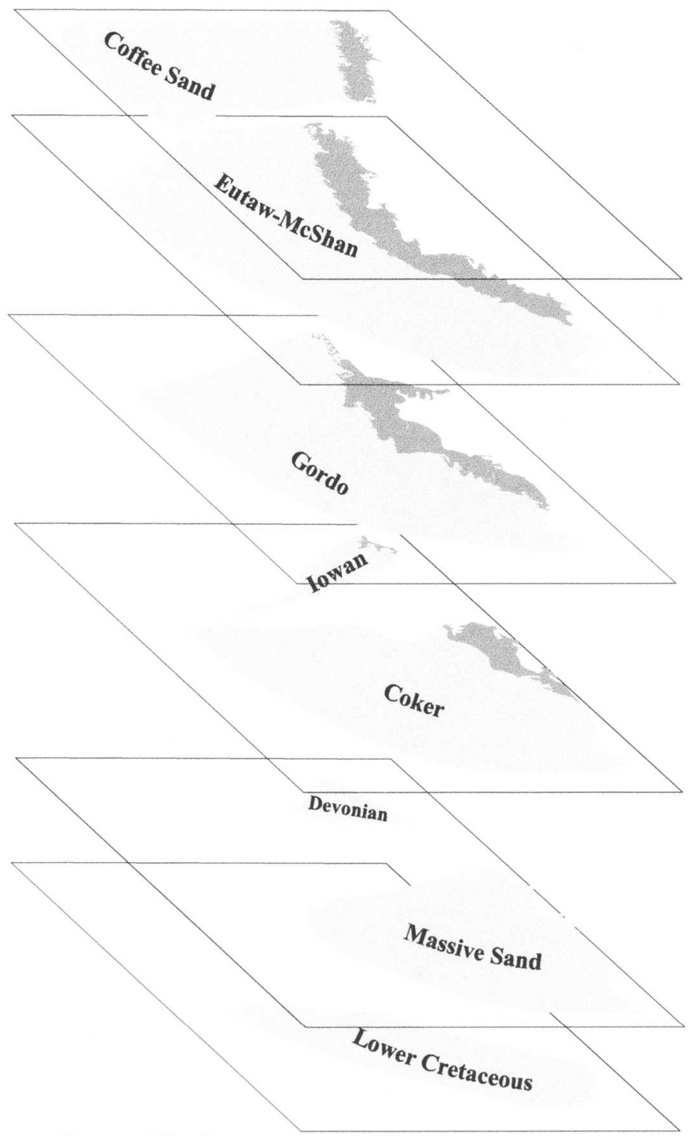
HYDROGEOLOGY AND SIMULATION OF GROUND-WATER FLOW IN THE CRETACEOUS-PALEOZOIC AQUIFER SYSTEM IN NORTHEASTERN MISSISSIPPI

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 98- 4171



Prepared in cooperation with the
MISSISSIPPI DEPARTMENT OF ENVIRONMENTAL QUALITY,
OFFICE OF LAND AND WATER RESOURCES

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By Eric W. Strom

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Jackson, Mississippi
1998

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS--Continued

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
foot	0.3048	meter
foot per day	0.3048	meter per day
inch	25.4	millimeter
mile	1.609	kilometer
million gallons per day	0.04381	cubic meter per second
cubic foot per second	0.02832	cubic meter per second
square mile	2.590	square kilometer
foot squared per day	0.0929	meter squared per day

Temperature in degrees Fahrenheit (°F) can be converted to degrees Celsius (°C) as follows: °C = (°F-32)/1.8.

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

The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness. In this report, the mathematically reduced form, foot squared per day, is used for convenience.

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ABSTRACT

An expansion was made of an existing model to incorporate new stratigraphic data, simulate the Coffee Sand aquifer, simulate aquifers in rocks of Paleozoic age, and incorporate new water-use data. The report describes the hydrogeology and simulations of ground-water flow in the Coffee Sand, Eutaw-McShan, Gordo, Coker, massive sand, and Lower Cretaceous aquifers, and two aquifers informally referred to in this report as the Iowa aquifer and the Devonian aquifer. The study area covers 34,960 square miles, primarily in northeastern Mississippi, but includes parts of northwestern Alabama, southwestern Tennessee, and eastern Arkansas. The finite-difference computer code MODFLOW was used to simulate the aquifers.

Simulations of 1995 ground-water flow conditions were made using hydraulic parameters determined during transient model calibration. Simulated 1995 conditions indicate for the Coffee Sand aquifer about 40 percent of the water entering the aquifer is captured by pumping wells, and about 60 percent of the water enters the underlying Eutaw-McShan aquifer. About 57 percent of recharge to the Eutaw-McShan aquifer enters through the outcrop area; the rest is from overlying and underlying aquifers. Model results indicate that water levels for the Gordo aquifer have continued to rise rapidly in the Lee County area from 1992 to 1995. Water levels in other areas have changed little from the 1992 simulated water levels. Much of the water that the Coker aquifer receives flows down to the underlying massive sand aquifer. The massive sand aquifer exchanges only minor flow with the underlying Lower Cretaceous aquifer. There is a small amount of ground water exchanged between the Iowa aquifer and the Devonian aquifer. Most of this water enters the Devonian aquifer near the updip limit of the Iowa aquifer where there is little separation between the two aquifers.

INTRODUCTION

Ground water from aquifers in formations of Cretaceous and Paleozoic age is an important resource to the counties of northeastern Mississippi, supplying most of the water used for industrial, municipal, and commercial purposes. Through time, increased pumpage resulted in large water-level declines at major pumping centers. In the late 1980's, water levels in the confined part of the Eutaw-McShan aquifer may have declined sufficiently to reach the upper part of the Eutaw Formation in the Tupelo, Mississippi, area (Jennings and others, 1994). As a result of the water-level declines, in 1987 the Permit Board of the State of Mississippi declined to issue permits for additional water wells in the City of Tupelo, and in 1991 the city began using surface water.

An investigation was begun in 1990 of the aquifers in northeastern Mississippi to better understand the hydrogeology and the flow of water in and between the aquifers, and to provide information necessary for water managers to address ground-water resource problems. As part of the investigation, a ground-water flow model was developed in cooperation with the Office of Land and Water Resources (OLWR) of the Mississippi Department of Environmental Quality (DEQ) to simulate ground-water flow (Strom and Mallory, 1995). The development of this model identified areas in far northeastern Mississippi where additional information was needed regarding the occurrence and relation among the Eutaw-McShan and Gordo aquifers and the underlying rocks of Paleozoic age. A subsequent drilling program by the OLWR provided additional data (Jennings, 1996). Maps were constructed showing the thicknesses, boundaries, and confinement of two aquifers in rocks of Paleozoic age (S.P. Jennings, OLWR, written commun., 1997). In addition to the new information regarding the Paleozoic aquifers, the OLWR provided extensive water-use data for northeastern Mississippi. Available ground-water withdrawal data for industrial and public supply wells of record with a diameter of 4 inches or greater were compiled for the period 1900 to 1995 for aquifers in northeastern Mississippi (J.H. Hoffmann and A.J. Warner, OLWR, written commun., 1997).

In October 1996, the U.S. Geological Survey (USGS), in cooperation with the OLWR, began a project to expand the existing ground-water flow model for northeastern Mississippi (Strom and Mallory, 1995). The expanded model would incorporate stratigraphic data collected by the OLWR subsequent to the completion of the previous model, simulate the Coffee Sand aquifer, simulate additional aquifers in rocks of Paleozoic age, and incorporate water-use data collected by the OLWR.

Purpose and Scope

This report describes the hydrogeology and simulations of ground-water flow in the Coffee Sand, Eutaw-McShan, Gordo, Coker, massive sand, and Lower Cretaceous aquifers, and two aquifers recently delineated in Paleozoic rocks in northeastern Mississippi. The report includes descriptions of the aquifers and of a numerical ground-water flow model used to simulate the aquifers. The scope of the report is limited to discussions on predevelopment and 1995 ground-water flow conditions. This report is intended to aid the public and Federal, State, and local water-supply and water-management agencies in planning ground-water use.

General Setting of the Study Area

The study area covers 34,960 square miles, primarily in northeastern Mississippi, but includes parts of northwestern Alabama, southwestern Tennessee, and eastern Arkansas (fig. 1). The area includes the extent of the aquifers that are a source of freshwater in sediments and rocks of Cretaceous and Paleozoic age (excluding the Cretaceous Ripley aquifer) and adjacent areas that affect ground-water flow and availability of water in northeastern Mississippi.

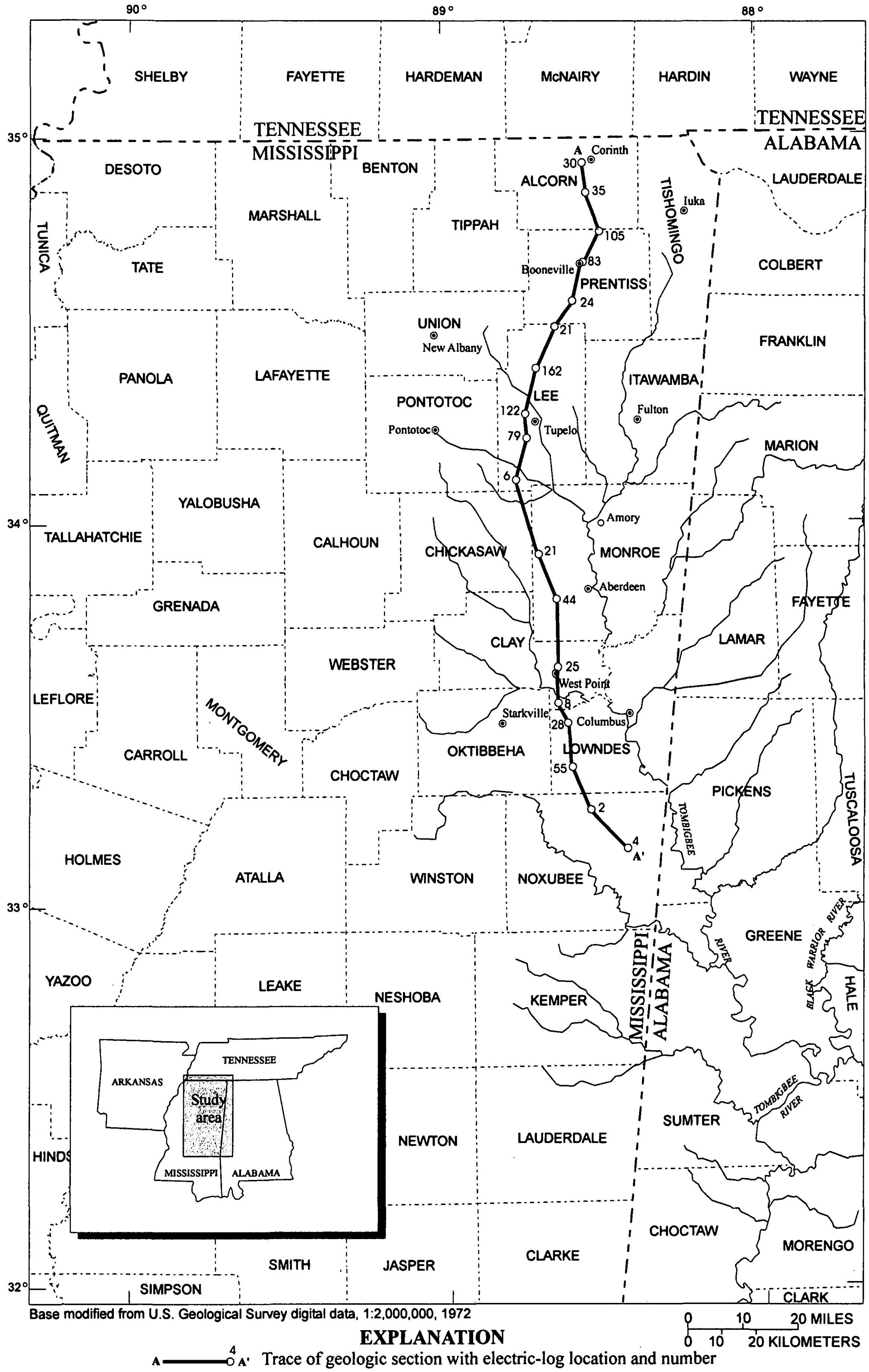

Figure 1. Location of the study area and trace of geologic section.

The study area is within the Gulf Coastal Plain physiographic province, mainly on the eastern flank of the Mississippi embayment subprovince (Mallory, 1993). Regionally, the study area is topographically highest in the northeastern part, and topographically lowest in the southeastern and western parts (fig. 2). The major surface-water drainages influencing flow in the aquifers studied are the Tombigbee and Black Warrior Rivers (fig.1). The climate of the study area is semitropical and humid, with a mean annual air temperature between 62 and 64 degrees Fahrenheit (Boswell, 1963).

Previous Investigations

Reports from previous investigations were published by the U.S. Geological Survey; the Mississippi Department of Environmental Quality, Office of Land and Water Resources; the Mississippi Geological Survey; the Mississippi Board of Water Commissioners; the Mississippi Research and Development Center; other State and Federal agencies; and others. Relevant investigations of the geology and hydrology have been reported by Boswell (1963, 1977, 1978), Boswell and others (1965), Cushing (1966), Hardeman (1966), Bicker (1969), Gandl (1982), Davis (1987), Mallory (1993), and Jennings (1994, 1996). Appraisals of the ground-water resources and water-use data have been reported by Crider and Johnson (1906), Stephenson and others (1928), Lang and Boswell (1960), Wasson and Thomson (1970), Newcome (1971), Callahan (1979), Wasson (1986), Slack and Darden (1991), and Oakley and Burt (1992). Potentiometric maps of the aquifers include Wasson (1979, 1980a, 1980b, 1980c), Darden (1984, 1985), Goldsmith (1990, 1991), Everett and Jennings (1994), Hoffmann and Hardin (1994), Jennings and Phillips (1994), Jennings and others (1994), Hardin and Everett (1994), and Phillips and Hoffmann (1994). Digital computer ground-water flow model studies including all or parts of the study area are reported by Gardner (1981), Kernodle (1981), Planert and Sparkes (1985), Mallory (1993), and Strom and Mallory (1995).

Acknowledgments

The author would like to thank several OLWR personnel for their contributions to this report: Ernest H. Boswell, Jo F. Everett, David L. Hardin, James H. Hoffmann, Stephen P. Jennings, and Patricia A. Phillips for the analyses of most of the borehole-geophysical log information used this study; Rodger Bergeron, James H. Hoffmann, Sherry Truesdill, A. John Warner, and L. Wayne Williams II for the collection and analyses of water-use information; and Stephen P. Jennings for information regarding the Paleozoic aquifers.

HYDROGEOLOGY

The eight aquifers studied, from youngest to oldest, are the Coffee Sand, Eutaw-McShan, Gordo, Coker, massive sand, and Lower Cretaceous aquifers, and two aquifers recently delineated in Paleozoic rocks. One of the Paleozoic aquifers comprises formations in what is referred to in Mississippi as the Iowa group (Jennings, 1994, OLWR) and is informally referred to in this report as the Iowa group and the Iowa aquifer, respectively. The other Paleozoic aquifer comprises Devonian chert and is

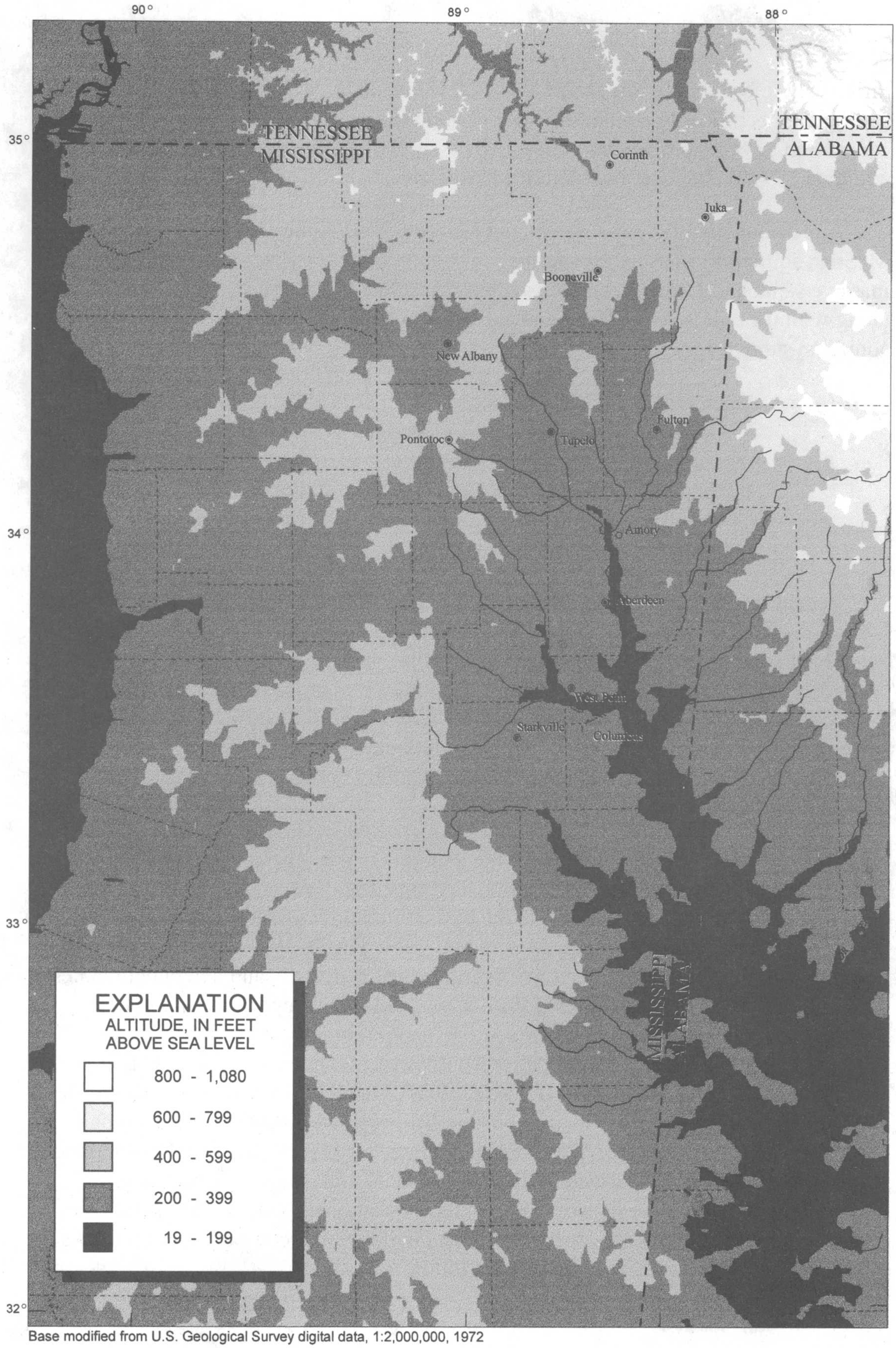

Figure 2. Average land-surface altitude in each square mile of the study area.

informally referred to in this report as the Devonian aquifer (fig. 3). Other Paleozoic geologic units probably contain freshwater in northeastern Mississippi, but they are not considered to be significant aquifers in Mississippi (S.P. Jennings, OLWR, written commun., 1998) and were not included in this investigation.

A previous investigation (Strom and Mallory, 1995) indicated that the Eutaw-McShan aquifer and Tuscaloosa aquifer system (which comprises the Gordo, Coker, massive sand, and Lower Cretaceous aquifers) collectively comprise an aquifer system along with the overlying Coffee Sand aquifer. Poland and others (1972) have defined an aquifer system as follows:

> A heterogeneous body of intercalated permeable and poorly permeable material that functions regionally as a water-yielding hydraulic unit; it comprises two or more permeable beds [aquifers] separated at least locally by aquitards [confining units] that impede ground-water movement but do not greatly affect the regional hydraulic continuity of the system.

Recent investigations indicate that the Iowa and Devonian aquifers are probably in hydraulic connection with the Eutaw-McShan and Gordo aquifers in far northeastern Mississippi (Jennings, 1994; Jennings and Phillips, 1994; Jennings, 1996; S.P. Jennings, OLWR, written commun., 1997). Using the definition of an aquifer system given by Poland (1972), this report informally uses the term "Cretaceous-Paleozoic aquifer system" to collectively refer to the Coffee Sand, Eutaw-McShan, Gordo, Coker, massive sand, Lower Cretaceous, Iowa, and Devonian aquifers in northeastern Mississippi.

Geologic and hydrologic data provided most of the necessary information for the interpretation and conceptualization of the aquifer system. About 600 borehole-geophysical logs and drillers' information, combined with pertinent stratigraphic and hydrologic data, were used to provide the basis for the identification, definition, and correlation of areally extensive hydrogeologic units. The OLWR provided most of the borehole-geophysical log analyses, including interpretation of sand and clay thickness data used in this report. Additional information used in this report pertaining to the physical boundaries of the individual aquifers and intervening confining units are reported by Mellen (1958), Boswell (1963), Boswell and others (1965), Cushing (1966), Hardeman (1966), Bicker (1969), Boswell (1978), Gandl (1982), Wasson (1986), Davis (1987), and Mallory (1993), Jennings (1994), Strom and Mallory (1995), Jennings (1996), and S.P. Jennings (OLWR, written commun., 1997). Hydraulic characteristics of aquifers and confining units were initially estimated from analyses of borehole-geophysical and lithologic logs of water wells and test holes, data on the specific capacity of water wells, and aquifer tests. A generalized hydrogeologic section (fig. 4) shows the general northeast to southwest dip of the aquifer units.

Erathem	System	Series	Group	Geologic unit	Principal aquifer or aquifer system	Model layers[1]
Cenozoic	Tertiary	Eocene	Wilcox Group	Hatchetigbee Formation		
				Tuscahoma Formation	Lower Wilcox aquifer	
				Nanafalia Formation	Lower Wilcox aquifer	
		Paleocene	Midway Group	Naheola Formation	Lower Wilcox aquifer	
				Porters Creek Clay		
Mesozoic	Cretaceous	Upper Cretaceous	Selma Group	Prairie Bluff Chalk and Owl Creek Formation		
				Ripley Formation	Ripley aquifer	
				Demopolis Chalk		
				Coffee Sand / Mooreville Chalk	Coffee Sand aquifer (Cretaceous-Paleozoic aquifer system)	1
			Eutaw Group	Eutaw Formation Tombigbee Sand Member McShan Formation	Eutaw-McShan aquifer (Cretaceous-Paleozoic aquifer system)	2
			Tuscaloosa Group	Gordo Formation	Gordo aquifer (Tuscaloosa aquifer system; Cretaceous-Paleozoic aquifer system)	3
				Coker Formation	Coker aquifer (Tuscaloosa aquifer system; Cretaceous-Paleozoic aquifer system)	4
				Massive sand	Massive sand aquifer (Tuscaloosa aquifer system; Cretaceous-Paleozoic aquifer system)	5
		Lower Cretaceous		Undifferentiated	Lower Cretaceous aquifer (Tuscaloosa aquifer system; Cretaceous-Paleozoic aquifer system)	6
Paleozoic	Mississippian			Tuscumbia Formation Fort Payne Formation	Iowa aquifer (Paleozoic aquifer system; Cretaceous-Paleozoic aquifer system)	4
	Devonian			Chatanooga Shale	(Paleozoic aquifer system; Cretaceous-Paleozoic aquifer system)	
				Harriman Formation Flat Gap Limestone Ross Formation	Devonian aquifer (Paleozoic aquifer system; Cretaceous-Paleozoic aquifer system)	5

[1]Discussed in the "Grid Design" section later in the report

Figure 3. Geologic units and principal aquifers in the study area (modified from Slack and Darden, 1991; Jennings, 1994).

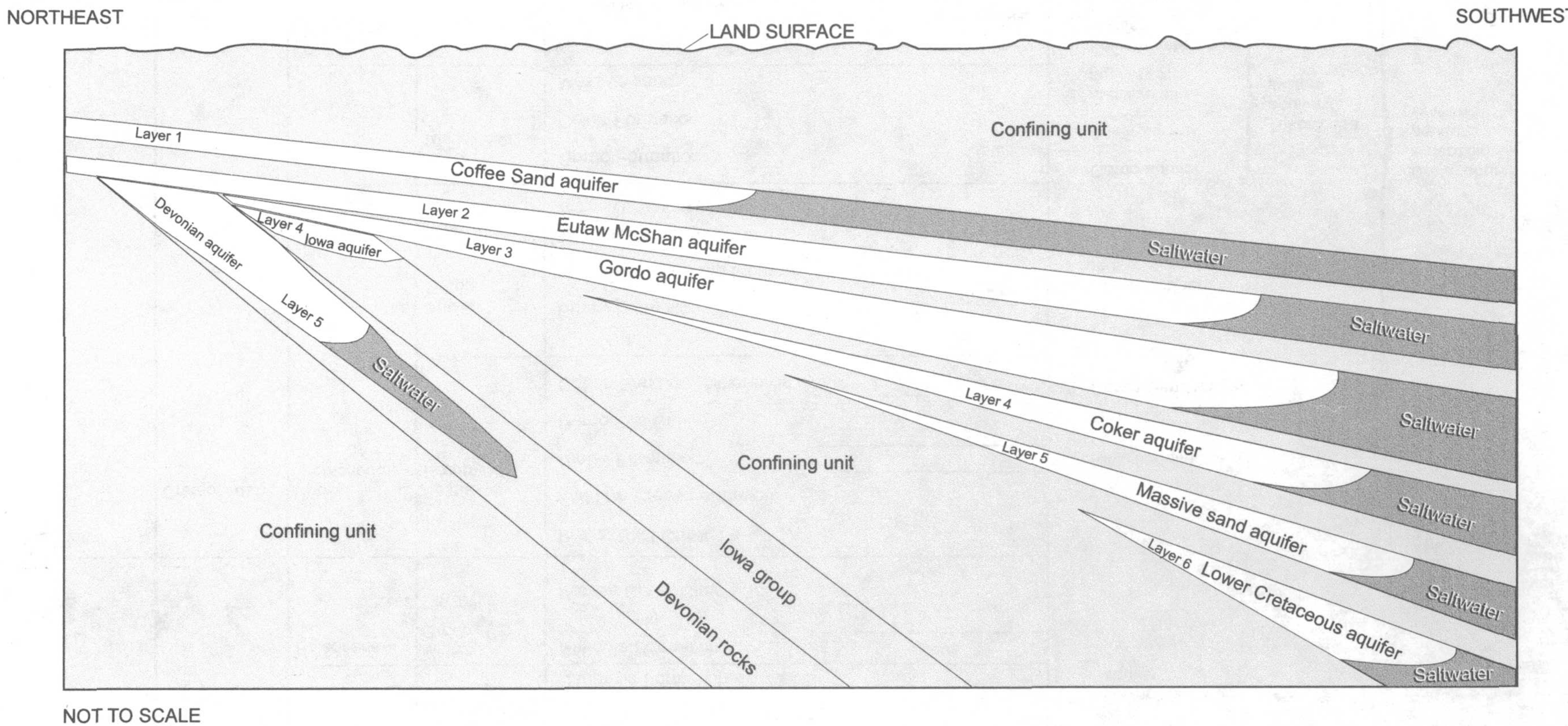

Figure 4. Diagrammatic hydrogeologic section showing the northeast to southwest dip and generalized relation of hydrogeologic units in the study area.

Geologic Setting

The geologic setting of the study area is described by Cushing and others (1964) as resulting from subsidence that may have begun during the late Paleozoic Era and continued through the Cretaceous Period. This subsidence formed the basins of the Gulf Coast geosyncline and of the southward plunging syncline of the Mississippi embayment. However, most of the syncline of the Mississippi embayment was not formed by the end of the Paleozoic Era. During the Jurassic Period of the Mesozoic Era is when evidence of a sedimentary basin became observable. By the end of the Cretaceous Period, the Mississippi embayment had formed the approximate size and shape present today. Since the Cretaceous Period, cyclic transgression and regression of the sea have subsequently deposited an assorted, but ordered array of sediments on top of Paleozoic rocks within the Mississippi embayment in northeastern Mississippi. The nature of the sediments is directly related to past depositional environments, which in turn are related to fluctuations of sea level and the shifting of the shoreline. The sediments include gravel, sand, clay, chalk, and marl of fluvial-deltaic, continental and marine shelf origins. Older geologic units crop out in northeastern Mississippi, and sequentially younger units are present at land surface to the west and south toward the axis of the Mississippi embayment. The dip of the Cretaceous units generally is toward the axis of the embayment, averaging about 40 feet per mile (Boswell and others, 1965), and the sediments generally become thicker downdip. The dip of the Paleozoic formations in northeastern Mississippi generally is toward the south-southwest, ranging from 25 to 50 feet per mile (Jennings, 1994). Geologic units that crop out in the study area range in age from the Quaternary to Devonian Periods. A geologic section (fig. 5) shows the northeast to southwest dip, and the relation of the geologic units.

Cretaceous Aquifers

All of the major Cretaceous aquifers in Mississippi were studied in this investigation with the exception of the Ripley aquifer (fig. 3). The Ripley aquifer is not hydraulically connected with the underlying Cretaceous aquifers due to a thick sequence of chalk, whereas the underlying Cretaceous aquifers are hydraulically connected. The Cretaceous aquifers in northeastern Mississippi consist primarily of unconsolidated deposits of clay, silt, sand, and gravel typical of the larger Southeastern Coastal Plain aquifer system.

Coffee Sand Aquifer

The Coffee Sand aquifer crops out predominantly in northeastern Mississippi and in eastern Tennessee (fig. 6). Although outcrops of the Coffee Sand aquifer occur as far north as southern Illinois, the aquifer in Mississippi appears to be a continuous unit extending northward to roughly an east-west line about 10 miles north of the Mississippi-Tennessee state line (E.F. Hollyday, USGS, oral commun., 1997; W.S. Parks, USGS, oral commun., 1997). To the west, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. To the south the aquifer is limited by a facies change where the sand grades into chalk (Mellen, 1958). The aquifer dips about 35 feet per mile westward toward the axis of the Mississippi embayment (Boswell, 1965).

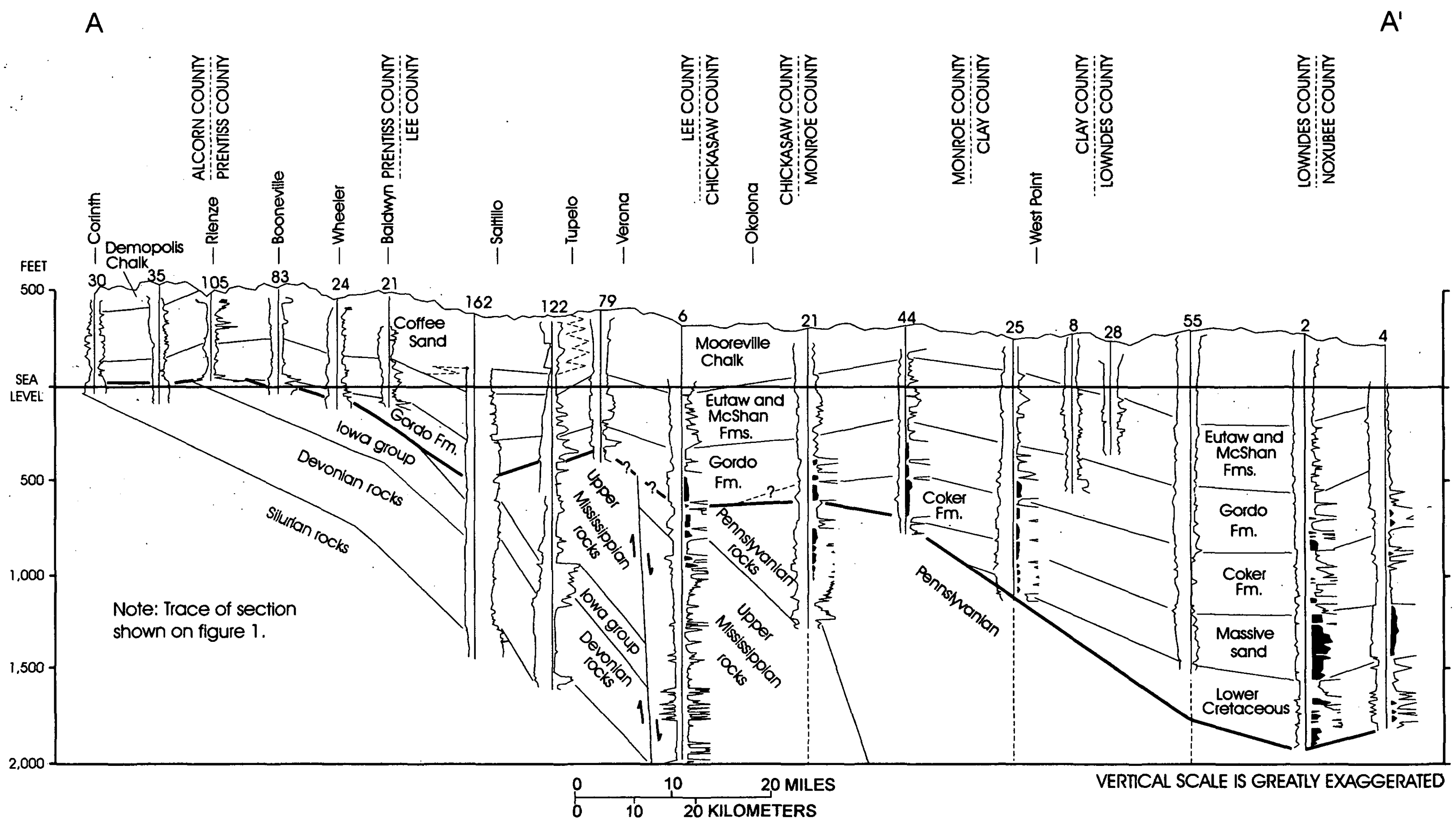

Figure 5. Geologic section showing relation of geologic units in northeastern Mississippi (modified from Boswell, 1978; J. H. Hoffmann and S.P. Jennings, OLWR, written commun., 1998).

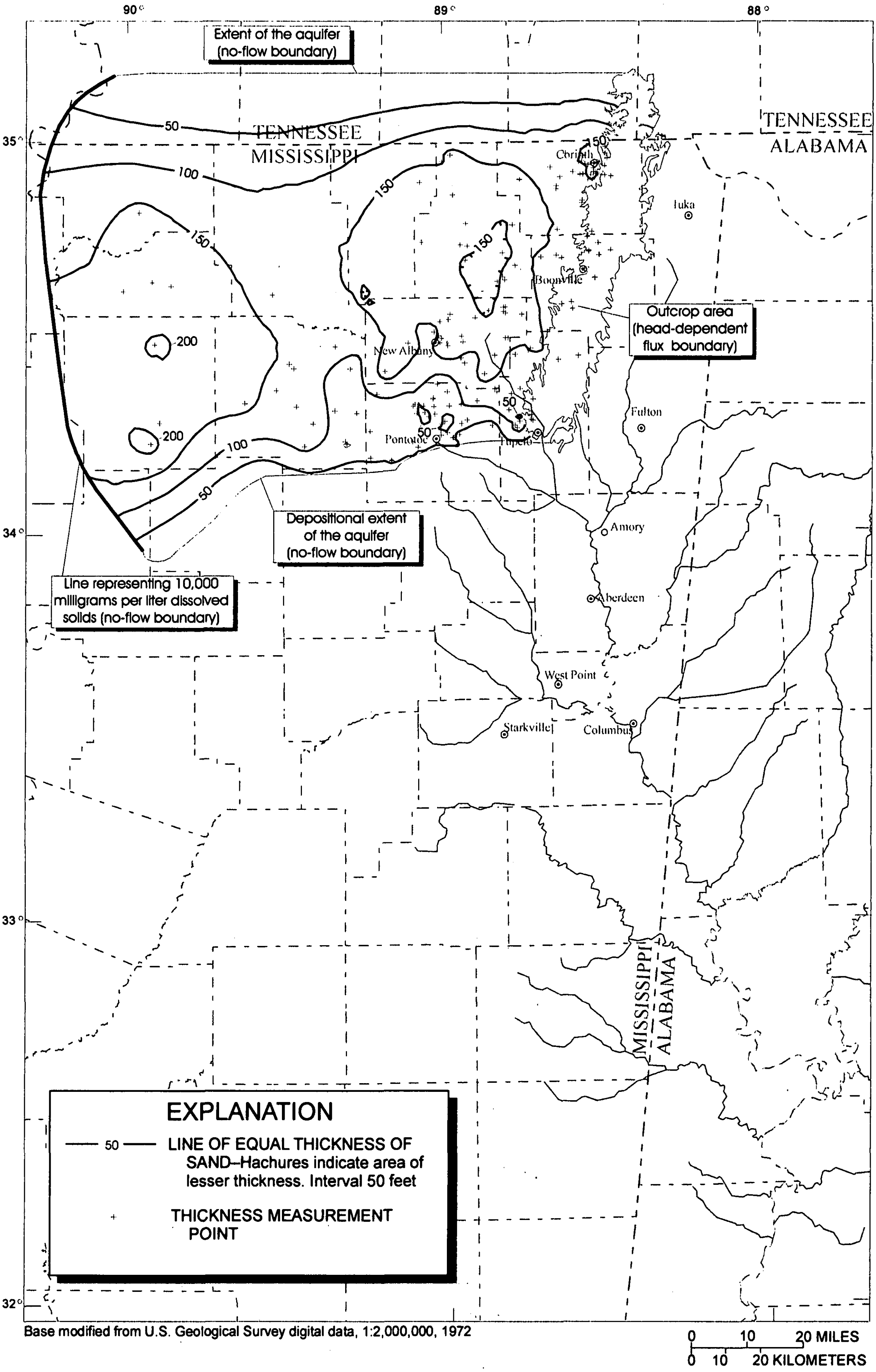

Figure 6. Extent and total sand thickness of the Coffee Sand aquifer and location of measurements.

The Coffee Sand aquifer generally is composed of fine to medium quartz sand that is generally calcareous and glauconitic, with lenses of silty sand and clay (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot in the eastern part of the outcrop area to more than 200 feet in the western part of the study area (fig. 6). The sand is thinnest near the outcrop and generally thickens downdip. Horizontal hydraulic conductivity values reported by Slack and Darden (1991) range from about 10 to 40 feet per day.

The Coffee Sand aquifer receives the majority of recharge from precipitation in the outcrop area. Water-level data indicate that discharge from the aquifer is to topographic lows in the outcrop area, to downdip areas of the Eutaw-McShan aquifer (Wasson, 1980a; Hoffmann and Hardin, 1994), and to wells screened in the aquifer. The Coffee Sand aquifer is well confined from overlying aquifers by a thick sequence of chalk of the Demopolis Chalk Formation.

Eutaw-McShan Aquifer

The Eutaw-McShan aquifer includes sediments of the Eutaw and McShan Formations (fig. 3). In Mississippi these formations are considered a single aquifer because the sands are hydraulically connected; however, intervening beds of clay and silt may result in localized vertical head gradients.

The Eutaw-McShan aquifer crops out primarily in the northeastern part of Mississippi and northwestern part of Alabama within the study area (fig. 7). The northern and northwestern extent of the aquifer is the extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile westward toward the axis of the Mississippi embayment in the northern part, and dips southwestward in the southern part.

The uppermost part of the Eutaw-McShan aquifer has a finer grain size and a larger silt content than the rest of the aquifer and is called the Tombigbee Sand Member. The Tombigbee Sand Member produces little water. The remainder of the Eutaw-McShan aquifer mainly consists of thin beds of fine to medium glauconitic sand (Boswell, 1963). Analysis of well-log data indicates that total sand thickness within the study area ranges from about 1 foot in the eastern part of the outcrop area to more than 300 feet in the southwestern part and southern part of the study area (fig. 7). An average horizontal hydraulic conductivity value of 12 feet per day, based on the results of 50 aquifer tests, was reported by Slack and Darden (1991).

The Eutaw-McShan aquifer receives recharge from precipitation in the outcrop area. Smaller amounts of recharge also come from overlying and underlying aquifers (Mallory, 1993; Strom and Mallory, 1995). Water-level data indicate that discharge from the aquifer is to topographic lows in the outcrop area, and to the Tombigbee and Black Warrior Rivers from upward leakage through units of the Selma Group (Wasson, 1980b; Gardner, 1981). The aquifer may also discharge water to the Gordo aquifer in parts of the

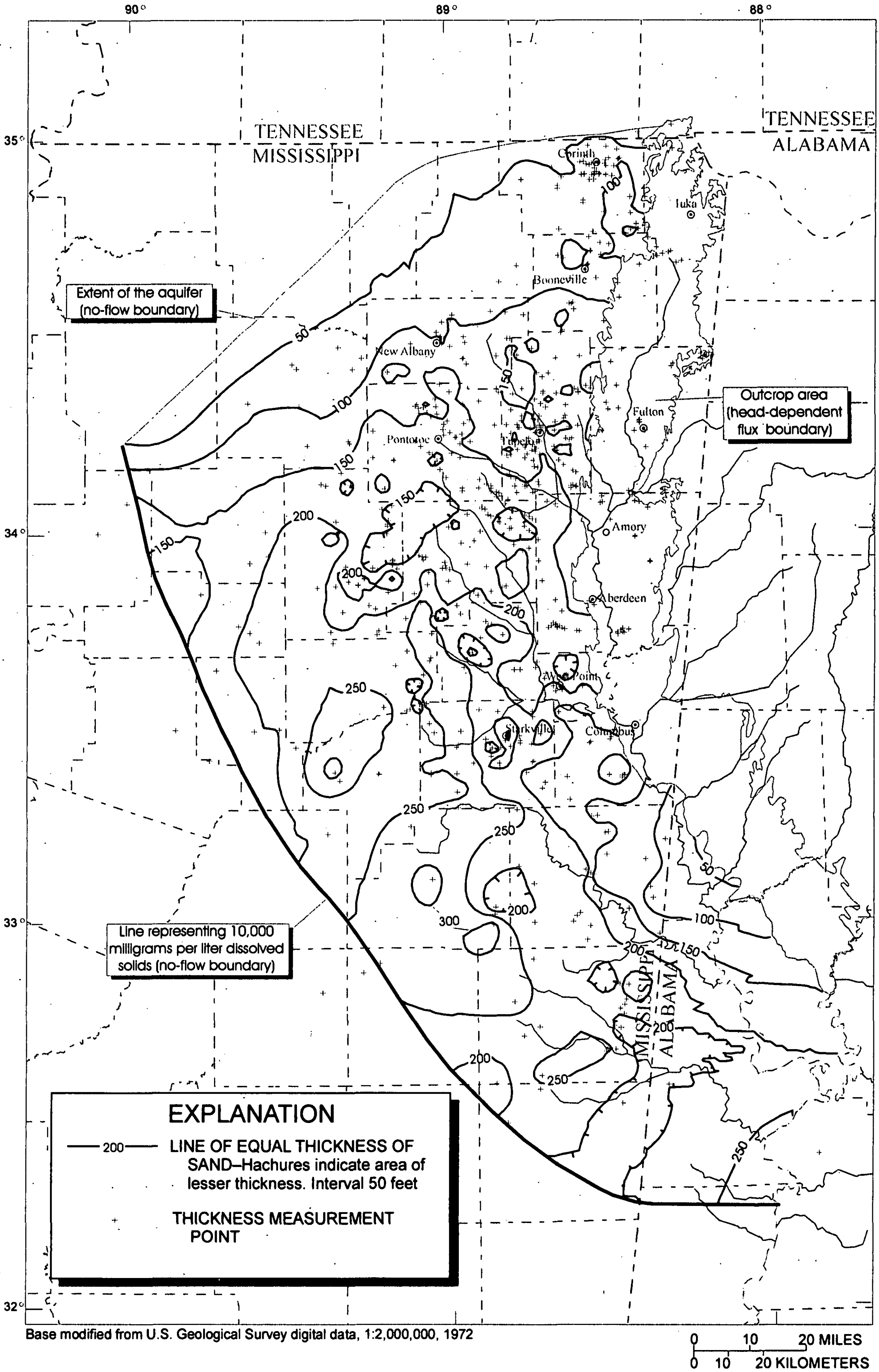

Figure 7. Extent and total sand thickness of the Eutaw-McShan aquifer and location of measurements.

updip area (J.H. Hoffmann, OLWR, oral commun., 1994), and to wells screened in the aquifer.

The geologic units overlying the Eutaw-McShan aquifer in the study area, from youngest to oldest, are the Wilcox Group; the Naheola Formation, Porters Creek Clay, and Clayton Formation of the Midway Group; and the Owl Creek Formation, Prairie Bluff Chalk, Ripley Formation, Demopolis Chalk, Coffee Sand, and Mooreville Chalk of the Selma Group (fig. 3). The Coffee Sand aquifer overlies the Eutaw-McShan aquifer, and is in turn overlain by the Ripley and lower Wilcox aquifers. The Eutaw-McShan aquifer is separated from the Coffee Sand by the Mooreville Chalk south of an approximate east-west line at about the latitude of the Union and Pontotoc County boundary. North of this line the Mooreville Chalk is absent, and the Eutaw-McShan aquifer is in contact with the Coffee Sand aquifer. However, data indicate that the Tombigbee Sand Member is very fine grained in this area and effectively acts as a confining unit, hydraulically separating the Eutaw-McShan and Coffee Sand aquifers (S.P. Jennings, OLWR, oral commun., 1994). The Eutaw-McShan aquifer is separated from the overlying Ripley and Wilcox aquifers by thick sequences of clay and chalk in the Selma and Midway Groups.

Gordo Aquifer

The Gordo aquifer crops out in extreme northeastern Mississippi and in northwestern Alabama (fig. 8). The northern and northwestern extent of the aquifer is the extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile westward toward the axis of the Mississippi embayment in the northern part of the study area, and dips southwestward in the southern part.

The lower part of the Gordo aquifer generally is composed of coarse quartz sand and chert gravel, and the upper part is interbedded sand and clay (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot in the eastern part of the outcrop area to about 350 feet in the western part of the study area (fig. 8). The sand is thinnest near the outcrop and generally thickens downdip. An average horizontal hydraulic conductivity value of about 48 feet per day, based on the results of 33 aquifer tests, was reported for the aquifer (Slack and Darden, 1991).

The Gordo aquifer receives recharge from precipitation in the outcrop area. Recharge also enters the aquifer from overlying and underlying aquifers (Mallory, 1993; Strom and Mallory, 1995). Water-level data indicate that discharge from the aquifer is to topographic lows in the outcrop area, and to the Eutaw-McShan aquifer in the Tombigbee and Black Warrior River valley areas (Wasson, 1980c; Gardner, 1981). Available water-level data indicate that the aquifer also discharges water to the Eutaw-McShan aquifer in parts of the downdip area, to the Coker aquifer in the updip area (J.H. Hoffmann, OLWR, oral commun., 1994), and to wells screened in the aquifer.

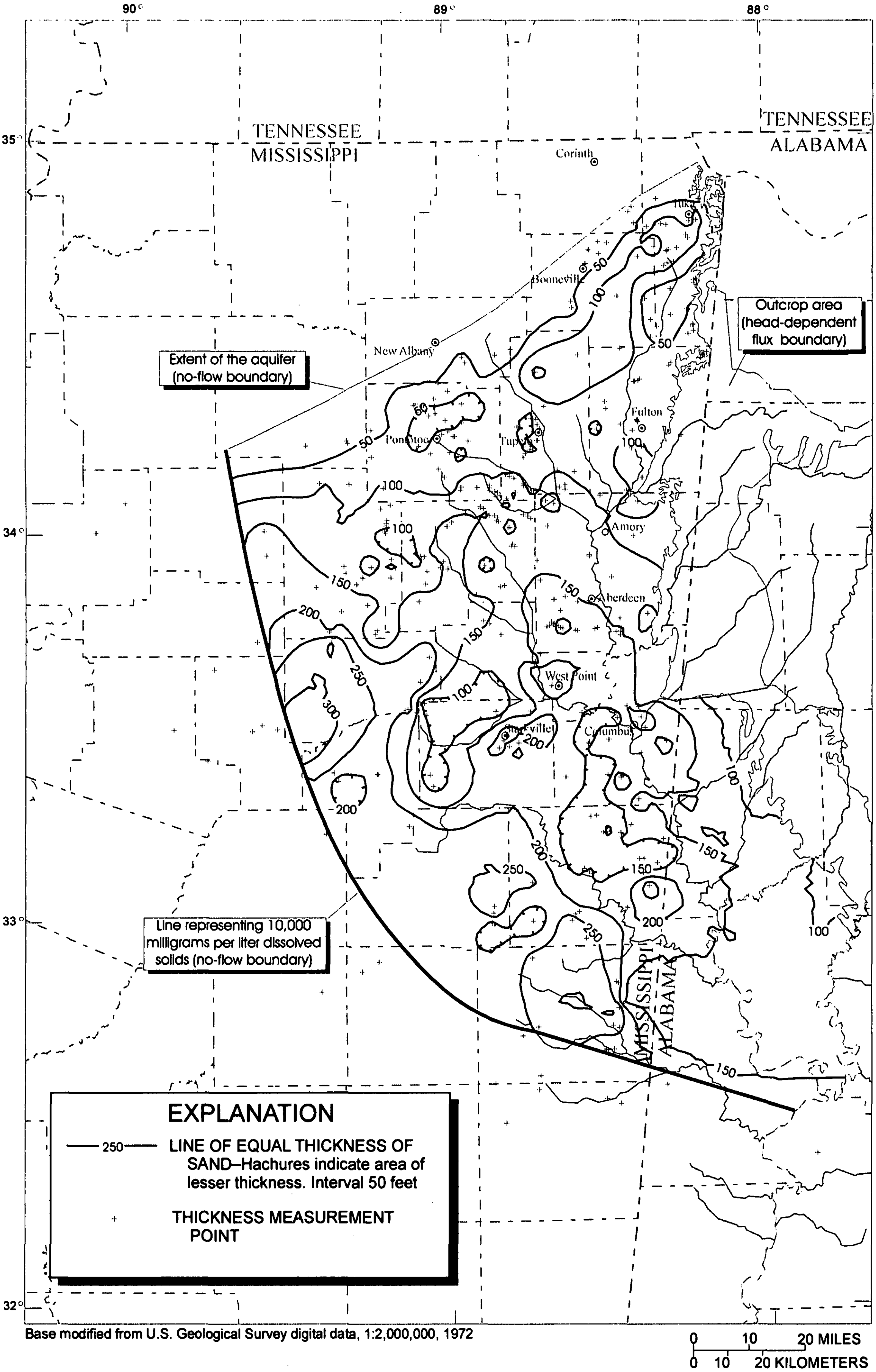

Figure 8. Extent and total sand thickness of the Gordo aquifer and location of measurements.

The Gordo aquifer is confined beneath the overlying Eutaw-McShan aquifer by clay and silt. Well-log data indicate that total clay thickness of the confining unit in the study area is thin in the eastern part of the outcrop area and occurs locally to about 175 feet in the southern part of the study area.

Coker Aquifer

The Coker aquifer does not crop out in Mississippi, but does crop out in the adjacent northwestern part of Alabama (fig. 9). The northern and northwestern extent of the aquifer is the extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile toward the southwest.

The Coker aquifer is composed of interbedded gray shale and lenticular beds of fine to medium sand (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot in the eastern part of the outcrop area to more than 300 feet in the western part of the study area (fig. 9). The sand is thinnest near the outcrop and generally thickens downdip. Horizontal hydraulic conductivity values range from 39 to 93 feet per day (Slack and Darden, 1991).

The Coker aquifer receives recharge from precipitation in the outcrop area. Recharge also enters the aquifer from overlying and underlying aquifers (Mallory, 1993; Strom and Mallory, 1995). Water-level data indicate that discharge from the aquifer is to topographic lows in the outcrop area. Limited water-level data indicate that the aquifer also may discharge water to the Gordo aquifer in the downdip area, and to the massive sand aquifer in the updip area (J.H. Hoffmann, oral commun., 1994), in addition to wells screened in the aquifer.

The Coker aquifer is confined from the overlying Gordo aquifer by clay and silt. Well-log data indicate that total clay thickness within the study area for the confining unit ranges from about 1 foot in part of the outcrop area to about 175 feet locally in the southern part of the study area.

Massive Sand Aquifer

The massive sand aquifer is often considered a lower part of the Coker aquifer. The easternmost limit of the massive sand aquifer is assumed coincident with the Coker aquifer in this study (fig. 10). However, west of the area where the massive sand underlies the Coker outcrop area, a confining clay unit is present that thickens to the west and effectively separates the two aquifers. The northern and northwestern extent of the aquifer is the extent of the sediments. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations. The aquifer dips about 35 to 40 feet per mile toward the southwest.

The massive sand aquifer predominantly contains nonmarine medium to coarse, brown to white quartz sand, commonly with a lower chert and quartz pea gravel

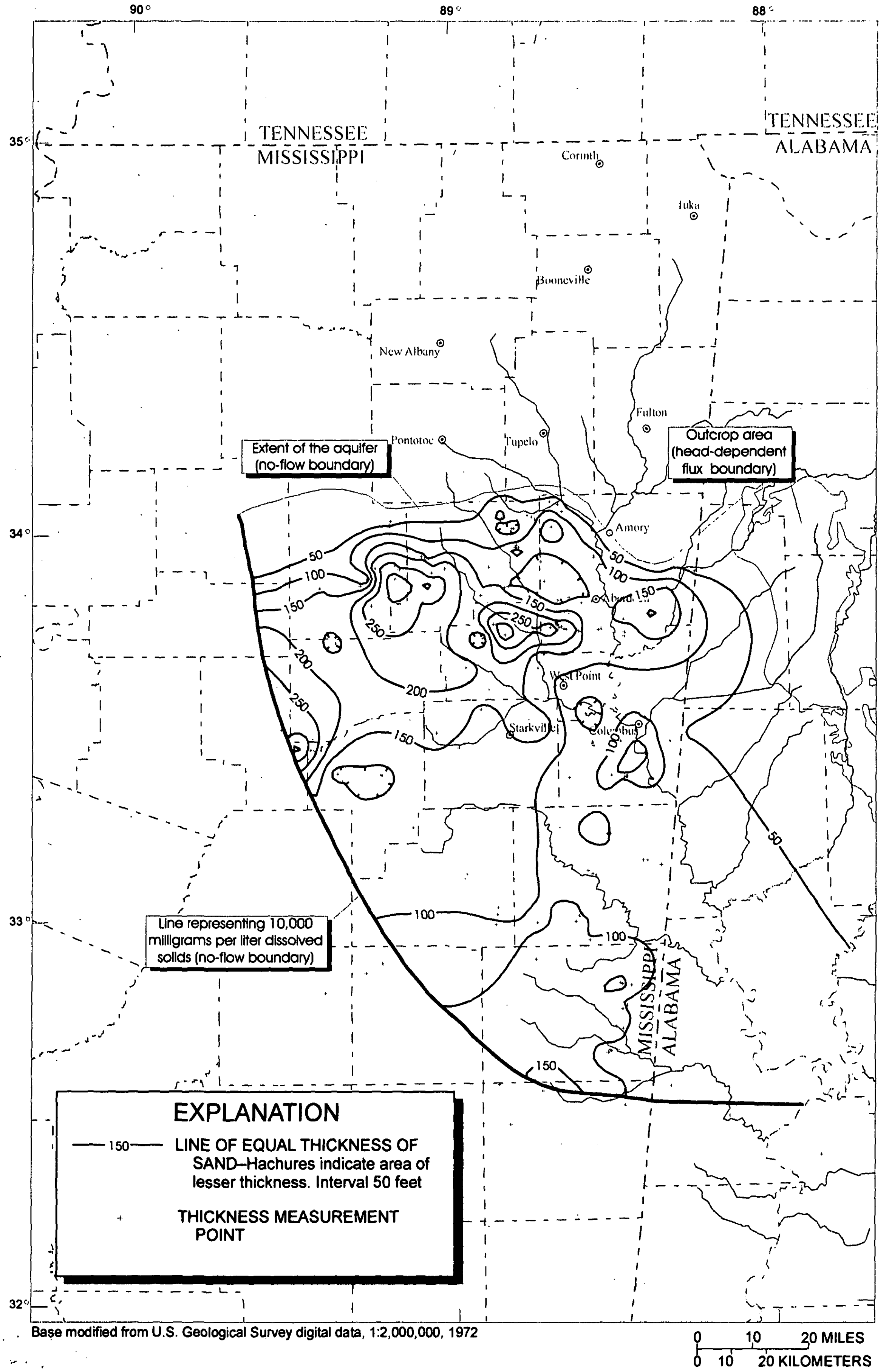

Figure 9. Extent and total sand thickness of the Coker aquifer and location of measurements.

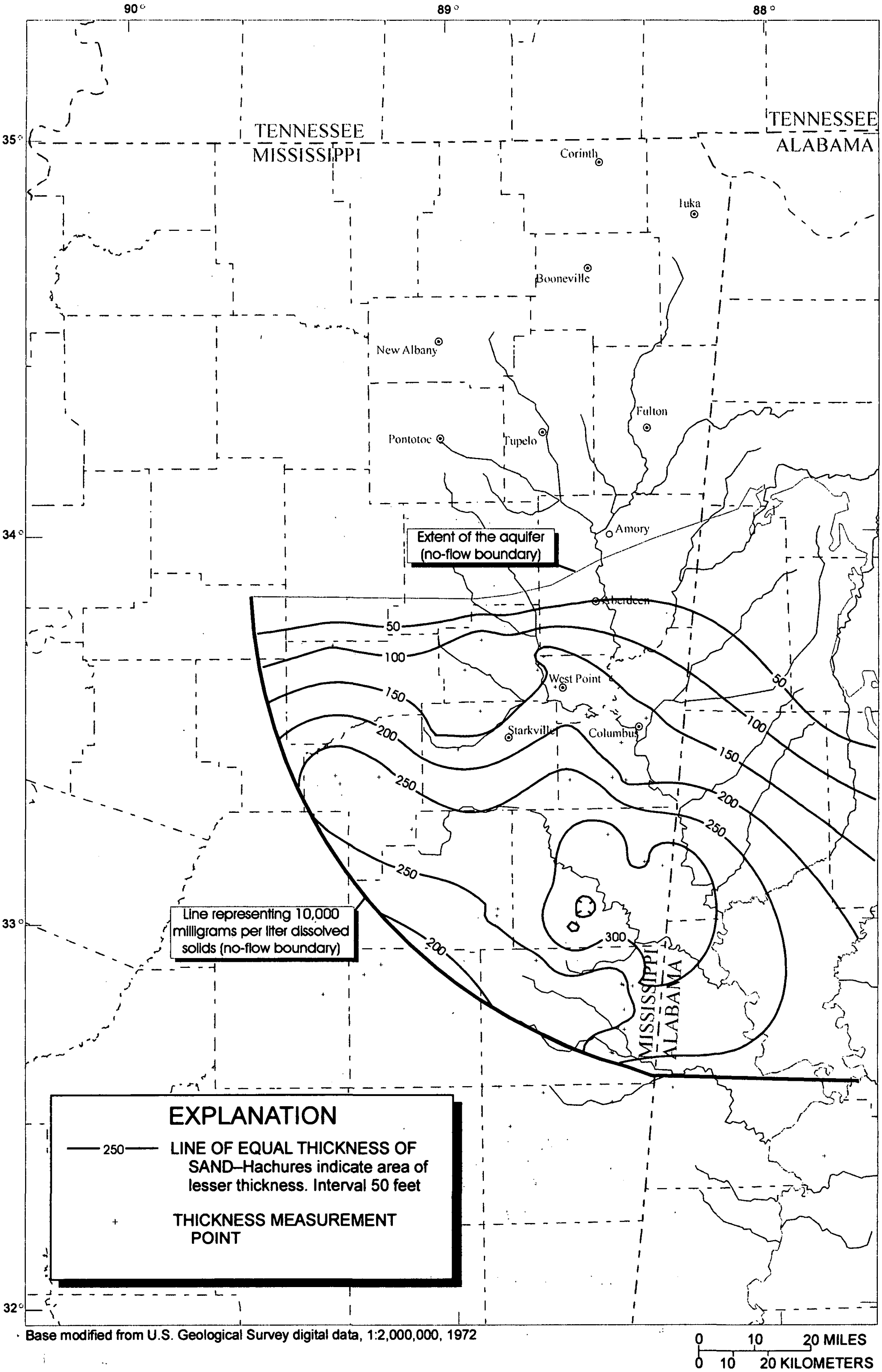

Figure 10. Extent and total sand thickness of the massive sand aquifer and location of measurements.

(Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot in the eastern part of the study area to more than 300 feet in the southern part. A horizontal hydraulic conductivity value of about 60 feet per day in the downdip region was calculated based on a recent aquifer test (J. H. Hoffmann, OLWR, oral commun., 1998); however, it is estimated that the aquifer has about twice that conductivity in the updip region (W.T. Oakley, USGS, oral commun., 1998).

The massive sand aquifer does not crop out and is recharged by leakage from the Coker aquifer in the Coker outcrop area because the separation between the two aquifers is thin in that region. Water-level data for the massive sand aquifer are limited, but it is generally assumed that the massive sand may also receive recharge in the downdip area from the underlying Lower Cretaceous aquifer (J.H. Hoffmann, OLWR, oral commun., 1994). Water may be discharged from the massive sand aquifer to the Coker aquifer in the downdip area, and to the Lower Cretaceous aquifer in the updip area (J.H. Hoffmann, OLWR, oral commun., 1994), in addition to wells screened in the aquifer.

The massive sand aquifer is separated from the overlying Coker aquifer by clay and silt in most of the study area. Well-log data indicate that total clay thickness within the study area for the confining unit ranges from about 1 foot in the eastern part of the study area to more than 175 feet in the southern part of the study area.

Lower Cretaceous Aquifer

The Lower Cretaceous aquifer does not crop out in Mississippi or in the study area. To the north and northeast, the aquifer pinches out against Paleozoic rocks. To the west, southwest, and south, in the downdip direction, the aquifer contains water with increasing dissolved-solids concentrations (fig. 11). The aquifer dips about 35 to 40 feet per mile toward the southwest.

The Lower Cretaceous aquifer consists of shale, clay, sand, gravel, and calcareous strata (Boswell, 1963). Well-log data indicate that total sand thickness within the study area ranges from about 1 foot where it pinches out against Paleozoic rocks in the northeast, to about 1,000 feet along the west, southwest, and southern edge of the study area (fig. 11). The sand is thinnest near the northeastern extent of the aquifer and generally thickens downdip. There have been no aquifer tests conducted in the Lower Cretaceous aquifer; however, comparisons of recent samples of Lower Cretaceous aquifer sediment with that of the massive sand aquifer indicate they may have similar hydraulic conductivities. An average horizontal hydraulic conductivity value for the Lower Cretaceous aquifer is estimated to be about 125 feet per day.

Although water-level data do not exist for the Lower Cretaceous aquifer, it is logical to assume that it receives recharge from the massive sand aquifer in the updip area. Discharge from the aquifer probably is to the massive sand aquifer in the downdip region; however, the hydraulic gradient would be relatively flat and there probably is only minor exchange (J.H. Hoffmann, OLWR, oral commun., 1994).

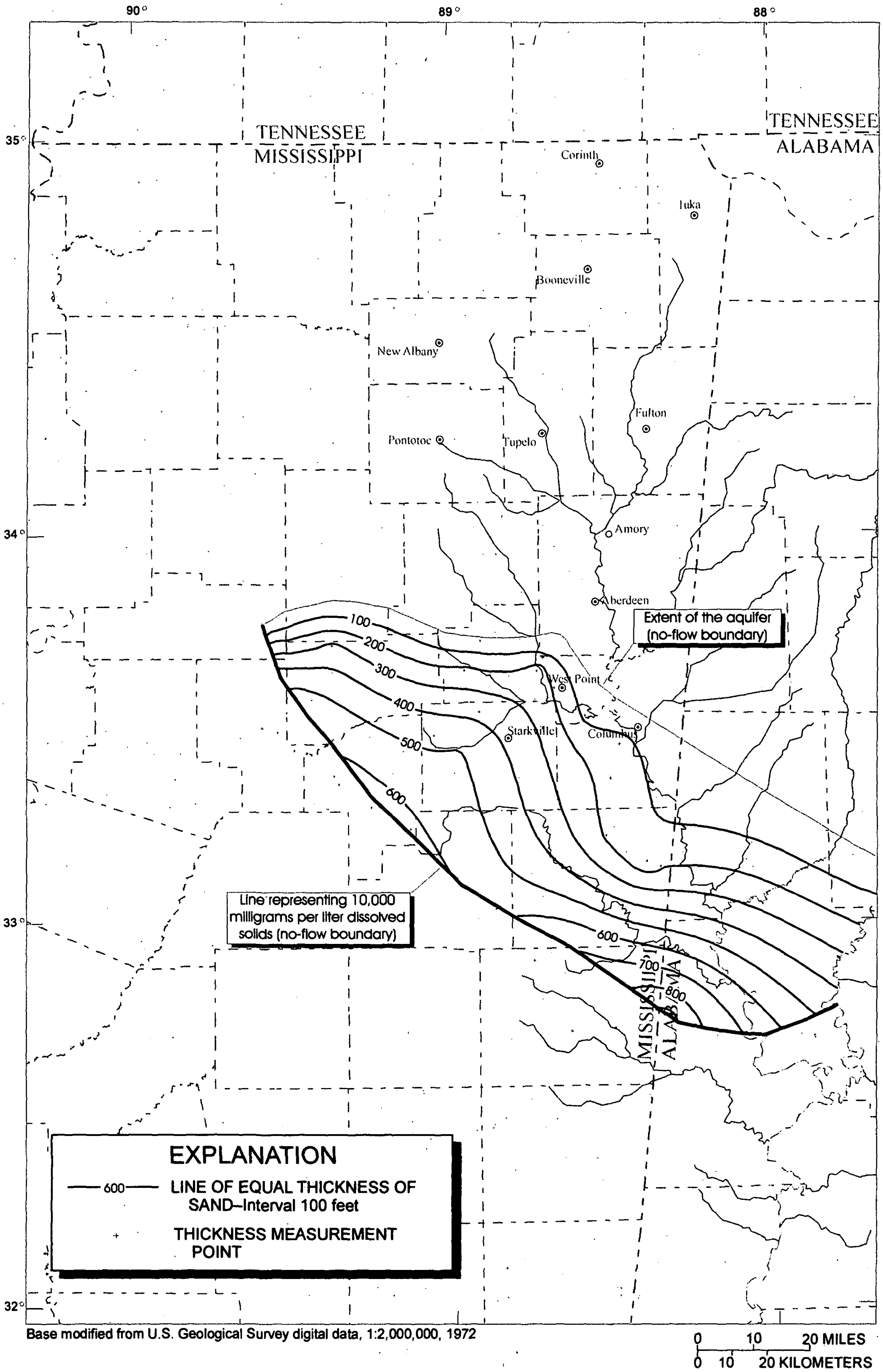

Figure 11. Extent and total sand thickness of the Lower Cretaceous aquifer and location of measurements.

The Lower Cretaceous aquifer is confined from the overlying massive sand aquifer by clay and silt. Well-log data indicate that total clay thickness within the study area for the confining unit ranges from about 1 foot in the northeastern part to almost 150 feet in the southern part.

Paleozoic Aquifers

The Paleozoic aquifers in Mississippi have generally been treated as undifferentiated in the literature due to lack of data. Recent investigations (Jennings, 1994; Jennings, 1996; S.P. Jennings, OLWR, written commun., 1997) have identified in the Paleozoic rocks in Mississippi two distinct water-bearing units that are discussed below.

Iowa Aquifer

The Iowa aquifer comprises a permeable and porous zone in the Fort Payne and the Tuscumbia Formations of the Iowa group (fig. 3) that is generally coincident with the upper part of the subcrop of those formations beneath the Cretaceous sediments (fig. 4). The zone of enhanced permeability and porosity in the Iowa group subcrop may have resulted from fracturing and weathering processes prior to deposition of the Cretaceous sediments (Jennings, 1994). The Iowa aquifer crops out in a very small area in northeastern Mississippi (fig. 12). To the northwest, the aquifer is limited by its erosional extent. To the southeast, the aquifer is limited by the extent of the permeable zone; that is, the downdip limit of the Iowa aquifer subcrop. To the northeast the Iowa aquifer crops out in the vicinity of and beneath Pickwick Lake.

The Iowa aquifer consists of chert, cherty limestone, shaley limestone, and medium- to coarse-grained bioclastic limestone (Jennings, 1994). Well-log data indicate that the aquifer is generally about 100 feet thick, but thins to the northwest until absent at its pre-Cretaceous erosional limit (fig. 12). An exception is the region surrounding Iuka in Tishomingo County, where the aquifer is generally 150 feet thick (S.P. Jennings, OLWR, written commun., 1997). Horizontal hydraulic conductivity values range from 10 to 34 feet per day as reported by Slack and Darden (1991) from aquifer tests in Tishomingo and eastern Alcorn Counties.

Well logs and outcrops indicate that the Iowa aquifer probably receives recharge through a relatively thin interval of unconsolidated Cretaceous sediments containing only minor clay from a topographically high area in northern and central Tishomingo County. Potentiometric-surface maps (Jennings and Phillips, 1994; Wasson, 1979) indicate that water levels in the Iowa aquifer are about 60 feet higher in the north-central Tishomingo County area than at the aquifer's outcrop area at Pickwick Lake; therefore, this area acts as a ground-water divide; ground water to the east of this divide eventually discharges into the outcrop area beneath the lake, ground water to the west of this divide flows into the deeper downdip flow system. The aquifer has little or no confinement from the overlying Cretaceous aquifers (Jennings, 1996; S.P. Jennings, OLWR, oral commun., 1997) and, therefore, exchanges water with the overlying Cretaceous aquifers (Jennings, 1994). Water is also discharged into wells screened in the aquifer.

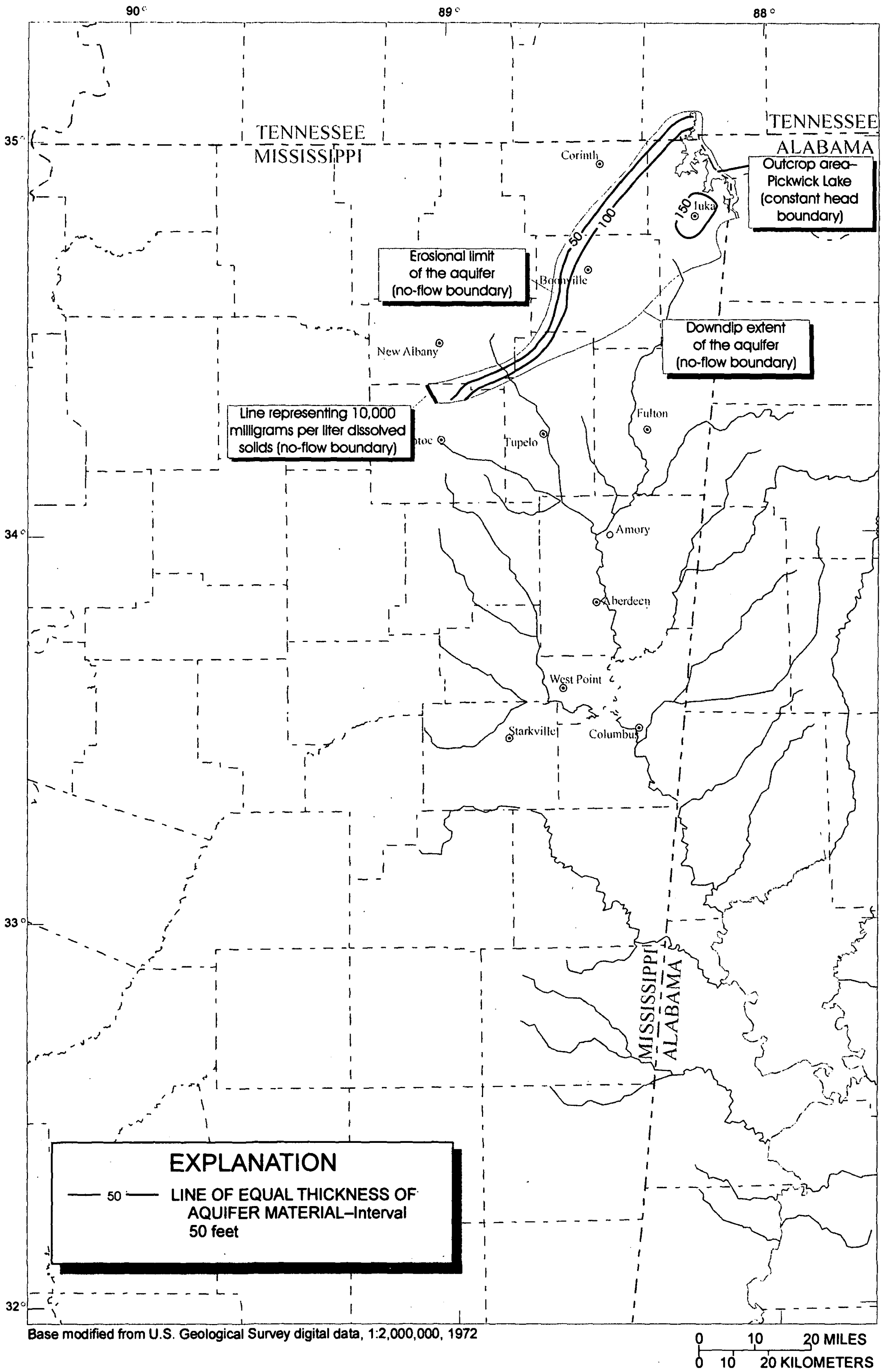

Figure 12. Extent and total aquifer thickness of the Iowa aquifer (S.P. Jennings, OLWR, written commun., 1997).

Devonian Aquifer

The Devonian aquifer comprises a permeable and porous zone in an undifferentiated interval of Devonian age rocks underlying the Chattanooga Shale (fig. 3) that is commonly referred to as the "Devonian Chert." This interval may include the subsurface equivalents of the Lower Devonian Ross Formation, Flat Gap Limestone, and Harriman Formation (Jennings, 1994). Unlike the Iowa aquifer, the Devonian aquifer is comprised of a porous and permeable zone that is not limited to its subcrop area, but extends downdip beneath younger Paleozoic units (fig. 4). The development of the porous and permeable zone is likely the result of depositional facies and a major episode of erosion and weathering that occurred prior to the deposition of the Chatanooga Shale (Jennings, 1994). Because outcrops of Devonian rocks are very sparse in the study area (Merrill and others, 1988), and well log data indicate the existence of no more than a few porous and permeable rocks in northeastern Tishomingo County, the Devonian aquifer is not considered to crop out in the study area (fig. 13). To the northeast and east, the aquifer is limited by the pinchout of porous and permeable rocks. To the southeast and southwest, the aquifer contains water with increasing dissolved-solids concentrations (Jennings, 1994). The unit is truncated to the northwest due to pre-Cretaceous erosion.

The Devonian aquifer consists of chert and cherty limestone (Jennings, 1994). Well-log data indicate that the aquifer is thinnest to the northwest near the erosional limit (fig. 13). In Lee County, the aquifer appears to thicken to more than 400 feet (S.P. Jennings, OLWR, written commun., 1997). Aquifer tests from Alcorn County indicate horizontal hydraulic conductivity values range from 20 to 116 feet per day (Slack and Darden, 1991).

Because the Devonian aquifer does not crop out in the study area, the only potential for ground-water exchange is with the overlying Cretaceous aquifers or with the Iowa aquifer. Water is also discharged to wells screened in the aquifer. Water-level data for the Devonian aquifer are limited; however, potentiometric-surface maps for the aquifer indicate water level declines around pumping centers in Alcorn County, and that ground-water flow is subsequently toward these pumping centers (Wasson, 1979; Jennings and Phillips, 1994). Where the Devonian aquifer is overlain by Cretaceous aquifers, there appears to be little or no hydraulic separation (Jennings, 1996; S.P. Jennings, OLWR, oral commun., 1997).

Ground-Water Movement

Potentiometric-surface maps for the Eutaw-McShan and Gordo aquifers based on 1992 water-level measurements (figs. 14-15) indicate that some ground water enters the deeper confined part of the aquifers from the northernmost counties in the outcrop area, and flows in an arcuate path toward the southeastern part of the aquifers. Flow also moves locally toward cones of depression in the potentiometric surfaces formed at large pumping centers. Water-level data indicate that ground-water flow in the southeastern part of the Eutaw-McShan and Gordo aquifers is upward through the overlying confining units, discharging into the Tombigbee River valley (Wasson, 1980b,1980c; Everett and

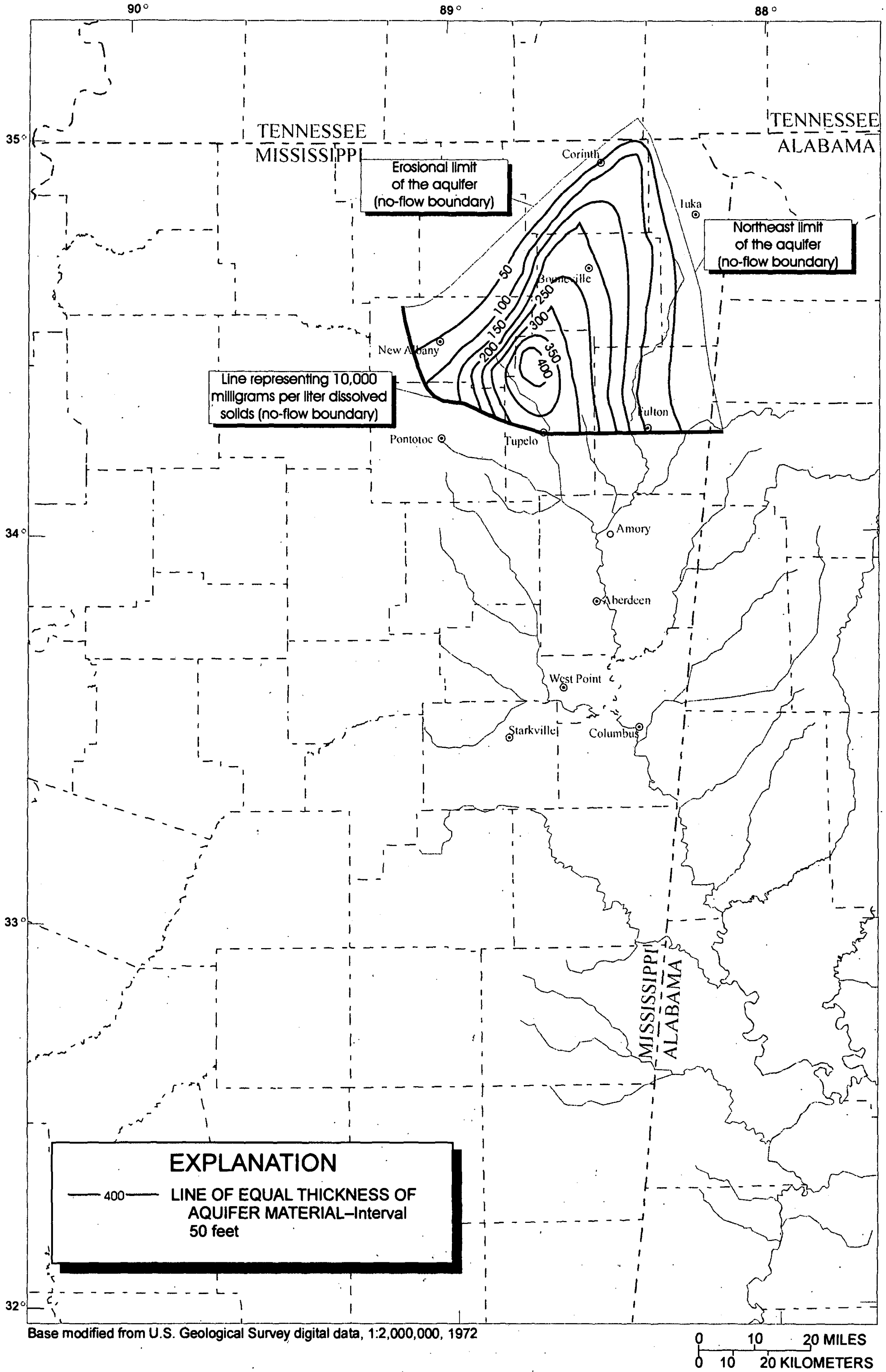

Figure 13. Extent and total aquifer thickness of the Devonian aquifer (S.P. Jennings, OLWR, written commun., 1997).

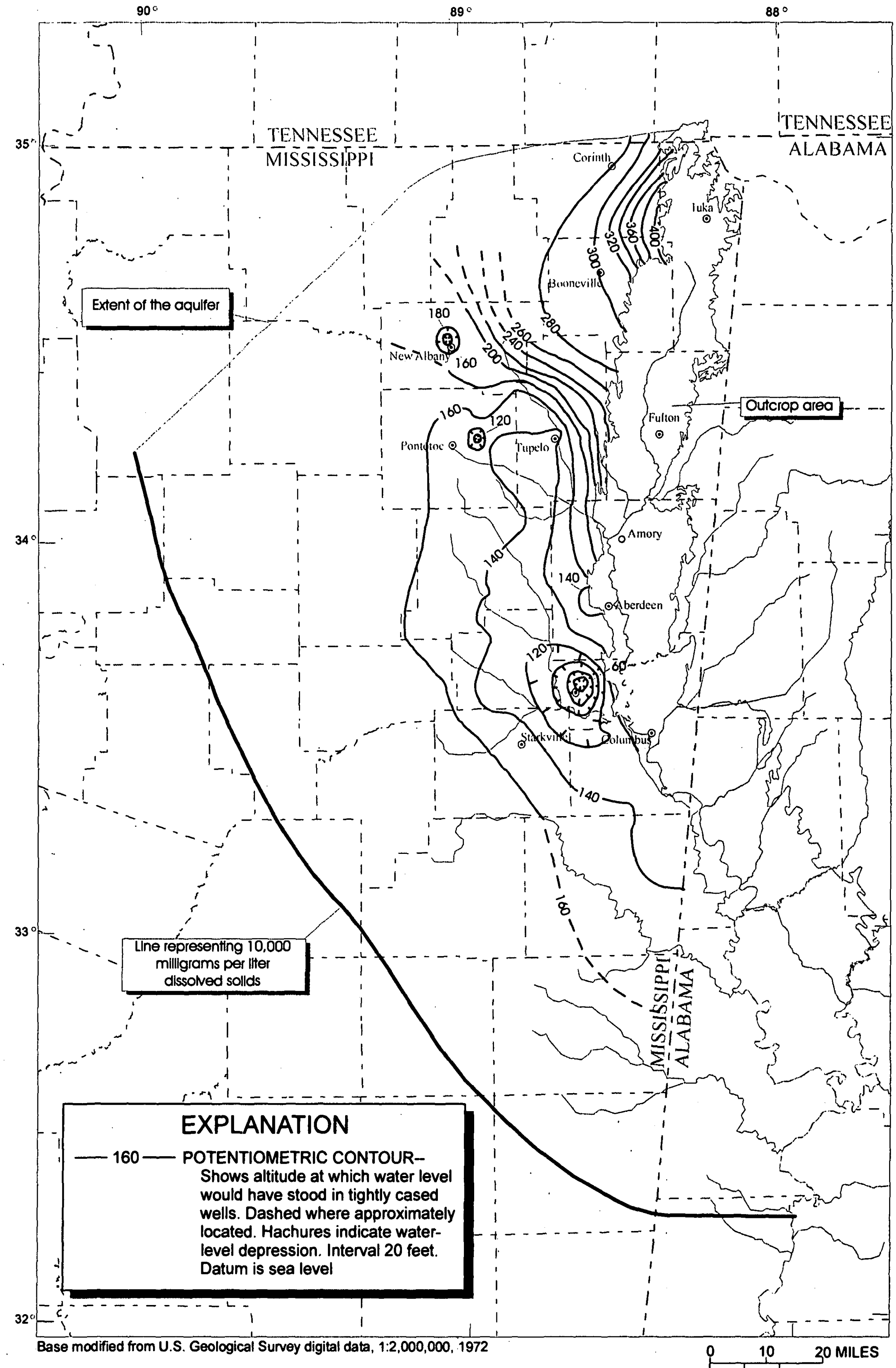

Figure 14. Potentiometric surface of the Eutaw-McShan aquifer based on 1992 water-level measurements (modified from Everett and Jennings, 1994).

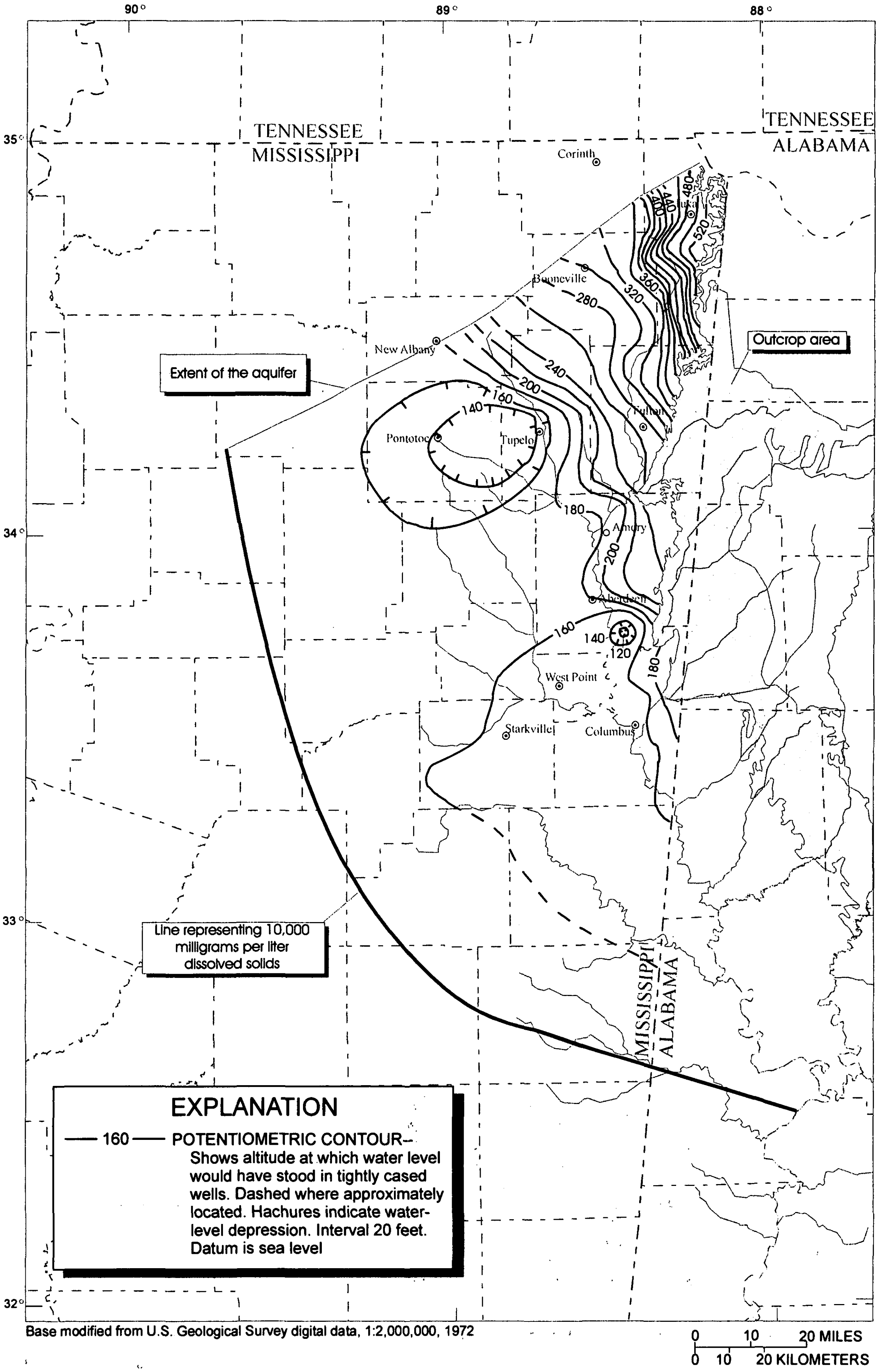

Figure 15. Potentiometric surface map of the Gordo aquifer based on 1992 water-level measurements (modified from Phillips and Hoffmann, 1994).

Jennings, 1994; Phillips and Hoffmann, 1994). A major discharge area also exists for the Eutaw-McShan and Gordo aquifers around the confluence of the Tombigbee and Black Warrior River valleys (Gardner, 1981). Vertical head gradients indicate that some flow enters the Eutaw-McShan aquifer from the overlying Coffee Sand aquifer (J.H. Hoffmann, OLWR, oral commun., 1994). Some water may also enter and exit the Eutaw-McShan and Gordo aquifers in areas underlying the Paleozoic aquifers (S.P. Jennings, OLWR, oral commun., 1994). Ground-water movement in the aquifer outcrop areas is from topographic highs to topographic lows. Limited water-level data in the Coffee Sand, Coker, massive sand, Iowa, and Devonian aquifers indicate that the regional flow patterns are generally similar to those in the Eutaw-McShan and Gordo aquifers. No water-level data exist for the Lower Cretaceous aquifer, and the flow pattern is unknown. However, any exchange of ground water would be with the overlying massive sand aquifer.

Ground-Water Withdrawal

Most water withdrawn for public and industrial use in northeastern Mississippi is from the Eutaw-McShan and Gordo aquifers. Ground-water use began steadily increasing since the 1940's, from about 3.4 million gallons per day for all of the aquifers, reaching a peak between about 1985 and 1990 of almost 90 million gallons per day (J.H. Hoffmann and A. John Warner, OLWR, written commun., 1997). Ground-water use declined to about 76 million gallons per day in 1995. Cones of depression in the potentiometric surfaces of the Eutaw-McShan and Gordo aquifers have recovered in some areas, such as Tupelo in Lee County, as a result of decreasing ground-water withdrawals. In most other areas the cones of depression in the potentiometric surfaces have stabilized or are increasing in size.

Relatively small ground-water withdrawals from the Coffee Sand aquifer have historically occurred in Alcorn, Tippah, and Union Counties (fig. 1). Only about 3.1 million gallons per day was withdrawn from the Coffee Sand aquifer in 1995.

Relatively large ground-water withdrawals from the Eutaw-McShan aquifer have historically occurred at Booneville in Prentiss County, at New Albany in Union County, at Pontotoc in Pontotoc County, at Tupelo in Lee County, at Aberdeen in Monroe County, and at West Point in Clay County (fig. 1). In 1995, about 15 million gallons per day was withdrawn from the Eutaw-McShan aquifer in and around these pumping centers.

Relatively large ground-water withdrawals from the Gordo aquifer have historically occurred at Booneville in Prentiss County, at Pontotoc in Pontotoc County, at Tupelo in Lee County, at Fulton in Itawamba County, at Amory and industries south of Aberdeen in Monroe County, at West Point in Clay County, at Starkville in Oktibbeha County, and at Columbus and industries south of Columbus in Lowndes County (fig. 1). In 1995, about 39 million gallons per day was withdrawn from the Gordo aquifer in and around these pumping centers.

Analysis of borehole-geophysical logs by the OLWR indicates that much of the water previously thought to have been withdrawn from the Coker aquifer was actually from the underlying massive sand aquifer (J.H. Hoffmann, OLWR, oral commun., 1994). As a result, relatively little water is currently (1998) thought to have been withdrawn from the Coker aquifer. Only about 1.6 million gallons per day was withdrawn from the Coker aquifer in 1995. Instead, the massive sand aquifer has relatively large withdrawals at Aberdeen in Monroe County, and at Columbus and industries south of Columbus in Lowndes County (fig. 1). In 1995, about 11.6 million gallons per day was withdrawn from the massive sand aquifer.

No significant ground-water withdrawal is thought to have occurred from the Lower Cretaceous aquifer within the study area. Relatively small ground-water withdrawals from the Iowa and Devonian aquifers have historically occurred in Alcorn and Tishomingo Counties (fig. 1). In 1995, about 1.9 million gallons per day was withdrawn from the Iowa aquifer, principally at Iuka, and about 3.9 million gallons per day was withdrawn from the Devonian aquifer, mainly in the Corinth area.

SIMULATION OF GROUND-WATER FLOW

A quasi-three-dimensional, numerical model of ground-water flow was developed for the Cretaceous-Paleozoic aquifer system in northeastern Mississippi, and analyses of ground-water flow were made using results from model simulations. Included in this section is a description of the model, simulations of predevelopment and transient ground-water flow conditions, and model limitations.

Model Description

Anisotropic and heterogeneous three-dimensional flow of ground water, assumed to have constant density, may be described by the partial-differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_S\frac{\partial h}{\partial t}$$

where

K_{xx}, K_{yy}, and K_{zz}	=	components of the hydraulic conductivity tensor,
S_S	=	specific storage,
W	=	source or sink term,
h	=	potentiometric head, and
t	=	time.

The finite-difference computer code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) numerically approximates this equation, and was used to simulate the Cretaceous-Paleozoic aquifer system. Published data and data from field investigations were collected and reviewed prior to model input. Data analysis included determining the geologic framework and conceptual model of the aquifer system (presented in the first part of this report) to be simulated. The aquifers were simulated as separate layers and discretized into two-dimensional finite-difference grids. Applying the field data to the grid required matching parameter values to the scale of the model. After determining the grid size, the hydraulic characteristics for aquifers and confining units were applied to the model.

Simulations were made under transient conditions for 12 pumping (stress) periods that began January 1, 1900, and ended on December 31, 1995. Each pumping period consisted of one time-step. The length of the pumping periods and their corresponding dates are listed in table 1. The pumping periods were chosen to represent large changes in pumpage; however, to some degree the pumping periods also indicate times at which pumpage and water-level data were available. The pumpage used during each pumping period is shown in figure 16.

Table 1. Pumping periods used in the model of the Cretaceous-Paleozoic aquifer system

Pumping period	Length of time (years)	Date
1	40	1900-39
2	20	1940-59
3	10	1960-69
4	5	1970-74
5	4	1975-78
6	6	1979-84
7	5	1985-89
8	2	1990-91
9	1	1992
10	1	1993
11	1	1994
12	1	1995

Grid Design

The model grid covers 34,960 square miles, primarily in northeastern Mississippi, but includes parts of northwestern Alabama, southwestern Tennessee, and eastern Arkansas (fig. 17). The model grid was oriented north-south because no predominant axes of transmissivity for the aquifers were indicated by the data. A lateral anisotropy ratio of one was used in the simulations. Each grid layer consists of 230 rows and 152 columns. The model was vertically discretized into six layers resulting in a total of 209,760 grid cells. Layers 1, 2, and 3 represent the Coffee Sand, Eutaw-McShan, and Gordo aquifers, respectively. The Coker and Iowa aquifers are represented by layer 4, and the massive sand and Devonian aquifers are represented by layer 5. Although the Coker and Iowa, and the massive sand and Devonian aquifers are not stratigraphically related, it is possible to simulate them on shared layers because their boundaries do not areally

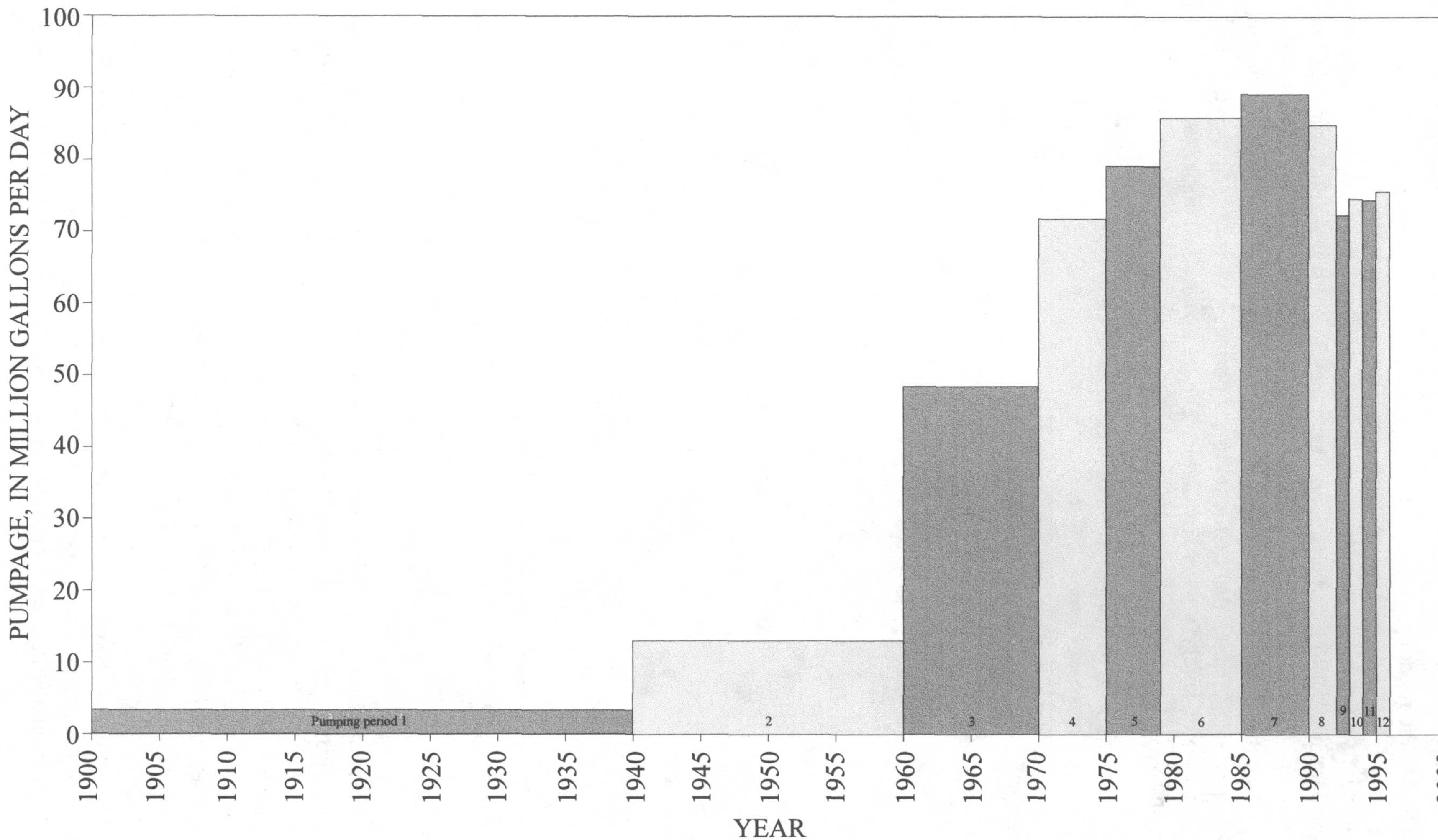

Figure 16. Total pumpage used for each pumping period simulated in the model of the Cretaceous-Paleozoic aquifer system (J. H. Hoffmann and A. J. Warner, OLWR, written commun., 1997).

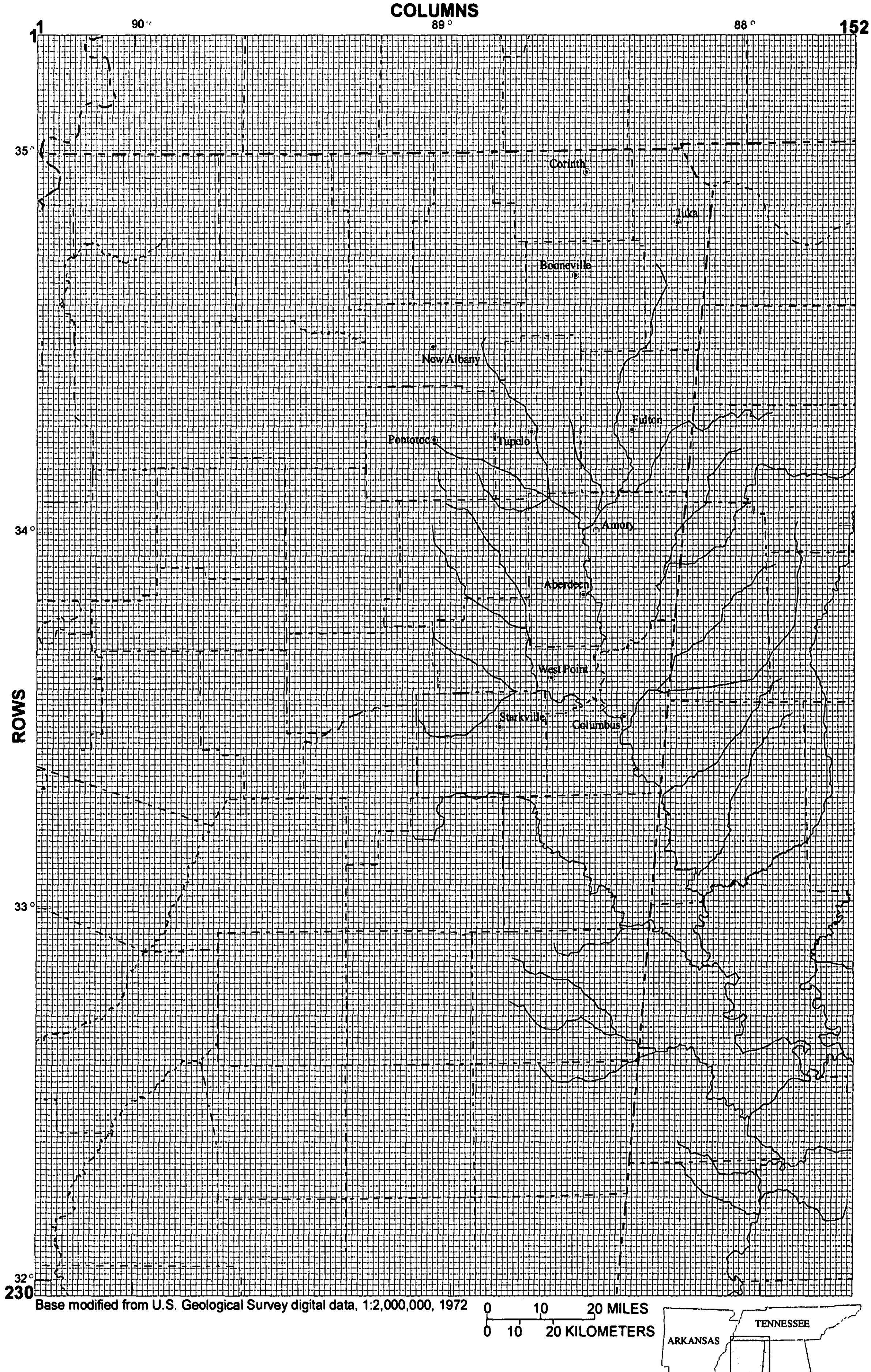

Figure 17. Finite-difference grid used in the numerical model of the Cretaceous-Paleozoic aquifer system.

coincide (figs. 4 and 18). The Lower Cretaceous aquifer is represented by layer 6. Each grid cell is 1 mile on a side because the distribution of input data used to determine structure and thicknesses for the aquifers was of a matching scale in many areas.

Boundaries

Model boundaries determine where and how much water enters and leaves the model; therefore, the selection of appropriate boundaries for the aquifers is a major concern in any modeling effort. The selection of model boundaries for the aquifers in this model was based on a conceptual interpretation of the flow system developed using information reported by Boswell (1963); Boswell and others (1965); Cushing (1966); Hardeman (1966); Bicker (1969); Boswell (1978); Gandl (1982); Wasson (1986); Davis (1987); E.H. Boswell, J.F. Everett, D.L. Hardin, J.H. Hoffman, S.P. Jennings, P.A. Phillips (OLWR, oral commun., 1993); Jennings (1994); S.P. Jennings, (OLWR, written commun., 1997); and J.H. Hoffmann (OLWR, oral commun., 1997).

The Coffee Sand aquifer is overlain by a thick, relatively impermeable sequence of units in the Selma Group (fig. 3); therefore, the area overlying the Coffee Sand aquifer was simulated as a no-flow boundary. Layer 1 represents the Coffee Sand aquifer in the northern part, but is also used in the southeastern part (fig. 19) as an upper constant-head boundary for the Eutaw-McShan aquifer (layer 2).The constant heads overlying the Eutaw-McShan in this region represent surficial water levels on the chalk and clay overlying the Eutaw-McShan aquifer (fig. 19). However, most of this potential water is separated from the Eutaw-McShan by the clay and chalk confining unit that sharply thickens westward, limiting most vertical flow due to the low vertical hydraulic conductivity of the confining unit.

The downdip extent of freshwater (defined for the purposes of this study as a concentration of 10,000 milligrams per liter of dissolved solids) represents no-flow lateral boundaries for all of the aquifers (figs. 6-13) due to the contrast in density across the freshwater-saltwater interface. Previous investigations (Mallory, 1993; Arthur, 1994; and Strom and Mallory, 1995) have indicated that this contrast in density effectively eliminates horizontal movement. A no-flow boundary at this location assumes a stable downdip freshwater-saltwater interface. For many of the aquifers, the region where the dissolved-solids concentrations are between 1,000 and 10,000 milligrams per liter is relatively small, which also implies there is little mixing and that flow is parallel to the freshwater-saltwater interface. If flow were to occur across the interface in the downdip direction, flow would eventually move upward at some point to discharge; flow upward is unlikely, however, because the confining units above the Eutaw-McShan thicken to the southwest in the downdip direction to more than 1,500 feet near the freshwater-saltwater interface. Any significant upward flow would need to be through secondary structural features, such as faults. The freshwater-saltwater interface has been similarly treated as a no-flow boundary in the Southeastern Coastal Plain aquifers in Mississippi by Mallory (1993), Arthur (1994), and Strom and Mallory (1995).

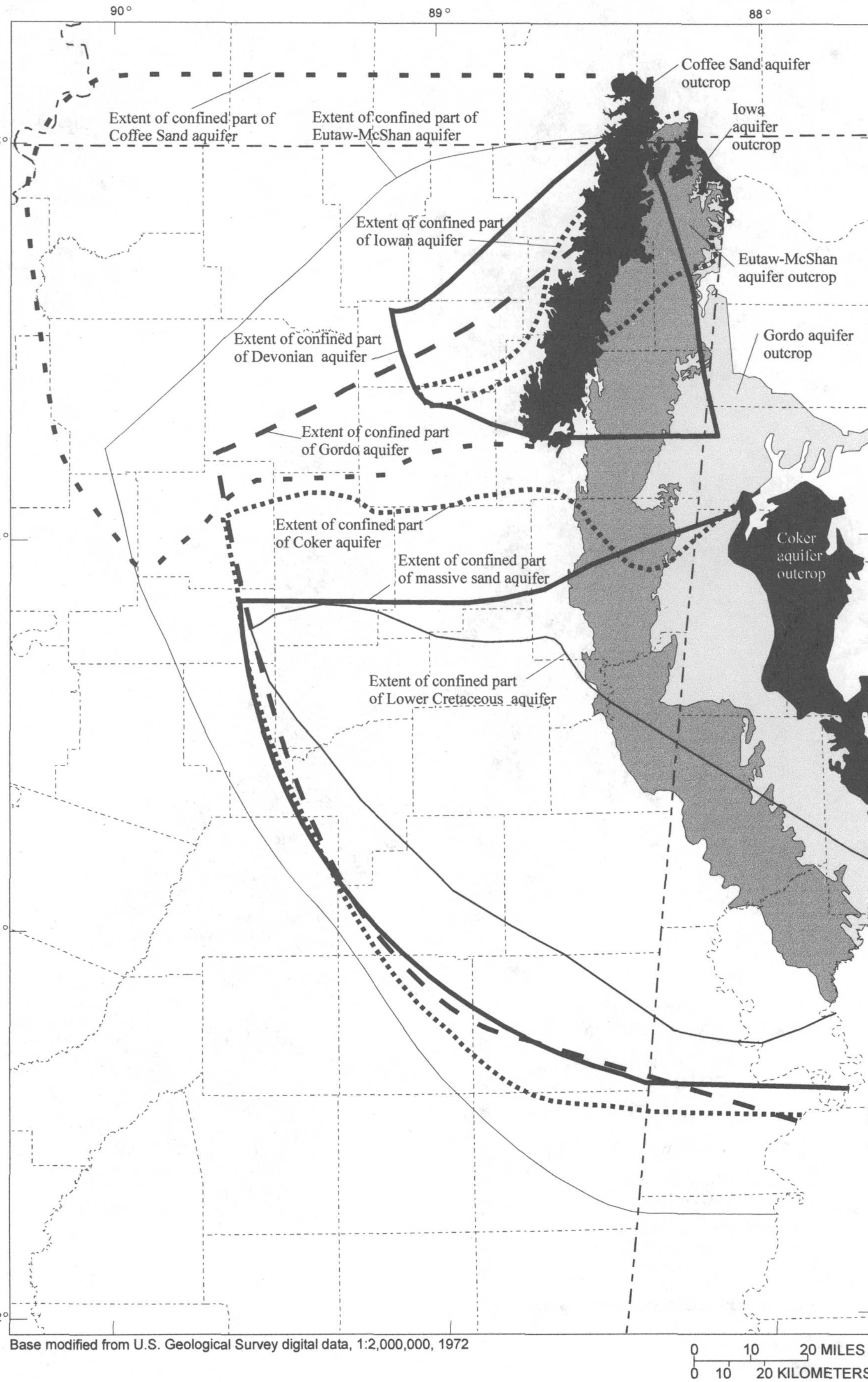

Figure 18. Overlap of areal extent of freshwater in the Cretaceous-Paleozoic aquifers in the study area.

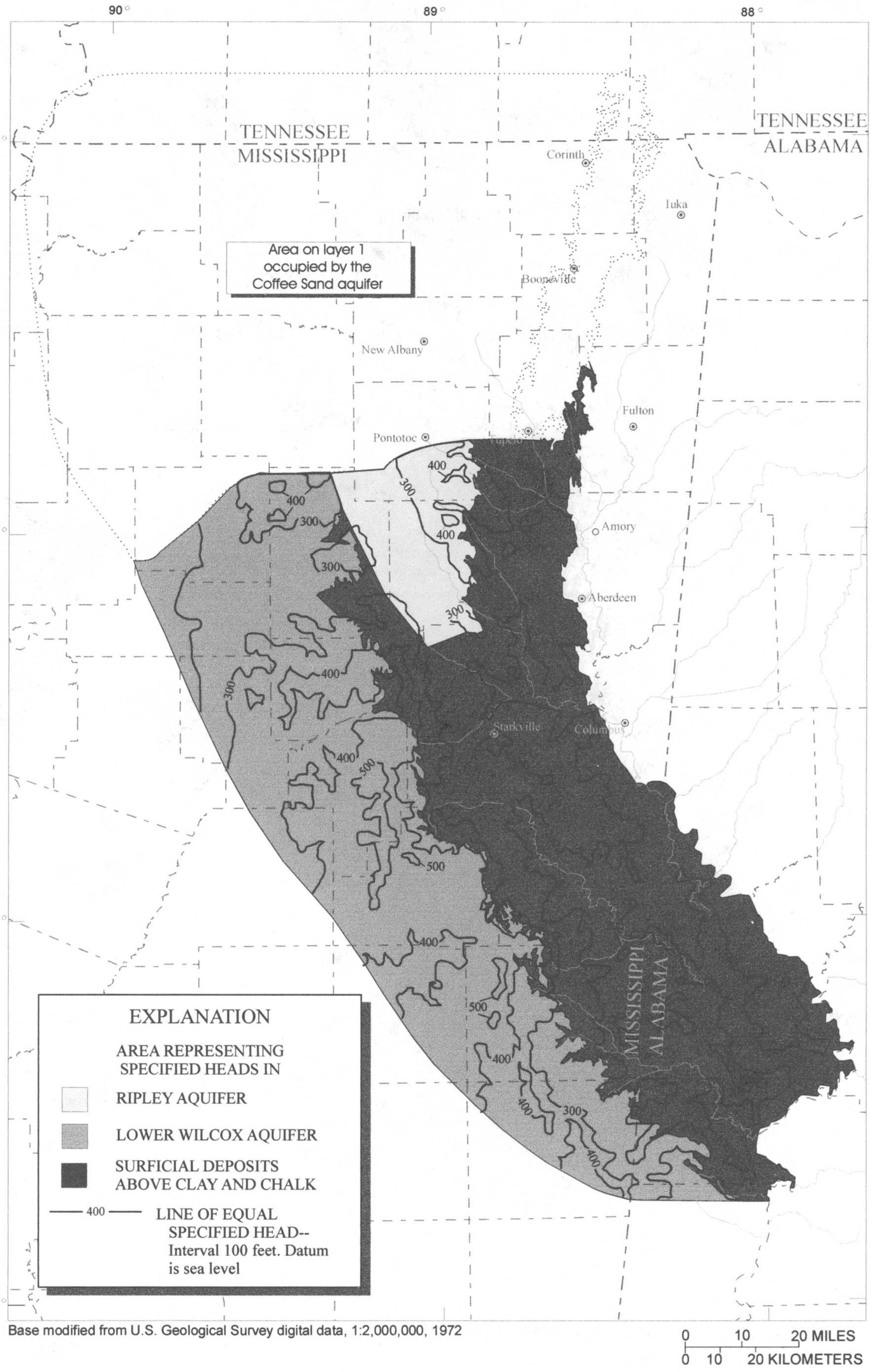

Figure 19. Contours of specified heads on model layer 1.

The northern or northwestern boundaries of all of the aquifers represent the limits of the sediments, and are simulated as no-flow boundaries (figs. 6-13). The southeastern boundaries of the Eutaw-McShan, Gordo, Coker, massive sand, and Lower Cretaceous aquifers are also simulated as no-flow boundaries. The southeastern boundaries are at a lateral ground-water flow divide (figs. 7-11) formed by the Tombigbee and Black Warrior Rivers. Water-level data indicate that these rivers, particularly near their confluence, are major discharge areas for the Eutaw-McShan and Gordo aquifers, with all lateral flow converging from both the east and the west being captured by the river channels (Gardner, 1981). Consequently, no lateral flow is assumed to move underneath the Tombigbee and Black Warrior Rivers. Water is discharged upward by leakage through the confining units. Although no water-level data are available for the Coker, massive sand, and Lower Cretaceous aquifers in this area, regional flow patterns are assumed to be similar throughout the Cretaceous aquifers (Mallory, 1993; J.H. Hoffmann, OLWR, oral commun., 1993), and a lateral ground-water flow divide was also simulated for these aquifers–with flow moving upward by leakage as a result of vertical head gradients with the overlying aquifers. In all of the Cretaceous aquifers except the Coffee Sand and Eutaw-McShan, the eastern grid-line boundary formed by the eastern edge of the model grid (figs. 8-11) was simulated as a lateral no-flow boundary because the eastern edge of the grid in this area was chosen to approximate the ground-water and surface-water divides between the Tombigbee River and Black Warrior River drainage basins.

An average of about 52 inches per year of precipitation falls on the aquifer outcrop areas in northeastern Mississippi (National Oceanic and Atmospheric Administration, 1981). Only a small fraction of this amount enters the ground-water flow system as recharge. Some of the water that enters the ground-water flow system travels only a short distance before being discharged locally; in terms of the digital model, much of this localized flow is not accounted for using a 1-mile grid discretization. The model simulations represent only the intermediate and regional scale flow system. The outcrop areas of the Coffee Sand, Eutaw-McShan, Gordo, and Coker aquifers were simulated with head-dependent flux boundaries (figs. 6-9). This was implemented using the river package in MODFLOW (Harbaugh and McDonald, 1996). The large base flows observed in even small streams in the outcrop area indicate that recharge from the precipitation-rich environment is more than sufficient to provide all the recharge that the aquifers can accept, and that much of the potential recharge is rejected by the aquifers and diverted into surface runoff due to the limited lateral transmissivities of the aquifers. The minimum land-surface altitude in each outcrop grid cell, which approximates stream baseflow water-level elevations, represents the river stages in the river package. This method of representing the outcrop areas allowed a better understanding of the distribution of recharge to the aquifer system.

The outcrop area of the Iowa aquifer was represented by constant heads because the Iowa aquifer crops out beneath Pickwick Lake, and is in effect connected to a constant water level, limited only by the lateral transmissivity of the aquifer. The heads were specified at 417 feet above sea level to represent the level of Pickwick Lake.

The massive sand, Lower Cretaceous, and Devonian aquifers are not considered to crop out; therefore, the northeastern boundaries which represent the limits of these aquifers are simulated with no-flow boundaries (figs. 10-11, 13). Previously, the massive sand aquifer has been considered a lower part of the Coker aquifer; however, in this study the Coker and Massive sand aquifers are simulated as separate aquifers because a confining unit separates them in much of the modeled area. The lateral eastern extent of the massive sand is assumed to be coincident with the lateral eastern extent of the Coker aquifer.

The lower model boundary is a no-flow boundary. This boundary represents a relatively impermeable zone of underlying Paleozoic rocks.

Model Calibration

The calibration strategy was to initially vary the best known parameters as little as possible, and vary the poorly known or unknown values the most to achieve the best overall agreement between simulated and measured water levels. Model calibration was based on transient conditions because few water-level data representing predevelopment, steady-state conditions for the aquifers are available. The calibrated parameters determined during transient simulations were used for determining simulated heads for predevelopment, steady-state conditions.

Sand and permeable-zone thickness data from borehole-geophysical logs were used to construct the initial transmissivity grids for the aquifers. Sand thicknesses represented the total sand thickness for the aquifer. The sand thickness data (or permeable zone thickness in the case of the Paleozoic aquifers) for each aquifer were gridded and contoured (figs. 6-13). For the Eutaw-McShan and Gordo aquifers, hydraulic conductivities reported from aquifer tests (Slack and Darden, 1991) were gridded and plotted. The hydraulic conductivity grids were multiplied by the corresponding gridded sand thickness data to generate the initial transmissivity grids for the Eutaw-McShan and Gordo aquifers. Horizontal hydraulic conductivity data for the other aquifers were insufficient to produce areally variable hydraulic conductivity grids. For these aquifers, reported (Slack and Darden, 1991) and estimated values of hydraulic conductivity were multiplied by the corresponding aquifer thickness grids to generate the initial transmissivity grids. The initial transmissivity grids were modified as necessary within the range of expected values during model calibration to construct the final transmissivity grids used in the model (figs. 20-26).

Few storage coefficient data are available for the aquifers in the model area and reported values (Boswell and others, 1965; Slack and Darden, 1991) are somewhat variable. A constant value of 0.0001 was used in the model for all of the aquifers to represent a typical aquifer under confined conditions, the exception being the Gordo aquifer where a constant value of 0.001 was used to represent the coarser grained material typical of the Gordo aquifer (Driscoll, 1989).

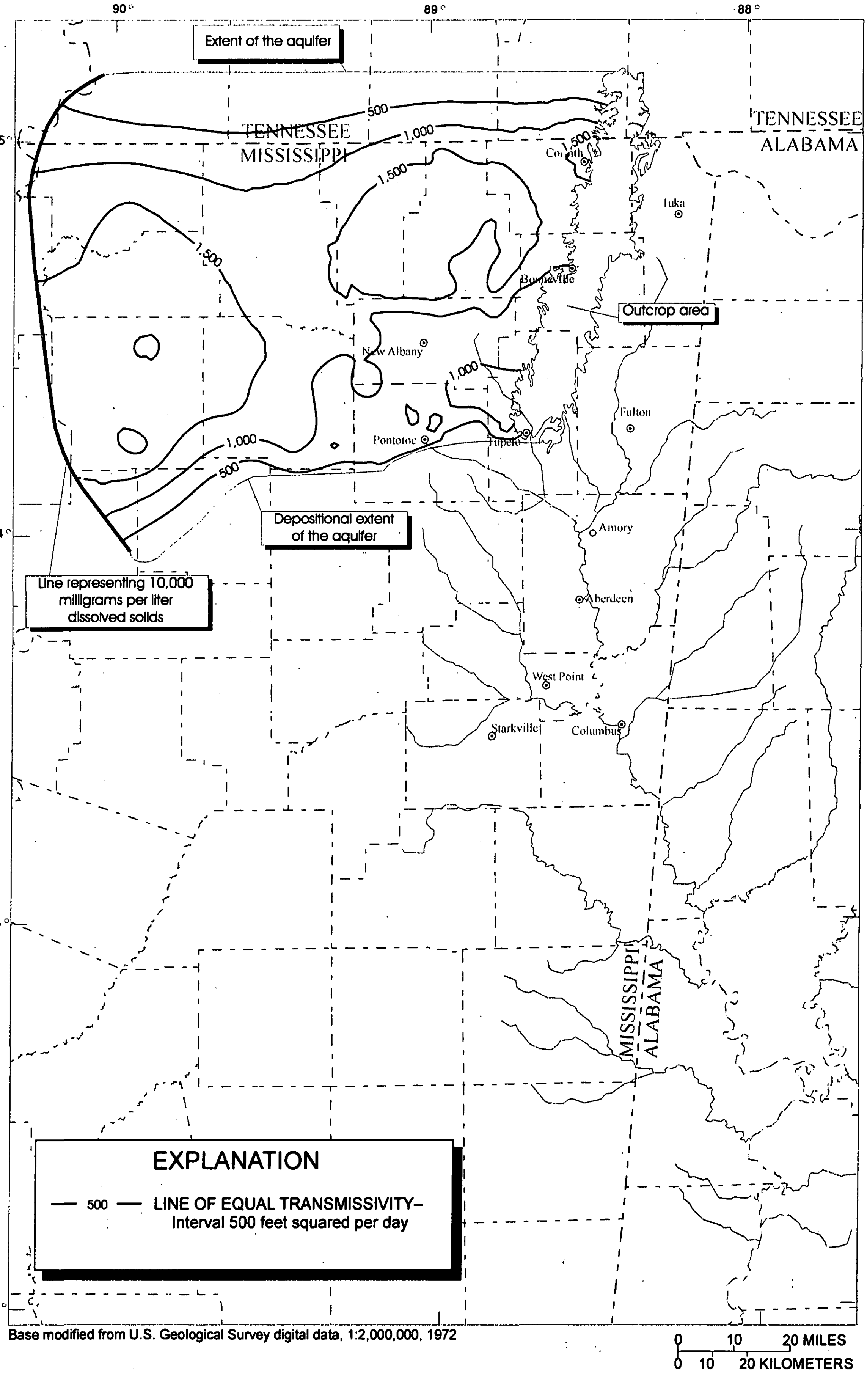

Figure 20. Transmissivity of the Coffee Sand aquifer used in model simulations.

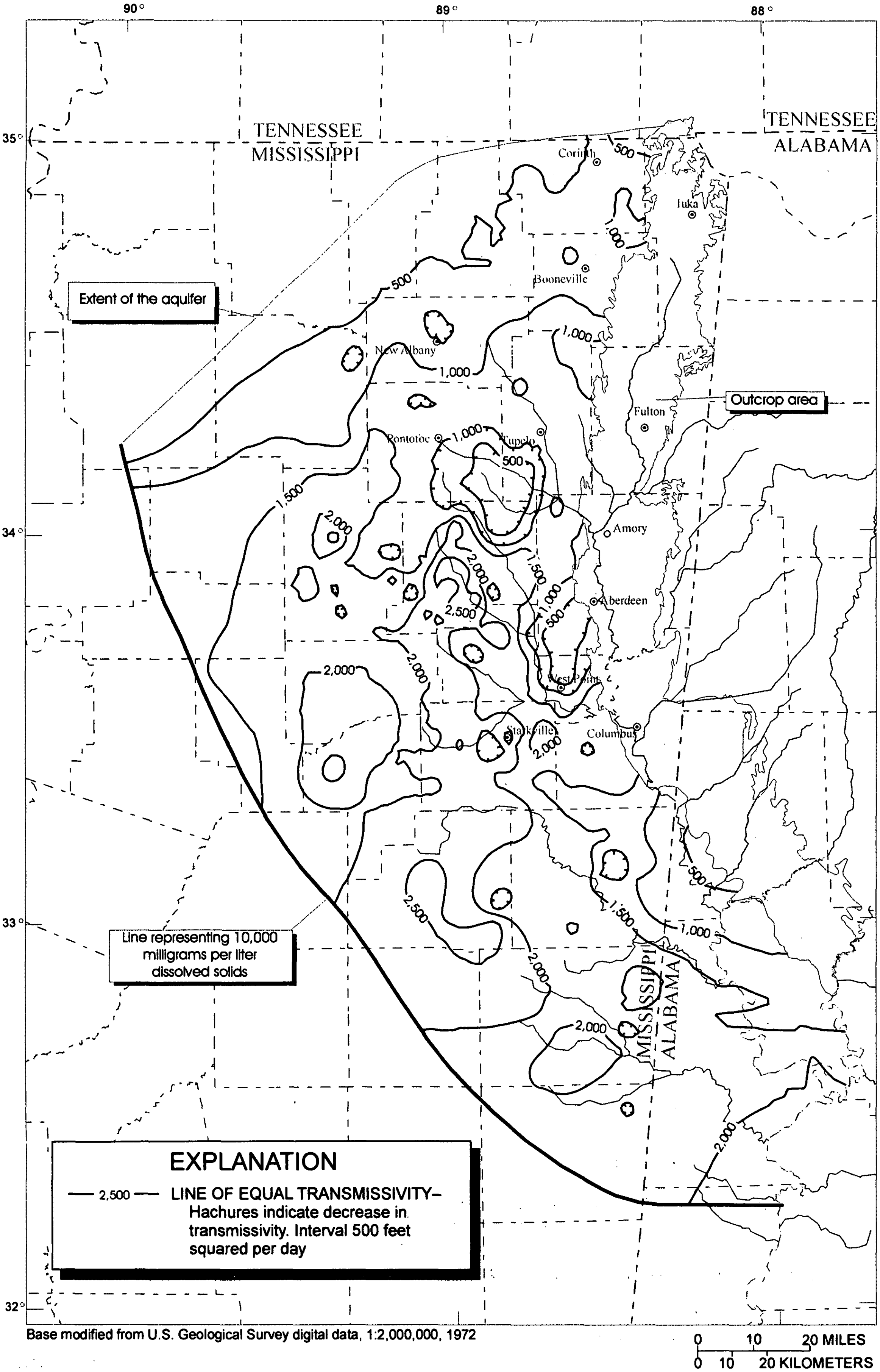

Figure 21. Transmissivity of the Eutaw-McShan aquifer used in model simulations.

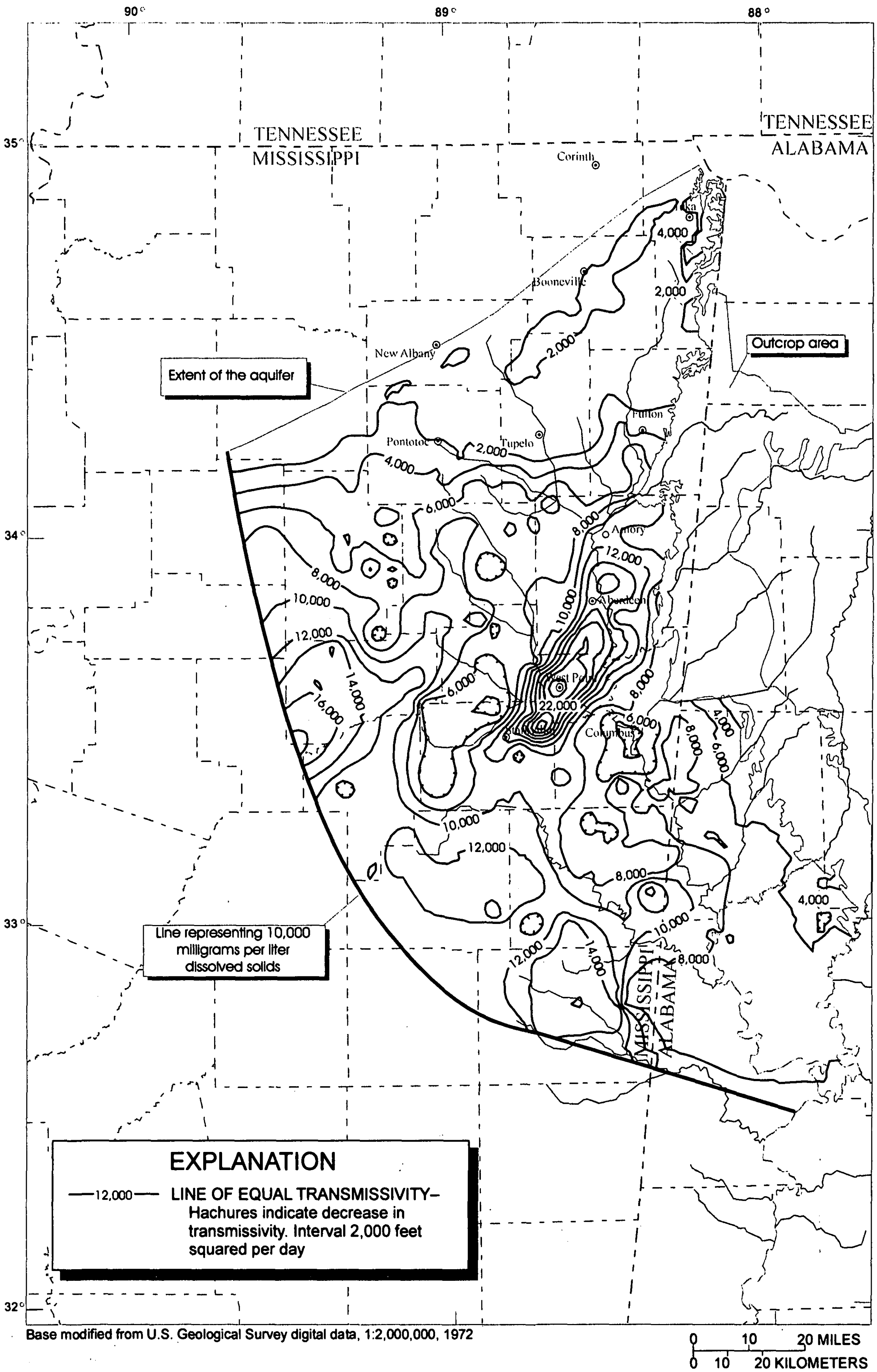

Figure 22. Transmissivity of the Gordo aquifer used in model simulations.

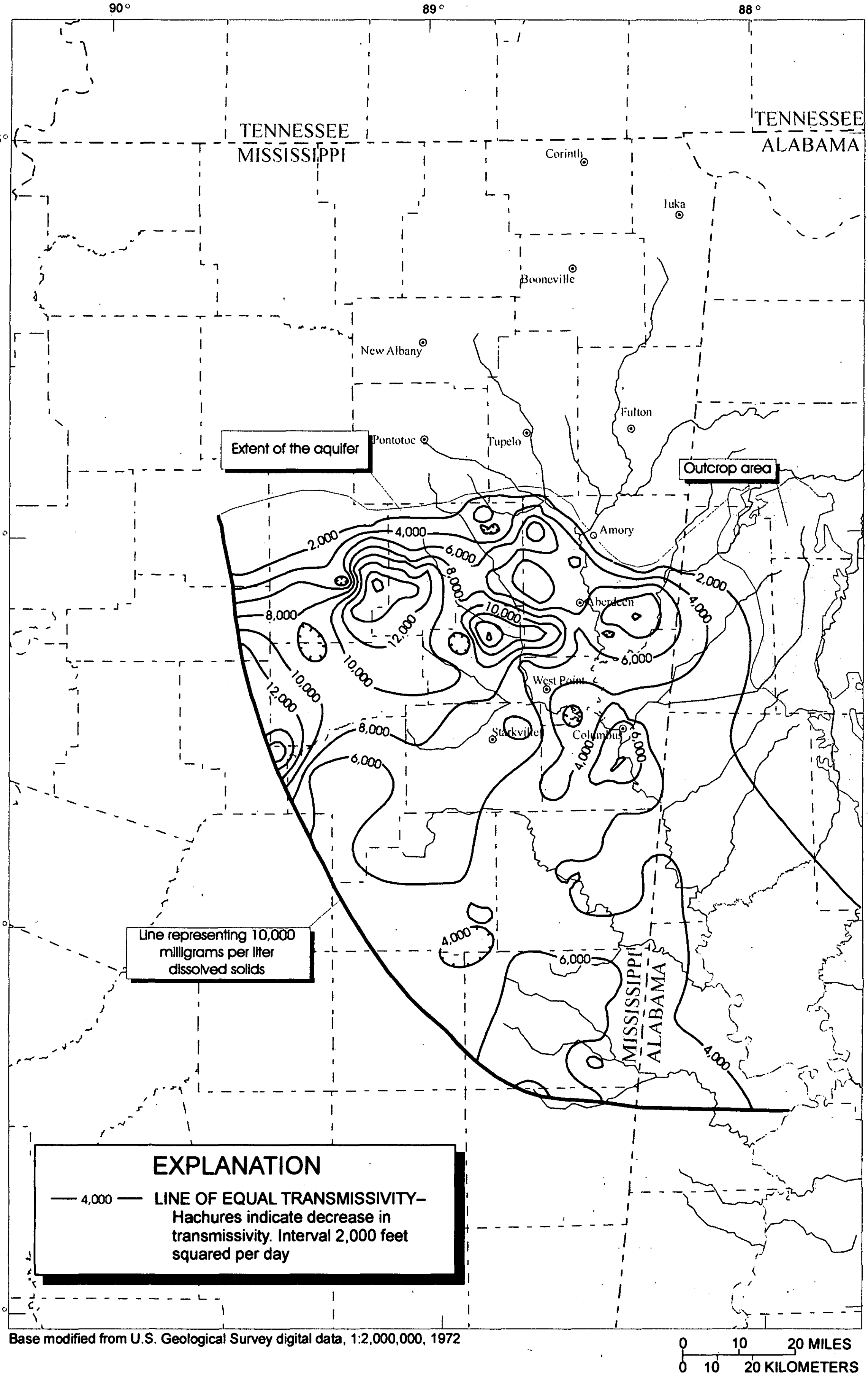

Figure 23. Transmissivity of the Coker aquifer used in model simulations.

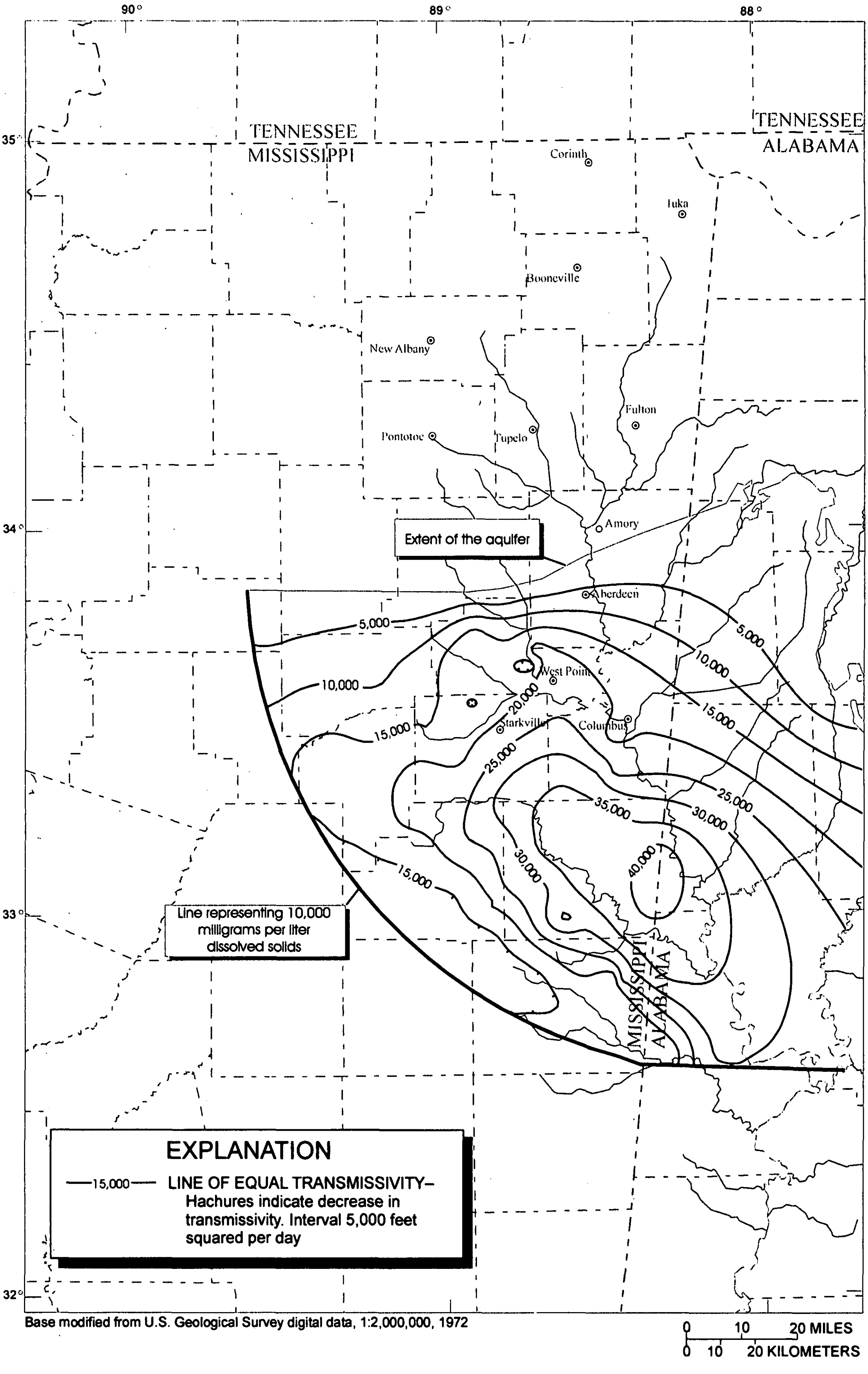

Figure 24. Transmissivity of the massive sand aquifer used in model simulations.

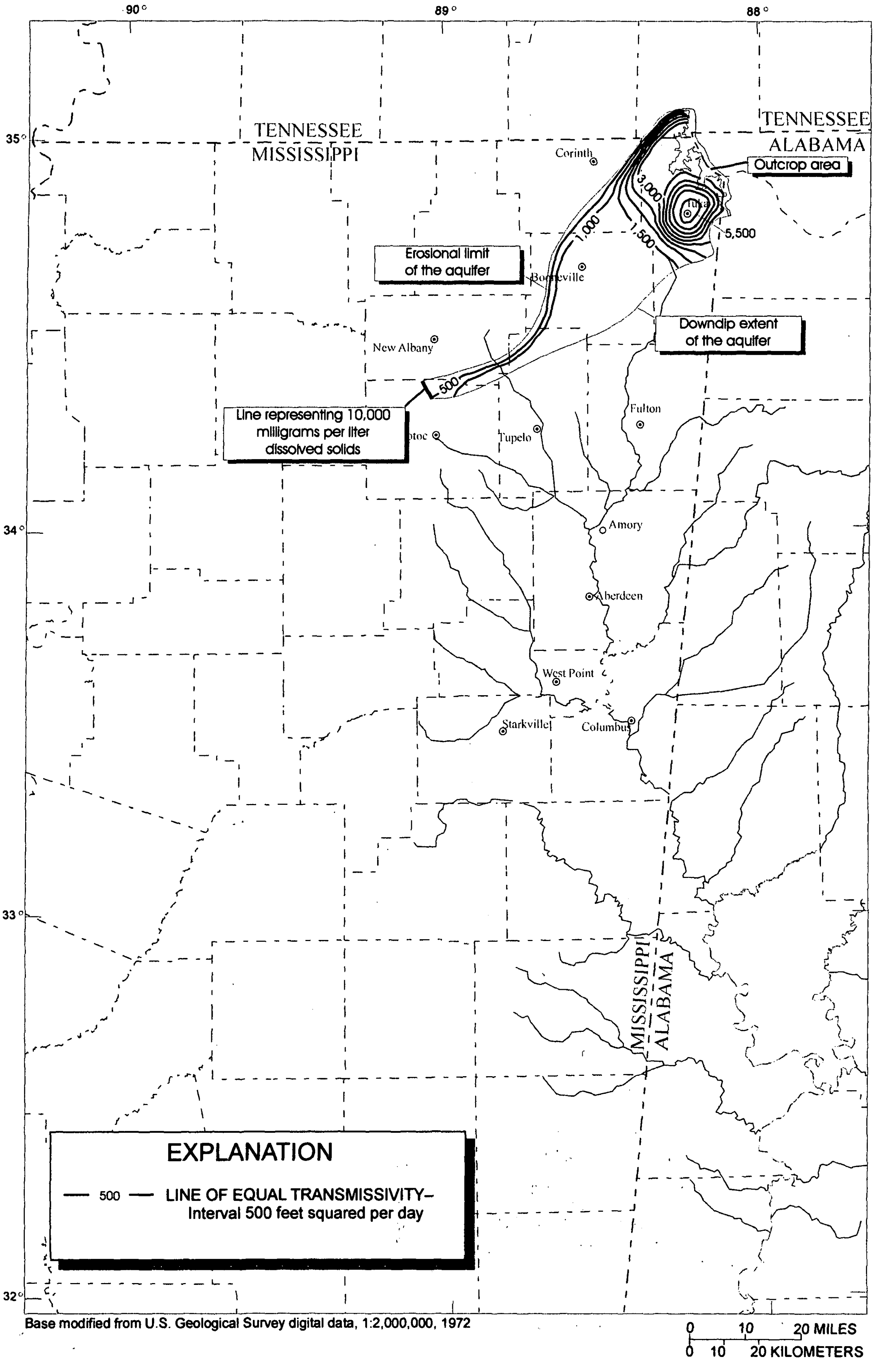

Figure 25. Transmissivity of the Iowa aquifer used in model simulations.

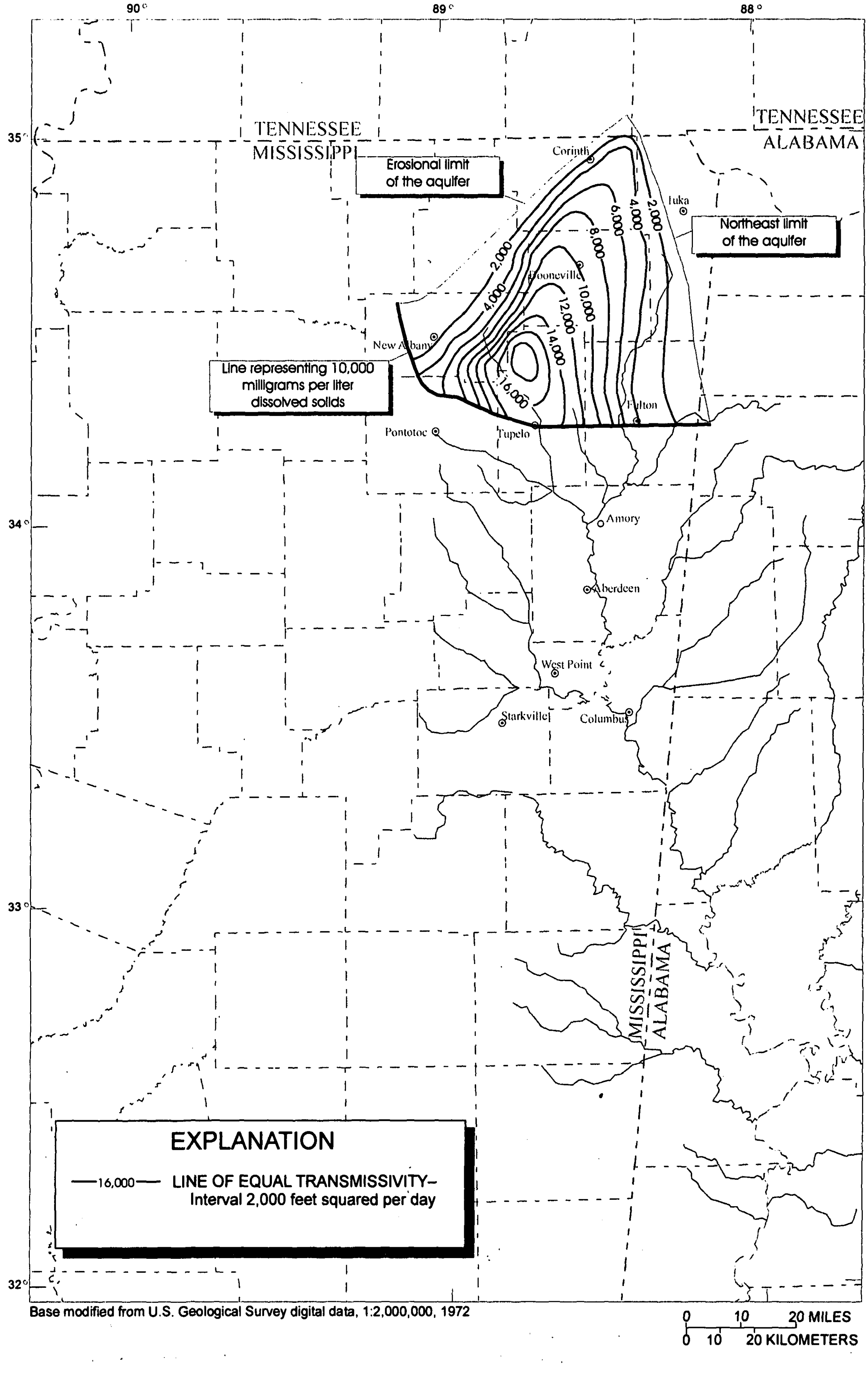

Figure 26. Transmissivity of the Devonian aquifer used in model simulations.

The confining unit between the Eutaw-McShan and the Coffee Sand aquifers is the Mooreville Chalk, and, to the north where the Mooreville Chalk is absent, the Tombigbee Sand Member acts as a confining unit (fig. 3). South of the extent of the Coffee Sand aquifer, the confining unit overlying the Eutaw-McShan aquifer is the Mooreville Chalk and Demopolis Chalk of the Selma Group.

For the Gordo, Coker, massive sand, and Lower Cretaceous aquifers, the confining unit represents the total clay thickness separating each aquifer from the overlying aquifer. The subcrop regions of the Iowa and Devonian aquifers are generally thought to be in good contact with the overlying Cretaceous aquifers; therefore, a uniform confining thickness of 1 foot was used in the model. Although the Iowa and Devonian aquifers have adjacent subcrops, the Iowa aquifer is confined from the Devonian aquifer by a wedge of low permeability rock that thickens towards the southeast (fig. 4).

The confining unit thickness data for all of the aquifers were gridded and contoured (figs. 27-32). Limited information on vertical hydraulic conductivity is available for the confining units. A constant vertical hydraulic conductivity value of 0.00001 foot per day was assumed for all of the confining units. This value is based on ranges of 0.00001 to 0.000001 reported by Planert and Sparks (1985) for the clay layer separating the Eutaw-McShan and Gordo aquifers in Marengo County, Alabama (fig. 1), and on horizontal hydraulic conductivity values for clay (Domenico and Schwartz, 1990) reduced to account for anisotropy between vertical and horizontal flow in a layered medium. Vertical flow through the confining units was simulated in the model by assigning a vertical-leakage coefficient (leakance) between model layers. Leakance values are used by the model to calculate a vertical conductance for each cell. Leakance values incorporate both vertical hydraulic conductivity and confining unit thickness into a single term. A thorough discussion on the use and formulation of the leakance values may be found in McDonald and Harbaugh (1988). The leakance grids were generated by dividing the average vertical hydraulic conductivity value of 0.00001 foot per day by the confining unit thickness grids.

The initial transmissivity grids were modified during model calibration to produce calibrated transmissivity grids for all of the aquifers. The modeled horizontal hydraulic conductivities for the Coffee Sand, Eutaw-McShan, Gordo, and Coker aquifers were 9.7, 8.4, 52.6, and 50 feet per day, respectively. The massive sand and Iowa aquifers were modeled using two zones of hydraulic conductivity—an updip zone and a downdip zone—as indicated by aquifer tests and calibrated water levels. The massive sand had modeled hydraulic conductivities of about 60 and 125 feet per day in the downdip and updip areas, respectively. The Iowa aquifer had modeled hydraulic conductivities of about 14 and 34 feet per day in the downdip and updip areas, respectively. The Devonian aquifer had a modeled hydraulic conductivity of about 45 feet per day. The Lower Cretaceous aquifer was modeled using a constant hydraulic conductivity of 125 feet per day.

Two changes were made to two of the initial leakance grids during model calibration. Water-level data indicate that the region of confluence for the Tombigbee and Black

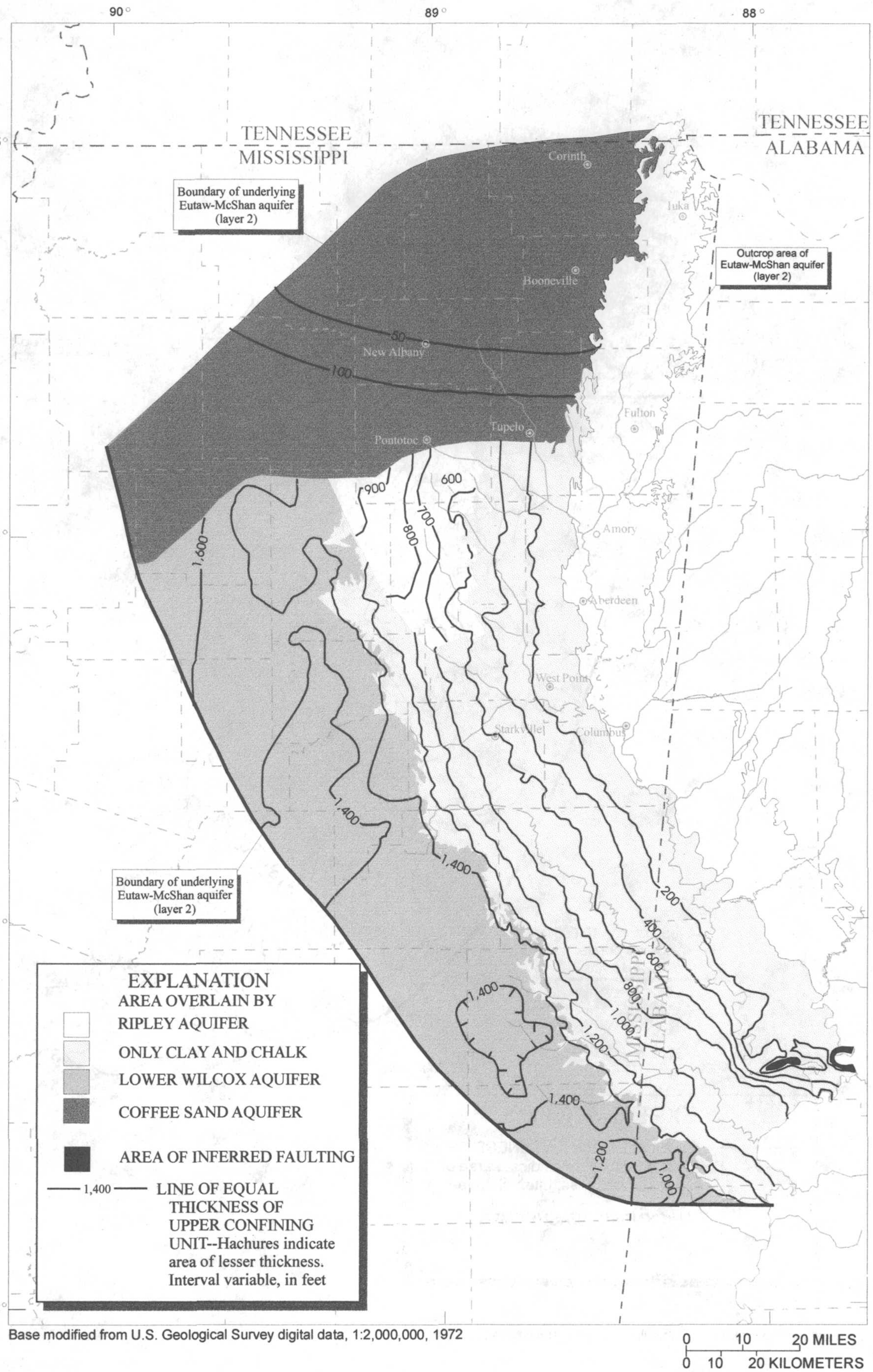

Figure 27. Thickness of the confining unit overlying the Eutaw-McShan aquifer used in model simulations.

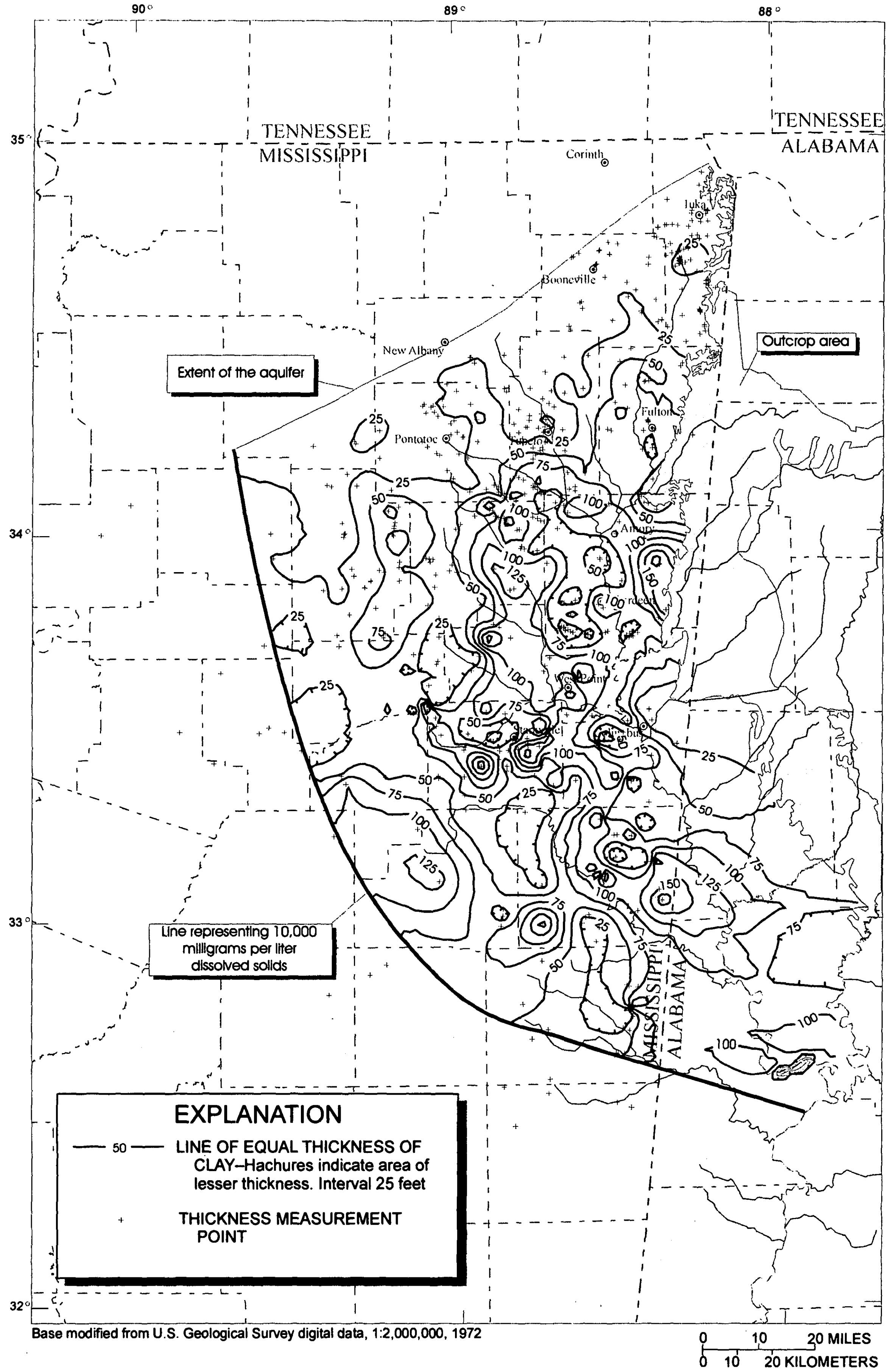

Figure 28. Total overlying clay thickness of the Gordo aquifer and location of measurements.

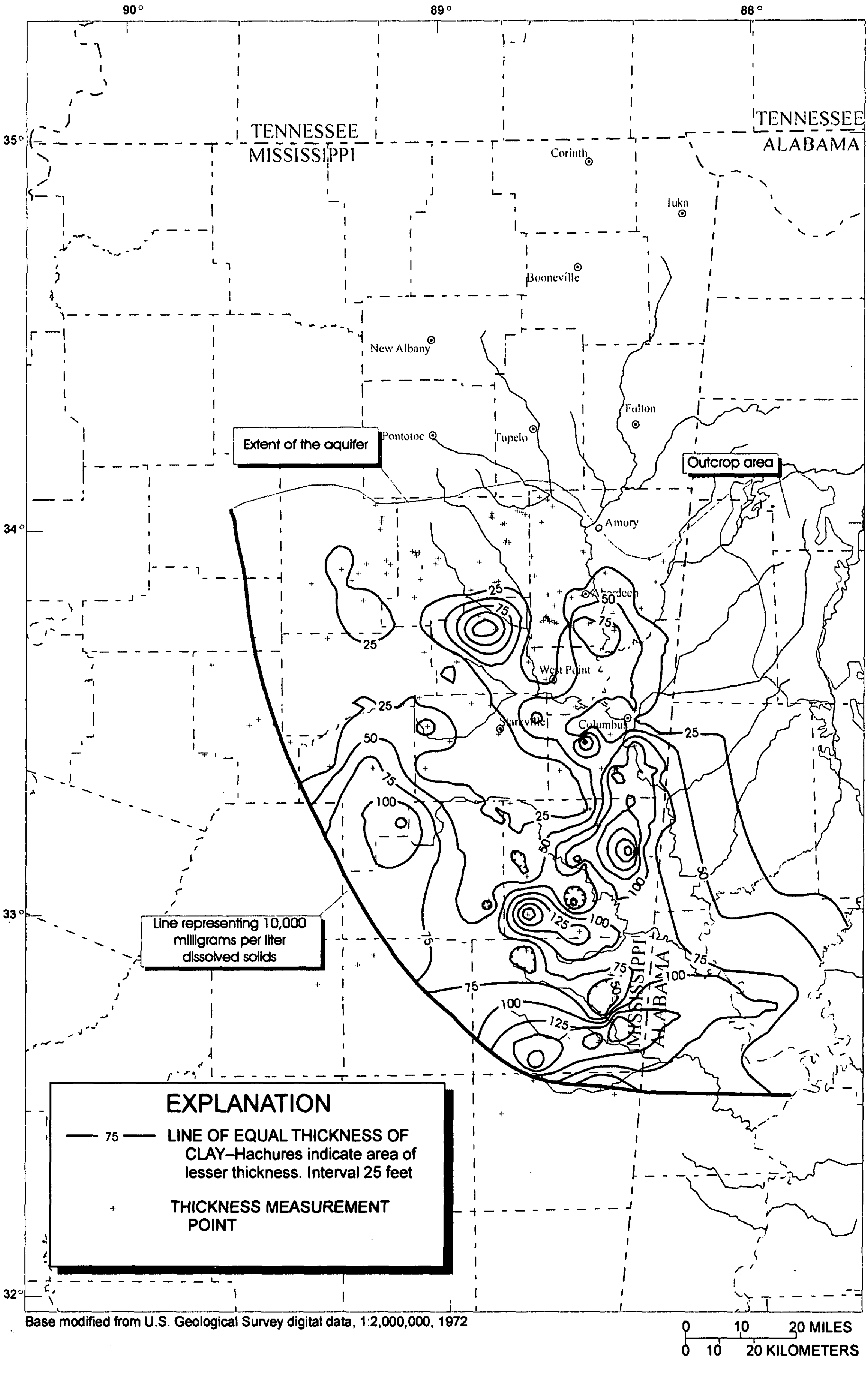

Figure 29. Total overlying clay thickness of the Coker aquifer and location of measurements.

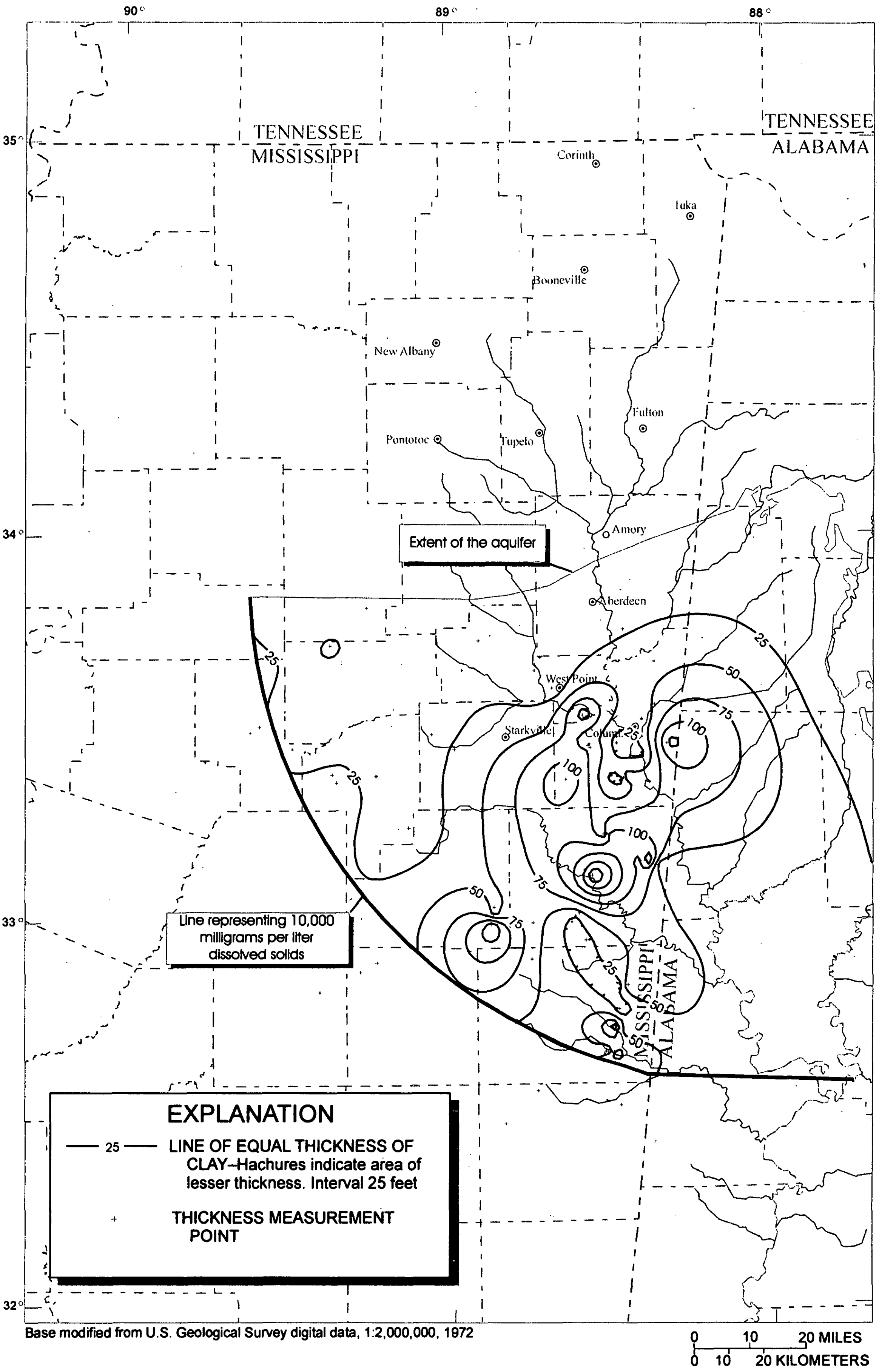

Figure 30. Total overlying clay thickness of the massive sand aquifer and location of measurements.

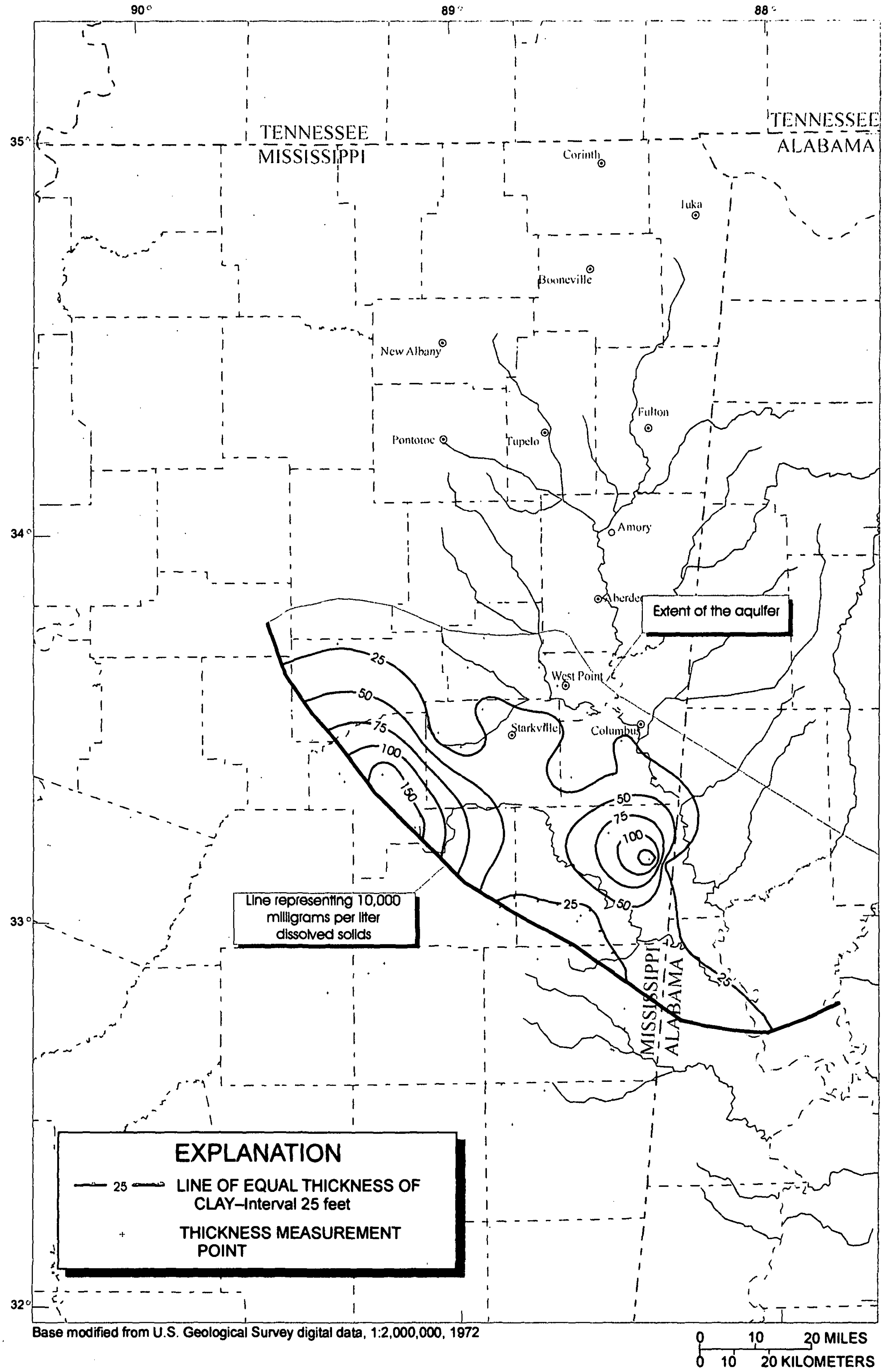

Figure 31. Total overlying clay thickness of the Lower Cretaceous aquifer and location of measurements.

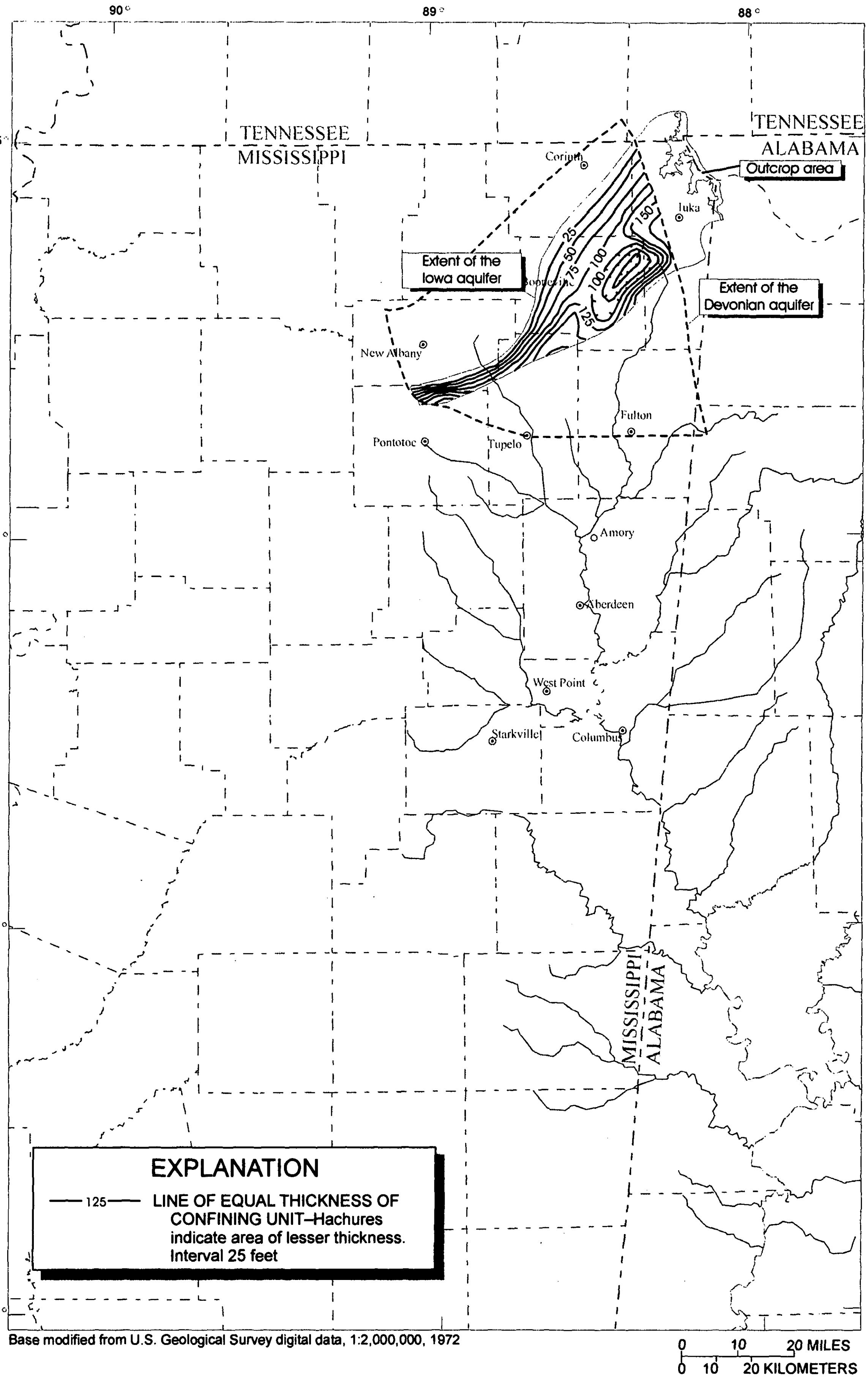

Figure 32. Total confining thickness between the Iowan and Devonian aquifers (S.P. Jennings, OLWR, written commun., 1997).

Warrior Rivers (fig. 1) is a major discharge area for the Eutaw-McShan and Gordo aquifers (Gardner, 1981). Seismic surveys also indicate faulting along parts of the river reaches in this area (Gardner, 1981). Water-level data indicate that this area is a major discharge area for the Eutaw-McShan and Gordo aquifers, yet the overlying chalk of the Selma Group is quite thick. It is likely that faults and other structural features increase vertical flow in this area (Mallory, 1993; Strom and Mallory, 1995). The vertical conductances were increased in this area for the confining layers overlying the Eutaw-McShan and Gordo aquifers (figs. 27-28) during model calibration to minimize the difference between simulated and measured water levels.

Published potentiometric maps are available for the Eutaw-McShan, Gordo, and Paleozoic aquifers for the end of pumping period 5 in 1978 (Wasson, 1980b,1980c; Wasson, 1979), and for the end of pumping period 9 in 1992 for the Eutaw-McShan (Everett and Jennings, 1994), Gordo (Phillips and Hoffmann, 1994), Coker, massive sand (Hardin and Everett, 1994) and Paleozoic aquifers (Jennings and Phillips, 1994). Potentiometric maps are also available for some of the aquifers during intermediate pumping periods (Darden, 1984 and 1985; Goldsmith, 1990 and 1991). Comparison of simulated and published potentiometric maps of the aquifers provided the primary means of model calibration, particularly for the Coffee Sand and Paleozoic aquifers where few observation wells are available. In addition, a total of 487 water-level measurements from published reports provided values for model calibration. These water-level measurements are separated by 14 years (1978 and 1992), and in some cases, by very different pumping histories, which is helpful in model verification. The total number of water-level measurements used to calibrate each aquifer, and the root-mean-square error of the simulated heads are listed in table 2. The root-mean-square error (RMS) is the square-root of the sum of the square of the differences between measured and simulated water levels divided by the total number of water-level measurements.

Table 2. Root-mean-square error of simulated head in the aquifers for 1978 and 1992
[-- indicates no data available]

Aquifer	Number of water-level measurements (1978)	Root-mean-square error of simulated heads, in feet (1978)	Number of water-level measurements (1992)	Root-mean-square error of simulated heads, in feet (1992)
Eutaw-McShan	89	14.7	162	16.7
Gordo	59	17.2	149	16.9
Coker	--	--	12	10.4
Massive sand	--	--	16	7.2

The 1992 simulated potentiometric surfaces for the Eutaw-McShan and Gordo aquifers (figs. 33-34) show the same regional flow patterns as the published maps (figs. 14-15). The 1992 potentiometric-surface maps used were based on data collected during a time of rapid recovery of water levels in the Tupelo area. To simulate water-level

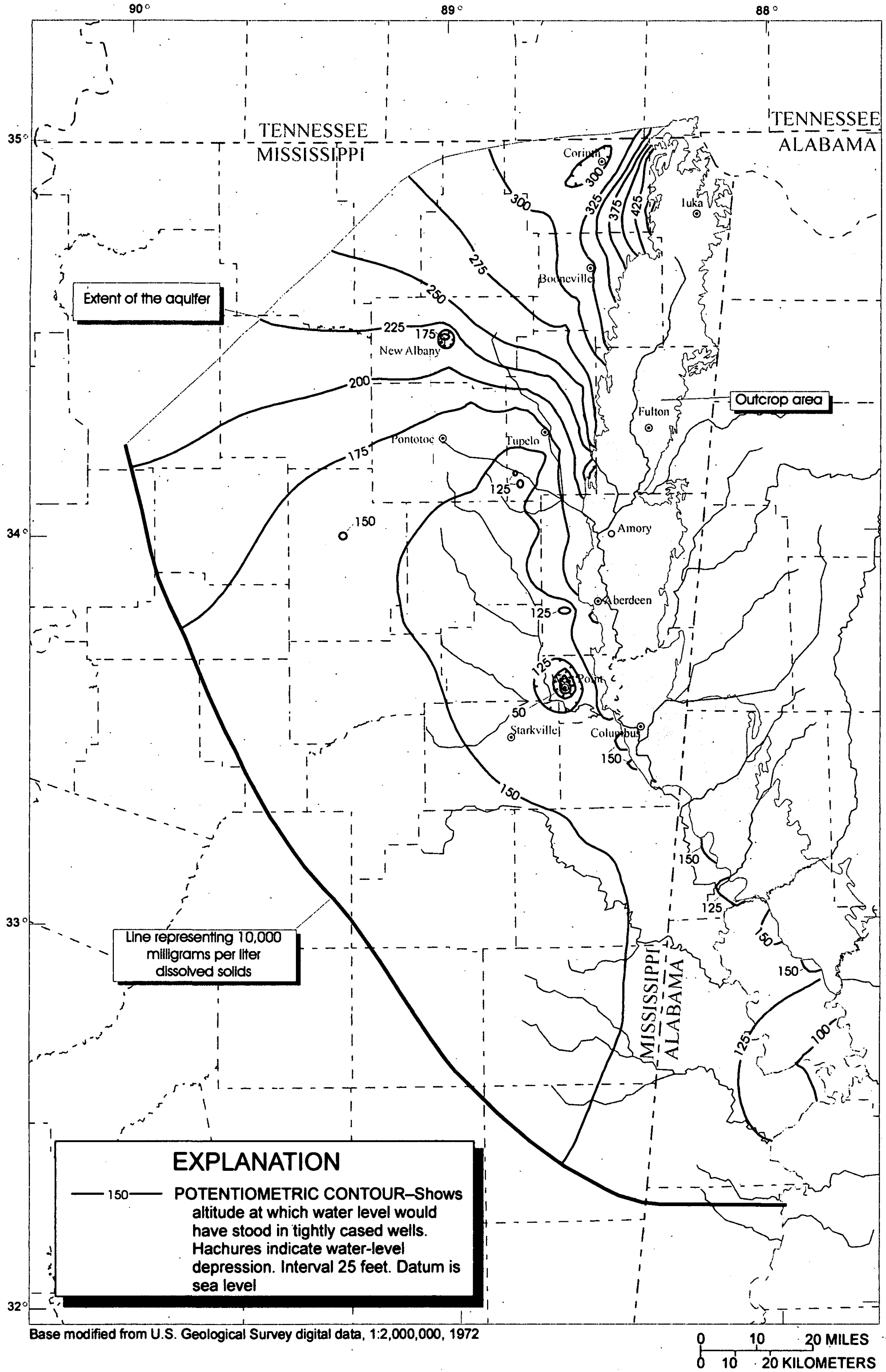

Figure 33. Simulated 1992 potentiometric surface of the Eutaw-McShan aquifer.

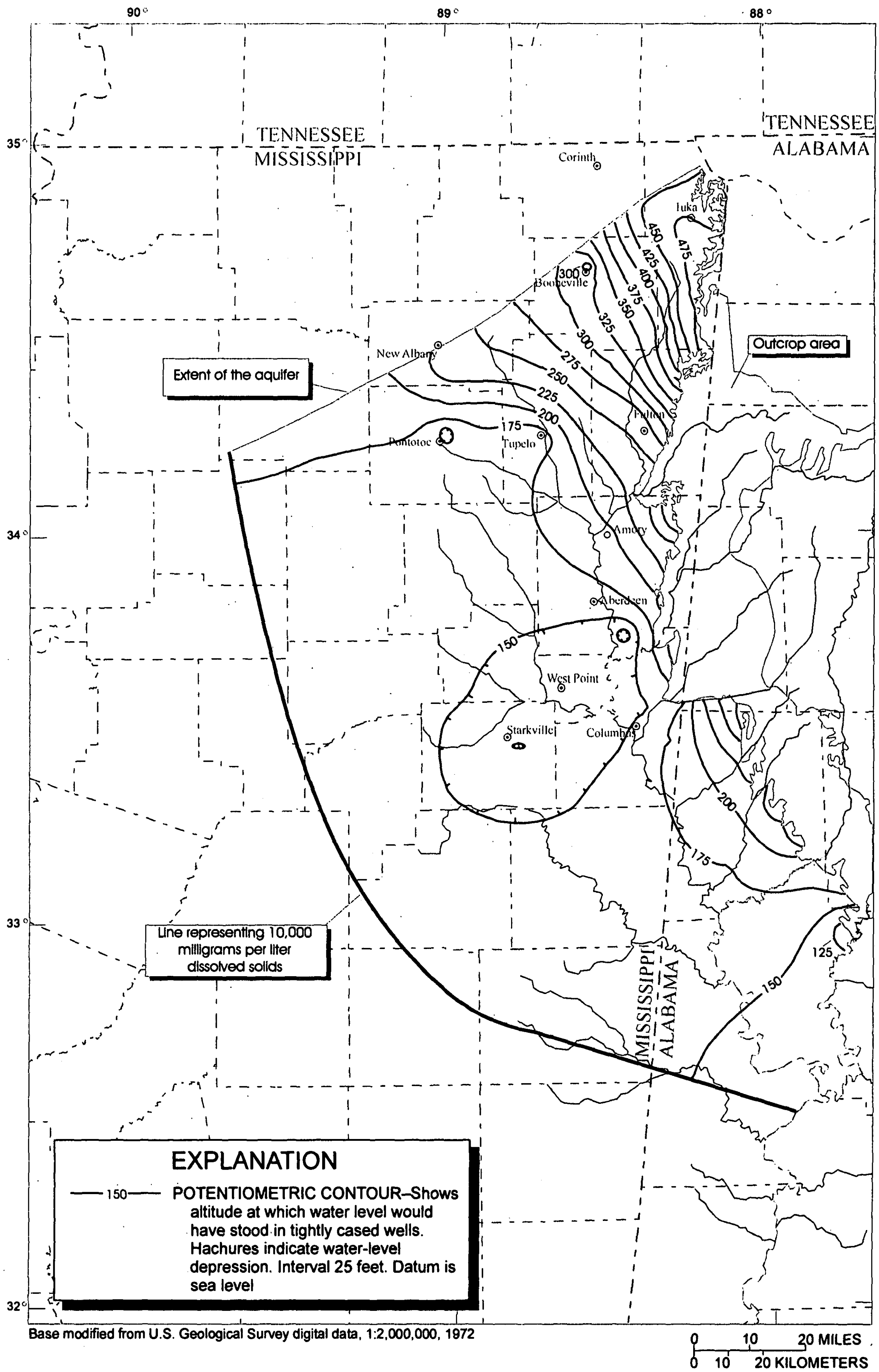

Figure 34. Simulated 1992 potentiometric surface of the Gordo aquifer.

recoveries accurately in the Tupelo area during this specific time of rapid water-level change, pumping periods of less than 1 year would be needed.

Few water-level measurements are available for the Coker and massive sand aquifers for 1978 (pumping period 5), and no measurements are available for the Lower Cretaceous aquifer in the modeled area. Although water-level data for the Coker and massive sand aquifers for 1992 (pumping period 9) were a good match, no potentiometric-surface maps were available for other pumping periods which precluded verification. Water levels from long-term observation wells were available for the Coffee Sand and massive sand aquifers, however, as well as for the Eutaw-McShan and Gordo aquifers; simulated and measured heads are in good agreement (fig. 35). The Lower Cretaceous aquifer was simulated primarily to provide a realistic lower boundary for the system. Because no water-level data are available for the Lower Cretaceous aquifer and only estimates of hydraulic parameters are available, verification of the hydraulic parameters for this model layer was not possible.

Simulation of Predevelopment Ground-Water Flow Conditions

Simulations of predevelopment ground-water flow conditions were made using hydraulic parameters determined from transient model calibration. The simulated predeveloped potentiometric surfaces for the aquifers are shown in figs. 36-42. Heads in the Cretaceous aquifers generally were highest to the northeast and lowest to the southeast, which is a general reflection of the topography (fig. 2). Regional ground-water flow in the Cretaceous aquifers generally was from the northeast to the southeast along an arcuate path. Ground water from the northernmost part of the outcrop areas entered the basal part of the aquifers. With the exception of the Coffee Sand aquifer, simulated predevelopment recharge generally entered the Cretaceous aquifers in the updip areas and was discharged to the overlying aquifer in the downdip areas.

In the Coffee Sand aquifer (fig. 36), water entering the aquifer from about the southern half of the outcrop area was discharged to rivers in the southernmost part of the outcrop area, while water entering the aquifer from about the northern half of the outcrop area enters the deeper flow system and eventually entered the underlying Eutaw-McShan aquifer. In the Eutaw-McShan aquifer (fig. 37), as ground water moves from the outcrop area southward, flow was captured by the Tombigbee River and its tributaries. In the extreme southeastern part of the area, flow moved upward through the confining unit into the Tombigbee and Black Warrior Rivers. The same general trends exist for the other Cretaceous aquifers (figs. 38-40). However, the Coker aquifer also received some recharge from the overlying Gordo aquifer in the far northeastern area near the depositional extent of the Coker aquifer (fig. 39). The Lower Cretaceous aquifer (not shown) had a very flat gradient with heads only ranging from about 248 to 254 feet above sea level.

Most recharge entered the Iowa aquifer through the overlying Cretaceous aquifers at a topographic high in north and central Tishomingo County (fig. 41). Flow was then either discharged to Pickwick Lake to the northeast, or entered the deeper flow system to

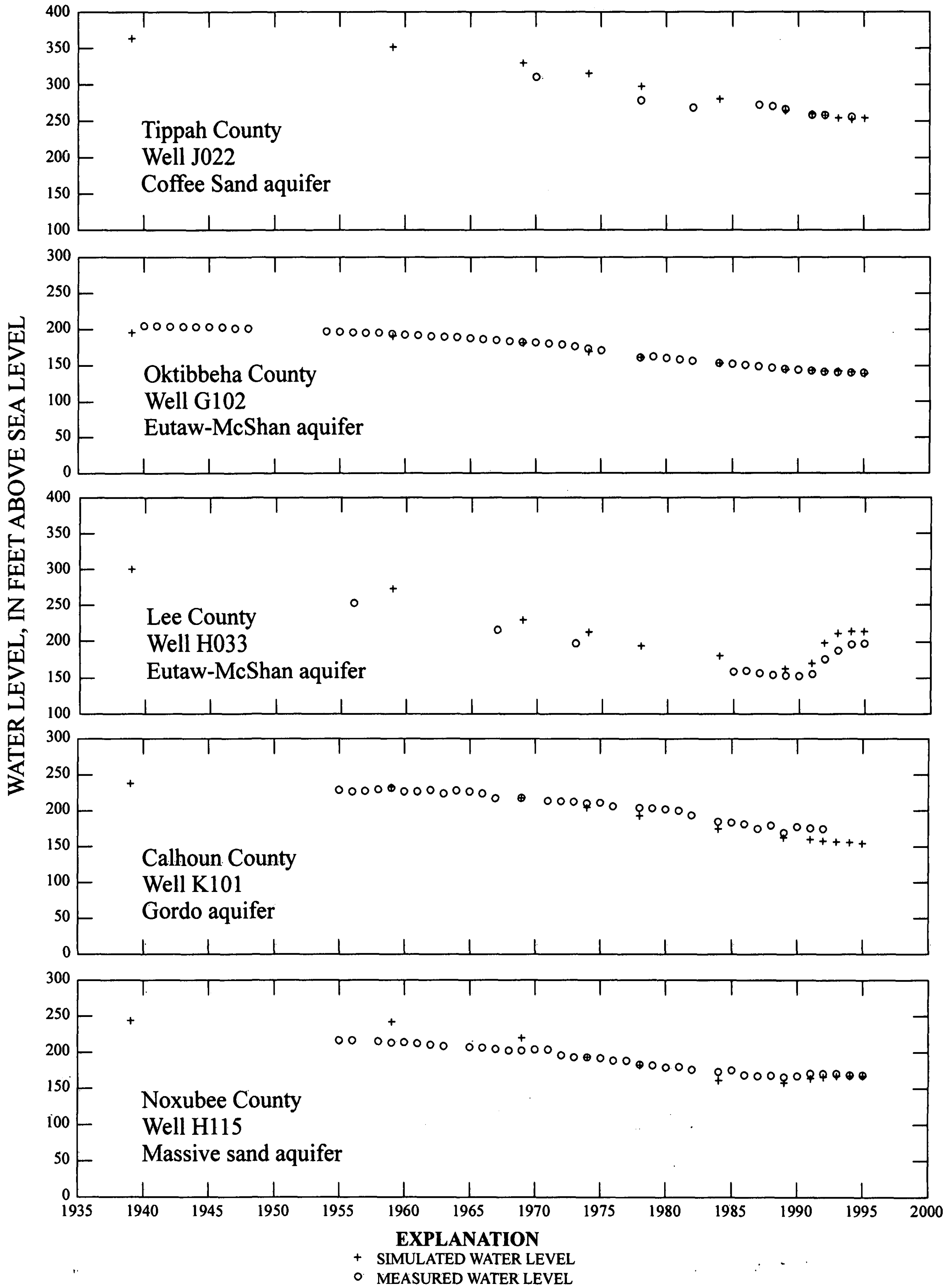

Figure 35. Simulated and measured water levels for selected observation wells screened in the Coffee Sand, Eutaw-McShan, massive sand, and Gordo aquifers (location of wells shown on figures 36-38, and 40).

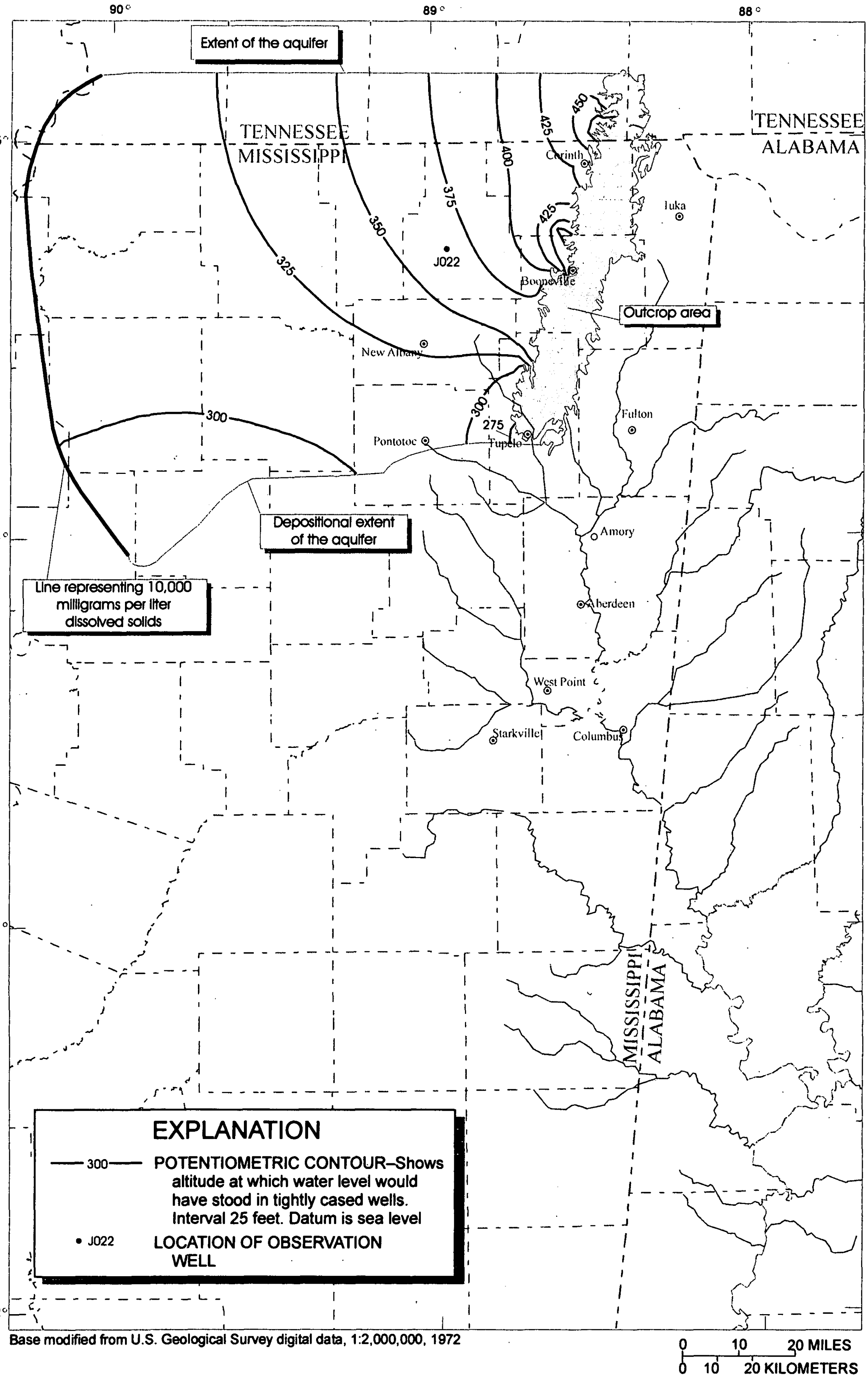

Figure 36. Simulated predevelopment potentiometric surface of the Coffee Sand aquifer.

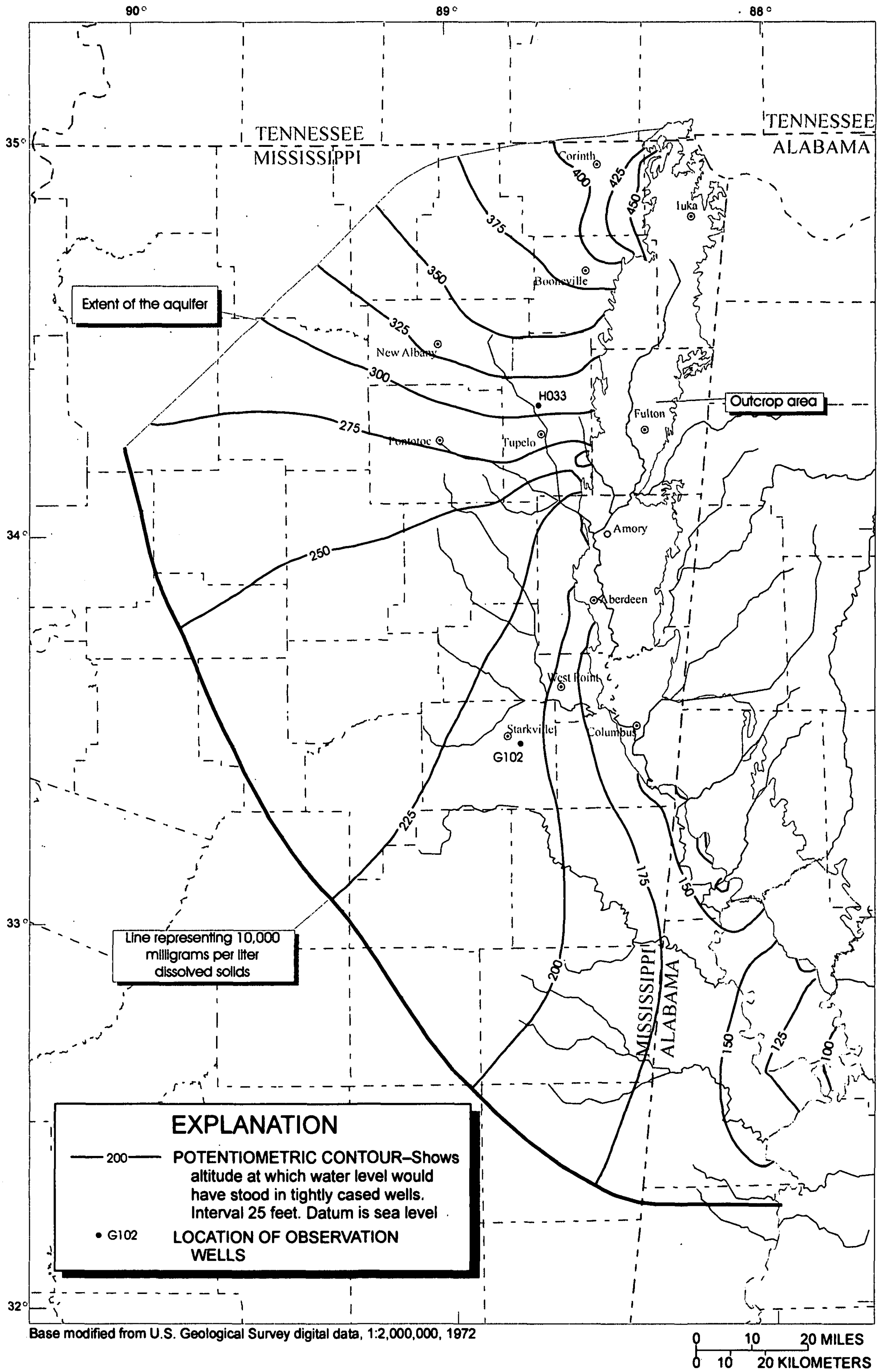

Figure 37. Simulated predevelopment potentiometric surface of the Eutaw-McShan aquifer.

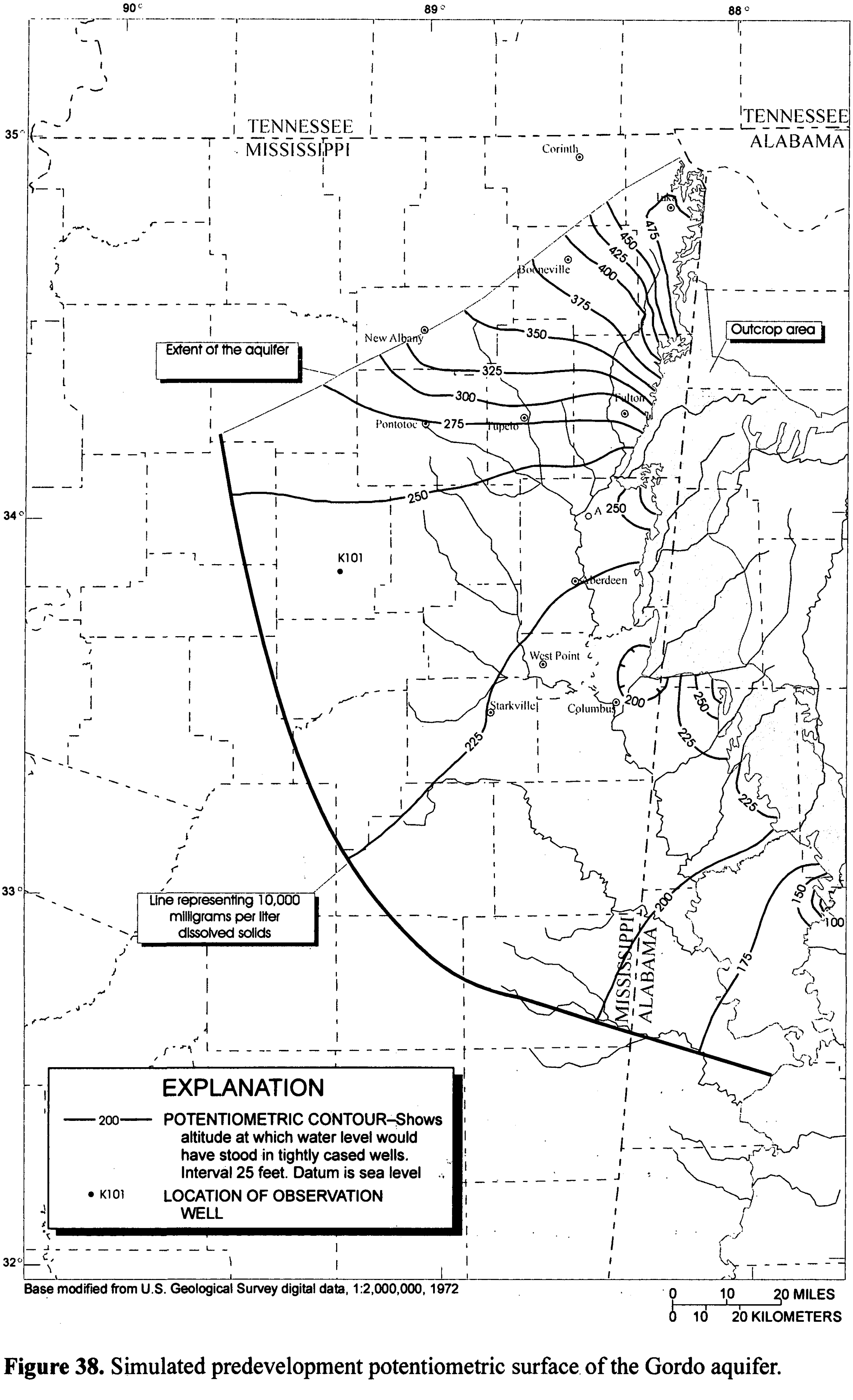

Figure 38. Simulated predevelopment potentiometric surface of the Gordo aquifer.

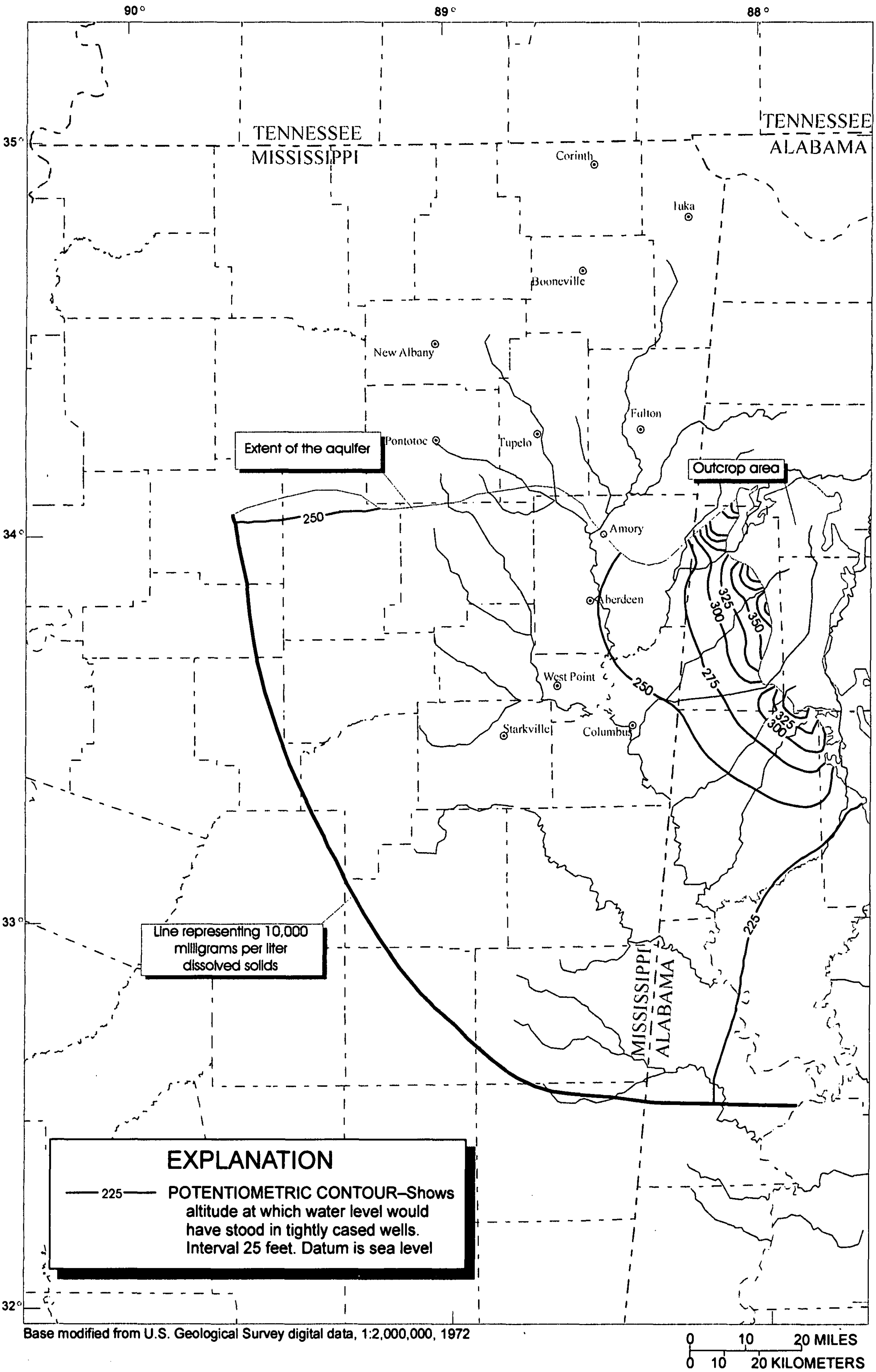

Figure 39. Simulated predevelopment potentiometric surface of the Coker aquifer.

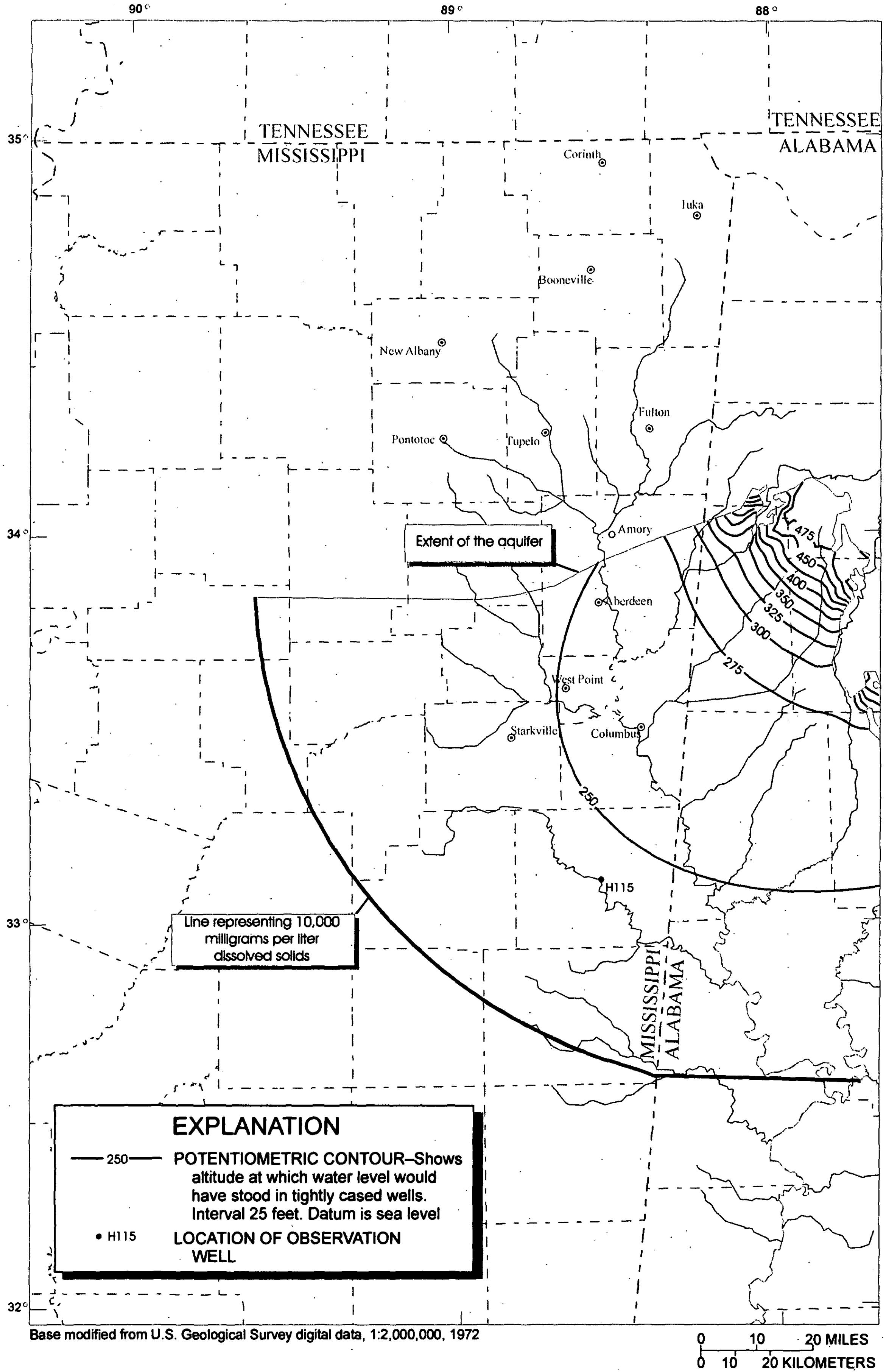

Figure 40. Simulated predevelopment potentiometric surface of the massive sand aquifer.

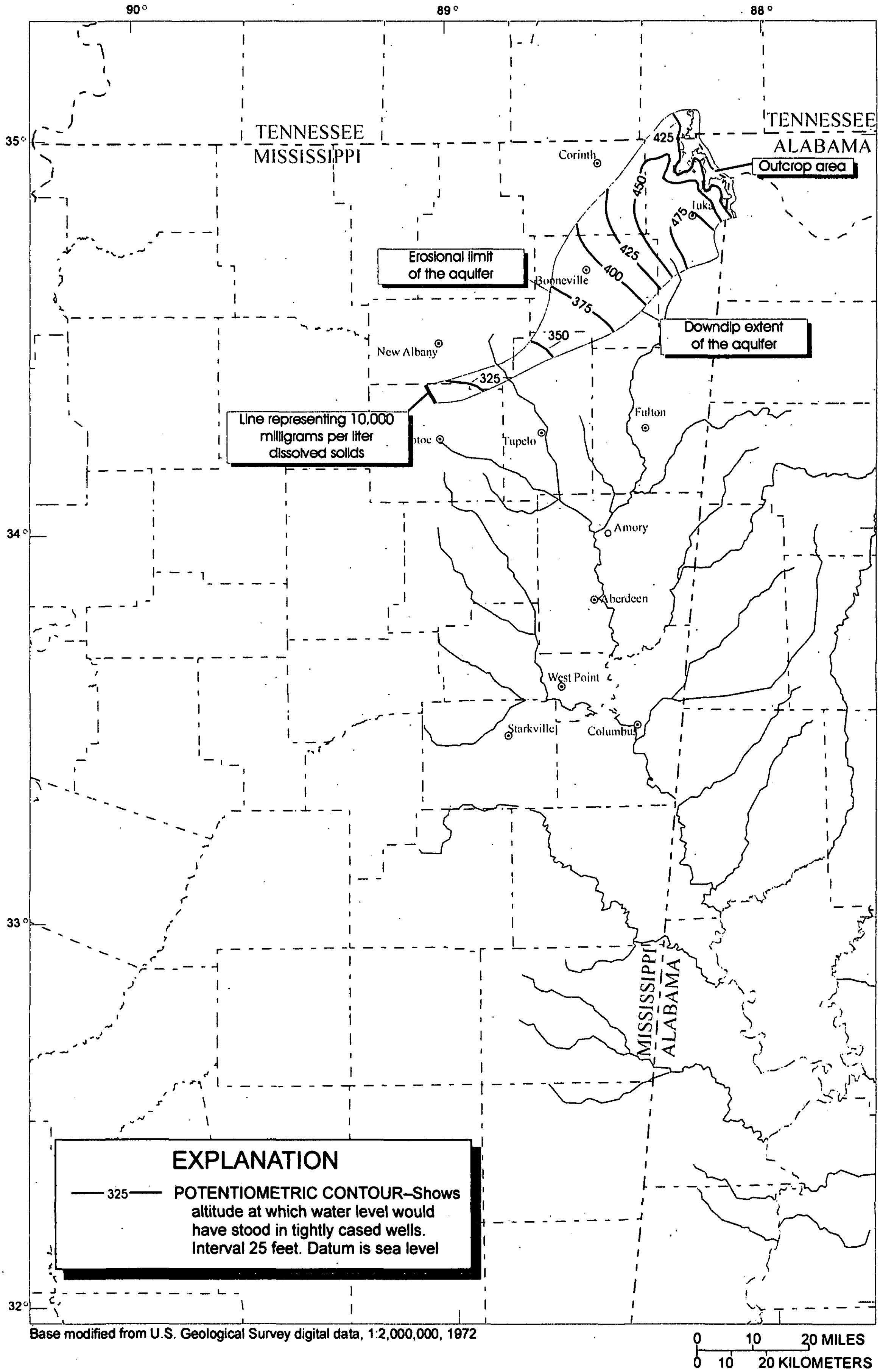

Figure 41. Simulated predevelopment potentiometric surface of the Iowa aquifer.

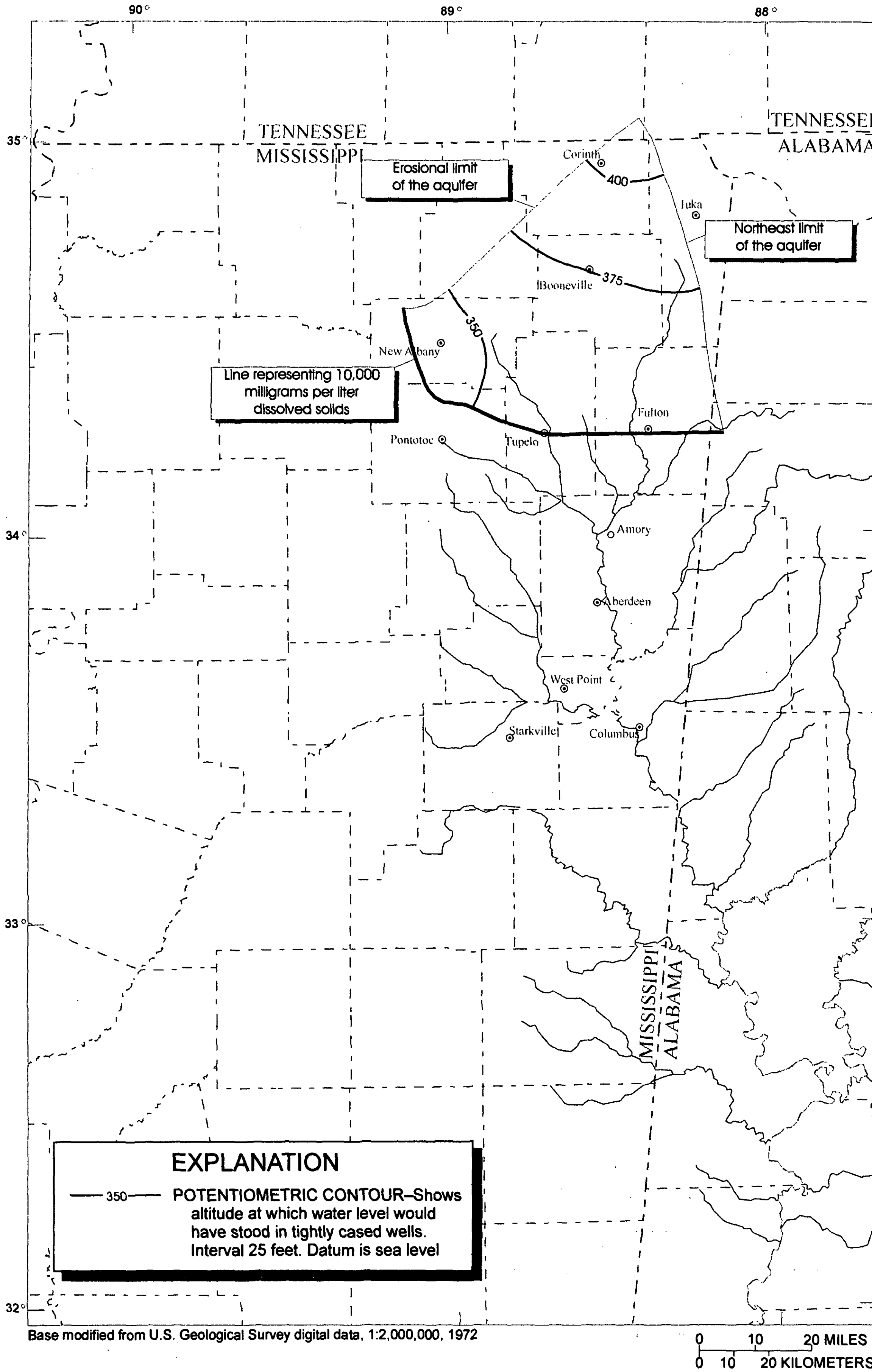

Figure 42. Simulated predevelopment potentiometric surface of the Devonian aquifer.

the southwest and eventually moved upward and entered the overlying Cretaceous aquifers in parts of Prentiss, Lee, and Pontotoc Counties. The Devonian aquifer received most of its recharge from the overlying Eutaw-McShan aquifer in Alcorn County (fig. 42). Flow was to the south and southwest and eventually moved upward and entered the overlying Gordo aquifer mostly in Union County.

Simulation of 1995 Ground-Water Flow Conditions

Simulation of 1995 ground-water flow conditions was made using hydraulic parameters determined during transient model calibration. The simulated 1995 water levels for the aquifers are shown in figures 43-50. The corresponding budget for flow between the aquifers is shown in figure 51, and it should be noted that rounding of significant digits may result in net flows slightly different than zero. It should also be noted that due to the relatively recent overall reduction in pumpage (fig. 16), most of the aquifers have simulated gains in storage in 1995. The distribution of areas of simulated 1995 recharge and discharge in the outcrop areas is shown in figure 52. Areas of recharge are mainly at topographic highs, and areas of discharge are mainly at topographic lows.

Simulated 1995 water levels for the Coffee Sand aquifer (fig. 43) indicate that most of the flow entering the aquifer from the outcrop area enters the deeper flow system, as opposed to flow entering the deeper flow system only from the northern half of the outcrop area during predevelopment simulations (fig. 36). About 40 percent of the water entering the aquifer is captured by pumping wells, and about 60 percent of the water enters the underlying Eutaw-McShan aquifer (fig. 51). Minor amounts of water from the Eutaw-McShan enter the Coffee Sand aquifer in the eastern Benton-western Tippah County area (fig. 1) due to lower heads in the Coffee Sand caused by pumpage.

Simulated 1995 water levels for the Eutaw-McShan aquifer (fig. 44) indicate the same regional flow patterns as predevelopment water-levels (fig. 37), but with cones of depression at the major pumping centers. About 57 percent of recharge to the aquifer enters through the outcrop area, the rest is from overlying and underlying aquifers. Much of the water from the Eutaw-McShan aquifer enters the underlying Gordo aquifer in central and northern Tishomingo County. Much of this water subsequently passes through the Gordo aquifer and enters the underlying Iowa aquifer (fig. 51). The Eutaw-McShan aquifer provides most of the recharge that the Devonian aquifer receives in northeastern Alcorn County, and about one-fourth of the water is returned from the Devonian aquifer to the Eutaw-McShan aquifer in the downdip region of the Devonian aquifer in Union County.

Model results indicate that water levels for the Gordo aquifer (fig. 45) have continued to rise rapidly in the Lee County area from 1992 to 1995 (fig. 34). Water-levels in other areas have changed little from the 1992 simulations. Pumping wells capture almost as much water as enters the aquifer as recharge in the outcrop area (fig. 51). Much of the water received from the overlying Eutaw-McShan aquifer occurs in Tishomingo County and flows to the underlying Iowa aquifer. Only about one-tenth of this water flows from the Iowa to the Gordo aquifer in the downdip areas of the Iowa aquifer. The

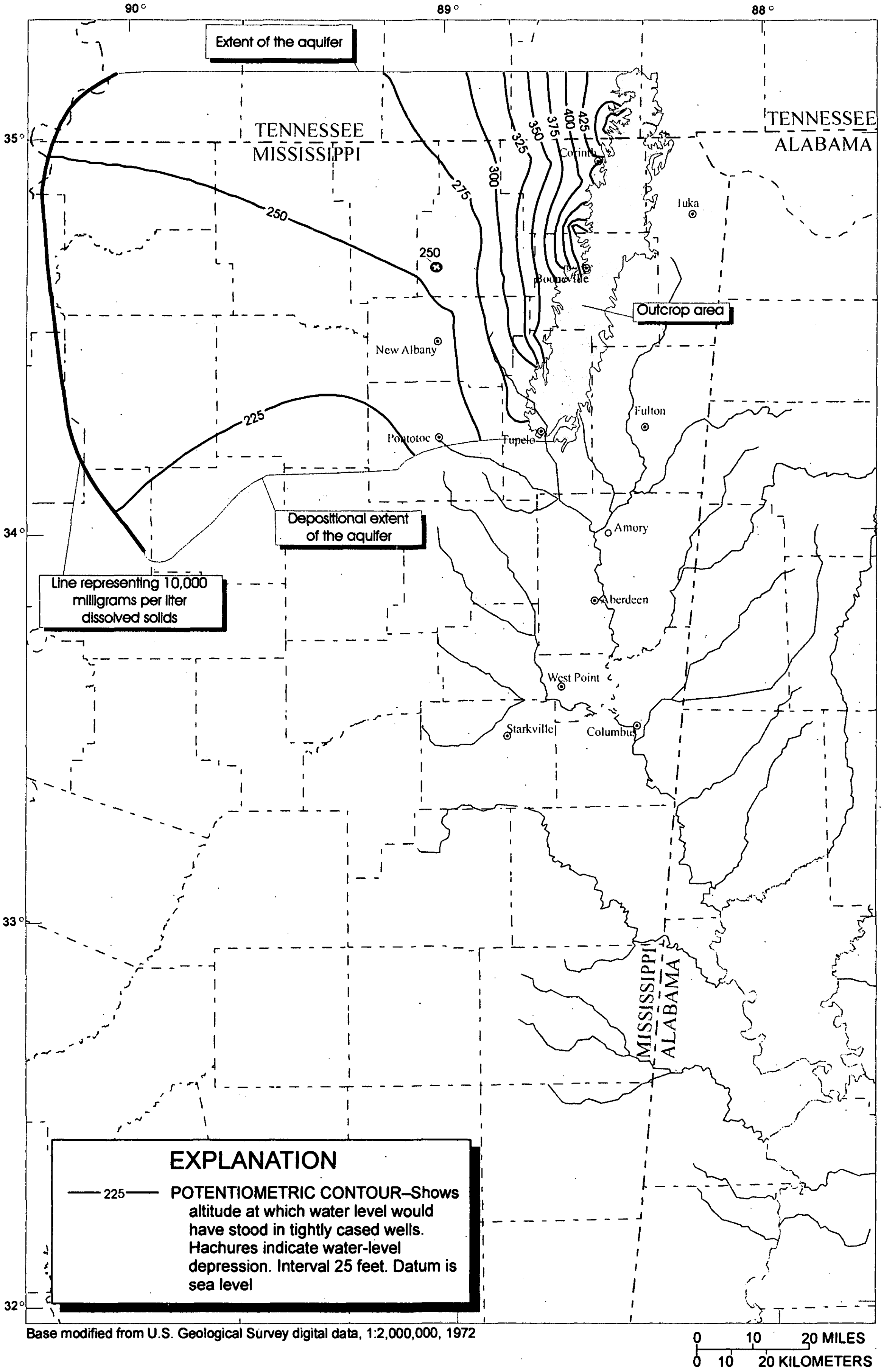

Figure 43. Simulated 1995 potentiometric surface of the Coffee Sand aquifer.

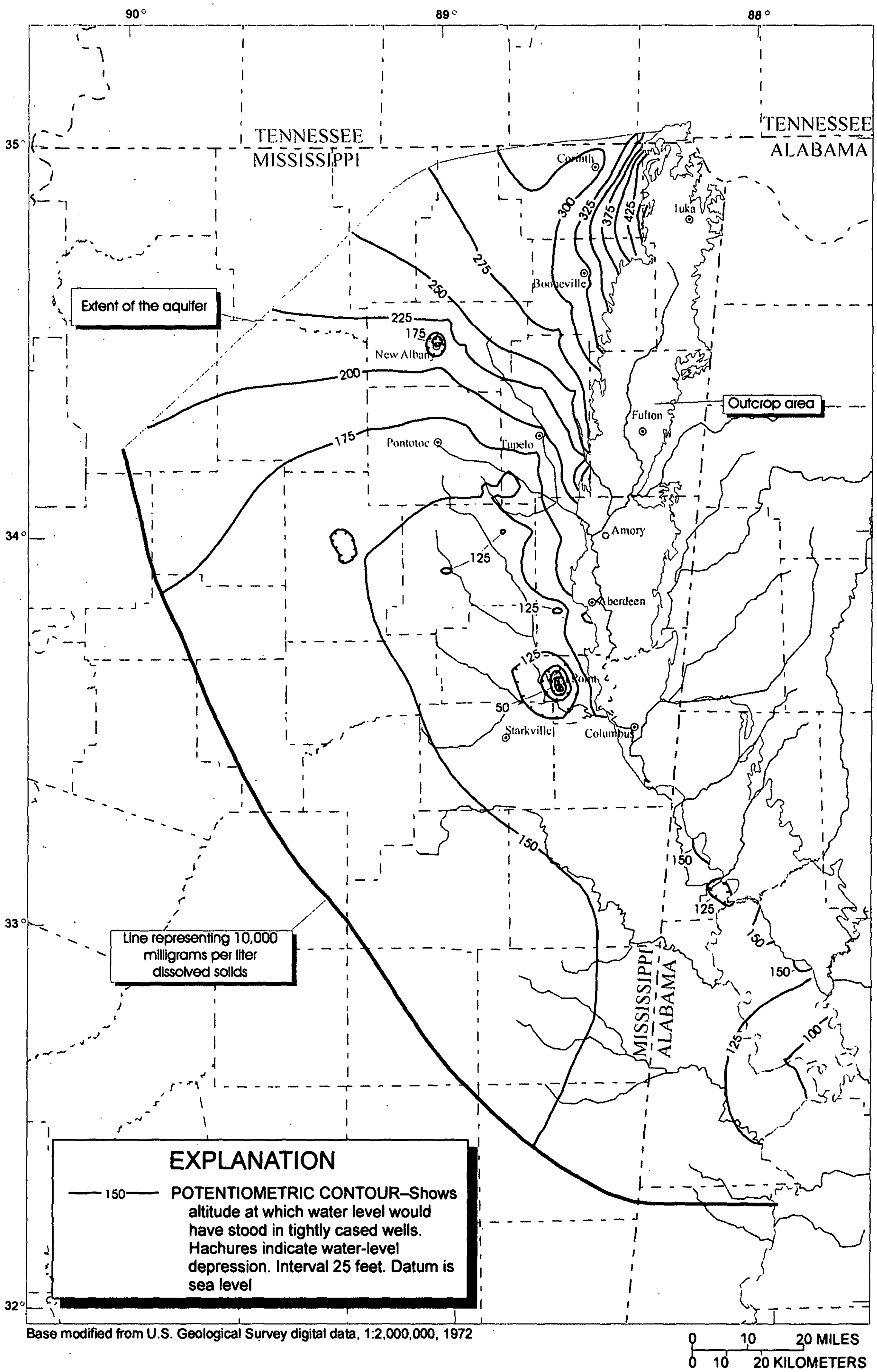

Figure 44. Simulated 1995 potentiometric surface of the Eutaw-McShan aquifer.

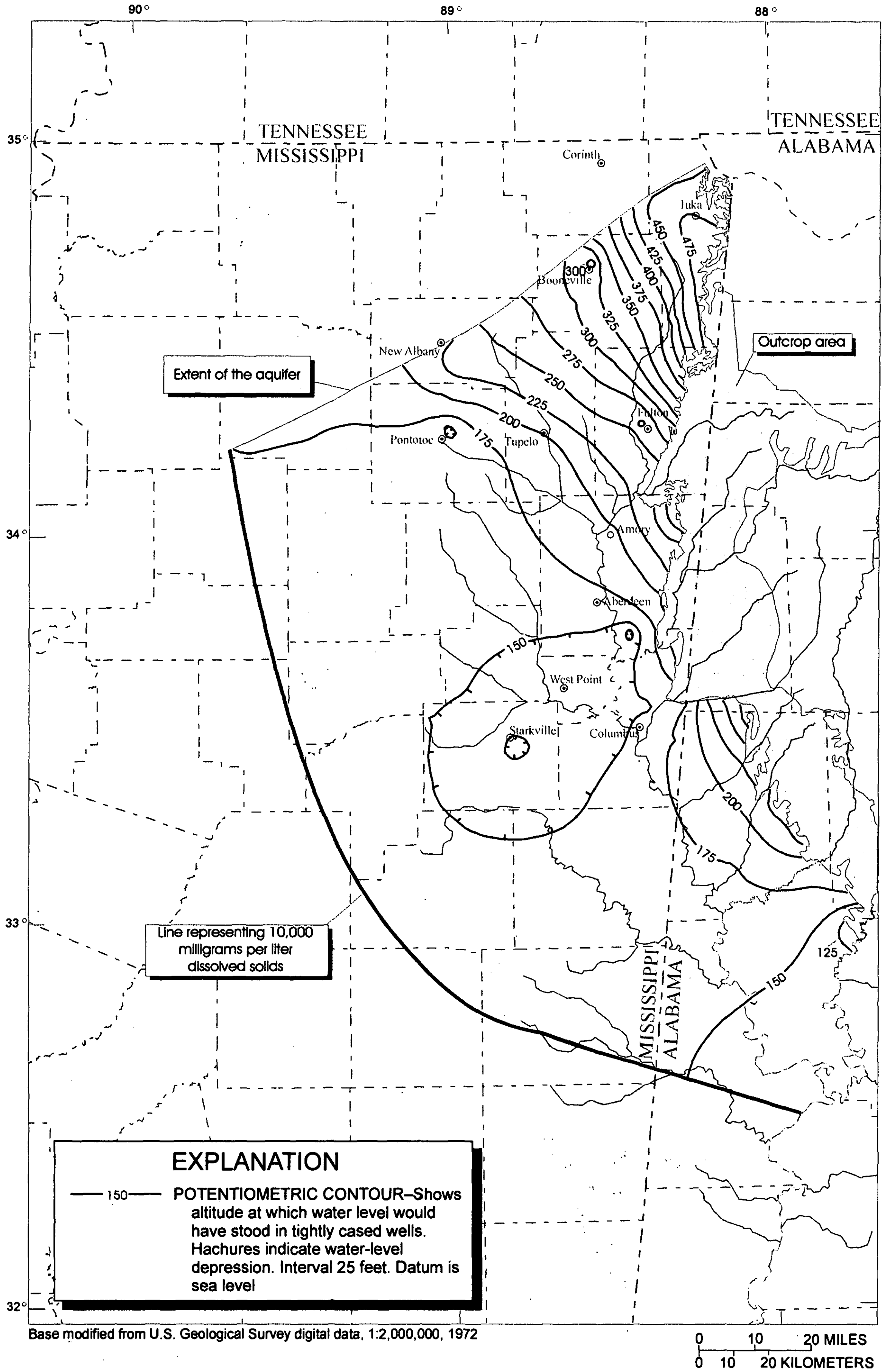

Figure 45. Simulated 1995 potentiometric surface of the Gordo aquifer.

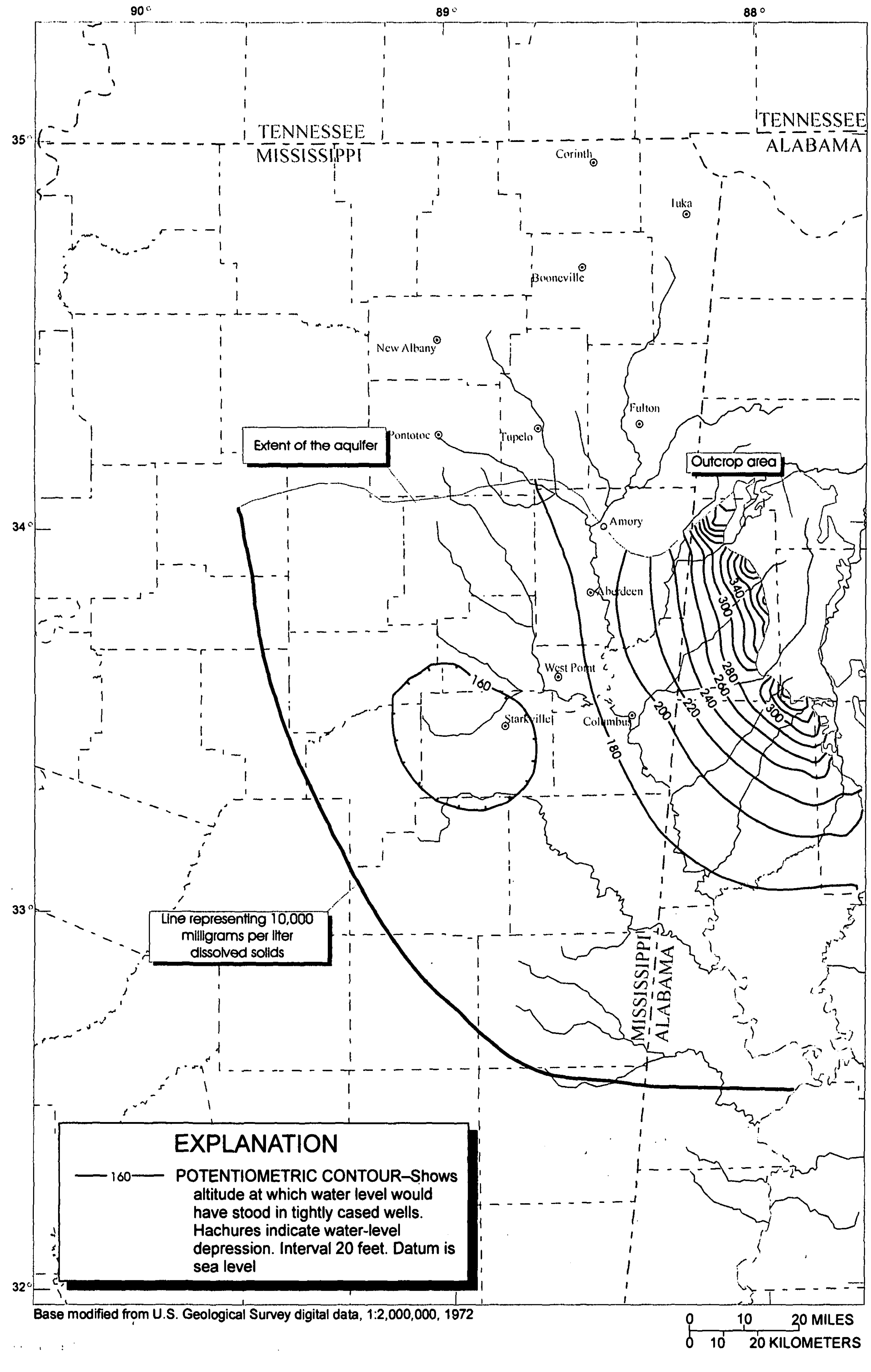

Figure 46. Simulated 1995 potentiometric surface of the Coker aquifer.

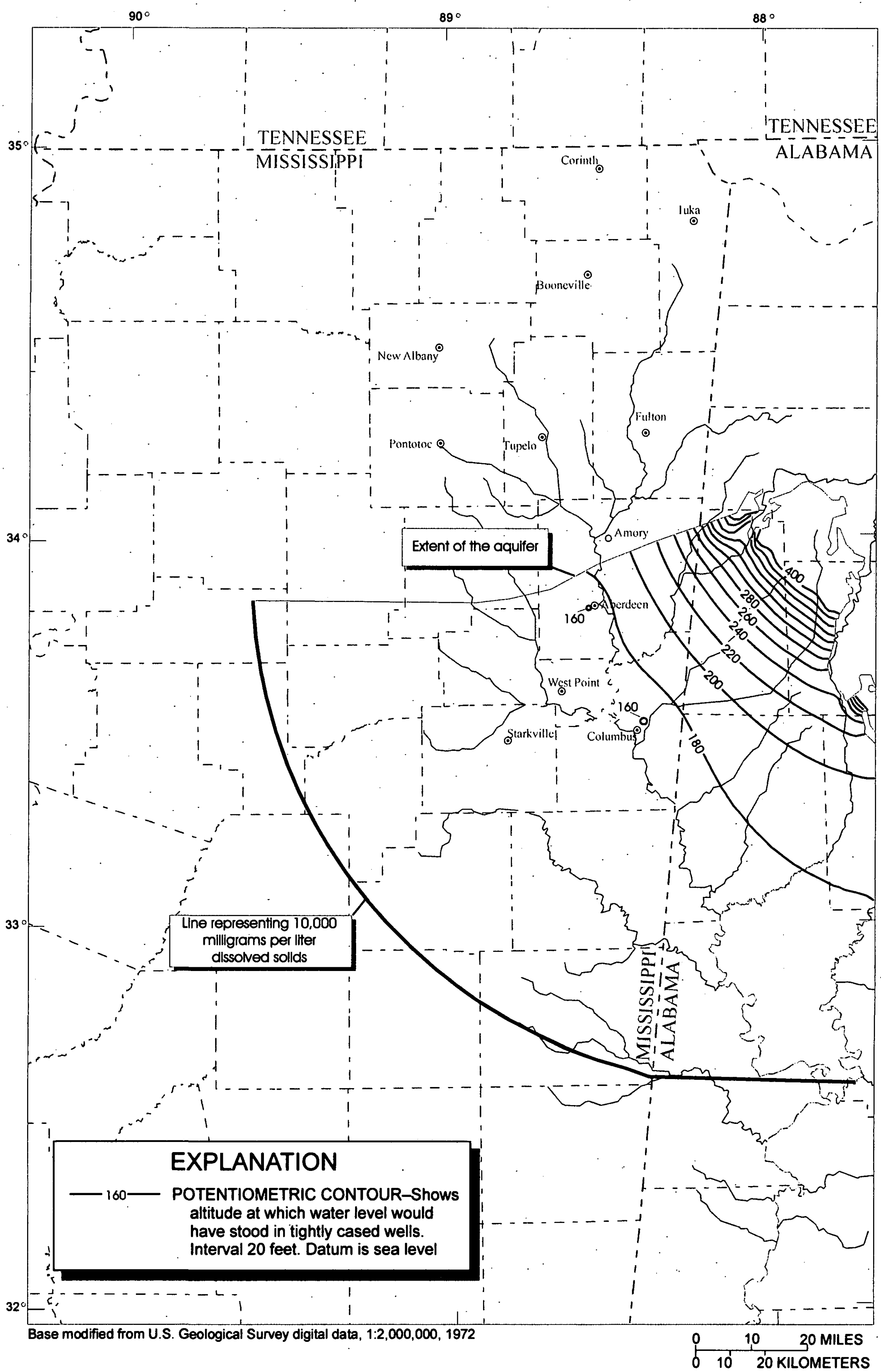

Figure 47. Simulated 1995 potentiometric surface of the massive sand aquifer.

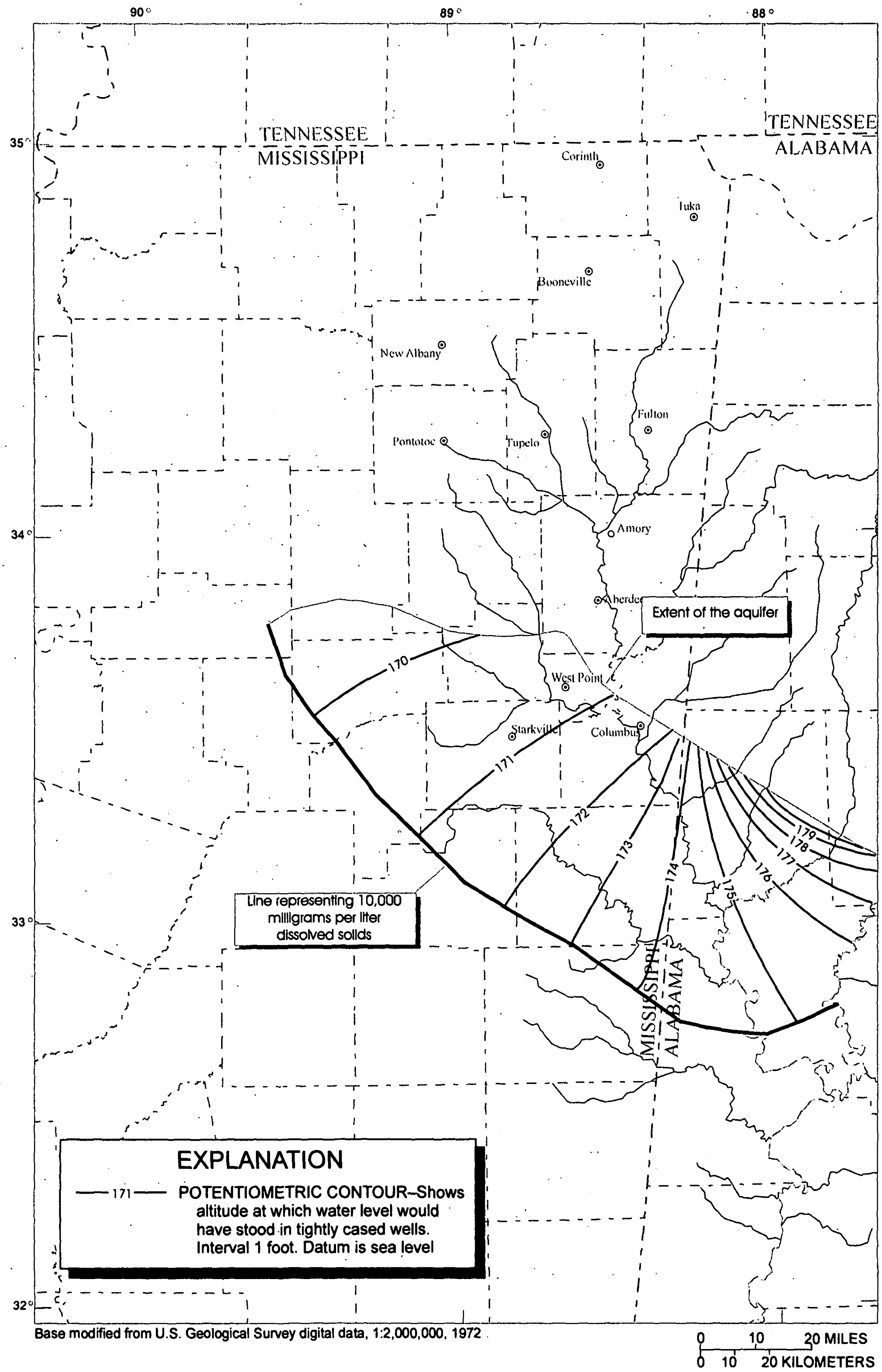

Figure 48. Simulated 1995 potentiometric surface of the Lower Cretaceous aquifer.

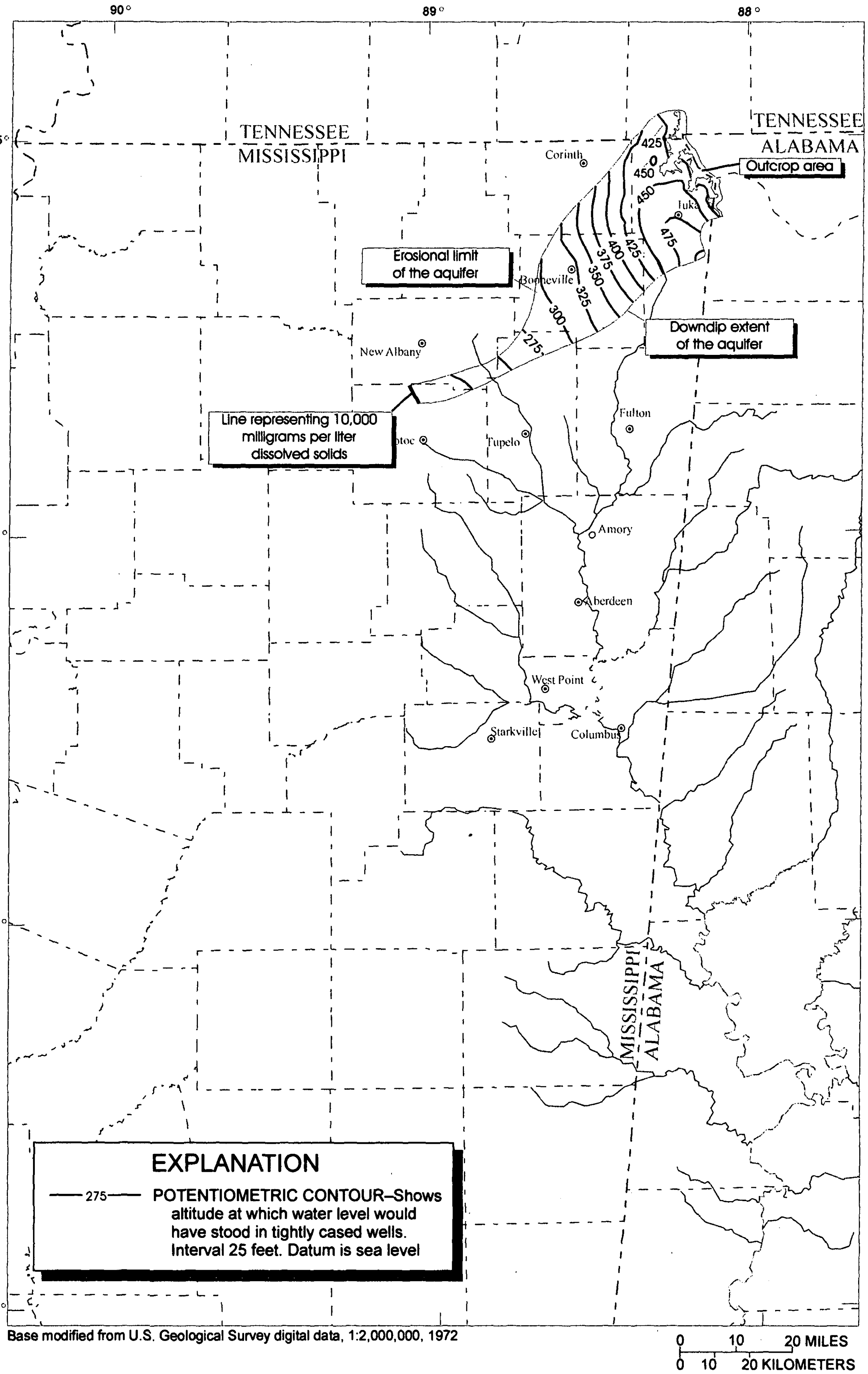

Figure 49. Simulated 1995 potentiometric surface of the Iowa aquifer.

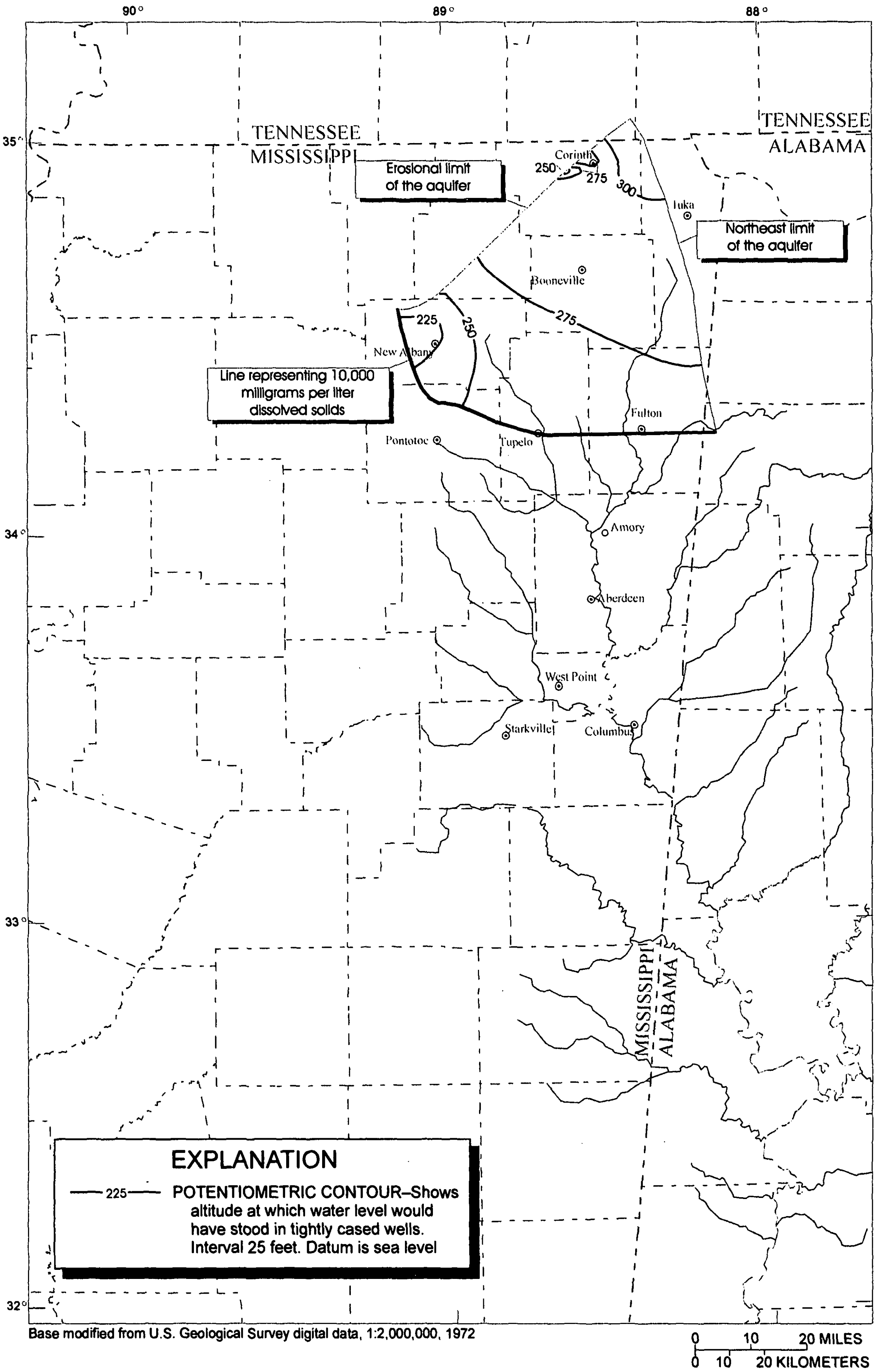

Figure 50. Simulated 1995 potentiometric surface of the Devonian aquifer.

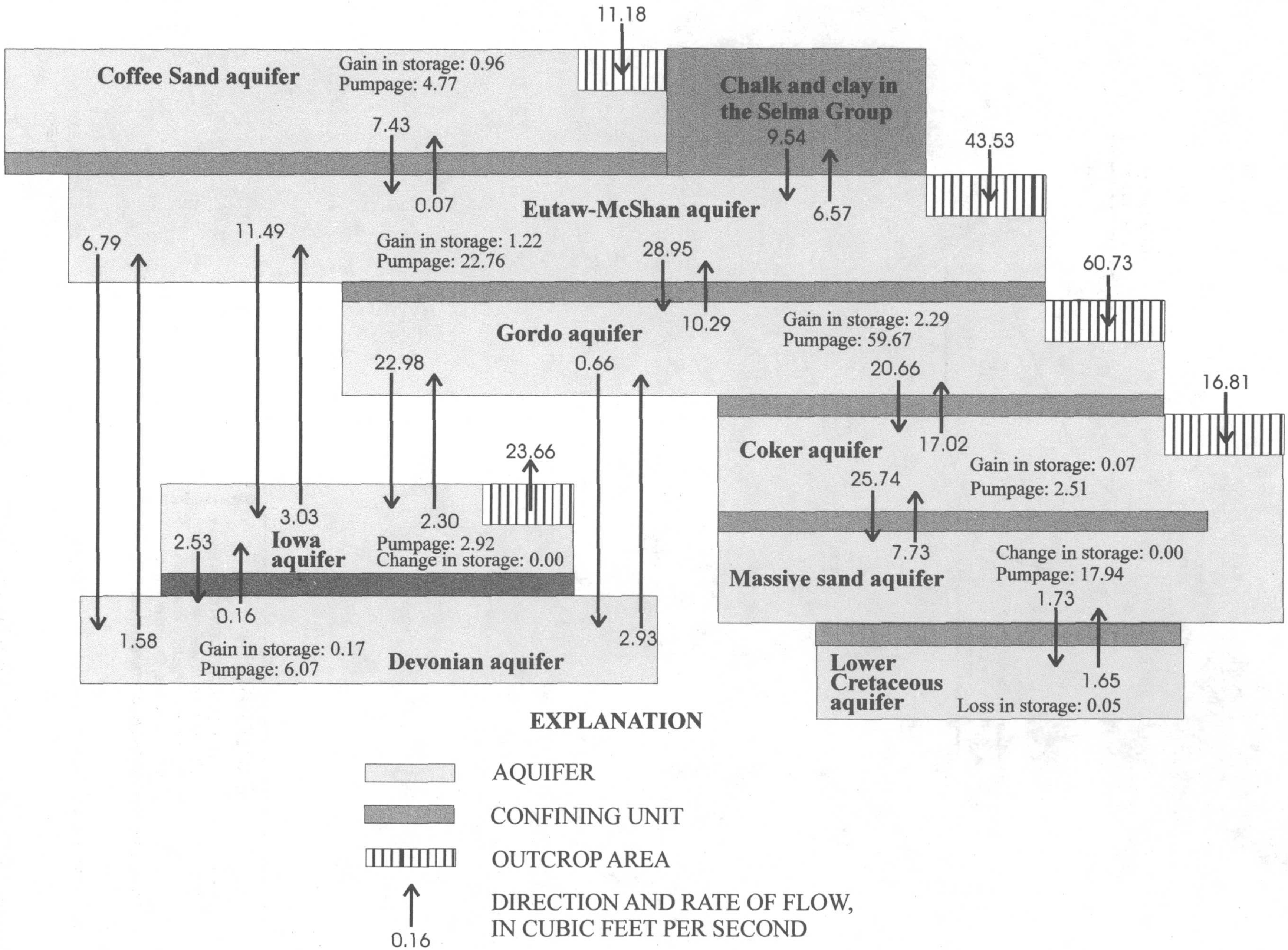

Figure 51. Simulated 1995 flow rates for the aquifers in the model area.

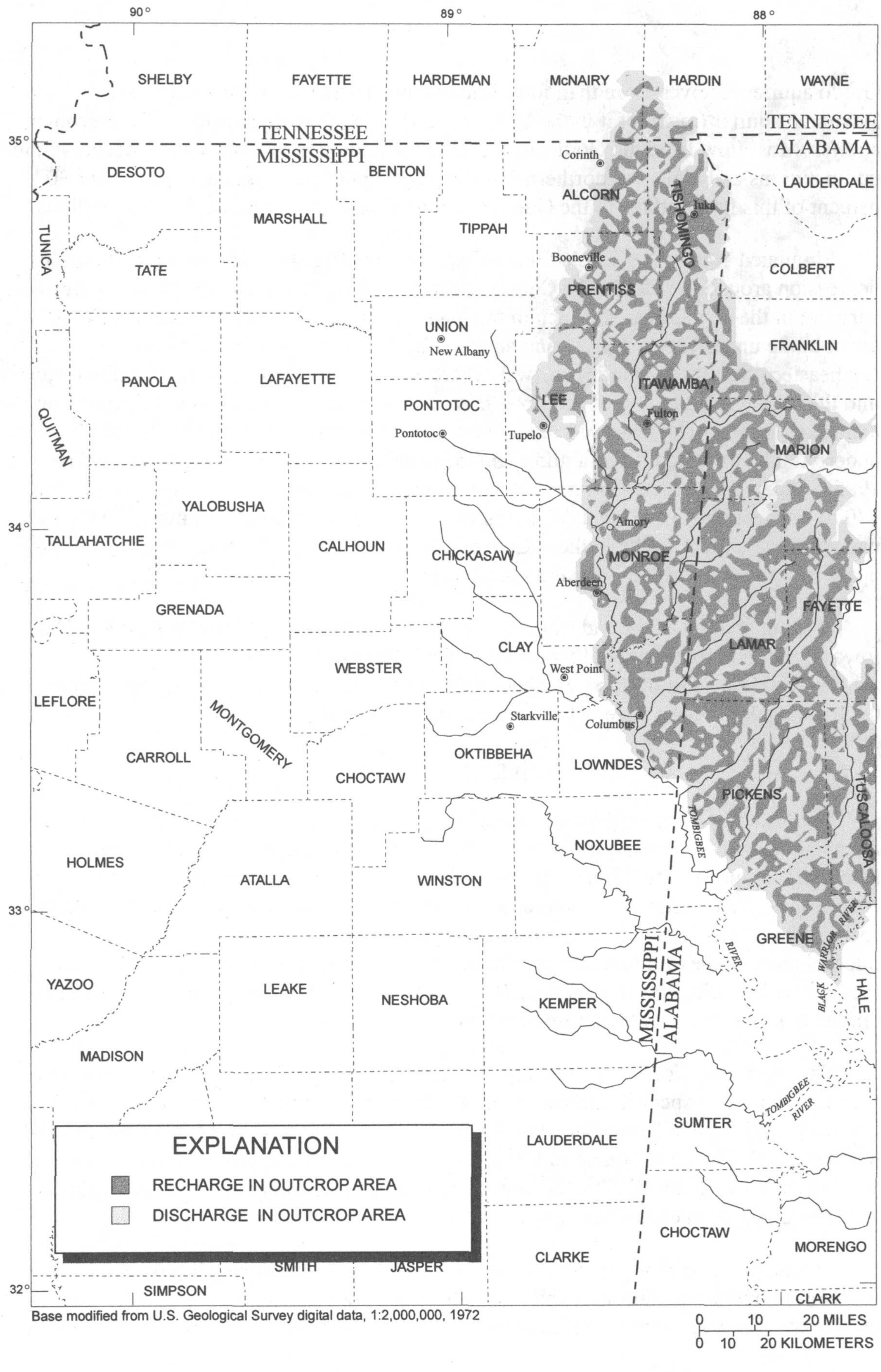

Figure 52. Areas of simulated 1995 recharge and discharge in aquifer outcrops.

Gordo aquifer receives more than four times as much water from the underlying Devonian aquifer (much of it in the Union County area) than it provides to the Devonian aquifer. Most flow from the Gordo aquifer into the underlying Coker aquifer occurs in the updip regions and along the northern depositional extent of the Coker aquifer. About 80 percent of this flow returns to the Gordo from the Coker aquifer in the downdip regions.

Simulated 1995 water levels for the Coker aquifer (fig. 46) indicate a broad cone of depression around the Oktibbeha County area; however, potentiometric gradients are still very flat in the downdip area. Much of the water that the Coker aquifer receives flows down to the underlying massive sand aquifer (fig. 51). From Monroe, Lowndes, and northeastern Noxubee Counties eastward there is flow from the Coker aquifer downward into the massive sand; west of this area there is flow from the massive sand upwards into the Coker aquifer. The massive sand aquifer exchanges only minor flow with the underlying Lower Cretaceous aquifer (fig. 51) due to small water-level gradients. The 1995 simulated water levels in the Lower Cretaceous aquifer (fig. 48) range from about 170 to 180 feet above sea level. Water enters the Lower Cretaceous aquifer from the massive sand aquifer in the Pickens County area and moves to the northwest, discharging upwards into the overlying massive sand aquifer.

A small amount of ground water is exchanged between the Paleozoic aquifers. The Iowa aquifer contibutes about 95 percent of the water exchanged with the Devonian aquifer (fig. 51). Most of this water enters the Devonian aquifer near the updip limit of the Iowa aquifer where there is little separation between the two aquifers.

Model Limitations

The accuracy of ground-water models is limited by assumptions made in the formulation of the governing flow equations, and in the assumptions made constructing an individual model. Models are also limited by cell size, number of layers, boundary conditions, time discretization, hydraulic values, accuracy of calibration, verification data, and parameter sensitivity. Finally, models are limited by the availability of data and the interpolations and extrapolations that are inherent in using these data in a model. The model may be calibrated and verified, but the calibrated parameter values may not be unique in satisfying a particular distribution of hydraulic head.

The model developed in this study is suitable for analyzing ground-water flow on a regional scale. Site specific analysis is limited by horizontal and vertical discretization of the model and the availability of site specific data. The model calculates an average head for the entire cell area (1 square mile), and may not be a good approximation for the water level in an individual well. The transmissivity and other hydraulic data for an aquifer are assumed constant in each 1-square-mile grid.

The model should not be used for analysis with large pumpages placed near any of the lateral boundaries. The assumption of a fixed freshwater-saltwater interface boundary used in the downdip areas of the aquifers may not be valid if pumping wells were placed nearby. The model is not designed to estimate movement of the freshwater-saltwater interface or to evaluate any change in water quality.

There are numerous water-level measurements for the Eutaw-McShan and Gordo aquifers through time; however, there are far less data for all of the other modeled aquifers. Therefore, simulation results for these aquifers should be used much more cautiously because fewer water-level measurements and other data were available for model verification. The Lower Cretaceous aquifer model results should not be used to make definitive water-resource management decisions until data concerning the aquifer become available to verify the model results. The model results for predevelopment conditions should only be used to illustrate general trends because the simulated water levels cannot be verified.

The sand and clay thickness maps are based on total thicknesses for the unit derived from borehole-geophysical log analyses that were gridded to a 1-square-mile grid. In some areas, sand and clay thicknesses for the aquifers can vary greatly over short lateral distances, and thicknesses may actually vary significantly within a grid cell. In some areas, data points were widely spaced, and sand and clay thicknesses had to be extrapolated or interpolated over a broad area, possibly misrepresenting actual conditions where data are not available.

The best available pumpage estimates were used in the simulations (J. H. Hoffmann and A. J. Warner, OLWR, written commun., 1997); however, it is not possible to ascertain the exact values of historical pumpage for the aquifers, and pumpage values for recent years are reported and cannot be verified for accuracy. If large inaccuracies in modeled pumpage exist, the model would not be considered properly calibrated.

Pumpage data were available for the model through 1995. For the model to be used as a tool to project water levels in the future, the pumpage data must be updated through the time of interest. Changes in the distribution of pumpage (such as large new wells, or the cessation of pumping in large existing wells) must be taken into account in any future projection scenarios.

As new hydraulic data become available, it is possible that some of the hydraulic parameters (such as transmissivity or leakance) used in the model will need to be revised, in which case the model must be recalibrated. The addition of other aquifers, changes in pumpage, additional aquifer tests, and new sand thickness information changed the calibration of the previous model (Strom and Mallory, 1995). This illustrates the fact that although models are constructed using the best available information at the time, their solutions are not unique. Models are imperfect representations of a complex natural system; however, if used with caution and good judgment, they can be very valuable tools.

SUMMARY

In October 1996, the U.S. Geological Survey, in cooperation with the OLWR, began a project to expand the existing ground-water flow model for northeastern Mississippi (Strom and Mallory, 1995) that would incorporate stratigraphic data collected by OLWR subsequent to the completion of the previous model; simulate the Coffee Sand aquifer; simulate additional aquifers in rocks of Paleozoic age; and incorporate water-use data collected by OLWR.

The study area covers 34,960 square miles, primarily in northeastern Mississippi, but includes parts of northwestern Alabama, southwestern Tennessee, and eastern Arkansas. The eight aquifers studied, from youngest to oldest, are the Coffee Sand, Eutaw-McShan, Gordo, Coker, massive sand, and Lower Cretaceous aquifers, and two aquifers recently delineated in Paleozoic rocks informally referred to in this report as the Iowa aquifer and the Devonian aquifer. The term "Cretaceous-Paleozoic aquifer system" is informally used to collectively refer to the aquifers in the study.

Geologic and hydrologic data provided most of the necessary information for the interpretation and conceptualization of the aquifer system. About 600 borehole-geophysical logs and drillers' information, combined with pertinent stratigraphic and hydrologic data, were used to provide the basis for the identification, definition, and correlation of areally extensive hydrogeologic units.

A quasi-three-dimensional, numerical model of ground-water flow was developed, and analyses of ground-water flow were made using results from model simulations. The finite-difference computer code MODFLOW was used to simulate the Cretaceous-Paleozoic aquifer system. The model grid covers 34,960 square miles. Each grid layer consists of 230 rows and 152 columns. The model was vertically discretized into six layers resulting in a total of 209,760 grid cells in the model.

Simulations of predevelopment ground-water flow conditions were made by using hydraulic parameters determined from transient model calibration. Heads in the Cretaceous aquifers generally were highest to the northeast and lowest to the southeast, which is a general reflection of the topography. Regional ground-water flow in the Cretaceous aquifers generally was from the northeast to the southeast along an arcuate path. Ground water from the northernmost parts of the outcrop areas enters the basal part of the aquifers. With the exception of the Coffee Sand aquifer, simulated predevelopment recharge generally entered the Cretaceous aquifers in the updip areas and discharged to the overlying aquifer in the downdip areas.

Simulation of 1995 ground-water flow conditions was made using hydraulic parameters determined during transient model calibration. Simulated 1995 water levels for the Coffee Sand aquifer indicate that most of the flow entering the aquifer from the outcrop area enters the deeper flow system. About 40 percent of the water entering the aquifer is captured by pumping wells, and about 60 percent of the water enters the underlying Eutaw-McShan aquifer.

Simulated 1995 water levels for the Eutaw-McShan aquifer indicate the same regional flow patterns as predevelopment water levels, but with cones of depression at the major pumping centers. About 57 percent of recharge to the aquifer enters through the outcrop area, the rest is from overlying and underlying aquifers. Much of the water from the Eutaw-McShan aquifer enters the underlying Gordo aquifer, subsequently flows through the Gordo aquifer, and enters the underlying Iowa aquifer. The Eutaw-McShan aquifer provides most of the recharge that the Devonian aquifer receives.

Model results indicate that water levels for the Gordo aquifer continued to rise rapidly in the Lee County area from 1992 to 1995. Water levels in other areas have changed little from the 1992 simulations. Pumping wells capture almost as much water as enters the aquifer as recharge in the outcrop area.

Simulated 1995 water levels for the Coker aquifer indicate a broad cone of depression around the Oktibbeha County area; however, water-level gradients are still small in the downdip area. Much of the water that the Coker aquifer receives flows down to the underlying massive sand aquifer. The massive sand aquifer exchanges only minor flow with the underlying Lower Cretaceous aquifer due to small water-level gradients.

There is a small amount of ground water exchanged between the Paleozoic aquifers. The Iowa aquifer contibutes about 95 percent of the water exchanged with the Devonian aquifer. Most of this water enters the Devonian aquifer near the updip limit of the Iowa aquifer where there is little separation between the two aquifers.

As new hydraulic data become available, it is possible that some of the hydraulic parameters (such as transmissivity or leakance) used in the model will need to be revised, in which case the model must be recalibrated. Models are imperfect representations of a complex natural system; however, if used with caution and good judgment, they can be very valuable tools.

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