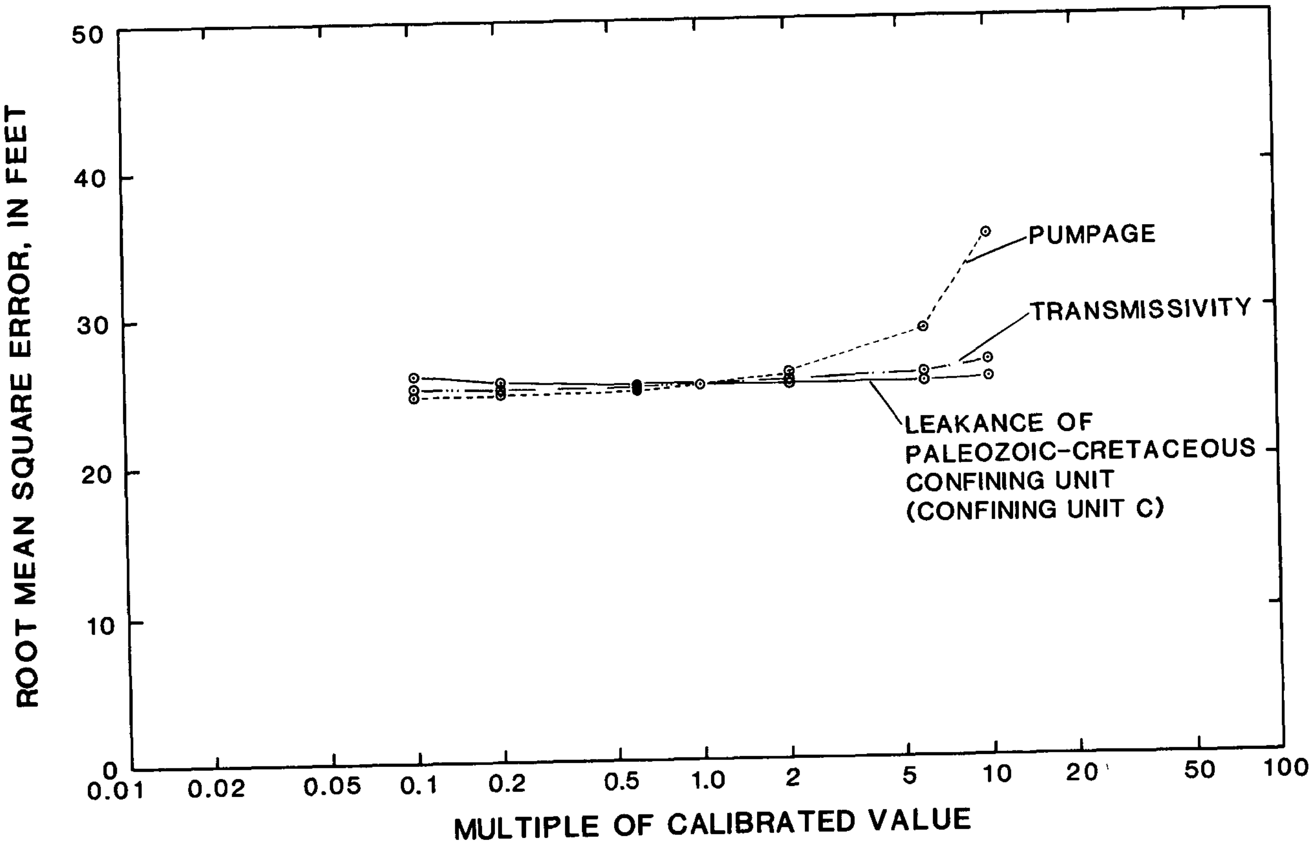


Figure 35.--Relation between changes in magnitude of input parameters and root mean square error of aquifer layer 4 (Ozark-St. Francois aquifer), calibration to 1980 as steady state.

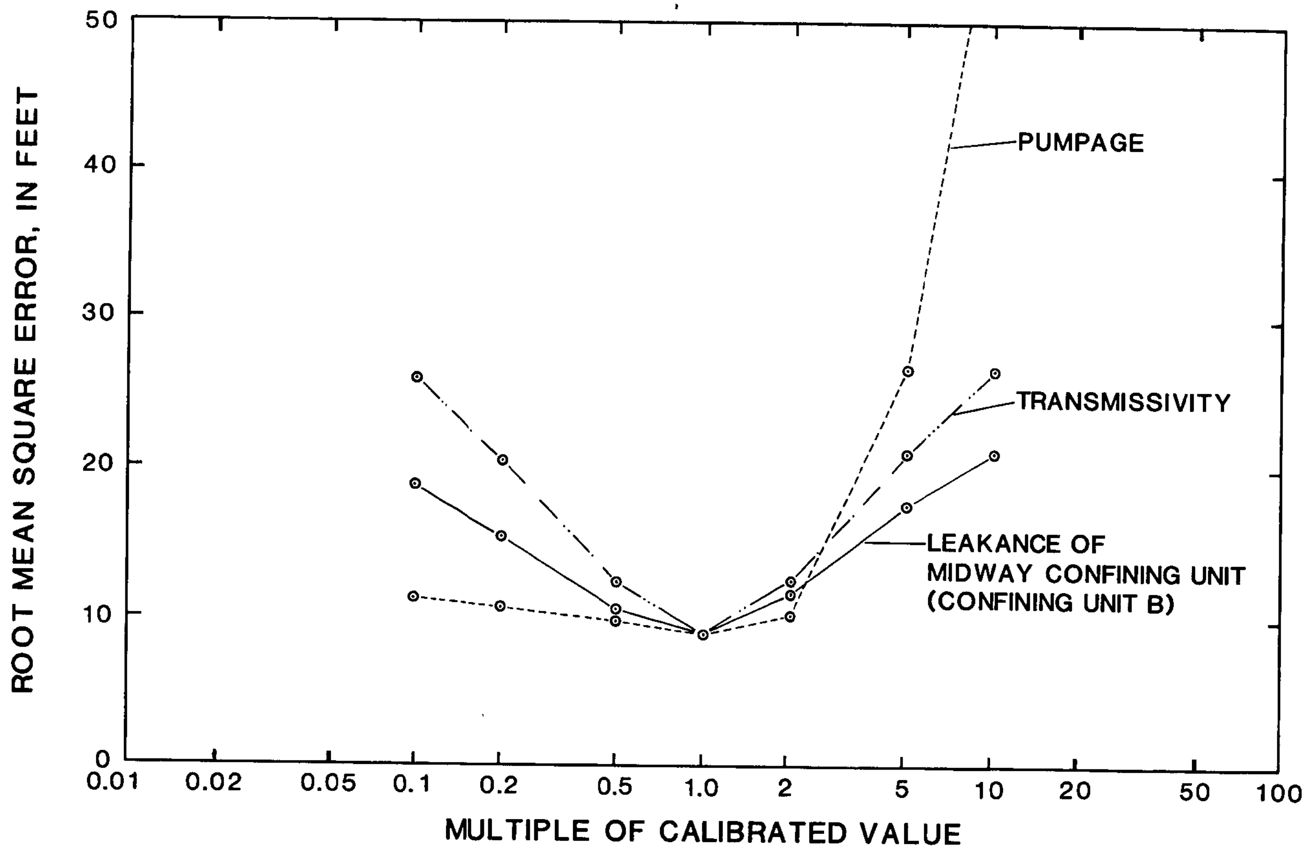


Figure 36.--Relation between changes in magnitude of input parameters and root mean square error of aquifer layer 3 (Upper Cretaceous aquifer), calibration to 1980 as steady state.

REGIONAL CONTRIBUTIONS TO THE HYDROLOGIC BUDGET

Calculations with the model allow a quantitative evaluation of flux across important hydrogeologic boundaries, as well as a determination of regional contributions to the hydrologic budget. Fluxes calculated for the main components of each layer are shown in an idealized cross section (fig. 37). The values are based on simulation with the calibrated models.

Preliminary results show that about 40 ft^3/s are added to the Ozark-St. Francois aquifer system from precipitation along the northwest boundary of the model. The model calculates that about 75 percent of this flux moves upward and discharges to rivers and springs in the outcrop area.

Approximately 28 ft^3/s of water moves into the Upper Cretaceous aquifer, either vertically through the Cretaceous-Paleozoic confining unit (L6), the rift zone (L5), or laterally through the geologic contact (F3) with the upper Ozark-St. Francois aquifer (fig. 37).

Deep recharge to the Upper Cretaceous aquifer is calculated from the outcrop nodes to be about 0.3 in/yr. This is determined by dividing the summation of flux across the boundary (465 ft^3/s to 380 ft^3/s) (fig. 37) by the area (146 blocks x 25 mi^2/block) (fig. 29), and converting to inches per year. The flux across the Midway confining unit is greatly influenced by representation of the western rift boundary. For the condition of high leakage along the rift, net flux across the Midway is 52 ft^3/s, with 49 ft^3/s in the vicinity of the rift boundary. At the subcrop of the Upper Cretaceous aquifer (L2), the model calculates a net flux upward of about 16 ft^3/s. For conditions of low leakage along the western rift boundary, the major area of leakage is shifted to a more diffuse zone located between the rift and the subcrop.

The lower Wilcox aquifer receives approximately as much recharge as the Upper Cretaceous aquifer, about 0.3 in/yr, but its areal distribution of discharge and discharge budget are different from the underlying Upper Cretaceous aquifer. Unlike the Upper Cretaceous, the lower Wilcox aquifer appears to exchange much more water by vertical leakage (74 ft^3/s) than to flow across the subcrop with the alluvium (F2) (13 ft^3/s). This is consistent with the potentiometric maps of the Upper Cretaceous and lower Wilcox aquifers (figs. 10 and 11) and with the known geology of the upper confining layers of each aquifer.

Results of the preliminary calibration indicated locations and magnitudes of discharge from the Ozark-St. Francois (fig. 38) and the Upper Cretaceous aquifers (fig. 39). The calibrated model indicates that although a zone of greater leakance overlies the western margin of the Mississippi embayment rift in the discharge area, order of magnitude flux variations by grid block are discontinuous and more diffuse than expected. This suggests that the geology and hydrology are more complex than originally envisioned in the conceptual model.

SUMMARY

The Upper Cretaceous aquifer of Late Cretaceous age, a regionally extensive but relatively little used aquifer in the northern Mississippi embayment, was studied as part of the Gulf Coast Regional Aquifer- System Analysis. Although data from the Upper Cretaceous aquifer are relatively sparse, this study improves understanding of the regional aquifer system by providing (1) a description of the Upper Cretaceous and adjacent aquifers, (2) a documentation of the development and calibration of a preliminary multilayer model used to simulate flow within this sequence of aquifers, and (3) a quantitative evaluation of the various aquifer-system components to the regional hydrologic budget.

On a regional scale, the ground-water system of the northern Mississippi embayment is composed of a series of nonindurated granular sediments that overlie a thick sequence of Paleozoic carbonate rocks, sandstones, and shales. Precambrian crystalline rocks form both the structural and the hydrogeologic basement throughout the northern embayment.

The units that comprise the hydrogeologic framework of the study are:

Alluvium-lower Wilcox aquifer
Midway confining unit
Upper Cretaceous aquifer
Cretaceous-Paleozoic confining unit
Ozark-St. Francois aquifer

The Ozark-St. Francois aquifer is composed of several thousand feet of indurated Cambrian and Lower Ordovician dolomite, sandstone, and shale that directly overlie the impermeable Precambrian basement. The Ozark-St. Francois is overlain by a highly diverse sequence of rocks that varies in thickness from a few feet to more than 11,000 feet. This diverse sequence of rocks, which includes shale, limestone, sandstone, clay, and marl, is called the Cretaceous-Paleozoic confining unit; the sequence includes rocks from Middle Ordovician to Late Cretaceous in age. The Upper Cretaceous aquifer ranges in thickness from a few to about 500 feet. The Upper Cretaceous aquifer is composed of glauconitic, clayey sand interbedded with clay and chalk, and includes the McNairy Sand in Missouri, Tennessee, and Kentucky; the Nacatoch Sand in

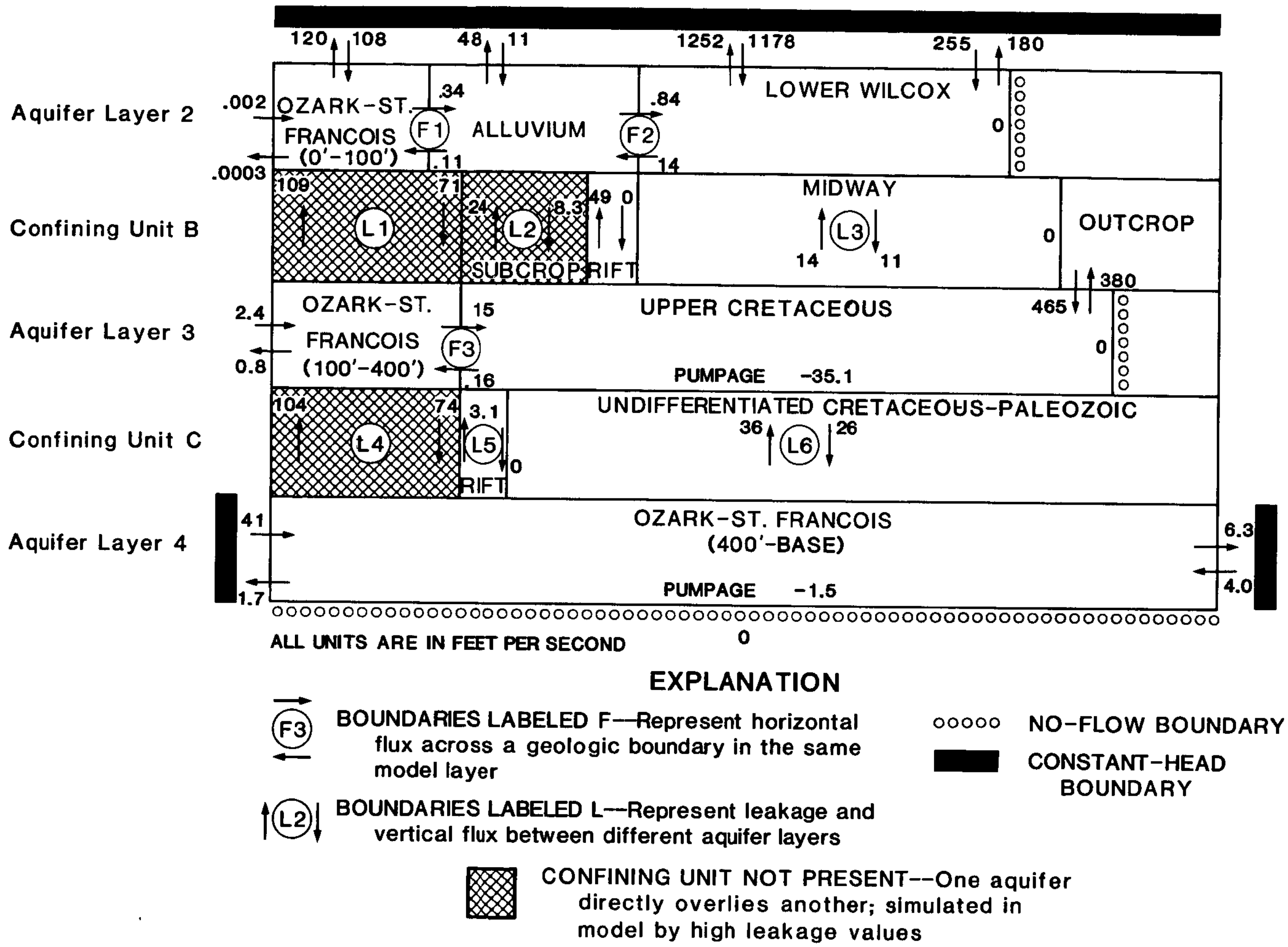
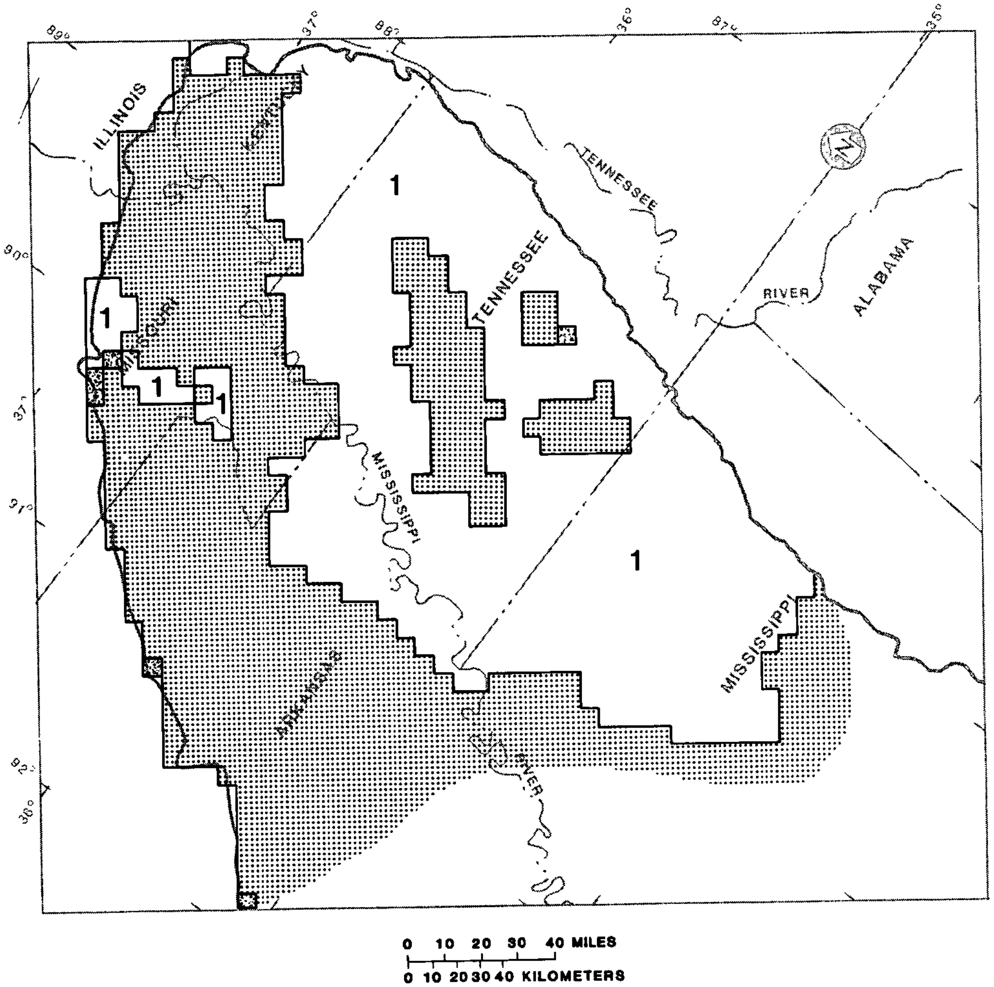


Figure 37.—Idealized cross section showing the main components of the hydrologic budget of the Upper Cretaceous and adjacent aquifers as calculated by the preliminary model, calibration to 1980 as steady state.



EXPLANATION

MARGIN OF MISSISSIPPI EMBAYMENT

AREA OF DISCHARGE

UPWARD DIFFUSE LEAKAGE--Ranges from 0 to 1 cubic feet per second per grid block beneath embayment

UPWARD LEAKAGE--Ranges from 1 to 10 cubic feet per second per grid block beneath embayment

AREA OF RECHARGE

1 DOWNWARD LEAKAGE--Ranges from 0 to 1 cubic feet per second per grid block for confined part of aquifer

Figure 38.--Areas of recharge and discharge with calculated flux as determined by calibration to 1980 as steady state; confined part of the Ozark-St. Francois aquifer.

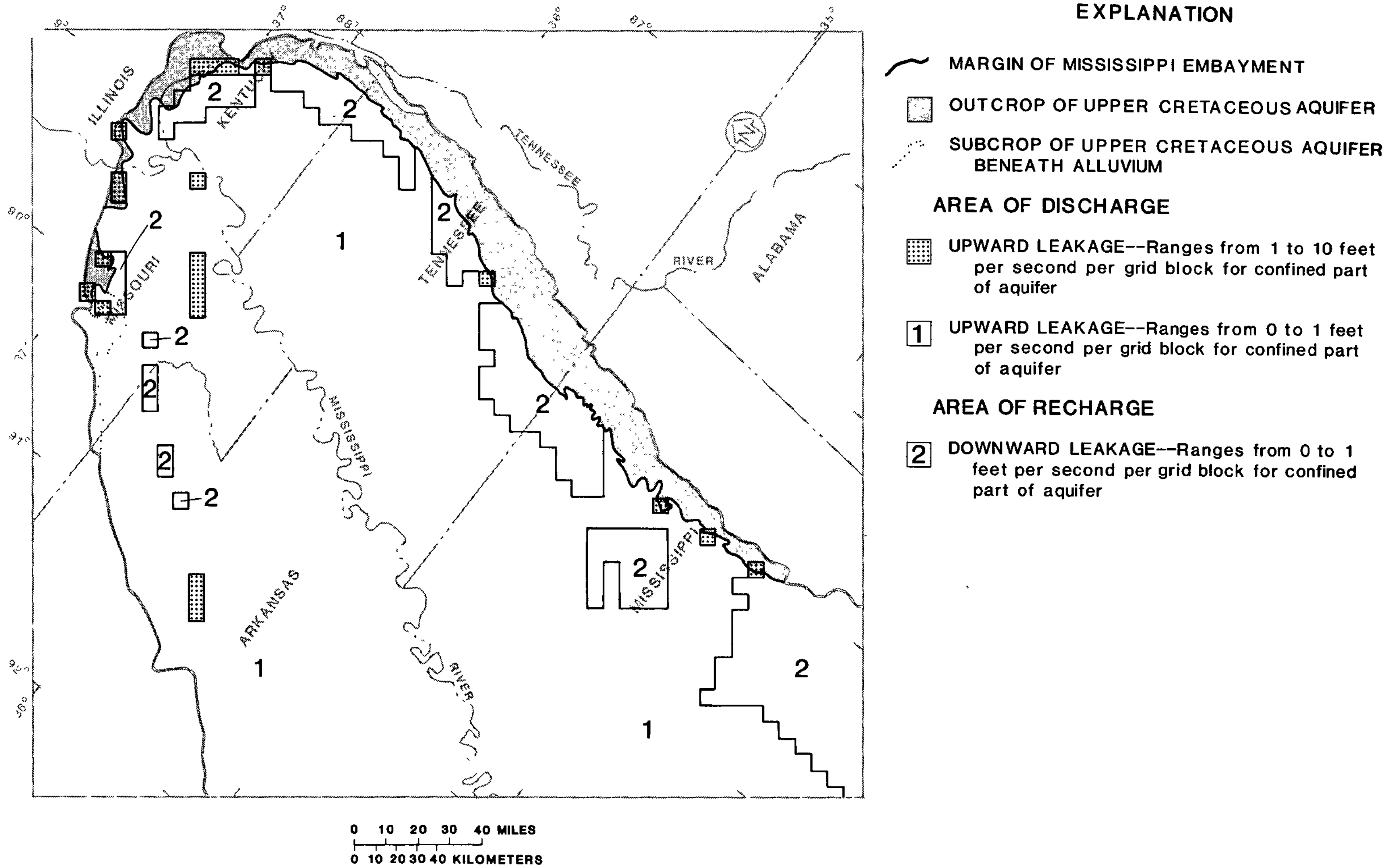


Figure 39.--Areas of recharge and discharge with calculated flux as determined by calibration to 1980 as steady state; confined part of the Upper Cretaceous aquifer.

Arkansas; and the Ripley Formation (including the McNairy Sand Member) in Tennessee and Mississippi. The Midway confining unit directly overlies the Upper Cretaceous aquifer. The Midway confining unit consists primarily of fine-grained sediments (predominantly clay) that range in thickness from a few feet to about 1,200 feet.

The alluvium-lower Wilcox aquifer overlies the Midway confining unit. The alluvium-lower Wilcox is composed of sand and clay of the Paleocene and Eocene Wilcox Group, and sand and gravel of the Mississippi River alluvial aquifer west of its subcrop with the lower Wilcox aquifer. Thicknesses of the lower Wilcox sand and alluvium, respectively, range from a few feet to more than 600 feet, and from a few feet to about 250 feet.

The Mississippi embayment rift is one of the dominant tectonic features of the northern Mississippi embayment. As a zone of crustal weakness, the rift is thought to be a potential propagator of faults into the overlying younger rocks and sediments. The rift is a potential hydrologic boundary.

Water levels in each of the aquifers were used to estimate regional flow directions. Locally, flow in outcrop areas of all aquifers is toward streams; regionally, flow in all aquifers is toward the Mississippi embayment, which is topographically lower than the recharge areas.

Water-quality data were helpful in describing hydrogeologic boundaries. Specifically, zones of hydrothermal and anomalously warm water that occur in the Upper Cretaceous aquifer on the western and eastern sides, respectively, of the western margin of the Mississippi embayment rift are believed to be an indicator of recharge from a deeper aquifer. Anomalous chloride and dissolved solids concentrations suggest other areas where inter-aquifer leakage may be occurring.

Aquifer tests were used to estimate the range of transmissivity, hydraulic conductivity, and storage coefficients of all aquifers except the Ozark-St. Francois. Because no aquifer tests have been conducted in the Ozark-St. Francois aquifer within the study area, average hydraulic conductivity (0.9 ft/d) was extrapolated from tests made at other locations. Hydraulic conductivity was the main parameter of interest: for the Upper Cretaceous aquifer, hydraulic conductivity was reported to range from 10 to 75 ft/d; for the lower Wilcox aquifer, hydraulic conductivity was reported to range from 25 to 470 ft/d, and for the alluvium, hydraulic conductivity was reported to range from 60 to 450 ft/d. On the basis of values reported in the literature, the Midway confining unit was assumed to have a vertical hydraulic conductivity of 10^{-6} ft/d, and the Cretaceous-Paleozoic confining unit was assumed to have a vertical hydraulic conductivity of 10^{-4} ft/d where the dominant lithology was limestone and dolomite, and 10^{-5} ft/d where the dominant lithology was shale.

Pumping from the Ozark-St. Francois aquifer was about 3 million gallons per day in 1980 in the study area; pumping from the Upper Cretaceous aquifer for the same time period was about 21 million gallons per day. Pumping was concentrated in the "bootheel area" of Missouri and near the outcrop areas in Kentucky and Tennessee.

As a first step in modeling the Upper Cretaceous aquifer, all known facts were incorporated into a conceptual model. The conceptual model includes pertinent boundaries, initial conditions, hydraulic characteristics, and stresses, for each hydrogeologic unit of interest.

A four-layer finite difference numerical model was constructed and calibrated to simulate flow in the aquifers defined by the conceptual model. A 48 row by 52 column grid was used to divide the study area. Grid spacing was equidimensional, resulting in blocks 5 miles on a side. The aquifers previously discussed formed layers 2 through 4. Layer 1 is an inactive layer of constant heads that represent shallow water levels. Shallow water levels are a major control on recharge to and discharge from the regional system, and are used to calculate fluxes to the deeper aquifers.

Heads in confining units in the model are not actively simulated. A matrix of leakance values is used to allow vertical interchange of water between different aquifers. For confining unit B (Midway Confining Unit), leakance was calculated by dividing an average vertical hydraulic conductivity by thickness; for confining units A (undifferentiated Claiborne-upper Wilcox Confining Unit) and C (undifferentiated Cretaceous-Paleozoic confining unit), leakance is input by zones, which have an average vertical hydraulic conductivity divided by an average thickness. The model was calibrated to 1980 conditions on the assumption that 1980 represented near steady-state conditions. The model was considered to simulate observed heads within acceptable limits. For the Ozark-St. Francois aquifer, the root mean square error was 25 feet for 14 comparison points having both observed and calculated heads. Eight of 14 of the comparison points had calculated heads within 20 feet of observed. The maximum variation between calculated and observed heads was 53 feet. Twenty-one of 29 of the comparison points had calculated heads within 10 feet of observed. For the Upper Cretaceous aquifer, the root mean square error was 9.7 feet for 29 comparison points having both observed and calculated heads. The maximum variation between calculated and observed heads in the Upper Cretaceous aquifer was 26 feet.

For the preliminary calibrated model, calculated heads were found to be most sensitive to pumping, and least sensitive to the hydraulic conductivity of the confining layer that separates the aquifers. The sensitivity analysis was based on the response of the model to adjustments in (1) pumping from aquifer layer 4 (Ozark-St. Francois); (2) transmissivity of aquifer layer 4; (3) leakance of confining unit C (Cretaceous-Paleozoic confining unit); (4) pumping from aquifer layer 3 (Upper Cretaceous aquifer); (5) transmissivity of aquifer layer 3; and (6) leakance of confining unit B (Midway confining unit).

The results of this preliminary modeling effort contribute to a better understanding of the regional hydrologic budget. Model results indicate that upward leakage from the Ozark-St. Francois aquifer to the Upper Cretaceous aquifer is about 43 ft^3/s, with about 30 ft^3/s occurring west of the western margin of the embayment. The model also indicates that throughout most of its area of occurrence, the Midway (Confining Unit B) is an effective confining unit (about 3 ft^3/s net leakage). In the discharge area defined by the potentiometric map, the Upper Cretaceous aquifer is leaking about 49 ft^3/s upward to the overlying alluvium-lower Wilcox aquifer, mostly in the vicinity of the rift zone.

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