HYDROGEOLOGY AND PREDEVELOPMENT FLOW IN THE TEXAS GULF COAST AQUIFER SYSTEMS

By Paul D. Ryder

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DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Water Resources Division
8011 Cameron Rd., Bldg. 1
Austin, TX 78753

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ABBREVIATIONS AND CONVERSION FACTORS

Factors for converting inch-pound units to metric (International System) units are given in the following table:

Multiply inch-pound units	By	To obtain metric units
inch (in.)	25.4	millimeter (mm)
inch per year (in./yr)	25.4	millimeter per year (mm/yr)
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.509	square kilometer (km^2)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)

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

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ABSTRACT

A multilayered ground-water flow system exists in the Coastal Plain sediments of Texas. The Tertiary and Quaternary clastic deposits have an areal extent of 128,000 square miles onshore and in the Gulf of Mexico. Two distinct aquifer systems are recognized for the sediments, which range in thickness from a few feet to more than 12,000 feet. The older system--the Texas coastal uplands aquifer system--consists of four aquifers and two confining units in the Wilcox and Claiborne Groups. It is bounded from below by the practically impermeable Midway confining unit or by the top of the geopressured zone. It is bounded from above by the poorly permeable Vicksburg-Jackson confining unit, which separates it from the younger coastal lowlands aquifer system. The coastal lowlands aquifer system consists of five permeable zones and two confining units that range in age from Oligocene to Holocene. The hydrogeologic units of both systems are exposed in bands that parallel the coastline. The units dip and thicken toward the Gulf.

Quality of water in the aquifer systems varies greatly, with dissolved solids ranging from a few hundred to more than 200,000 milligrams per liter.

A three-dimensional, variable-density digital model was developed to simulate predevelopment flow in the aquifer systems, for which steady-state conditions were assumed. Horizontal hydraulic conductivities of the aquifers and permeable zones in the calibrated model range from 15 feet per day for the middle Wilcox aquifer, to 170 feet per day for the Holocene-upper Pleistocene aquifer. Vertical hydraulic conductivities range from 1×10^{-5} foot per day for the Vicksburg-Jackson confining unit, to 1×10^{-2} foot per day for four of the aquifers and permeable zones. The simulated values of transmissivity and leakance are functions of the percent of sand that is present in each model grid block.

There is a large range in precipitation across the study area, from about 21 inches per year in the west to about 56 inches per year in the east. Eastward from a line through Corpus Christi and San Antonio, average annual precipitation ranges from about 30 to about 56 inches. A few inches per year reaches the saturated zone in topographically high areas and is discharged in low areas as evapotranspiration, seepage, springflow, and stream base flow. A smaller amount of water flows through the aquifers and permeable zones downdip from the outcrop areas. This flow results in upward or downward leakage into adjacent hydrogeologic units, but is generally upward into overlying units.

Westward from the line through Corpus Christi and San Antonio, average annual precipitation ranges from about 30 to about 21 inches. The general pattern of flow in the aquifers and permeable zones is similar to that in the east, but rates of flow are somewhat smaller. In contrast to the east, ground-water discharge in the west is generally not visible. Evapotranspiration is the main mechanism for ground-water discharge, with most ground water being discharged through evapotranspiration by phreatophytes.

Simulated discharge and recharge rates in the combined outcrop areas of all units do not exceed 6 inches per year. The large rates occur in small, local topographically low and high areas. The average discharge rate simulated in the outcrops of the units is 0.45 inch per year. The recharge area is considerably smaller than the discharge area, and the average recharge rate over this smaller area is 0.74 inch per year.

Total simulated recharge in the outcrop areas is 269 million cubic feet per day, which is offset by an equal amount of discharge in the outcrop areas. The smallest rates of leakage are across the Vicksburg-Jackson confining unit, with downward and upward rates of less than one million cubic feet per day. The greatest rate of leakage is 47 million cubic feet per day upward into the Holocene-upper Pleistocene permeable zone.

INTRODUCTION

The Gulf Coast Regional Aquifer-System Analysis (GCRASA) study was begun in 1980 as part of a federally funded program of the U.S. Geological Survey to provide a regional understanding and assessment of major aquifer systems in the United States. The GCRASA study is focused on the Gulf Coastal Plain sediments of Tertiary and Quaternary age. The study area consists of about 230,000 mi^2 onshore and about 65,000 mi^2 offshore (about 295,000 mi^2 total) in parts of Alabama, Arkansas, Florida, Illinois, Kentucky, Mississippi, Missouri, Tennessee, Texas, and all of Louisiana (fig. 1). A complete discussion and description of the GCRASA study is given in Grubb (1984).

The Texas Gulf Coast study is a part of the GCRASA study (fig. 1). Parts of the Texas Gulf Coast aquifer systems have sustained intensive ground-water development that has resulted in problems associated with large decreases of aquifer head, land subsidence, and saltwater encroachment. Baker (1985) reports that ground-water withdrawals of almost 500 Mgal/d in the Houston area caused some water levels in wells to decline from about 50 ft below land surface in 1931 to about 250 ft below land surface in 1983. The decreased artesian pressure head has caused land subsidence of almost 10 ft in some places. Extensive pumpage has caused land subsidence in other areas, although less severe than in the Houston area.

Potential for saltwater encroachment is particularly great in the southwestern part of the study area. The city of Alice in Jim Wells County and the city of Brownsville in Cameron County have supplemented ground-water supplies with surface water because of saltwater encroachment (Texas Department of Water Resources, 1984, p. III-22-1). Because of saltwater encroachment, the cities of Agua Dulce, Banquette, Driscoll, and Bishop in Nueces County, and Kingsville in Kleberg County, plan to supplement ground-water supplies with water from the Nueces River (Texas Department of Water Resources, 1984, p. III-22-1).

Other areas within the Texas part of the GCRASA study area have potential for significant, additional ground-water development, but the effects of large increases in development are not known. Management of the regional ground-water resource will require quantitative evaluation of the geologic, hydrologic, and chemical-quality characteristics of the system in addition to definition of the hydrogeologic boundaries that affect development potential.

Purpose and Scope

The objectives of the Texas Gulf Coast study are to define the hydrogeologic framework and hydraulic characteristics of the aquifer systems, delineate the extent of freshwater and density of saline water in the various hydrogeologic units, and describe the regional ground-water flow system. This report describes the preliminary, or interim results of the study, and thus concerns only the steady-state predevelopment flow system. Some of the hydrologic properties presented in this report, for example the vertical and horizontal hydraulic conductivities of the units, are preliminary and can be expected to change with further analysis and model simulation. The digital model used in this report is being refined to provide an analysis of the

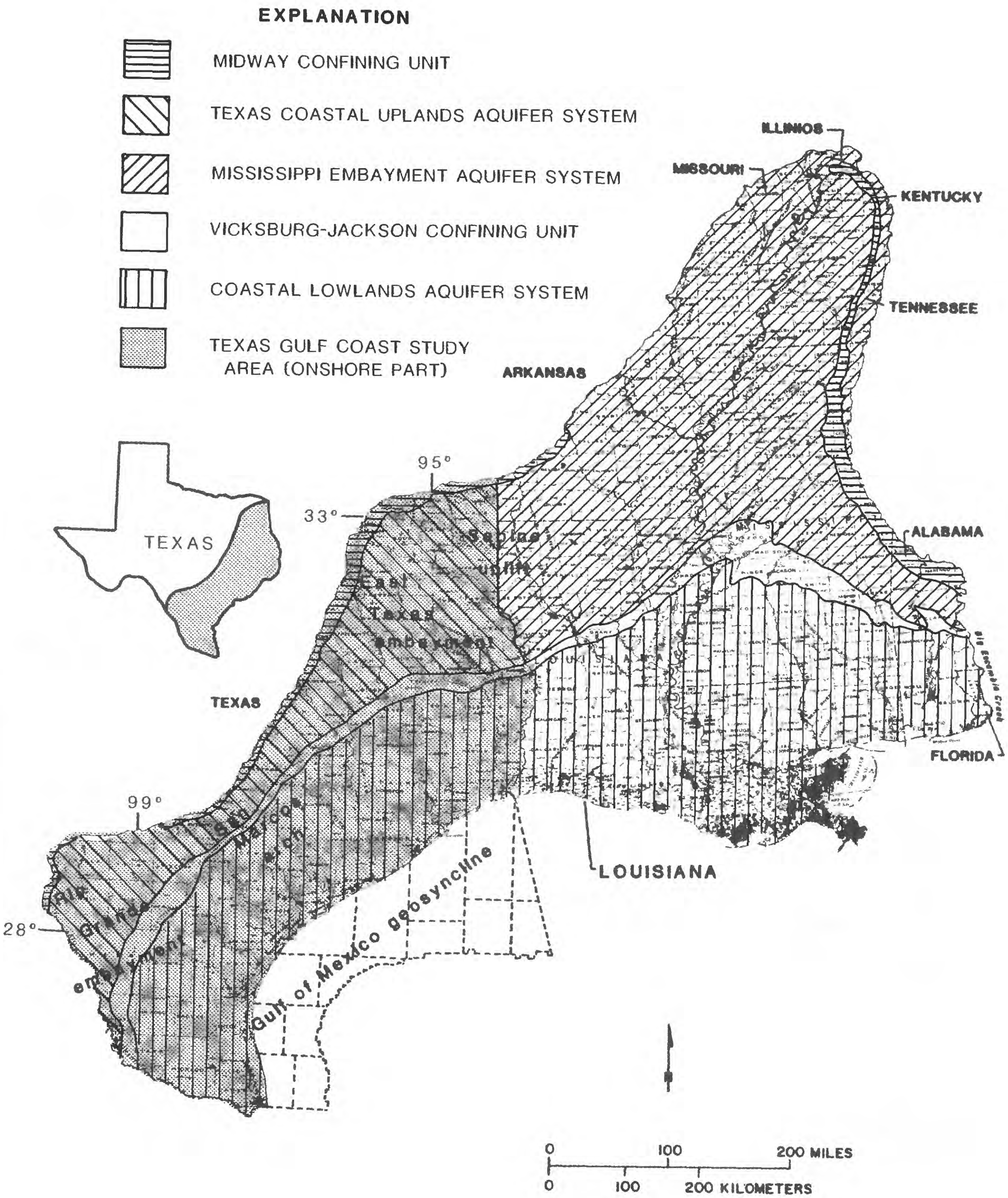


Figure 1.--Relation of Texas Gulf Coast study area to onshore part of the Gulf Coast Regional Aquifer-System Analysis study area. (Modified from Grubb, 1984)

effects of ground-water development on the flow system, and a quantitative description of the storage properties of the Texas Gulf Coast aquifers.

Method of Investigation

The basic approach to meet the study objectives is to collect and analyze hundreds of borehole geophysical logs, to review previously published interpretative reports, and to use data files from the U.S. Geological Survey and other Federal and State agencies and commercially available files from the petroleum industry. From these analyses a regionally consistent hydrogeologic framework is generated. Additionally, the analyses provide: 1) the hydrologic boundaries of the aquifer systems; 2) a definition of selected water-quality properties; 3) initial estimates of aquifer and confining-unit hydraulic charactistics; and 4) where sufficient data exist, potentiometric-surface maps that show the general direction of ground-water flow. All of these resulting data are incorporated into a multilayered, digital ground-water flow model. Calibration of the model provides an improved estimate of aquifer and confining-unit hydraulic characteristics, a quantitative analysis of flow within and between each of the various aquifers, and a better understanding of the total flow system.

The data that describe essential components of the aquifer systems, including aquifer and confining-unit thicknesses, sand ratios, water densities, water-table heads, and measured artesian heads, are given in the following sections of the report. The data are converted to a form that is suitable for use in a digital ground-water flow model by a process known as discretization. In the process, the model grid (fig. 42) is generally superimposed on a continuous or contoured distribution of point data; for example, thickness values for a particular aquifer as interpreted from electric logs at hundreds of locations in the study area. The point values are then extrapolated to the block locations so that a mean value of thickness is determined and assigned to each 25-mi^2 grid block.

The terms head and hydraulic head as used in this report are equivalent to static head, as defined by Lohman and others (1972, p. 7), with a reference datum of sea level.

Description of the Area

The study area extends from Mexico in the west to Louisiana in the east, and consists of about 90,000 mi^2 onshore and an additional 24,000 mi^2 in the Gulf for a total area of about 114,000 mi^2 (fig. 2). The northern boundary is the updip limit of the Texas Gulf Coast aquifer systems--the practically impermeable, predominantly marine clays of the Midway Group. The southern boundary extends well into the Gulf of Mexico where ground-water flow is believed to be insignificant.

The area encompasses all or parts of 109 counties. The principal physiographic province is the Gulf Coastal Plain, and the major structural features are the Rio Grande embayment, San Marcos arch, East Texas embayment, Sabine uplift, and the Gulf of Mexico geosyncline (fig. 1). Land surface is characterized by a smooth, low-lying coastal plain that gradually rises toward

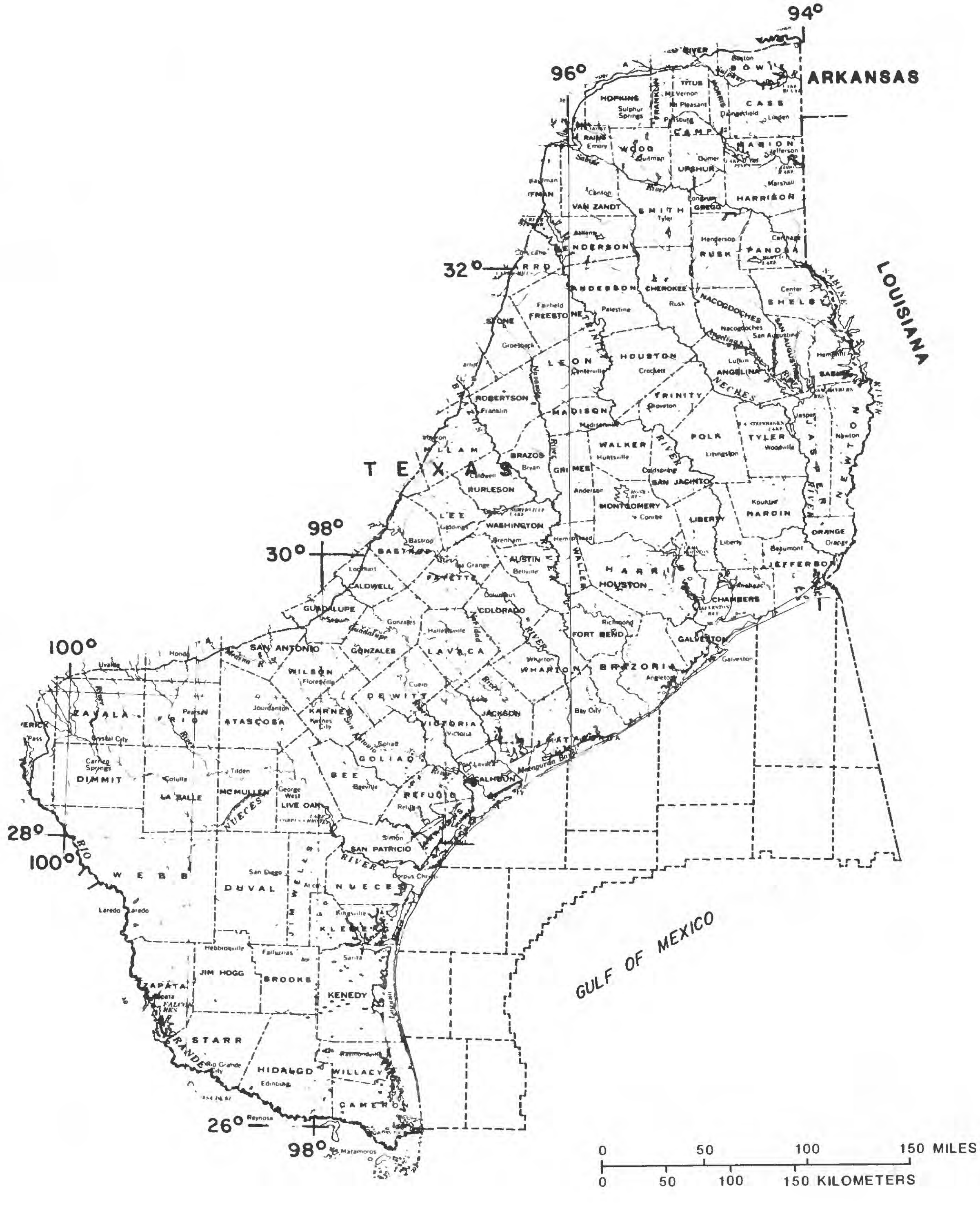


Figure 2.--Location of Texas Gulf Coast study area.

the north and northwest where the more dissected and rolling terrain reaches altitudes of as much as 600 ft in the eastern and central areas, and to as much as 900 ft in the west. The coastal uplands end at the contact with Cretaceous clay and limestone where the land surface generally rises sharply. Twelve major streams drain the area, flowing generally south-southeastward toward the Gulf. These are, from west to east, the Rio Grande, Nueces, Frio, San Antonio, Guadalupe, Colorado, Brazos, Navasota, Trinity, Neches, Angelina, and Sabine Rivers. Many large reservoirs that have been constructed on these and other streams supply important quantities of water.

Annual precipitation varies greatly, ranging from about 21 in. in most of the Rio Grande valley in the southwest, to about 56 in. at the eastern boundary of the study area (fig. 3).

Previous Investigations

Numerous reports concerning the geology and hydrogeology of all or part of the study area have been written by the U.S. Geological Survey and other Federal and State agencies, consulting firms, and others. Several reports are more regional in nature; these include: a report by the Texas Department of Water Resources (1984) that describes the hydrology of the area and presents a comprehensive plan for future water development; a report by Baker and Wall (1976) that covers most of the area and emphasizes the desirability of conjunctive use of ground water and surface water in any plans for future development; a report by Carr and others (1985) that covers much of the area and applies digital modeling techniques to simulate flow in Miocene and younger deposits; a report by Baker (1979) that covers an area from Mexico to Louisiana that emphasizes the hydrogeologic framework of Miocene and younger units; a report by Baker (1986) that applies digital modeling to simulate predevelopment flow in Miocene deposits in a 25,000 mi^2 area in the eastern part; a report by Jones and others (1976) that describes the hydrogeology of the Wilcox Group; and a series of reports by Payne that describe the hydrogeology of the Sparta Sand (1968), Yegua Formation (1970), Reklaw Formation and Queen City Sand (1972), and the Carrizo Sand (1975) of the Claiborne Group.

Acknowledgements

Extensive amounts of data collection and interpretation were done by Sergio Garza, E.T. Baker, Jr., and the GCRASA central staff (all with the U.S. Geological Survey). A.F. Ardis (U.S. Geological Survey) rendered valuable assistance with preparation of illustrations.

HYDROGEOLOGIC FRAMEWORK

Tertiary and Quaternary deposits of clay, silt, sand, and gravel up to several thousand feet thick underlie the Gulf Coastal Plain in Texas. The clastic sediments dip toward the Gulf of Mexico and thicken in that direction. A basic task is the subdivision of this thick sequence of alternating fine and coarse-grained sediments into hydrogeologic units that can be represented as layers in a digital ground-water flow model. The number of hydrogeologic

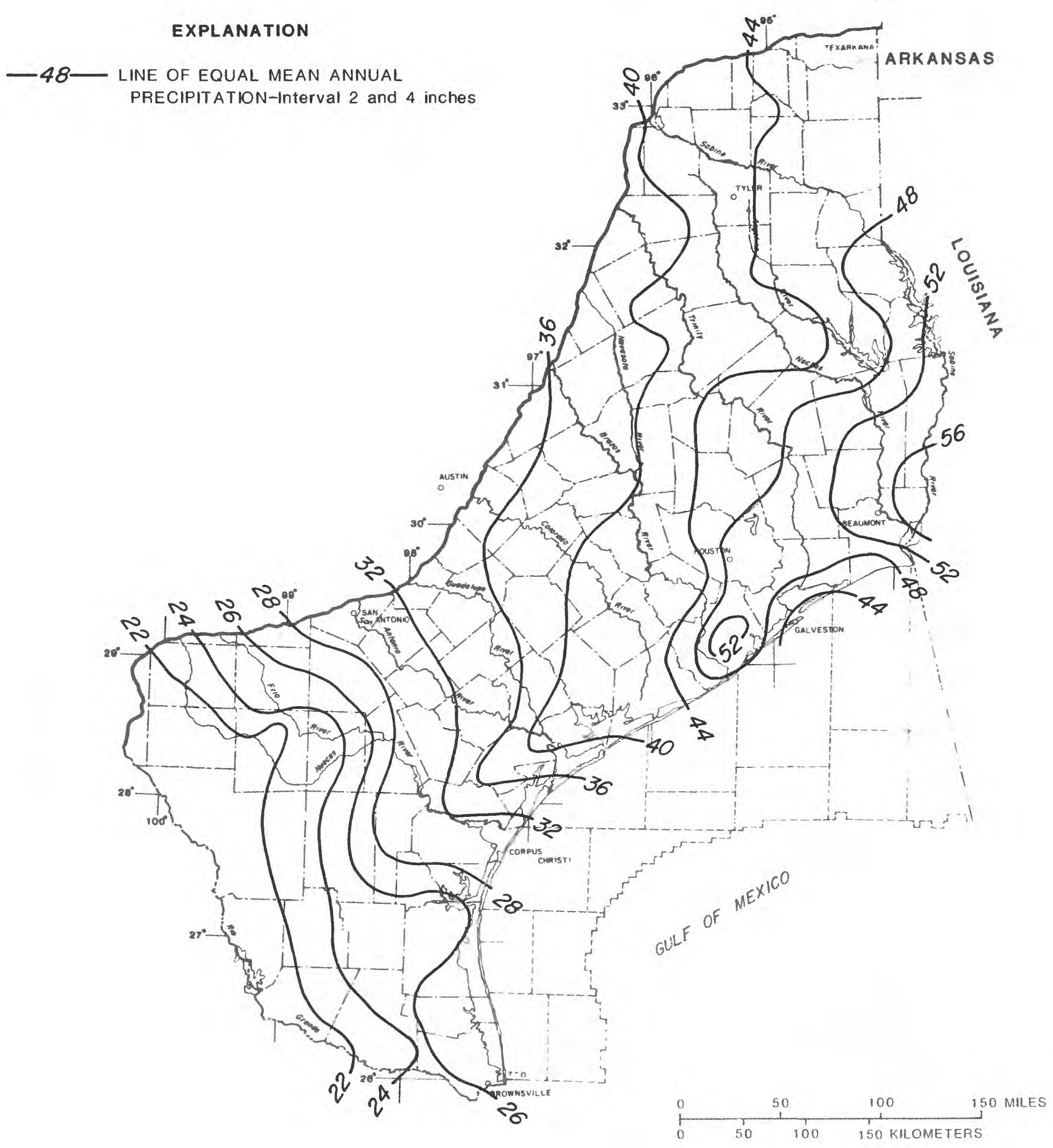


Figure 3.--Mean annual precipitation in the Texas Gulf Coast study area. Based on National Oceanic and Atmospheric Administration records for the period 1951-80. (Modified from Texas Department of Water Resources, 1984, fig. 5).

units (model layers) chosen is based on practical considerations for the scale of the system, objectives of the model study, and computer-cost limitations. Weiss and Williamson (1985) discuss the rationale and methodology for subdividing the Coastal Plain sediments into discrete hydrogeologic units for the GCRASA study.

Pre-Miocene sediments are distributed as relatively uniform sequences of predominantly fine or coarse-grained material. Borehole geophysical data can be used to identify the intervals and to designate aquifers and confining units. Figure 4 shows part of an electric log that was used to define hydrogeologic units in an interval of Eocene deposits. The percentage sand is an index of the relative permeability of a unit, and will be discussed later in the report.

Miocene and younger deposits differ from pre-Miocene deposits. They exhibit more heterogeneity--the interfingering of many thin beds of differing texture and limited areal extent. Where the system is heterogeneous, Weiss and Williamson (1985) state that the subdivision into layers should include an evaluation of depths of producing zones and the resultant vertical distribution of hydraulic head. Thus, Miocene and younger deposits at large pumping centers in Houston, Texas, and Baton Rouge, Louisiana, were subdivided into discrete units (Weiss and Williamson, 1985). These units are called "permeable zones" and confining units. The permeable zones typically contain discontinuous clay beds, in contrast to the pre-Miocene aquifers that are typically massive sand beds separated by regionally extensive clay beds.

After appropriate intervals are chosen for aquifers, permeable zones, and confining units, they are extended across the study area by interpolating between points with geophysical borehole data. Figure 5 shows the location of the data points. Well locations and log data were selected to give an even distribution and a consistent regional pattern of hydrologic interpretations.

The logs also provide data that are useful in determining the top of the geopressured zone (a zone with higher than normal fluid pressure). This zone or the top of the Midway confining unit, whichever is higher, forms the base of the flow system. Estimates of dissolved solids concentrations, from which water density can be estimated for modeling purposes, are based on the resistivity curves of the logs.

The hydrogeologic units of the GCRASA study have been grouped into three major aquifer systems (fig. 1). The Texas coastal uplands aquifer system and the coastal lowlands aquifer system occur in Texas; the Mississippi embayment aquifer system does not. The two systems in Texas are separated by the poorly permeable Vicksburg-Jackson confining unit and are underlain by the practically impermeable Midway confining unit (tables 1 and 2). The Texas coastal uplands (hereafter simply the coastal uplands) and coastal lowlands aquifer systems consist of four aquifers, five permeable zones, and six confining units (including the Midway and Vicksburg-Jackson confining units). The definitions of the hydrogeologic units and the names assigned to them may or may not conform to conventional definitions and names as found in the published literature. The hydrogeologic units are named for the group or series designation of the sediments that comprise the units. Specifically, a group name (subdivision of a series) was applied by R.L. Hosman and J.S. Weiss (U.S. Geological Survey, written commun., 1986) to units of the coastal

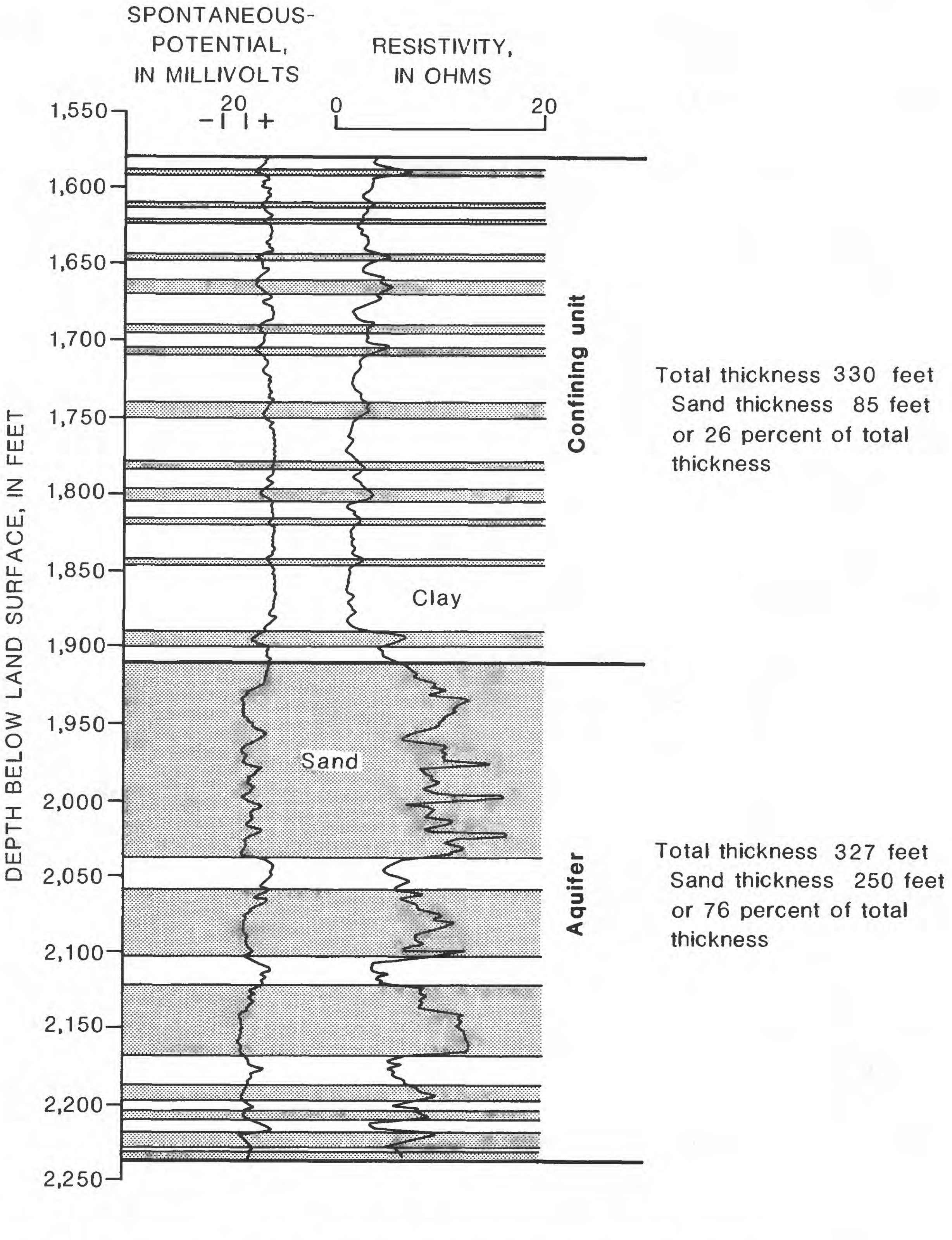


Figure 4.--Representative electric-log interpretation of sand and clay beds within hydrogeologic units.

EXPLANATION

● WELL WITH GEOPHYSICAL LOG DATA USED FOR HYDROLOGIC INTERPRETATIONS

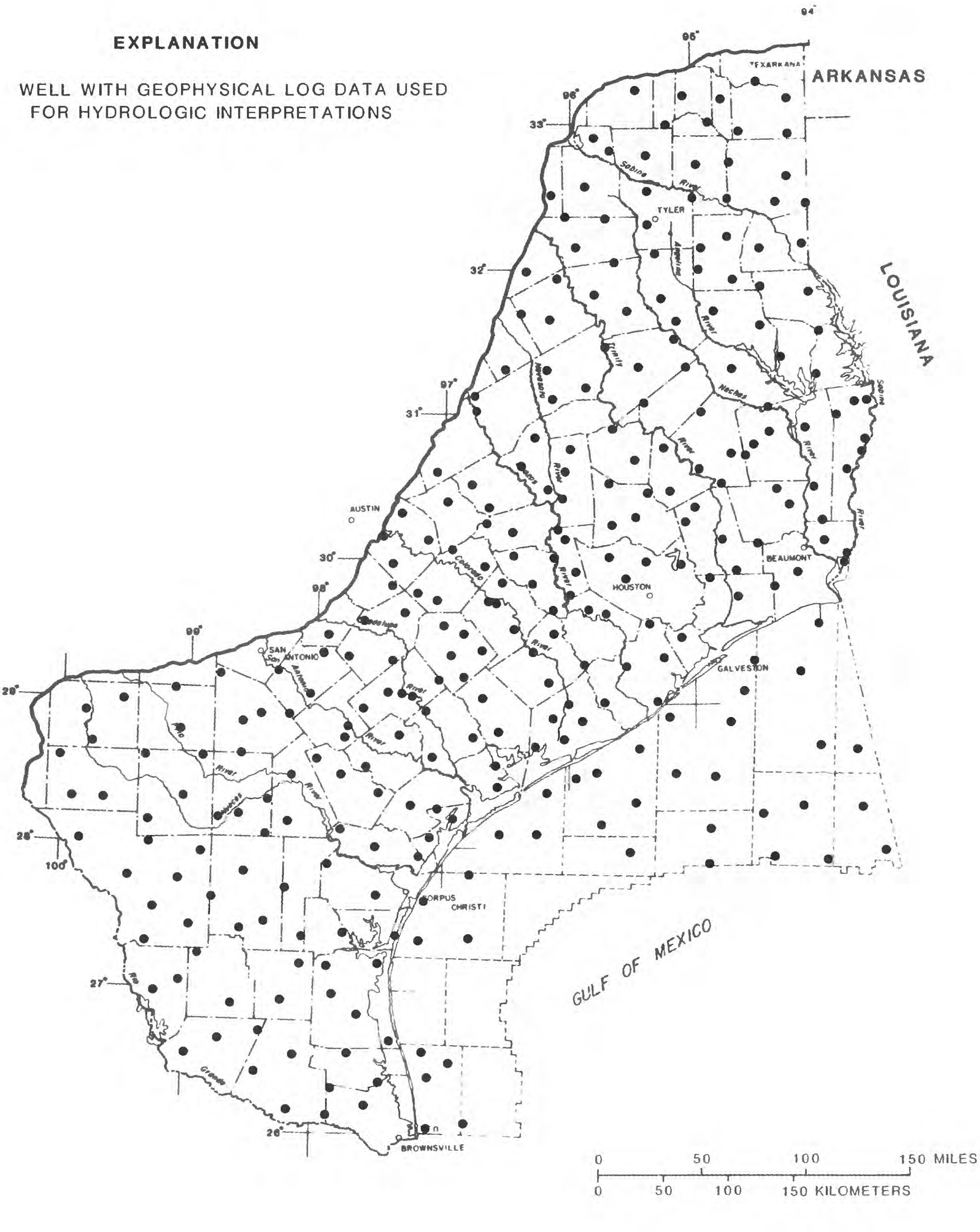


Figure 5.--Locations of selected wells with geophysical log data.

Table 1.--Stratigraphic and hydrogeologic units for the coastal uplands aquifer system.

<table>
<tr><th rowspan="2">SYSTEM</th><th rowspan="2">SERIES</th><th colspan="3">TEXAS COASTAL UPLANDS</th></tr>
<tr><th colspan="2">STRATIGRAPHIC UNITS</th><th>HYDROGEOLOGIC UNITS</th></tr>
<tr><td rowspan="10">TERTIARY</td><td>OLIGOCENE</td><td>Frio Clay</td><td>Vicksburg Group [1]</td><td rowspan="2">Vicksburg-Jackson confining unit</td></tr>
<tr><td rowspan="8">EOCENE</td><td>Jackson Group</td><td>Whitsett Formation
Manning Clay
Wellborn Sandstone
Caddell Formation</td></tr>
<tr><td rowspan="5">Claiborne Group</td><td>Yegua Formation</td><td>Upper Claiborne aquifer</td></tr>
<tr><td>Cook Mountain Fm.</td><td>Middle Claiborne confining unit</td></tr>
<tr><td>Sparta Sand
Weches Formation
Queen City Sand</td><td>Middle Claiborne aquifer</td></tr>
<tr><td>Reklaw Formation</td><td>Lower Claiborne confining unit</td></tr>
<tr><td>Carrizo Sand</td><td rowspan="2">Lower Claiborne-upper Wilcox aquifer</td></tr>
<tr><td rowspan="2">Wilcox Group</td><td rowspan="2">Undifferentiated</td></tr>
<tr><td>Middle Wilcox aquifer</td></tr>
<tr><td>PALOCENE</td><td>Midway Group</td><td>Wills Point Formation
Kincaid Formation</td><td>Midway confining unit</td></tr>
</table>

[1] Present only in the subsurface

Table 2.--Stratigraphic and hydrogeologic units for the coastal lowlands aquifer system.

TEXAS COASTAL LOWLANDS

Modified from Baker (1979)

System	Series	Stratigraphic units	Hydrogeologic units	Hydrogeologic units in this report
Quaternary	Holocene	Alluvium	Chicot aquifer	Holocene-upper Pleistocene permeable zone
Quaternary	Holocene / Pleistocene	Beaumont Clay	Chicot aquifer	Holocene-upper Pleistocene permeable zone
Quaternary	Pleistocene	Montgomery Formation	Chicot aquifer	Holocene-upper Pleistocene permeable zone
Quaternary	Pleistocene	Bentley Formation	Chicot aquifer	Lower Pleistocene-upper Pliocene permeable zone
Quaternary	Pleistocene	Willis Sand	Chicot aquifer	Lower Pleistocene-upper Pliocene permeable zone
Tertiary	Pliocene	Goliad Sand	Evangeline aquifer	Lower Pleistocene-upper Pliocene permeable zone; Lower Pliocene-upper Miocene permeable zone
Tertiary	Miocene	Fleming Formation	Evangeline aquifer; Burkeville confining system	Lower Pliocene-upper Miocene permeable zone; Middle Miocene confining unit 1/
Tertiary	Miocene	Oakville Sandstone	Burkeville confining system	Middle Miocene confining unit 1/; Middle Miocene permeable zone
Tertiary	Miocene	Catahoula Sandstone or Tuff 2/	Catahoula confining system (restricted); Jasper aquifer	Middle Miocene permeable zone
Tertiary	Miocene	Anahuac Formation 1/	Catahoula confining system (restricted); Jasper aquifer	Lower Miocene-upper Oligocene confining unit 1/
Tertiary	-?- Oligocene	"Frio" Formation 1/	Catahoula confining system (restricted); Jasper aquifer	Lower Miocene-upper Oligocene permeable zone

1/ Present only in the subsurface

2/ Catahoula Tuff west of Lavaca County

uplands system, and a series name was applied by J.S. Weiss and R.L. Hosman (U.S. Geological Survey, written commun., 1986) to units of the coastal lowlands system. Correlation of stratigraphic and hydrogeologic units is shown in table 1 for the coastal uplands aquifer system, and in table 2 for the coastal lowlands aquifer system.

The hydrogeologic units are, from oldest to youngest, the: Midway confining unit; middle Wilcox aquifer; lower Claiborne-upper Wilcox aquifer; lower Claiborne confining unit; middle Claiborne aquifer; middle Claiborne confining unit; upper Claiborne aquifer; Vicksburg-Jackson confining unit; lower Miocene-upper Oligocene permeable zone; lower Miocene-upper Oligocene confining unit; middle Miocene permeable zone; middle Miocene confining unit; lower Pliocene-upper Miocene permeable zone; lower Pleistocene-upper Pliocene permeable zone; Holocene-upper Pleistocene permeable zone.

All but two of the units (the lower Miocene-upper Oligocene and middle Miocene confining units exist only in the subsurface) crop out in bands that are essentially parallel to the coastline (fig. 6). Generally, the units dip south-southeastward toward the Gulf of Mexico and thicken in that direction. An exception is in the Sabine uplift in the northeast, where older units are again exposed at the surface and dip in all directions.

The arrangement and disposition of the hydrogeologic units that comprise the aquifer systems are shown by the hydrogeologic sections in figures 7-9. The hydrogeologic sections are useful in that they present simple, two-dimensional views of the interrelationship of aquifers, confining units, and hydrologic boundaries. The sections were drawn along three rows of a finite-difference grid (fig. 42) that was used for digital modeling (to be discussed later). They were constructed using mean layer thickness values for the 25-mi^2 grid blocks. The sections are representative of the area, and they are nearly parallel to the dips of the units. The vertical scales are greatly exaggerated (more than 50 times); an absence of vertical exaggeration would show the attitude of the units as being more nearly horizontal.

The base of the combined systems, as shown by the sections, is either the top of the Midway confining unit or the top of the geopressured zone. The irregular nature of the top of the geopressured zone is evident in all sections. Also evident is the irregular nature of the units themselves. In some areas, they may be exposed but pinch out downdip, or they may not be exposed but exist only in the subsurface. For discussion purposes, both the Midway and Vicksburg-Jackson confining units will be included in the next section of text that describes in more detail the coastal uplands aquifer system.

The structure-contour map in figure 10 shows the altitude of the base of the aquifer systems. In the updip areas where the base is the top of the Midway confining unit, the surface is relatively smooth and the contours parallel the coastline. Where the top of the geopressured zone becomes the base, the surface becomes distorted. Many lows and highs are present, attesting to the irregular and discontinuous nature of the geopressured zone. Altitude of the base ranges from less than 1,000 ft above sea level near the updip limit of the middle Wilcox aquifer to more than 11,000 ft below sea level in the Montgomery County area north of Houston.

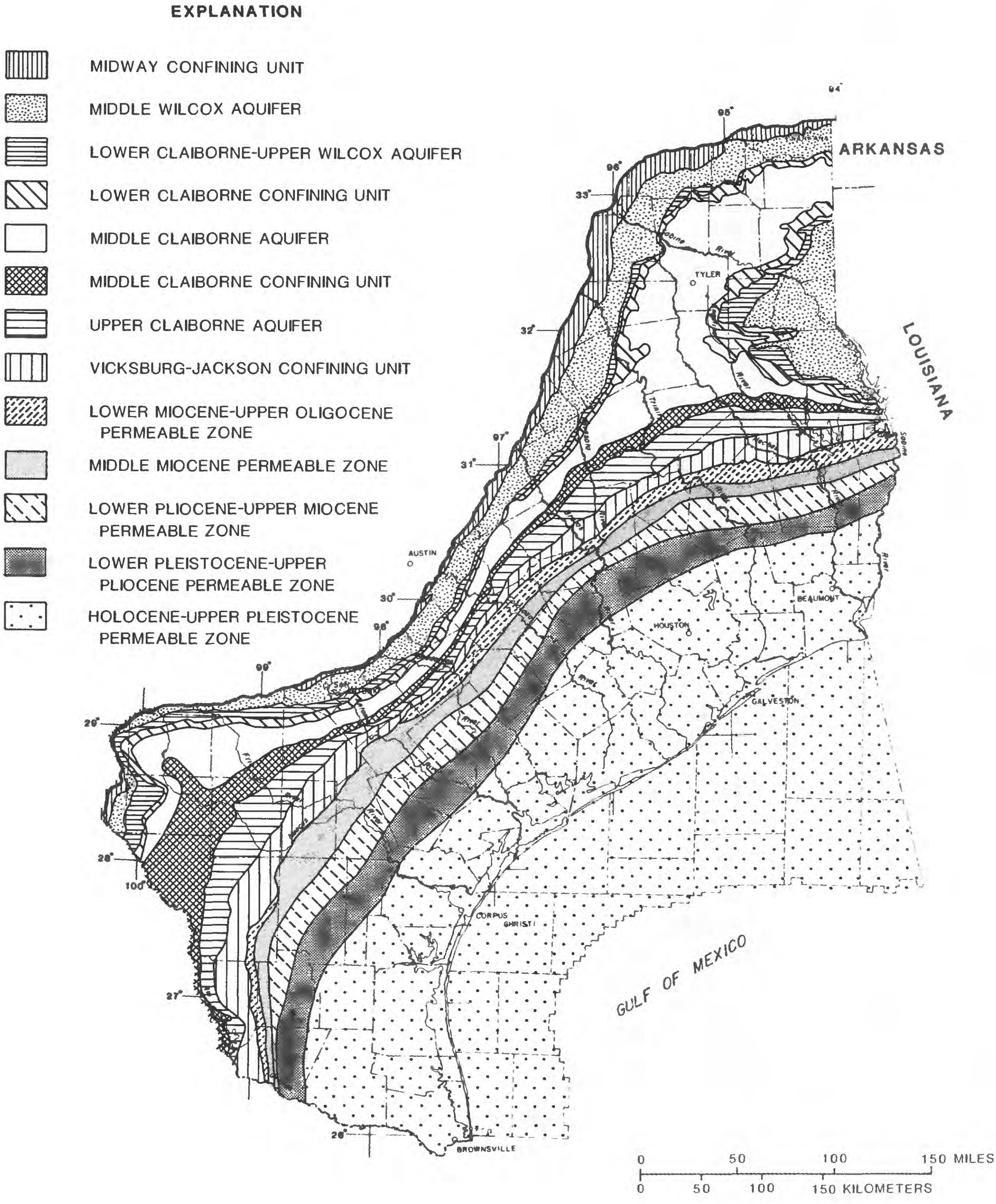
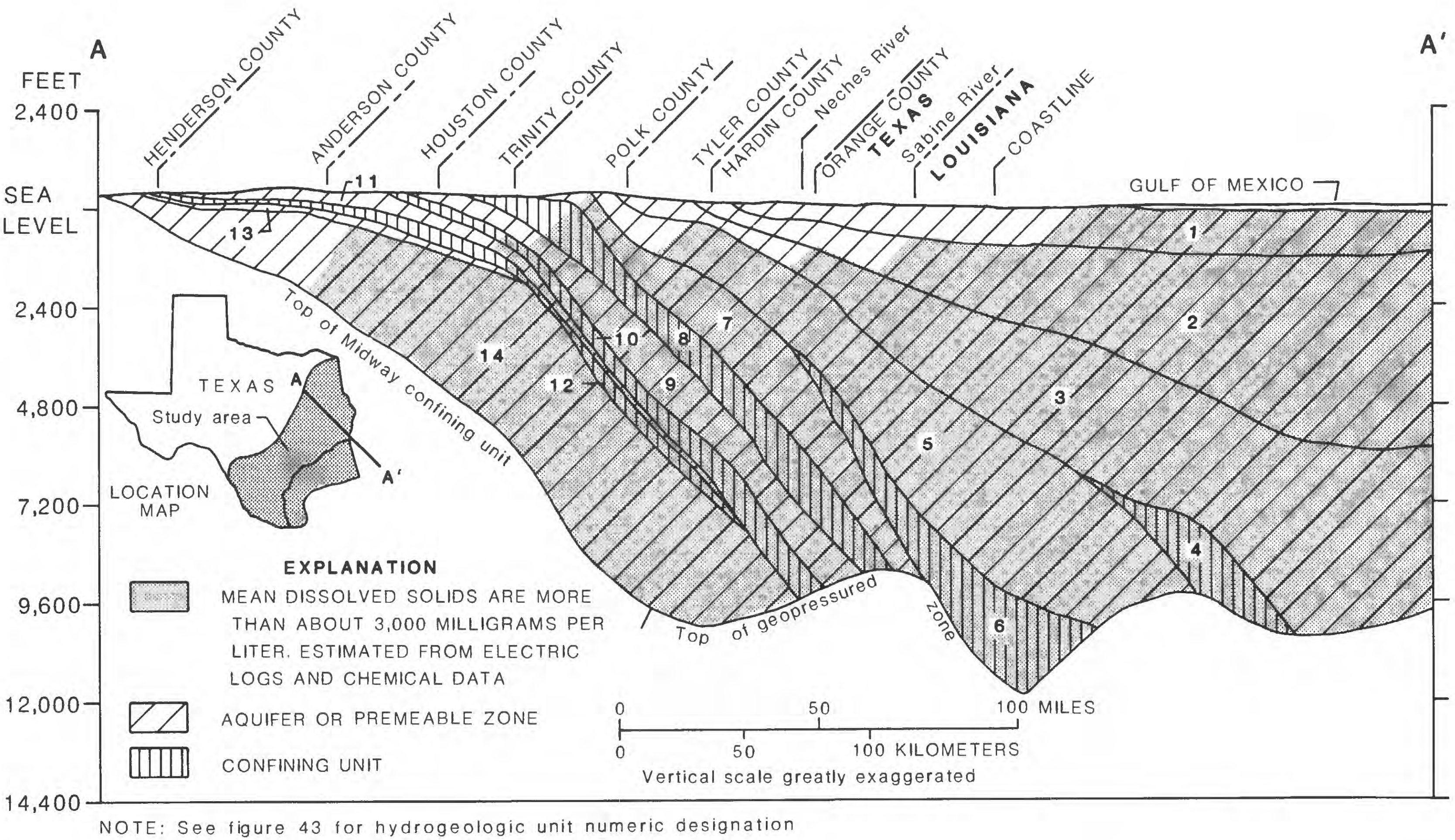
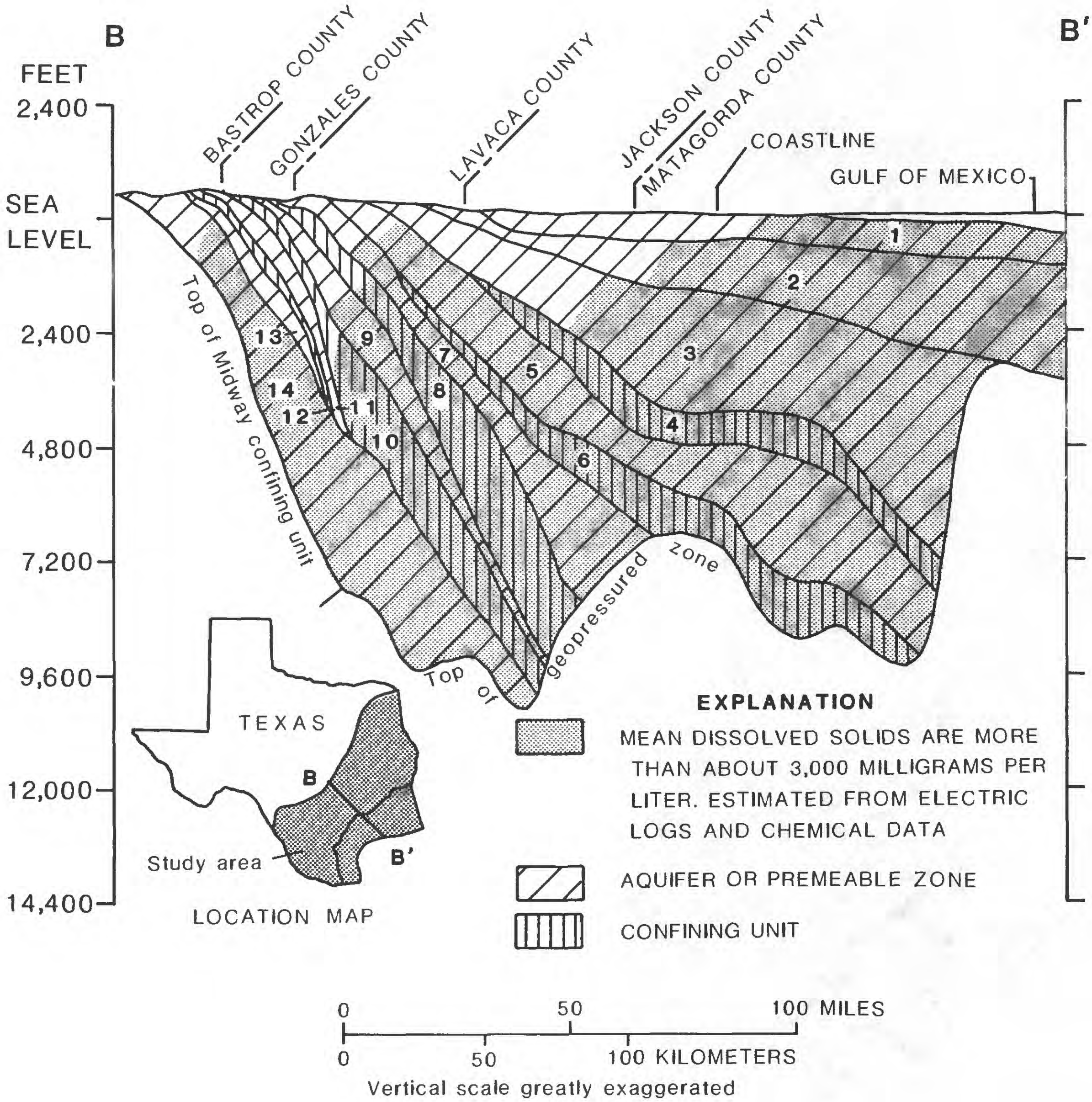


Figure 6.--Generalized outcrops of aquifers, permeable zones, and confining units.



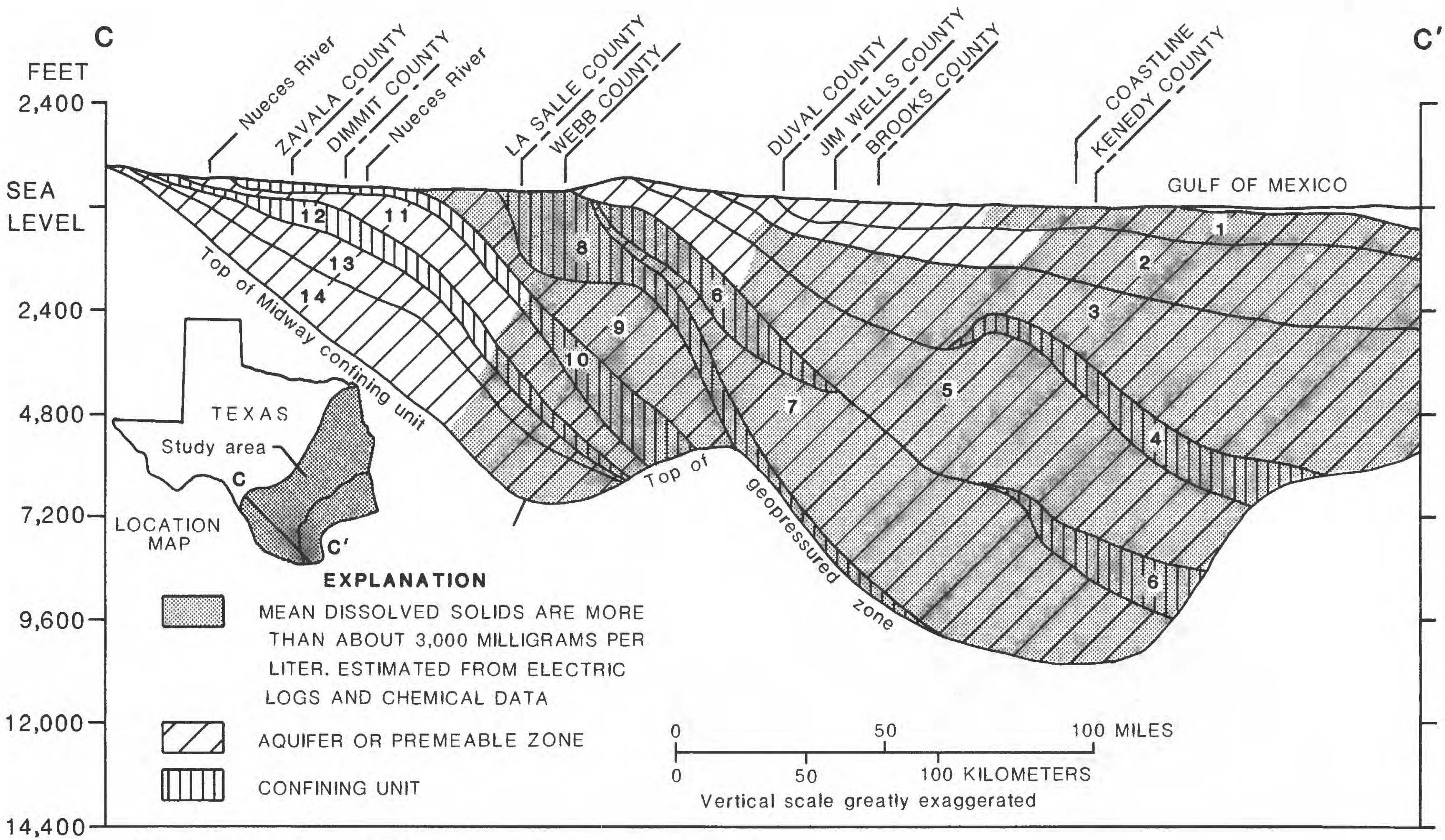
NOTE: See figure 43 for hydrogeologic unit numeric designation

Figure 7.--Hydrogeologic section A-A'.



NOTE: See figure 43 for hydrogeologic unit numeric designation

Figure 8.--Hydrogeologic section B-B'.



NOTE: See figure 43 for hydrogeologic unit numeric designation

Figure 9.--Hydrogeologic section C-C.

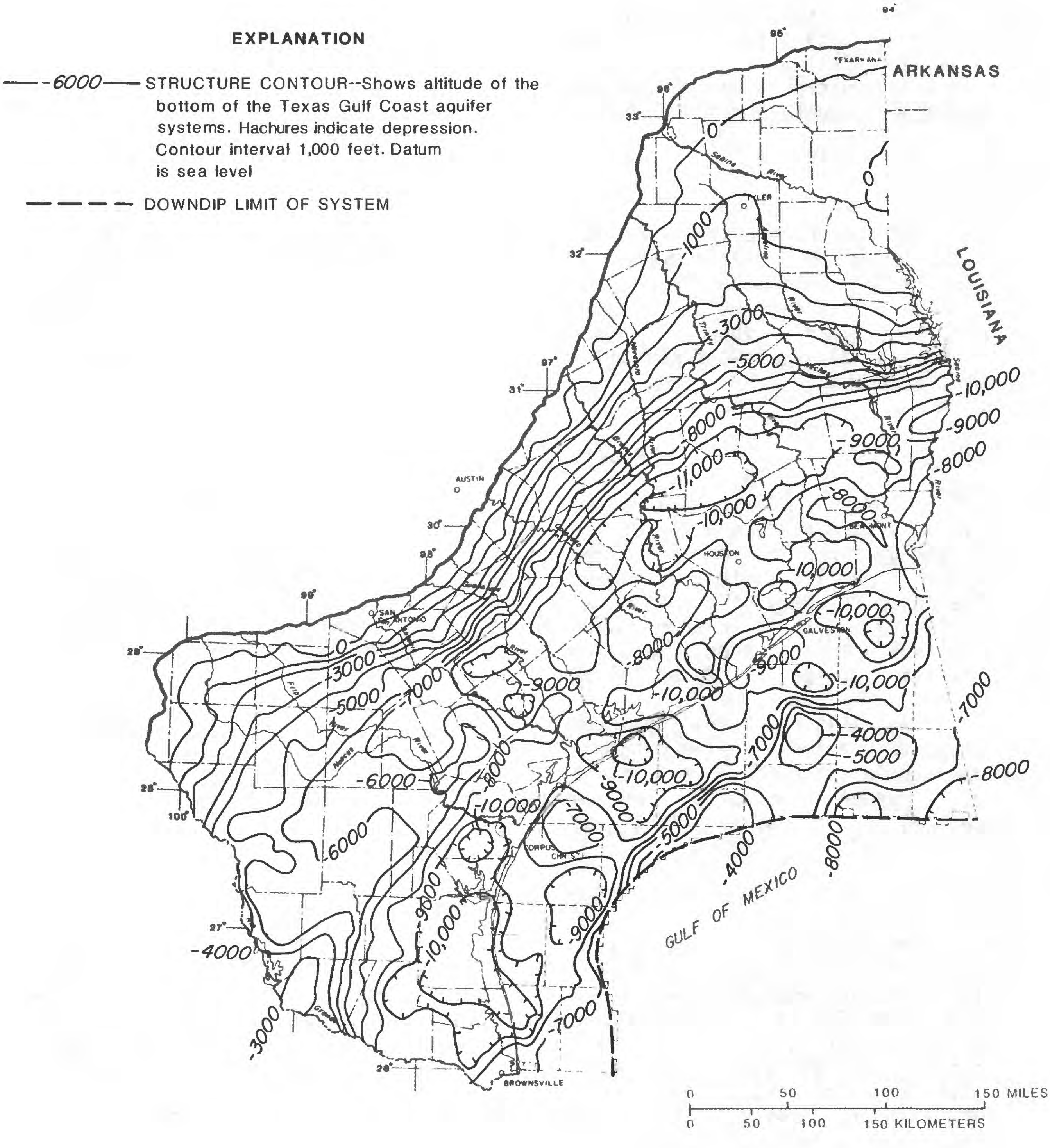


Figure 10.--Altitude of the base of the Texas Gulf Coast aquifer systems.

Contours showing thickness of the aquifer systems also are relatively smooth and parallel to the coastline where the base is at the top of the Midway confining unit (fig. 11). Thickness of the aquifer systems ranges from 0 in the outcrop areas of the middle Wilcox aquifer to more than 12,000 ft in Montgomery County north of Houston.

Coastal Uplands Aquifer System

Hydrogeologic units of the Wilcox Group and Claiborne Group comprise the coastal uplands aquifer system (table 1). They are, from oldest to youngest, the: middle Wilcox aquifer; lower Claiborne-upper Wilcox aquifer; lower Claiborne confining unit; middle Claiborne aquifer; middle Claiborne confining unit; and upper Claiborne aquifer. Descriptions of the underlying Midway and overlying Vicksburg-Jackson confining units are also included in this section of the report.

Midway Confining Unit

The Midway confining unit is composed predominantly of dense, marine clays of the Paleocene Midway Group that are considered impermeable. The top of the unit and the top of the geopressured zone form the base of the coastal uplands aquifer system. The updip limit of the confining unit is essentially the updip boundary of the study area (fig. 12). The outcrop of the Midway confining unit is discontinuous due to an approximately 70-mi length in the west where it exists only in the subsurface. Outcrop width ranges from about 1 to 15 mi (figs. 6, 12, and 13).

The altitude of the top of the confining unit ranges from less than 500 ft above sea level in the outcrop areas to more than 11,000 ft below sea level downdip in the central part of the study area (fig. 12). Thickness of the unit ranges from 0 in the outcrop areas to over 3,200 ft downdip in the central part of the area (fig. 13).

Middle Wilcox Aquifer

The middle Wilcox aquifer, as opposed to more typical massive sand aquifers, is composed of thinly interbedded fine sands, silts, and clays of the Paleocene and Eocene Wilcox Group. It overlies the Midway confining unit and underlies the lower Claiborne-upper Wilcox aquifer. The outcrop belt is relatively broad and ranges from about 1 to 25 mi. The unit is exposed again over a relatively large area at the center of the Sabine uplift in the northeast (figs. 6, 14, and 15). Altitude of the top of the unit ranges from about 500 ft above sea level in the outcrop areas to more than 10,500 ft below sea level in the east-central area (fig. 14). Thickness of the unit ranges from 0 in the outcrop areas to more than 5,000 ft in the east-central area (fig. 15).

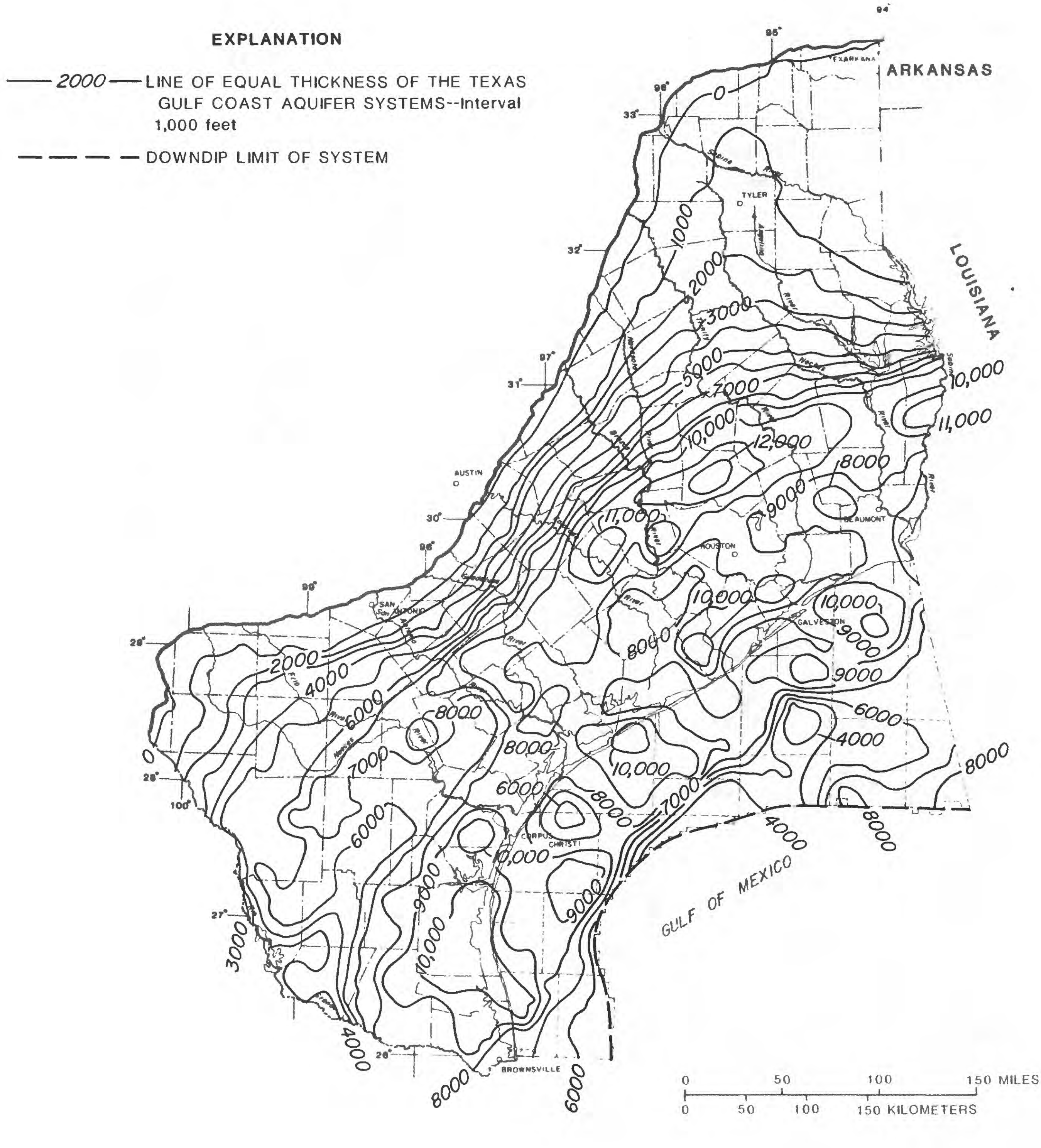


Figure 11.--Thickness of the Texas Gulf Coast aquifer systems.

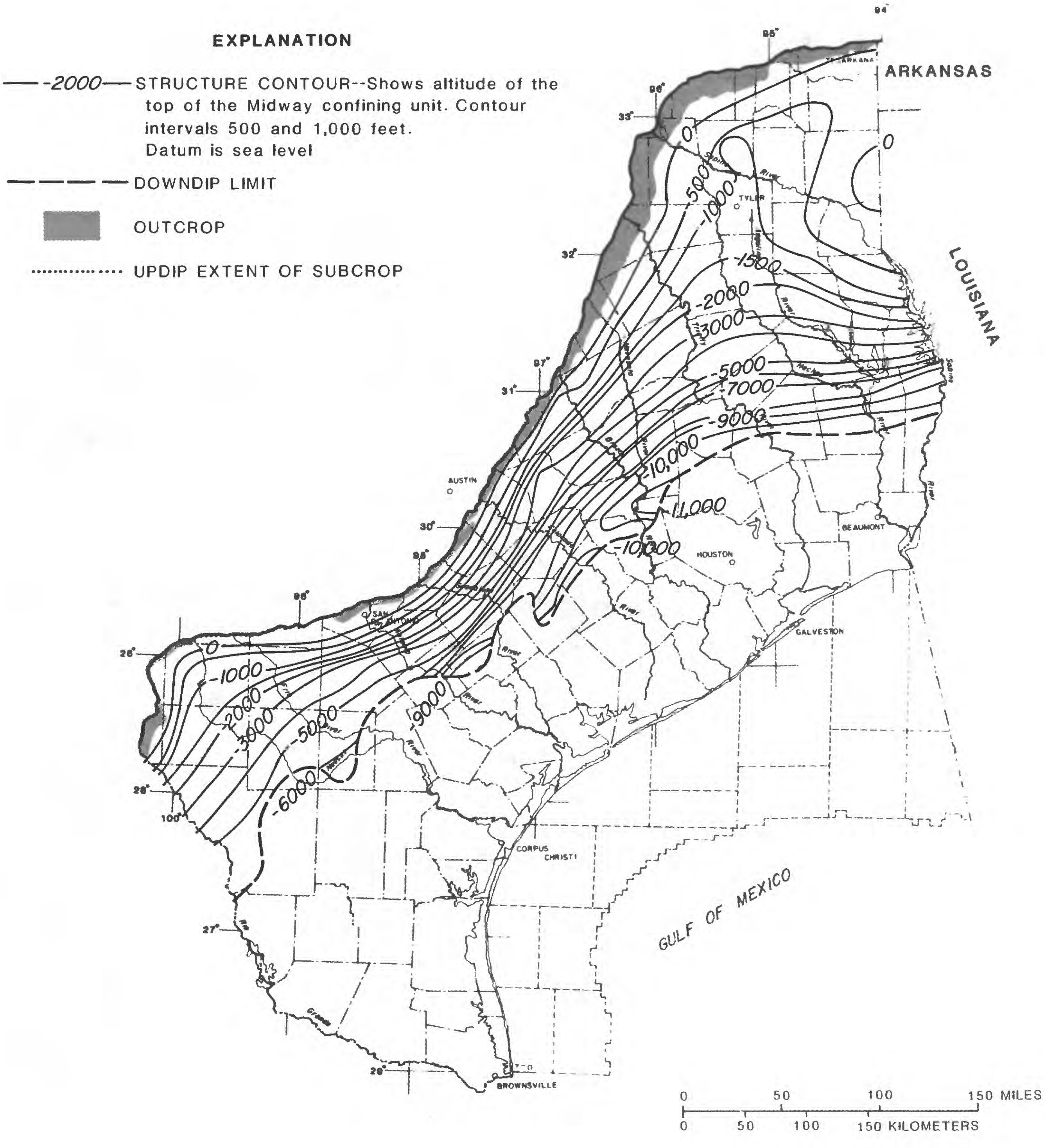


Figure 12.--Altitude of the top of the Midway confining unit.

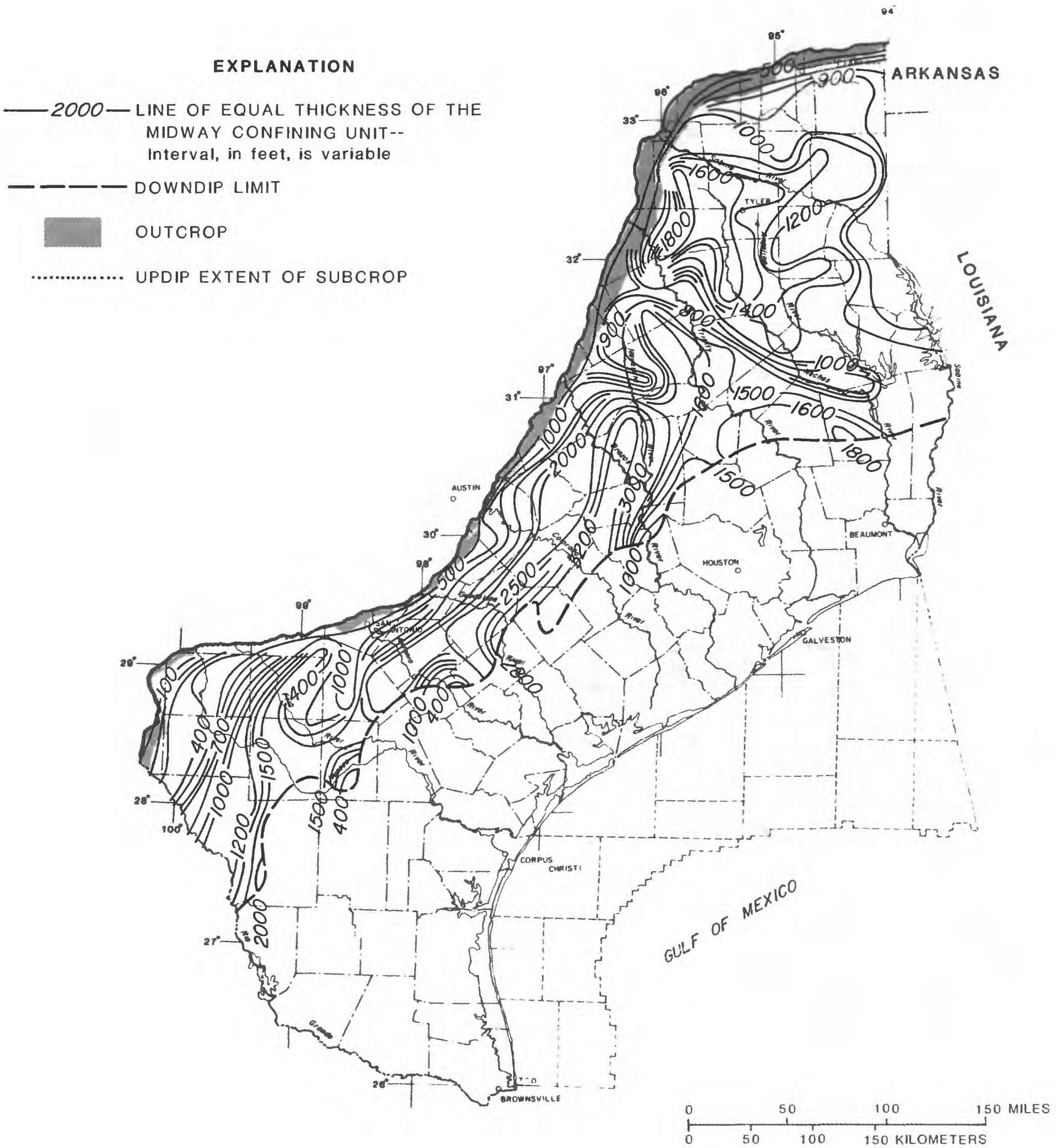


Figure 13.--Thickness of the Midway confining unit.

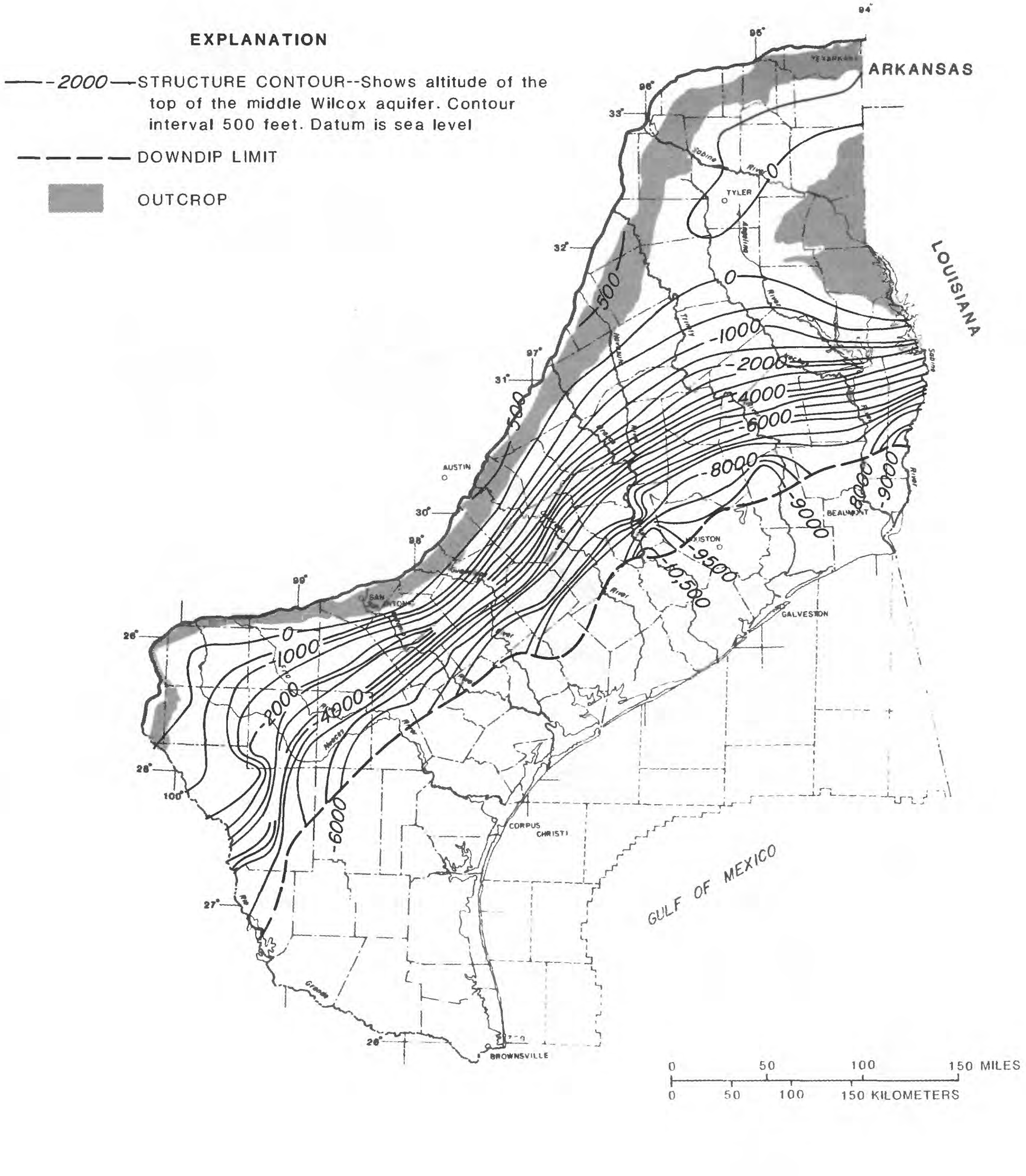


Figure 14.--Altitude of the top of the middle Wilcox aquifer.

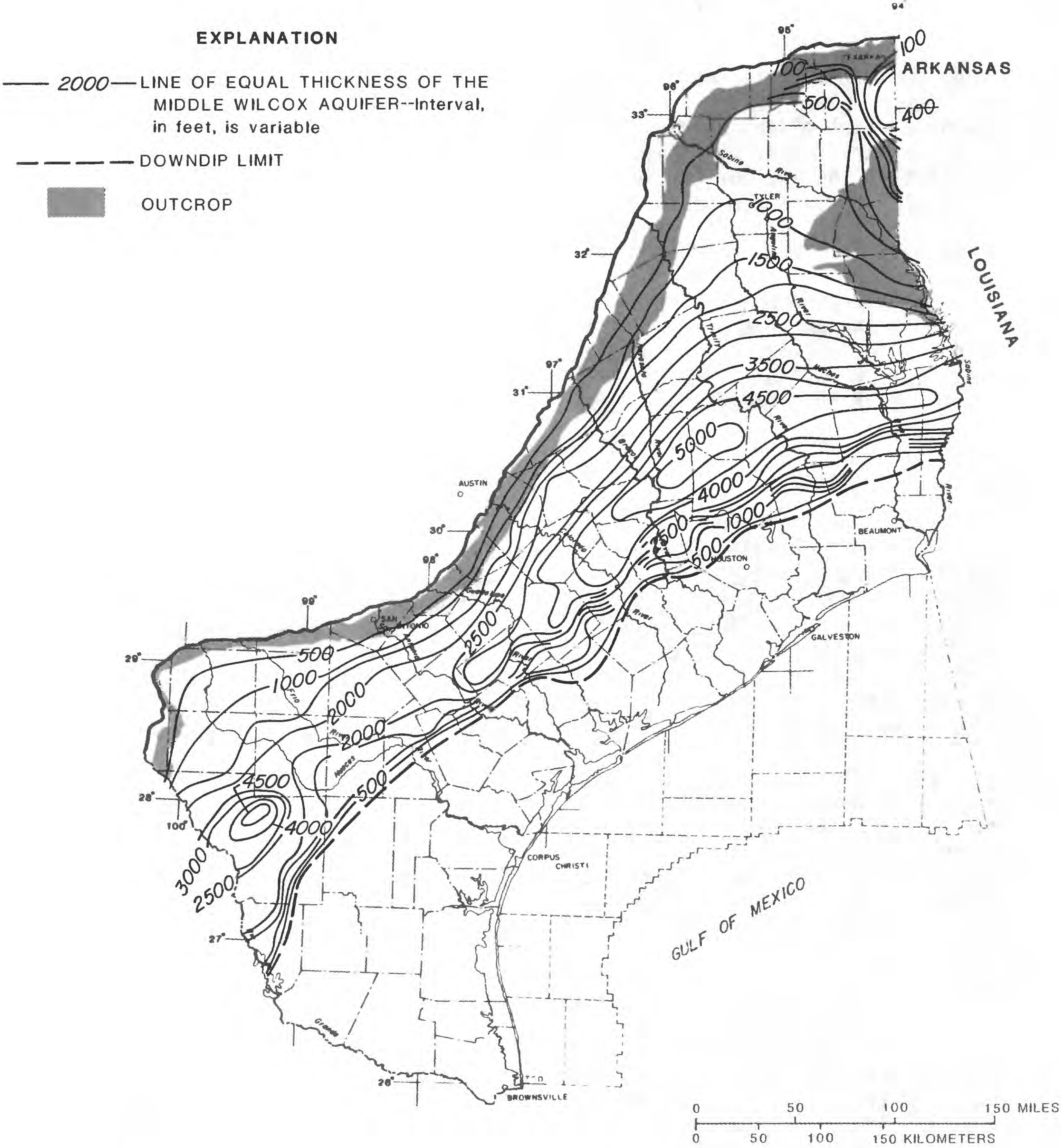


Figure 15.--Thickness of the middle Wilcox aquifer.

Lower Claiborne-Upper Wilcox Aquifer

The lower Claiborne-upper Wilcox aquifer is composed of predominantly sandy sediments of the upper part of the Wilcox Group and the Carrizo Sand of the lower part of the Eocene Claiborne Group (table 1). Where sediments in the lower part of the overlying Reklaw Formation are sandy, they are part of the aquifer. This aquifer has the highest percentage of sand of all the aquifers in the aquifer systems. The outcrop is relatively narrow, the greatest outcrop width being about 15 mi in the extreme west (figs. 6, 16, and 17). In the eastern half of the area the unit alternately is exposed and found only in the subsurface.

The altitude of the top of the aquifer ranges from about 500 ft above sea level in the outcrop areas to more than 8,000 ft below sea level northwest of Corpus Christi (fig. 16). Thickness of the unit ranges from 0 in the outcrop areas to more than 1,200 ft in the west. The aquifer is much thicker in the western half than in the eastern half of the area (fig. 17).

Lower Claiborne Confining Unit

The lower Claiborne confining unit consists mostly of clays and other fine-grained clastics of the Reklaw Formation in the lower part of the Claiborne Group (table 1). The unit, as well as most of the confining units in both aquifer systems, may contain significant amounts of sand, particularly in the updip areas. The confining unit shown on the representative electric log in figure 4 is the lower Claiborne confining unit. The well is in west-central Brazos County in the northeast part of the area, and is about midway between the updip and downdip limits of the unit. At this location, the thin sand layers comprise about 26 percent of the total unit thickness.

The outcrop width of the lower Claiborne confining unit is relatively narrow; it widens to a maximum of about 15 mi near the Trinity River in the east (figs. 6, 18, and 19). The unit also is exposed on the flanks of the Sabine uplift in the northeast. The altitude of the top of the unit ranges from about 500 ft above sea level in the outcrop areas to more than 6,000 ft below sea level in the west (fig. 18). Thickness of the unit ranges from 0 in outcrop areas to more than 1,000 ft in the west (fig. 18).

Middle Claiborne Aquifer

The middle Claiborne aquifer consists of sands with lesser amounts of finer-grained clastics of the Queen City Sand, Weches Formation, and Sparta Sand in the middle part of the Claiborne Group (table 1). The outcrop of the unit is generally broad throughout its extent, but occupies an unusually large area in the east where it is the uppermost unit in the structural feature known as the East Texas embayment (figs. 1, 6, 20, and 21). The outcrop width ranges from about 1 mi on the south flank of the Sabine uplift, to about 45 mi across the embayment. The unit extends a relatively short distance downdip in the central area, as shown in the hydrogeologic section in figure 8.

The altitude of the top of the unit ranges from about 700 ft above sea level in outcrop areas in the west to more than 5,500 ft below sea level in

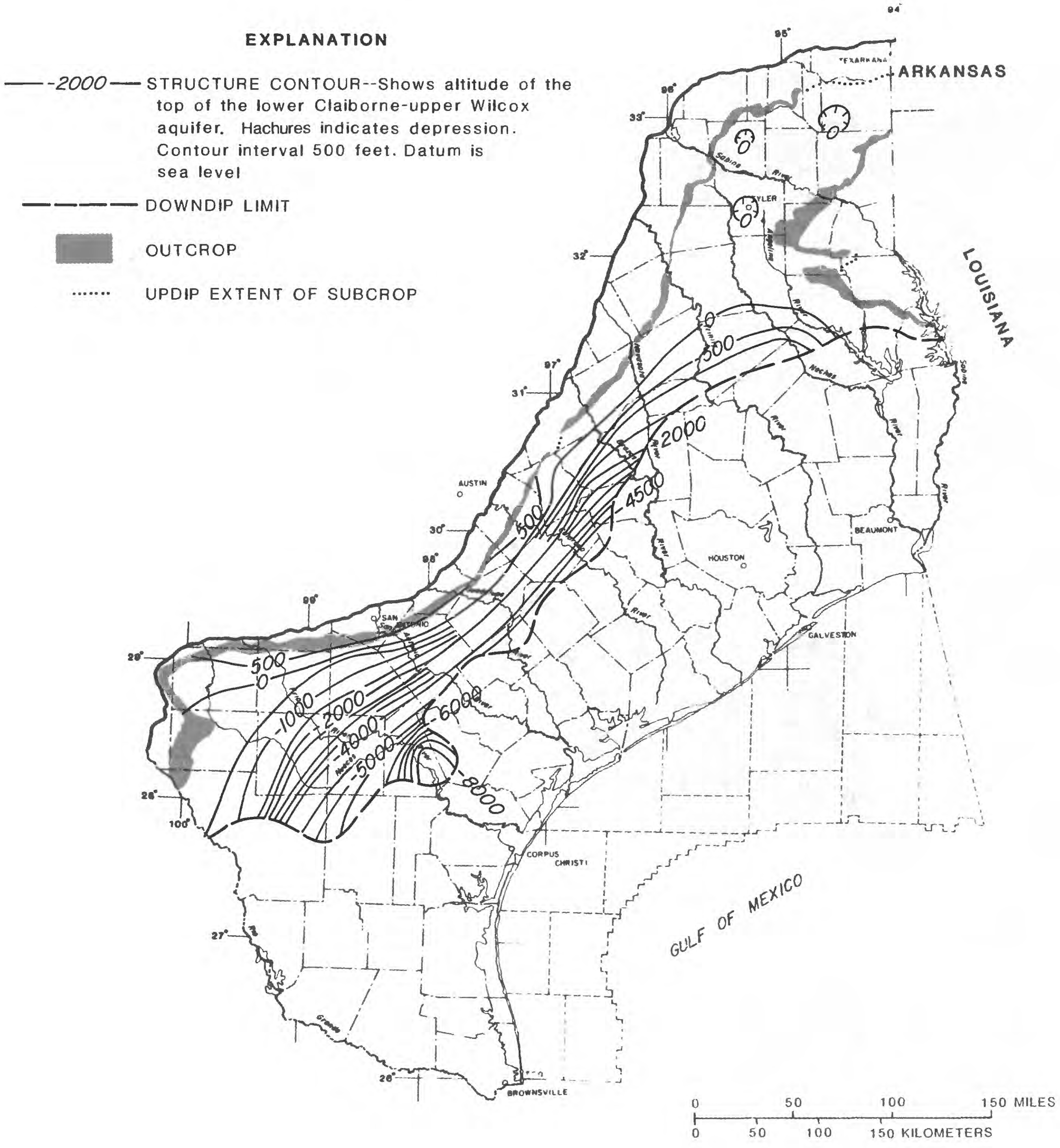


Figure 16.--Altitude of the top of the lower Claiborne-upper Wilcox aquifer.

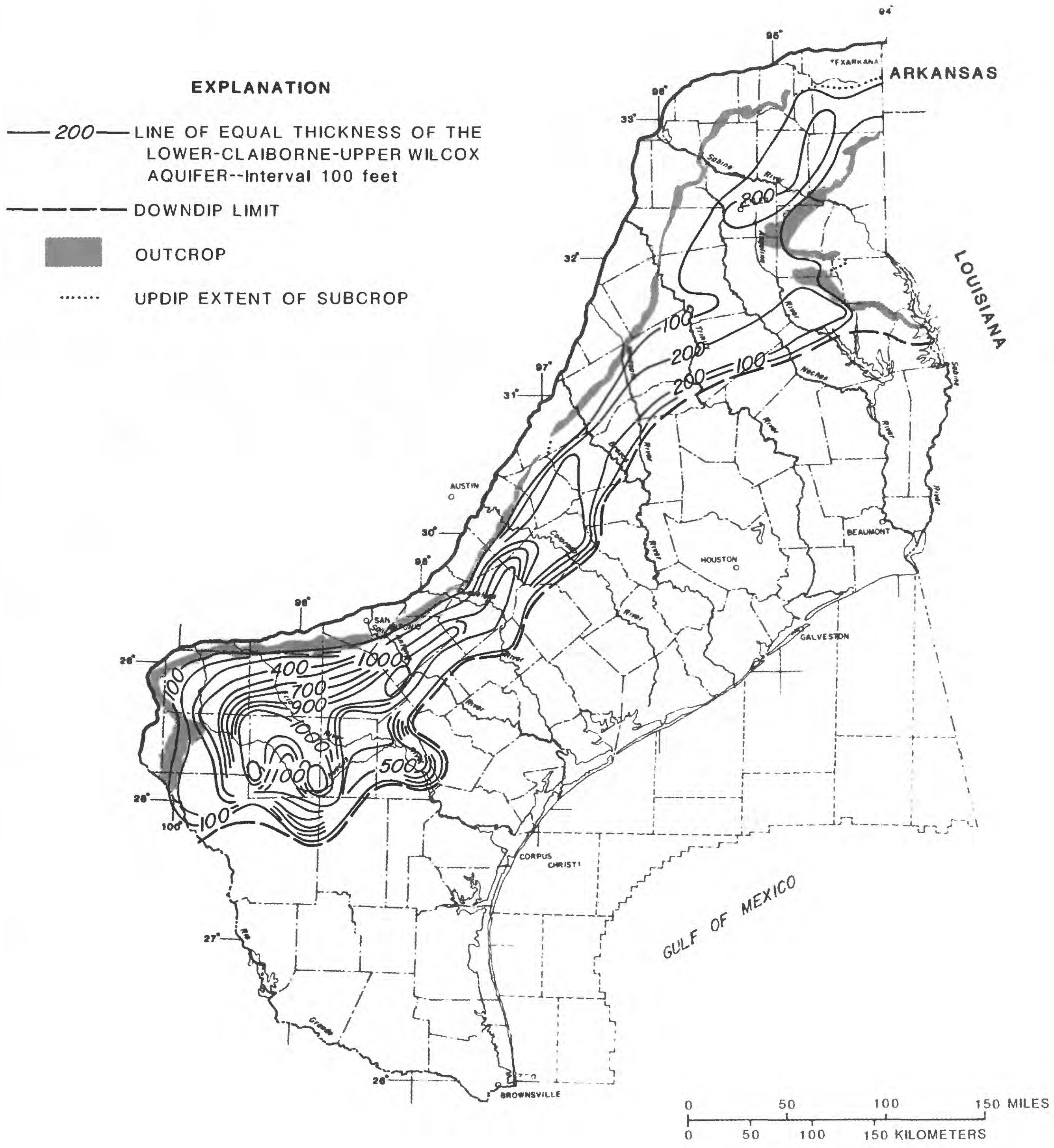


Figure 17.--Thickness of the lower Claiborne-upper Wilcox aquifer.

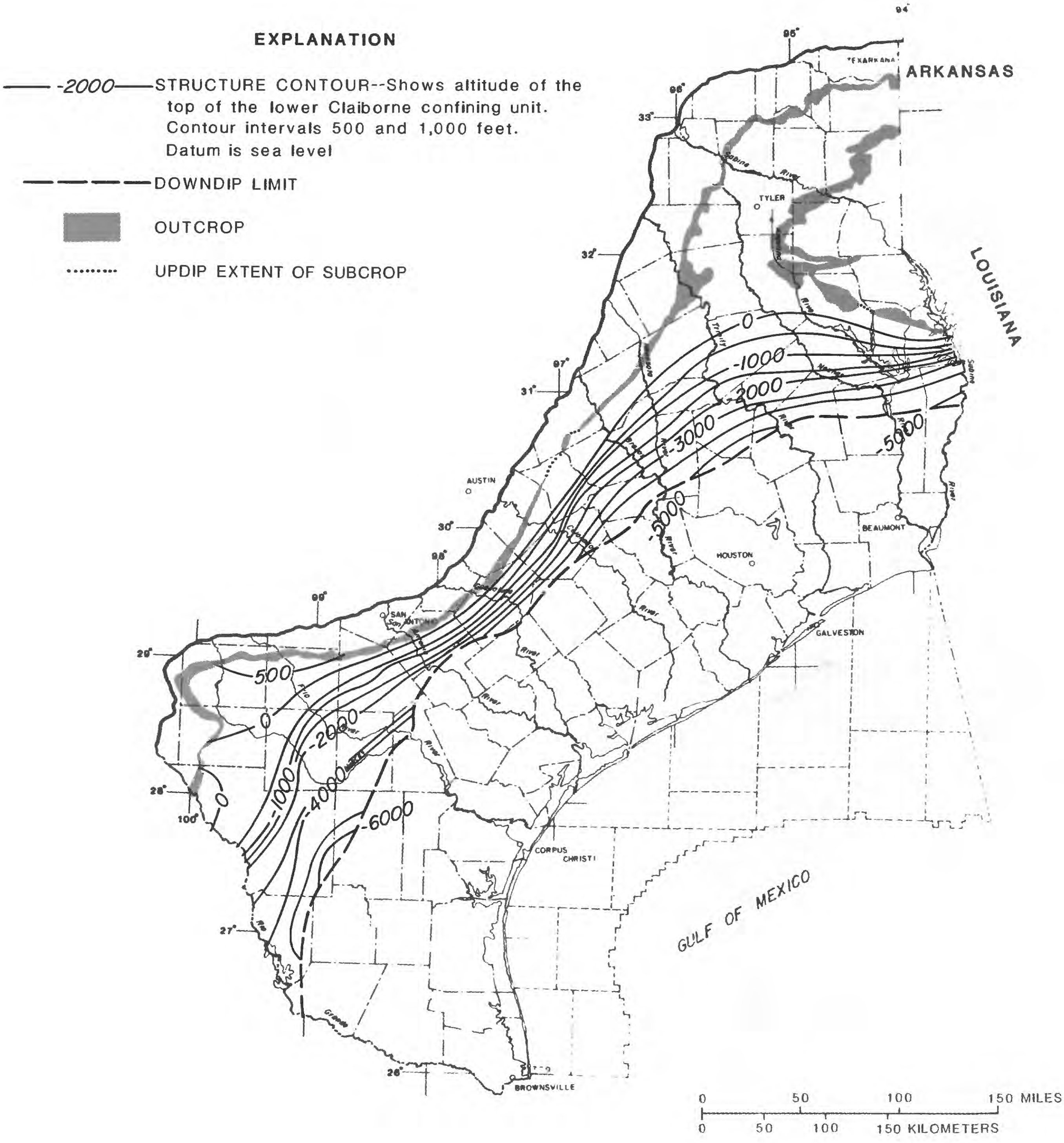


Figure 18.--Altitude of the top of the lower Claiborne confining unit.

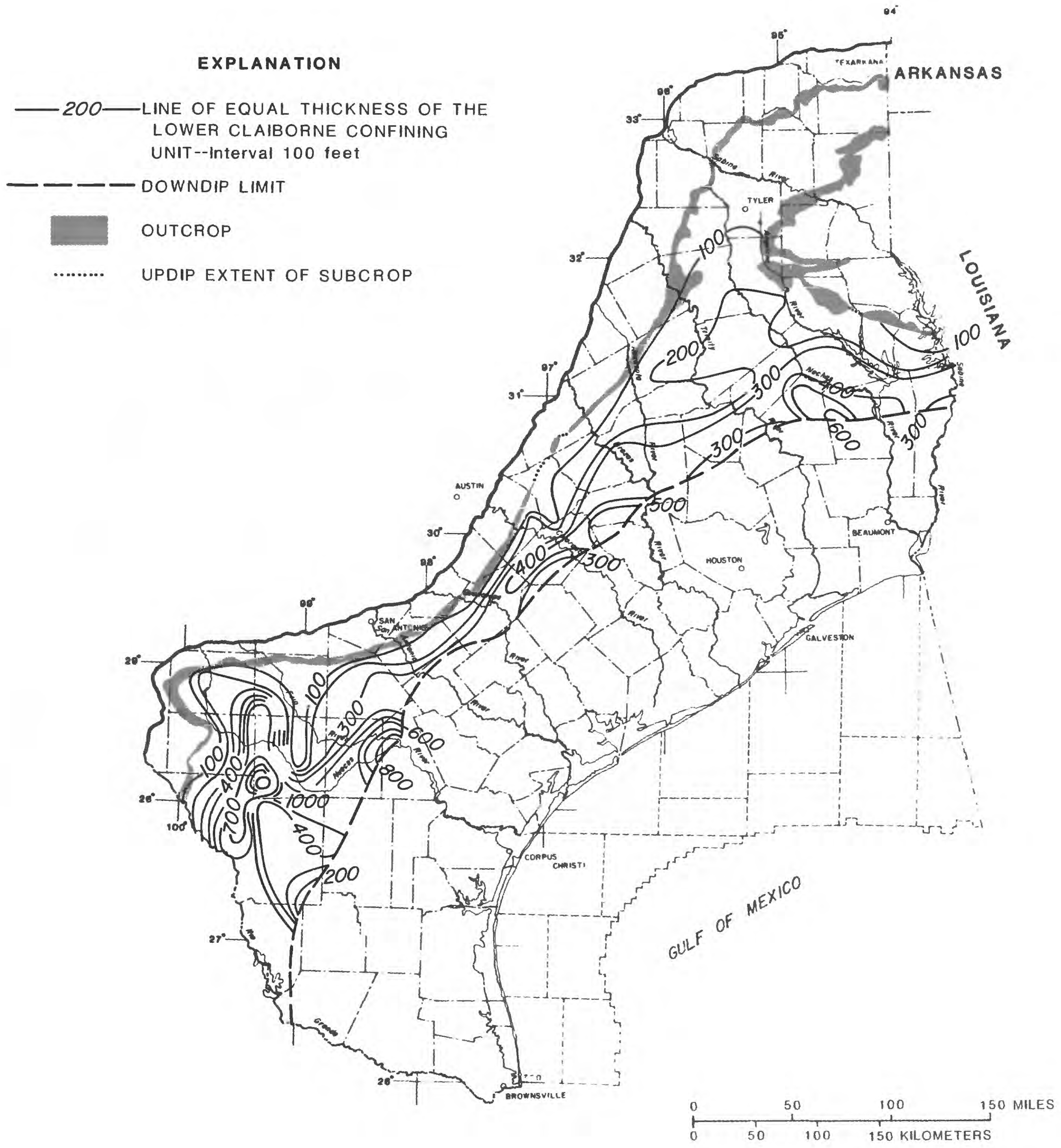


Figure 19.--Thickness of the lower Claiborne confining unit.

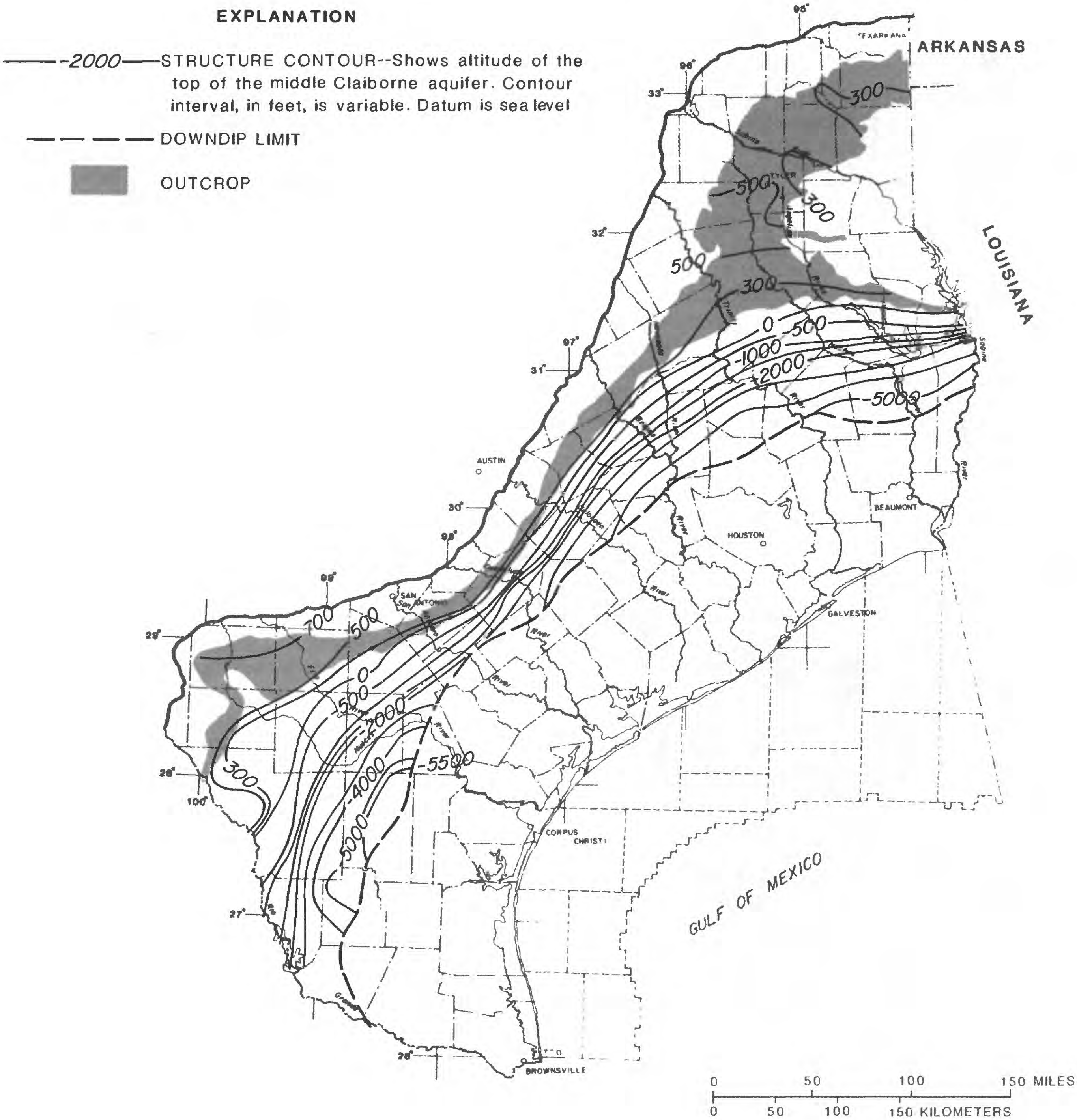


Figure 20.--Altitude of the top of the middle Claiborne aquifer.

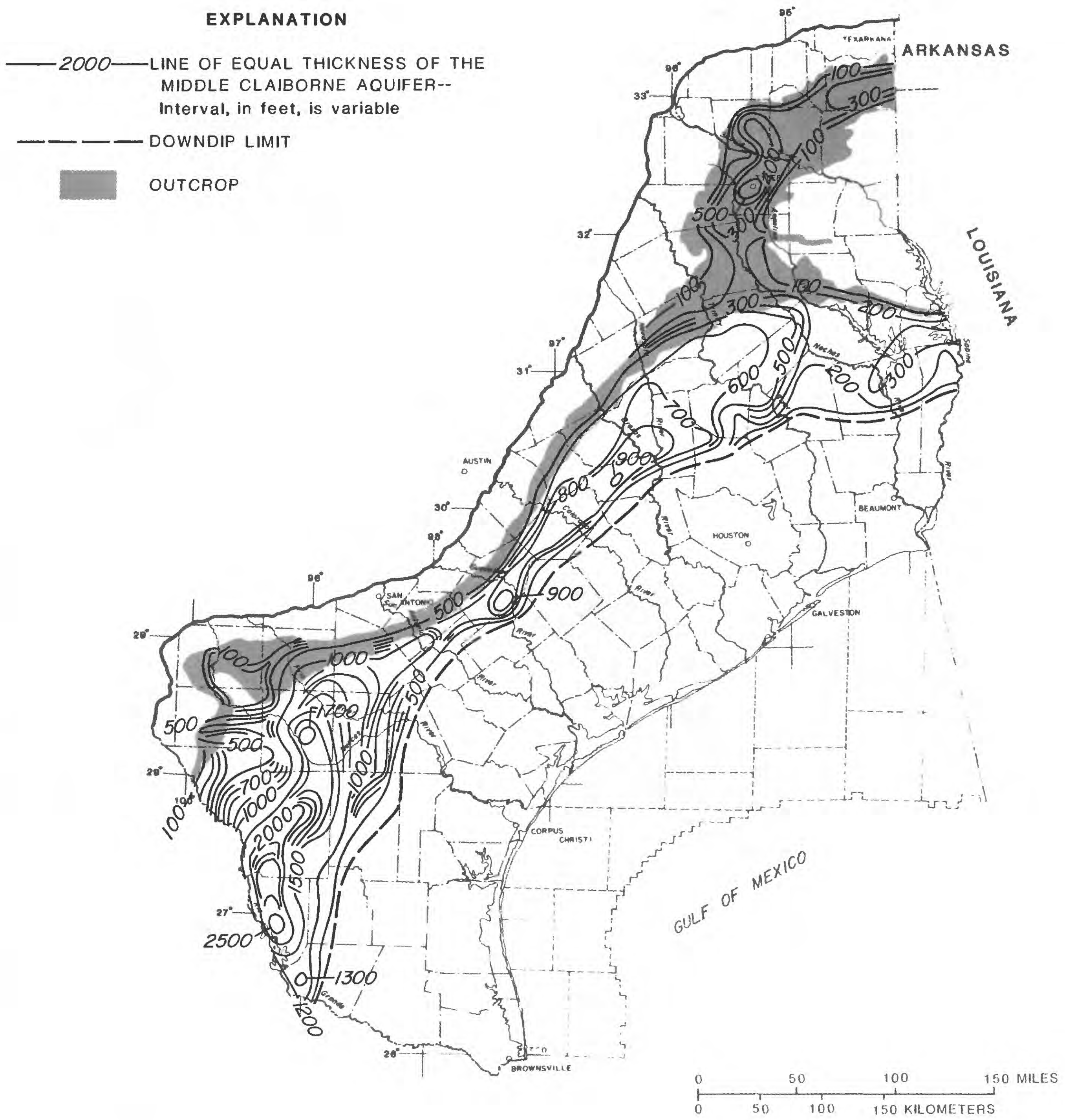


Figure 21.--Thickness of the middle Claiborne aquifer.

the southwest (fig. 20). Thickness of the unit ranges from 0 in the outcrop areas to more than 2,500 ft in the Rio Grande valley (fig. 21).

Middle Claiborne Confining Unit

The middle Claiborne confining unit consists of marine clay of the Cook Mountain Formation in the middle part of the Claiborne Group (table 1). The unit is exposed in a relatively narrow band except in the extreme west, where the outcrop widens to more than 40 mi at the Rio Grande (figs. 3, 22, and 23). The altitude of the top of the unit ranges from about 500 ft above sea level in the outcrop areas in the west to 8,000 ft below sea level in the east (fig. 22). Thickness of the confining unit ranges from 0 in the outcrop area to more than 3,000 ft in Bee and Live Oak Counties (fig. 21).

Upper Claiborne Aquifer

The upper Claiborne aquifer underlies the Vicksburg-Jackson confining unit and is the uppermost aquifer in the coastal uplands aquifer system. It consists of interbedded fine sand, silt, and clay of the Yegua Formation of the upper part of the Claiborne Group (table 1). The outcrop width is narrowest in the central area where it is about 2 mi in width; it widens to about 25 mi in the west near the Nueces River (figs. 3, 24, and 25). The altitude of the top of the aquifer ranges from about 500 ft above sea level in the outcrop area in the west to more than 8,000 ft below sea level in the east (fig. 24). Thickness of the unit ranges from 0 in the outcrop area to more than 2,400 ft in northern Duval County (fig. 25).

Vicksburg-Jackson Confining Unit

The Vicksburg-Jackson confining unit separates the coastal uplands aquifer system from the coastal lowlands aquifer system. It consists primarily of marine clays of the Eocene Jackson Group, and of marine clays of the Frio Clay and its subsurface equivalent, the Oligocene Vicksburg Group (table 1). Where the upper part of the underlying Yegua Formation contains clay, it is included in the Vicksburg-Jackson confining unit. The outcrop is narrowest, less than 1 mi, in the central area, and widens to a maximum of about 20 mi in the southwest (figs. 3, 26, and 27). The altitude of the top of the unit ranges from about 300 ft above sea level in the outcrop area in the southwest to more than 10,000 ft below sea level near Corpus Christi (fig. 26). Thickness of the unit ranges from 0 in the outcrop area to more than 5,000 ft in Goliad County in the west-central area (fig.27).

Coastal Lowlands Aquifer System

Hydrogeologic units belonging to the Oligocene(?), Miocene, Pliocene, Pleistocene, and Holocene series comprise the coastal lowlands aquifer system (table 2). Many investigators disagree as to the position of the top of Oligocene deposits (Baker, 1979, p.36). It is possible that all of the coastal lowlands units are Miocene or younger. The units are, from oldest to youngest, the: lower Miocene-upper Oligocene permeable zone; lower Miocene-

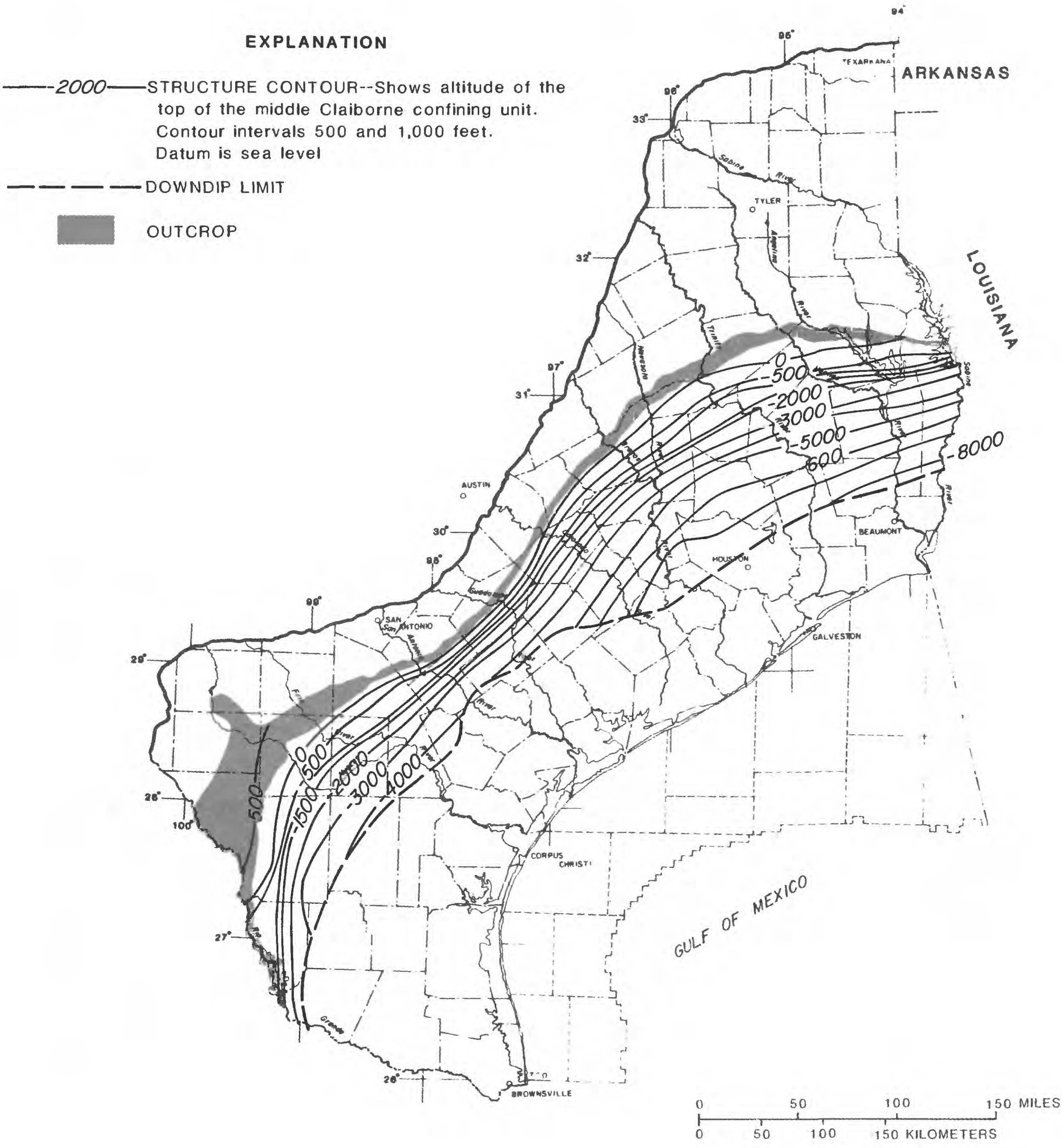


Figure 22.--Altitude of the top of the middle Claiborne confining unit.

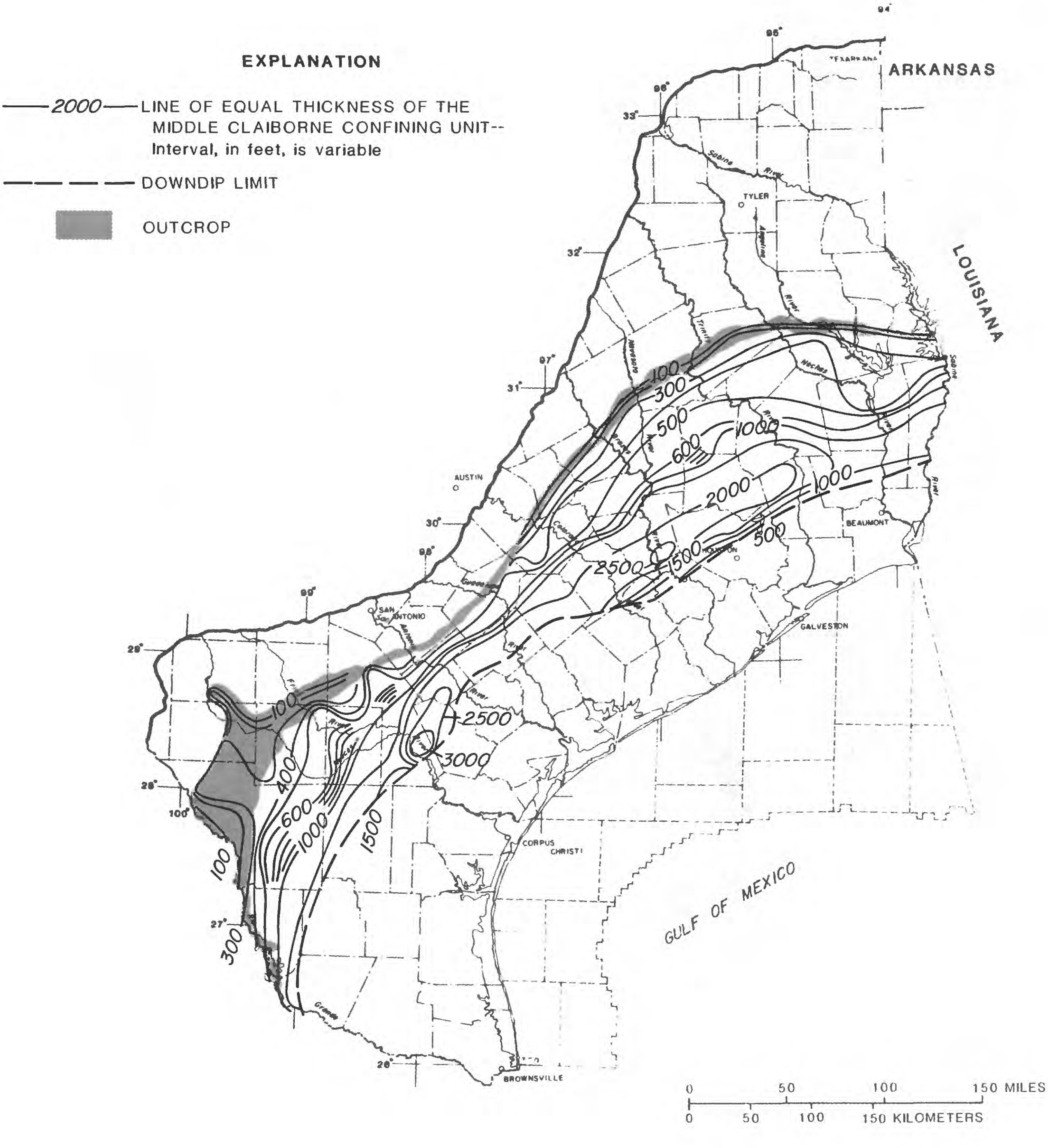


Figure 23.--Thickness of the middle Claiborne confining unit.

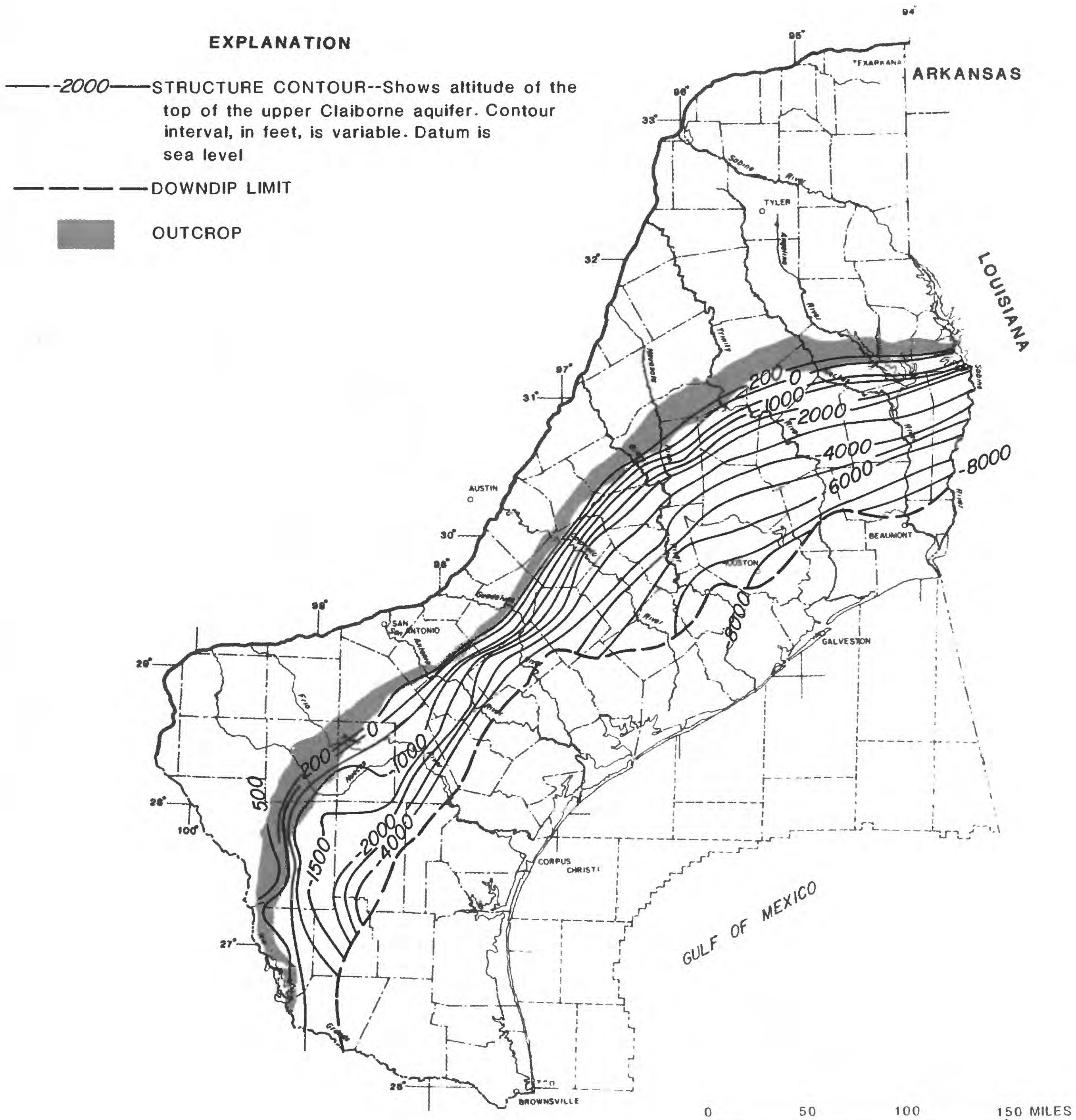


Figure 24.--Altitude of the top of the upper Claiborne aquifer.

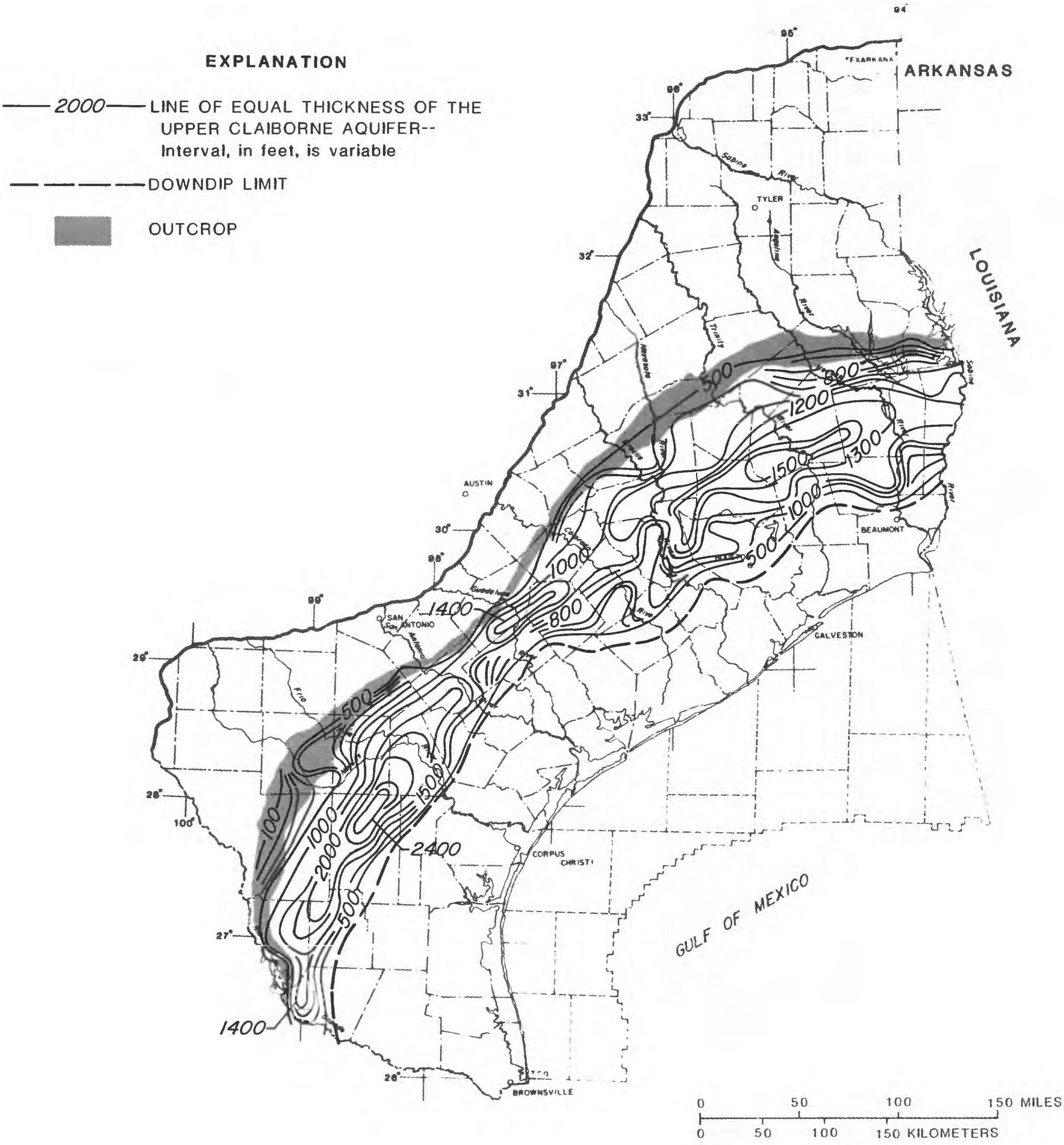


Figure 25.--Thickness of the upper Claiborne aquifer.

EXPLANATION

——-2000—— STRUCTURE CONTOUR--Shows altitude of the top of the Vicksburg-Jackson confining unit. Contour interval, in feet, is variable. Datum is sea level

— — — — — DOWNDIP LIMIT

▇ OUTCROP

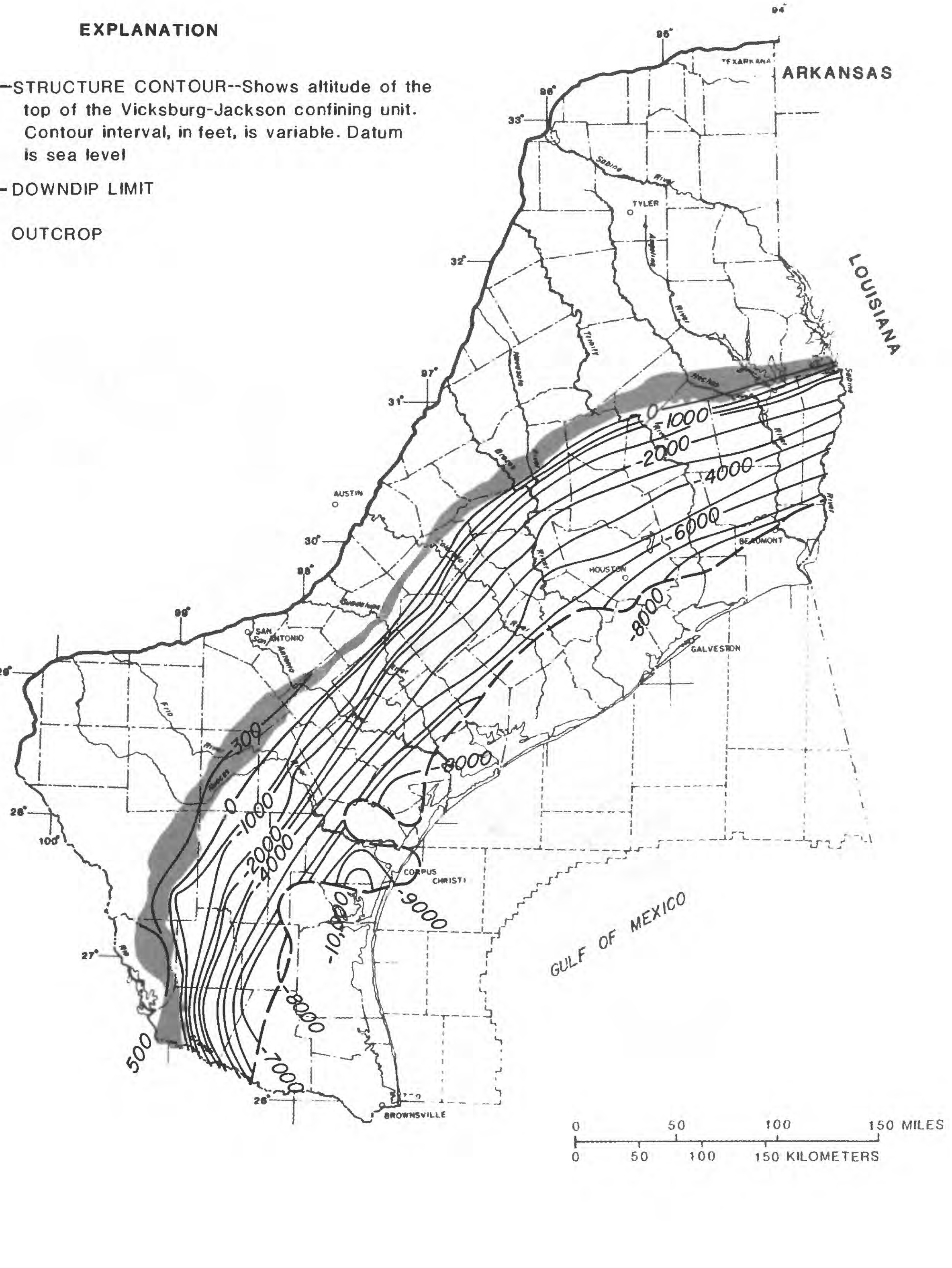


Figure 26.--Altitude of the top of the Vicksburg-Jackson confining unit.

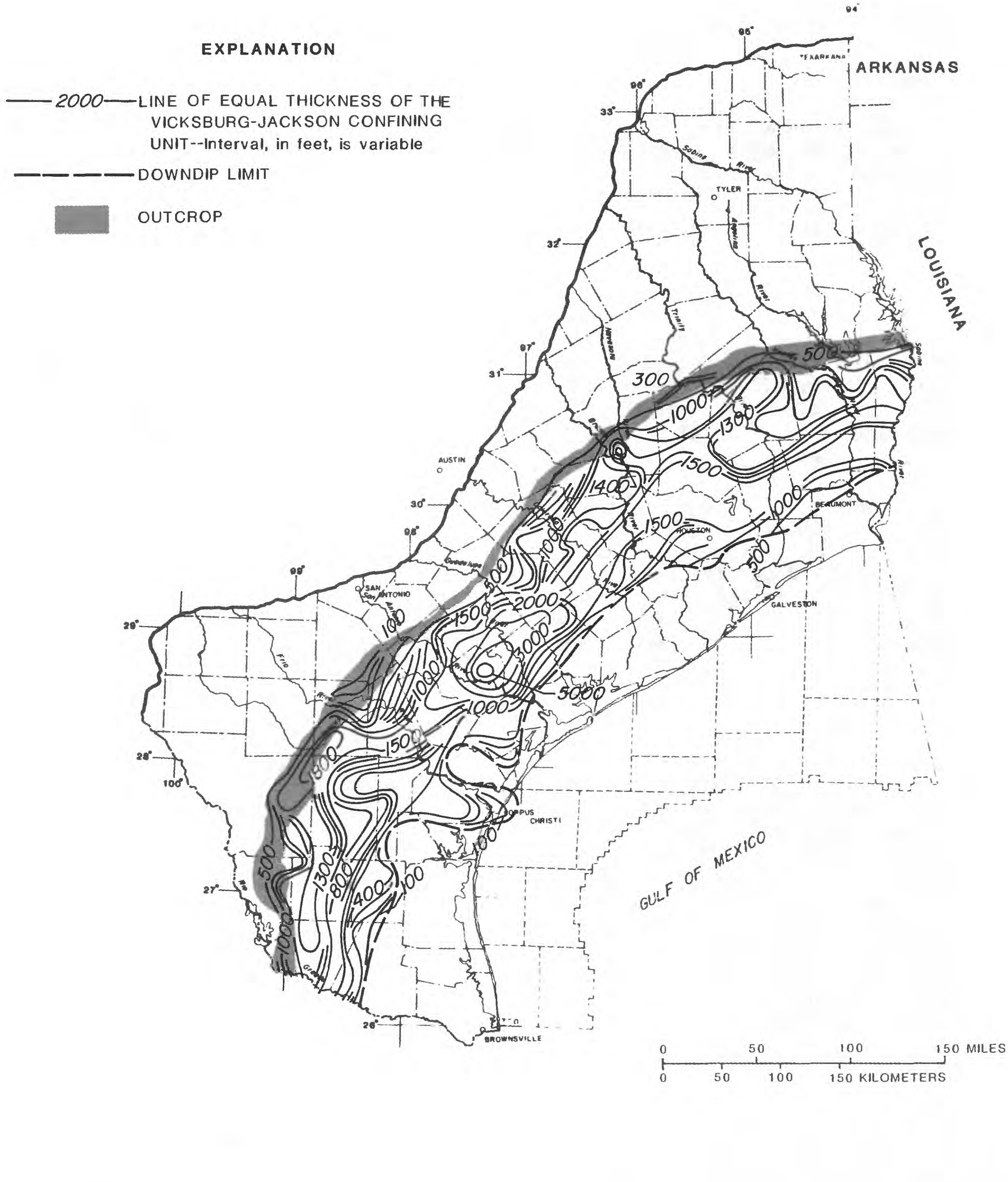


Figure 27.--Thickness of the Vicksburg-Jackson confining unit.

upper Oligocene confining unit; middle Miocene permeable zone; middle Miocene confining unit; lower Pliocene-upper Miocene permeable zone; lower Pleistocene-upper Pliocene permeable zone; Holocene-upper Pleistocene permeable zone.

Table 2 shows the definitions and names of hydrogeologic units that may be found in recent published reports; the example shown is from Baker (1979). Essentially every unit has been redefined and renamed for the GCRASA study. A detailed explanation for these changes was provided by J.S. Weiss and R.L. Hosman (U.S. Geological Survey, written commun., 1986).

Lower Miocene-Upper Oligocene Permeable Zone

The lower Miocene-upper Oligocene permeable zone is the lowermost permeable zone in the coastal lowlands aquifer system, and is underlain by the nearly impermeable Vicksburg-Jackson confining unit. The zone consists of sand or tuff with interbedded clays in the lower part of the Catahoula Sandstone or Tuff of Oligocene(?) and Miocene age, and of sands in its subsurface equivalent, the "Frio" Formation (table 2).

The unit is exposed across most of the area; however, it is present only in the subsurface in a large part of the west-central area (figs. 3, 28, and 29). Outcrop width ranges from about 2 mi at the Rio Grande to about 13 mi at the Sabine River (fig. 28). The altitude of the top of the unit ranges from less than 500 ft above sea level in the outcrop areas to more than 10,000 ft below sea level in Brazoria County (fig. 28). Thickness of the unit ranges from 0 in the outcrop areas to more than 4,000 ft in the west (fig. 29).

Lower Miocene-Upper Oligocene Confining Unit

The lower Miocene-upper Oligocene confining unit consists of massive clays with some interbedded thin sands belonging generally to the Anahuac Formation (Ellisor, 1944) of Oligocene(?) and Miocene age (table 2). The unit is not exposed in the study area; it exists only in the subsurface (figs. 30 and 31). All of the permeable zones in the coastal lowlands system are in contact in the updip areas, without intervening confining units (figs. 7-9). The confining unit in the west pinches out in its downdip direction and then continues again farther downdip (figs. 9, 30, and 31). The altitude of the top of the unit ranges from less than 500 ft above sea level in the west to more than 10,000 ft below sea level offshore in the extreme southwest (fig. 30). Thickness of the unit ranges from 0 in updip areas to more than 3,000 ft in the east and in Calhoun County in the central area (fig. 31).

Middle Miocene Permeable Zone

The middle Miocene permeable zone consists of sands in the upper part of the Catahoula Sandstone or Tuff, and of sands in the lower parts of the Oakville Sandstone and Fleming Formation (table 2). The unit is exposed across the area, with widths ranging from about 3 mi in the Rio Grande valley to about 20 mi in McMullen County in the west-central area (figs. 6, 32, and 33). The altitude of the top of the permeable zone ranges from about 500 ft

EXPLANATION

-2000 STRUCTURE CONTOUR--Shows altitude of the top of the lower Miocene-upper Oligocene permeable zone. Contour intervals 500 and 1,000 feet. Datum is sea level

DOWNDIP LIMIT

OUTCROP

UPDIP EXTENT OF SUBCROP

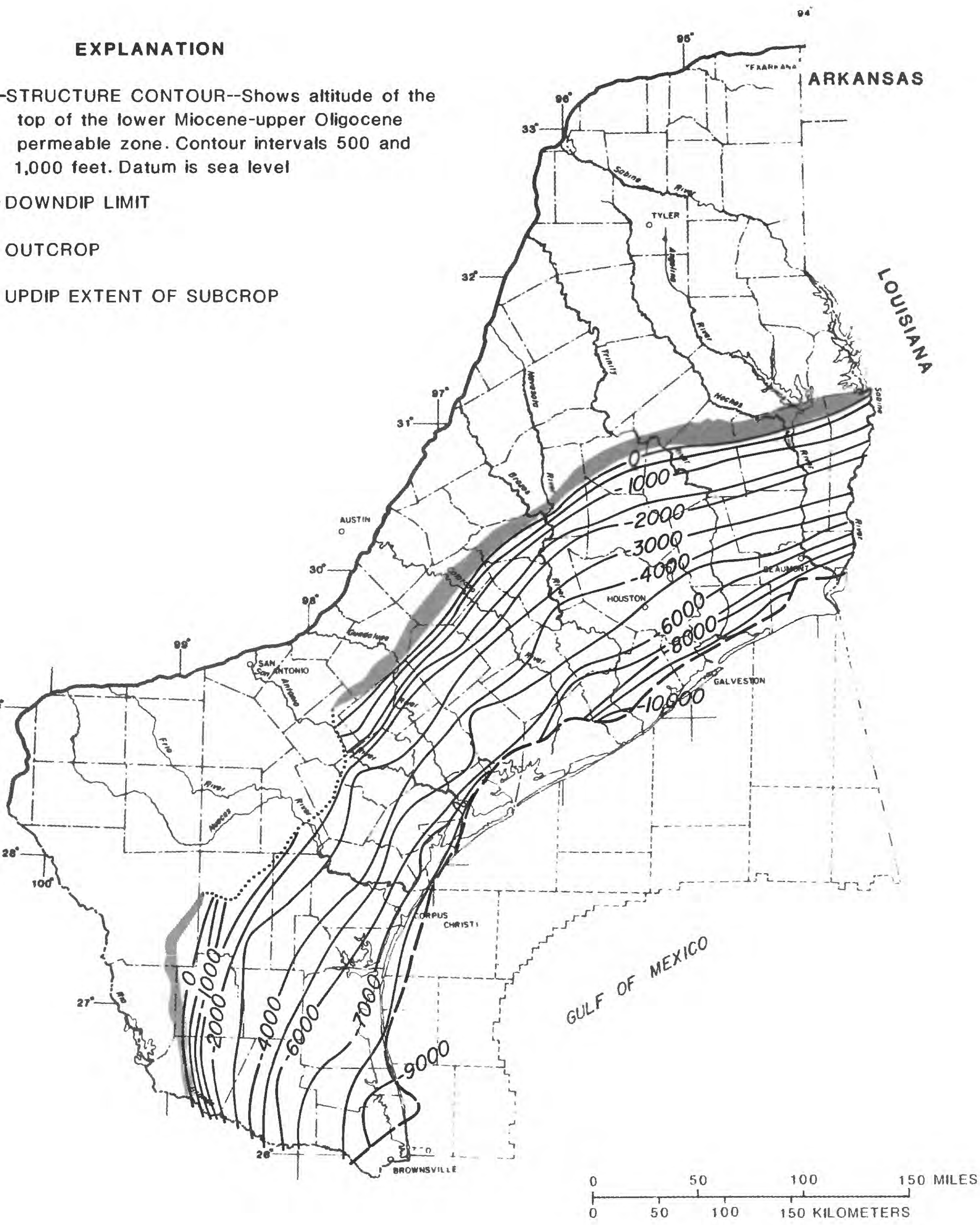


Figure 28.-- Altitude of the top of the lower Miocene-upper Oligocene permeable zone.

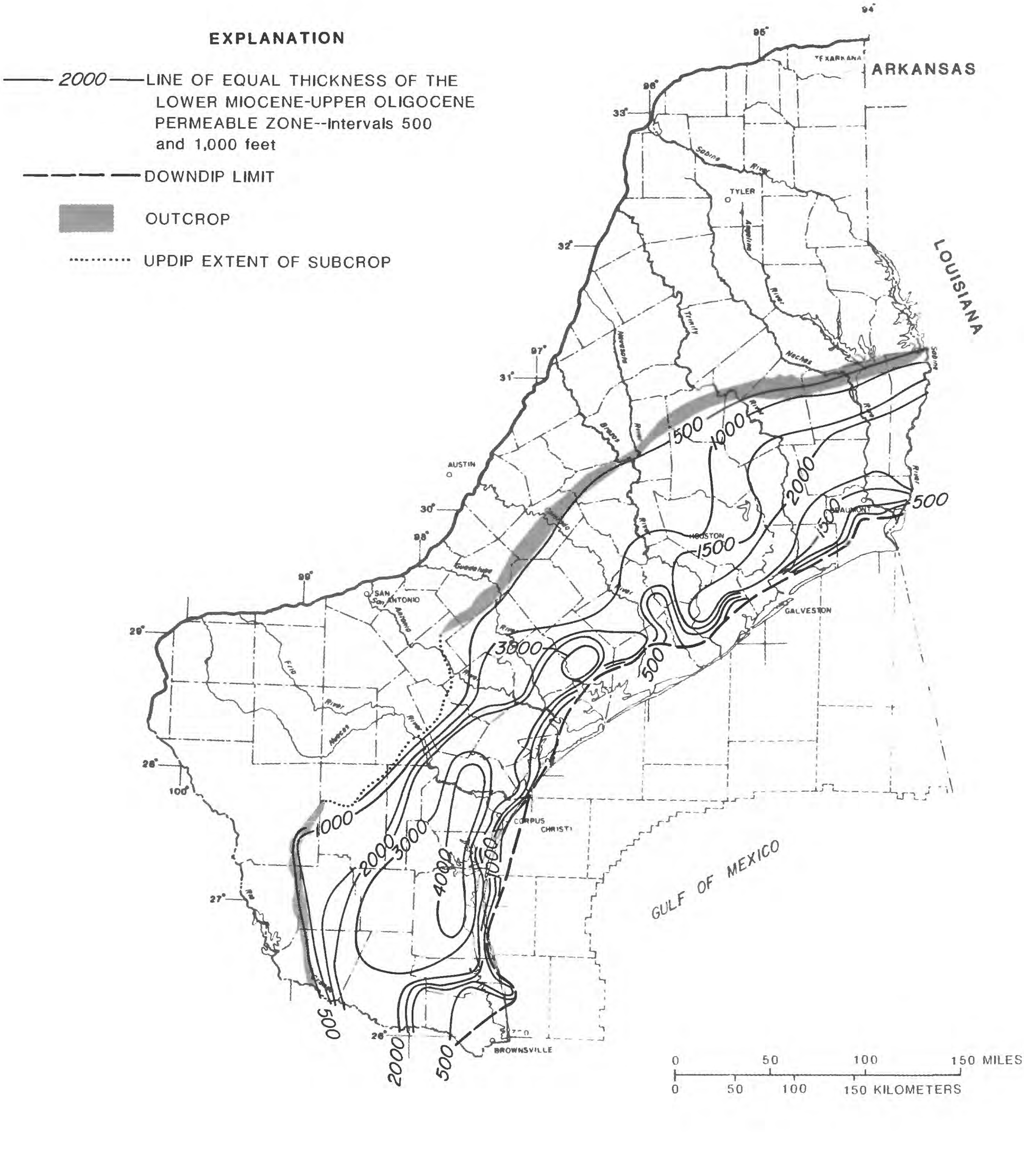


Figure 29.--Thickness of the lower Miocene-upper Oligocene permeable zone.

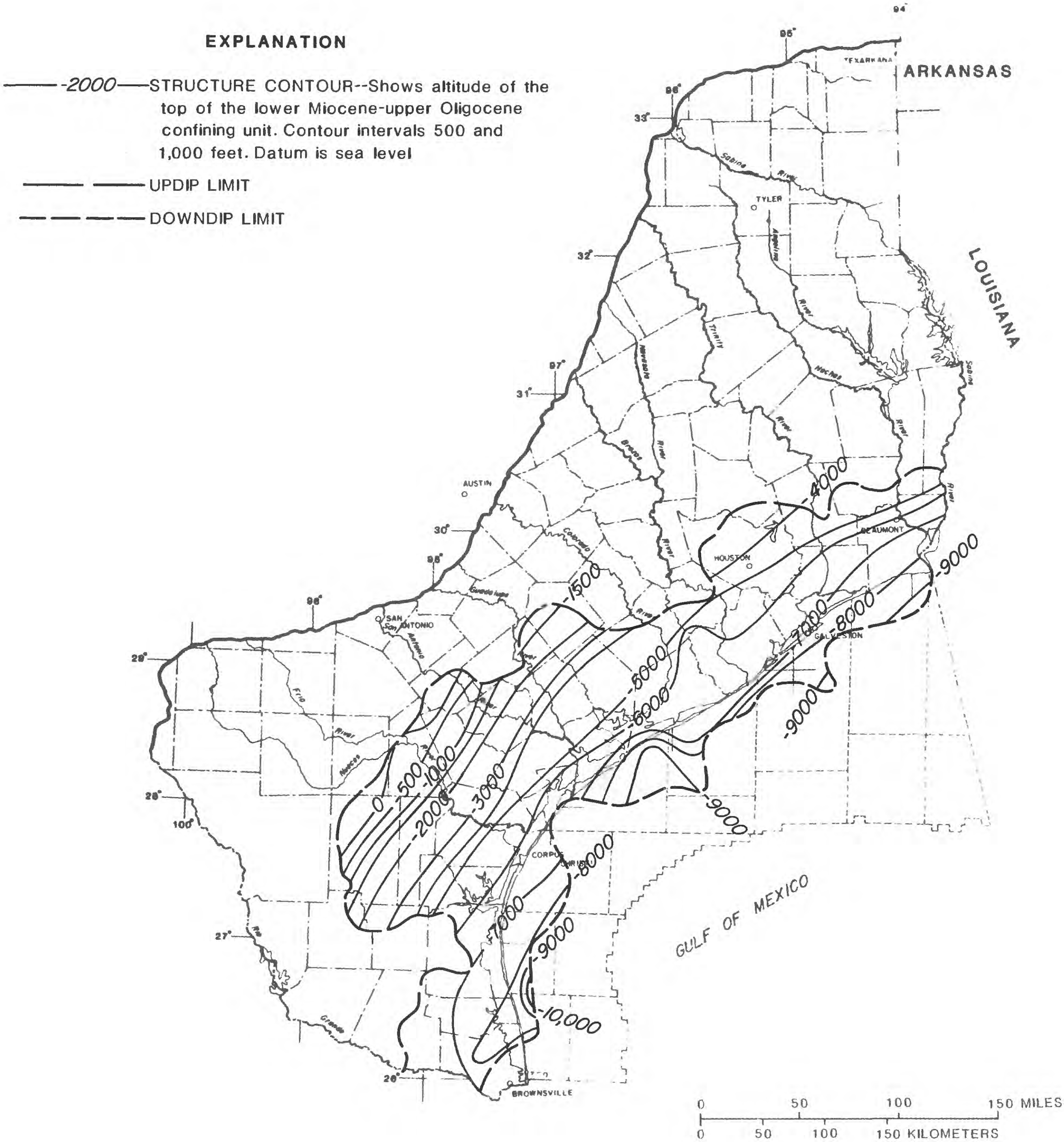


Figure 30.--Altitude of the top of the lower Miocene-upper Oligocene confining unit.

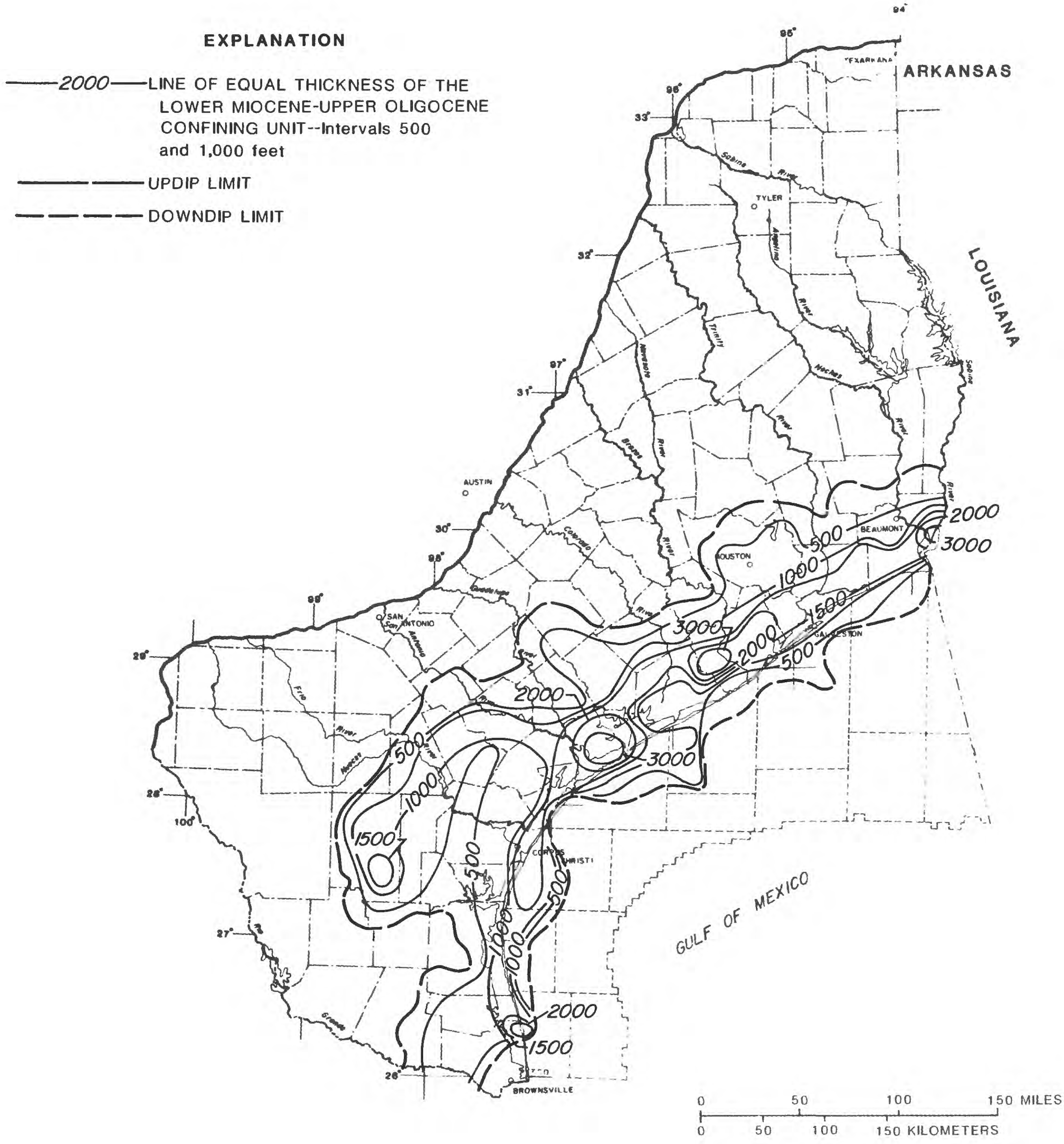


Figure 31.--Thickness of the lower Miocene-upper Oligocene confining unit.

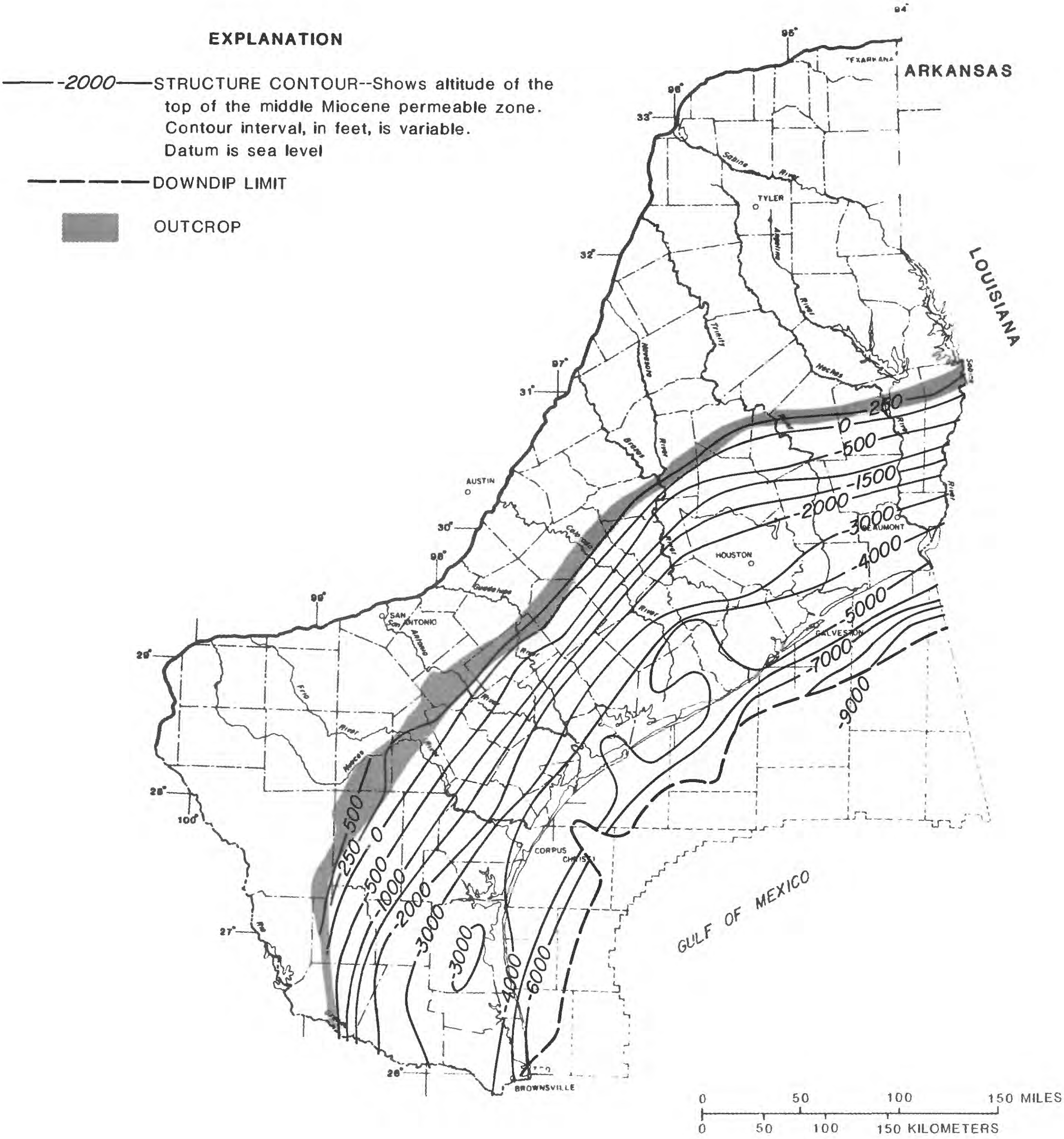


Figure 32.--Altitude of the top of the middle Miocene permeable zone.

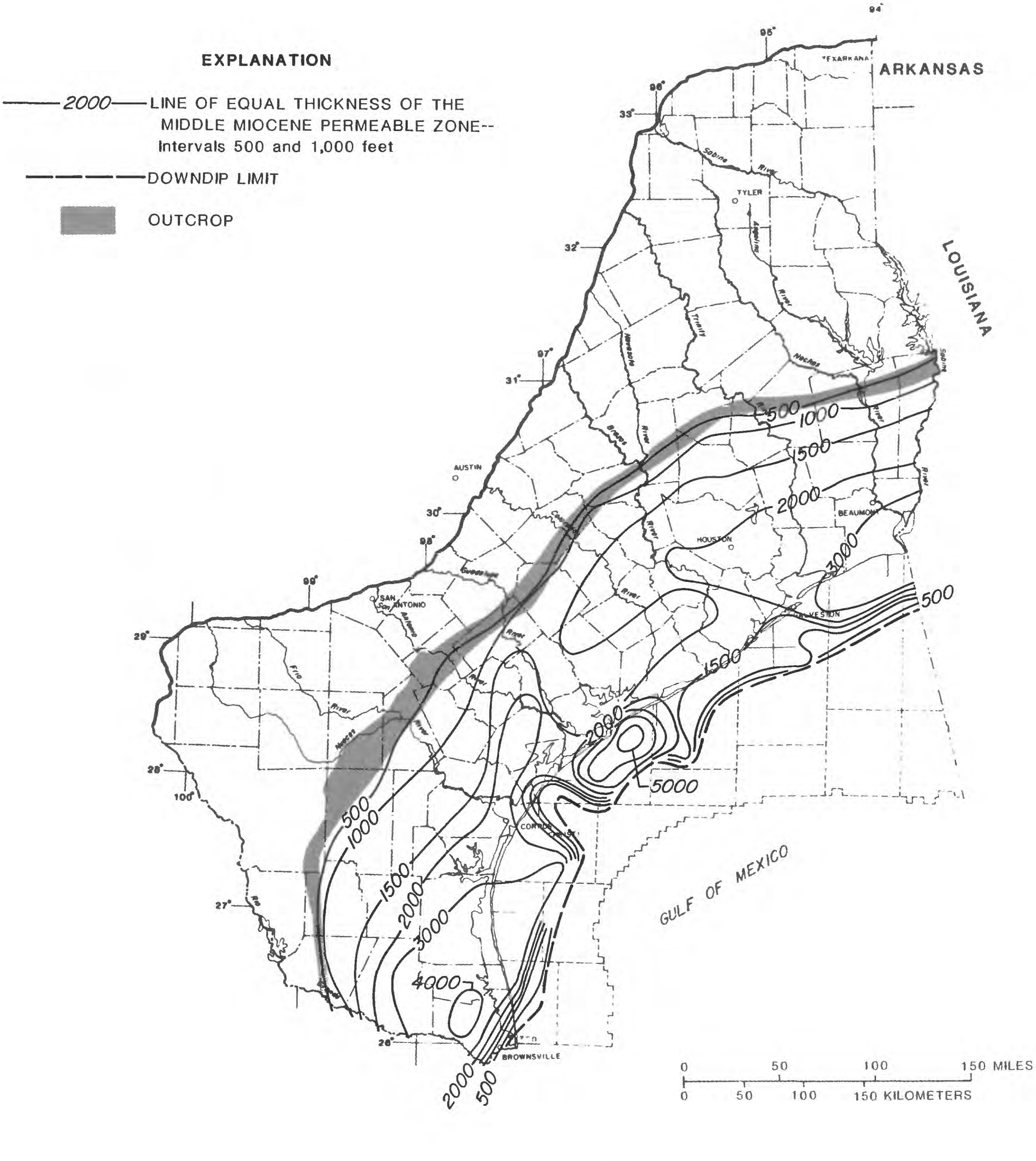


Figure 33.--Thickness of the middle Miocene permeable zone.

above sea level in the southwest outcrop area to more than 9,000 ft below sea level in the east (fig. 32). Thickness of the unit ranges from 0 in the outcrop area to more than 5,000 ft near Matagorda Bay in the central area (fig. 33).

Middle Miocene Confining Unit

The middle Miocene confining unit consists of clayey sediments in the upper part of the Oakville Sandstone and in the middle part of the Fleming Formation (table 2). The unit is not exposed at the surface, but exists only in the subsurface (figs. 34 and 35), as indicated by the sections in figures 7-9. Altitude of the top of the unit ranges from about 250 ft below sea level to more than 7,500 ft below sea level in the southeast (fig. 34). Thickness of the unit ranges from about 500 ft in the updip areas to more than 1,500 ft in several places downdip (fig. 35).

Lower Pliocene-Upper Miocene Permeable Zone

The lower Pliocene-upper Miocene permeable zone consists mainly of sands in the lower part of the Goliad Sand of Pliocene age, and of sand and interbedded clays in the upper part of the Fleming Formation of Miocene age (table 2). The unit is underlain by a confining unit only in downdip areas; in updip areas it directly overlies the middle Miocene permeable zone (figs. 7-9). The unit crops out across the area, with widths ranging from about 2 mi in the Rio Grande valley to about 18 mi at the Guadalupe River in the central area (figs. 6, 36, and 37). The altitude of the top of the unit ranges from about 500 ft above sea level in the outcrop area to more than 5,500 ft below sea level in the east in the Gulf of Mexico (fig. 36). Thickness of the unit ranges from 0 in the outcrop area to more than 4,000 ft in the east in the Gulf (fig. 37).

Lower Pleistocene-Upper Pliocene Permeable Zone

The lower Pleistocene-upper Pliocene permeable zone consists of sands and clays in the upper part of the Goliad Sand of Pliocene age, and of sands and clays of the Willis Sand and Bentley Formation of early Pleistocene age (table 2). The unit is neither underlain nor overlain by a confining unit; it directly overlies the lower Pliocene-upper Miocene permeable zone and underlies the Holocene-upper Pleistocene permeable zone.

The permeable zone has a relatively large outcrop area; the width ranges from about 9 mi in the east to about 23 mi at the Brazos River (figs. 6, 38, 39). The altitude of the top of the unit ranges from about 250 ft above sea level in the outcrop area to more than 1,100 ft below sea level in the Gulf (fig. 38). Thickness of the unit ranges from 0 in the outcrop area to more than 4,000 ft in the east in the Gulf (fig. 39).

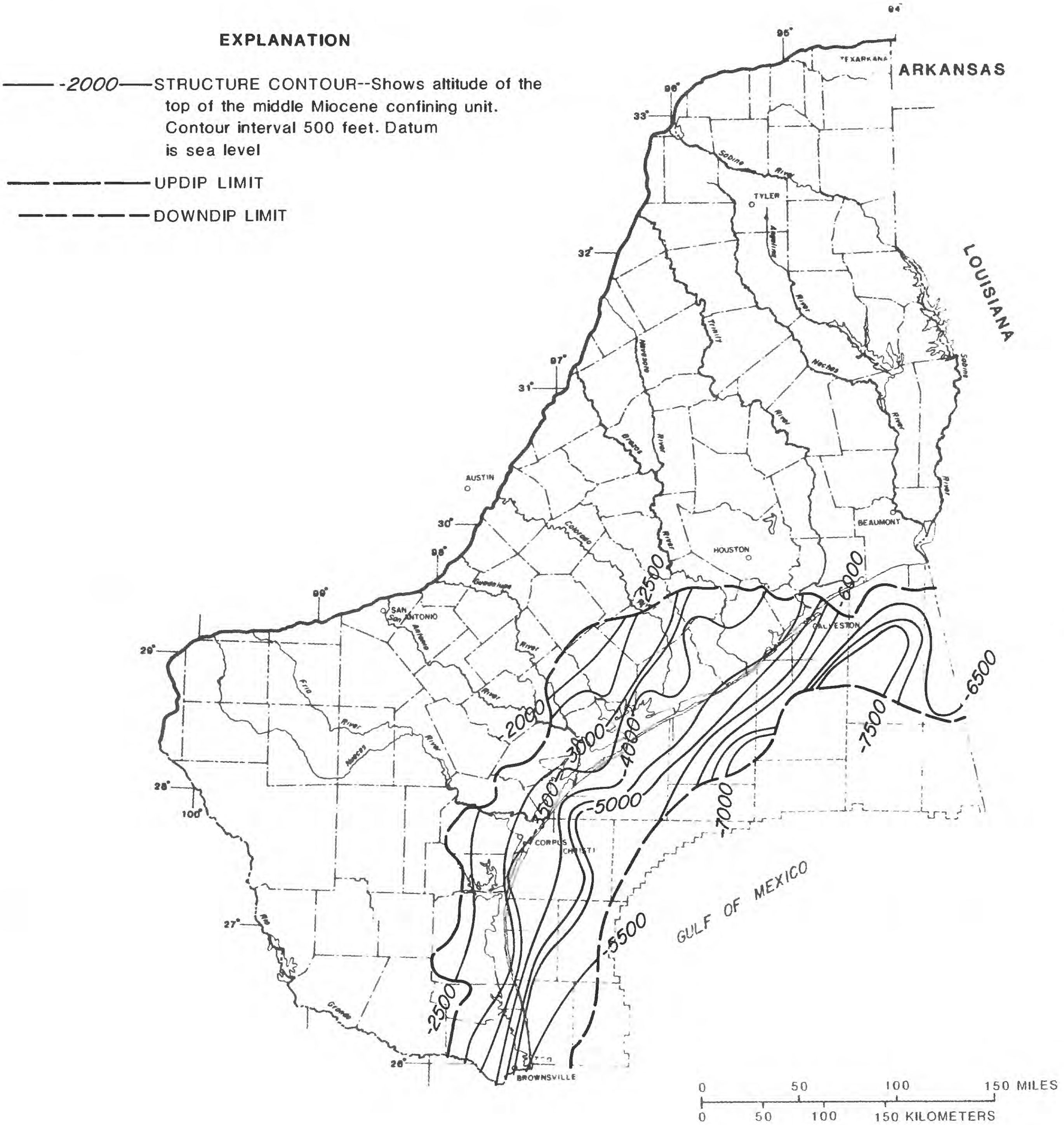


Figure 34.--Altitude of the top of the middle Miocene confining unit.

EXPLANATION

——1000—— LINE OF EQUAL THICKNESS OF THE MIDDLE MIOCENE CONFINING UNIT-- Interval 500 feet

— — — UPDIP LIMIT

— — — — DOWNDIP LIMIT

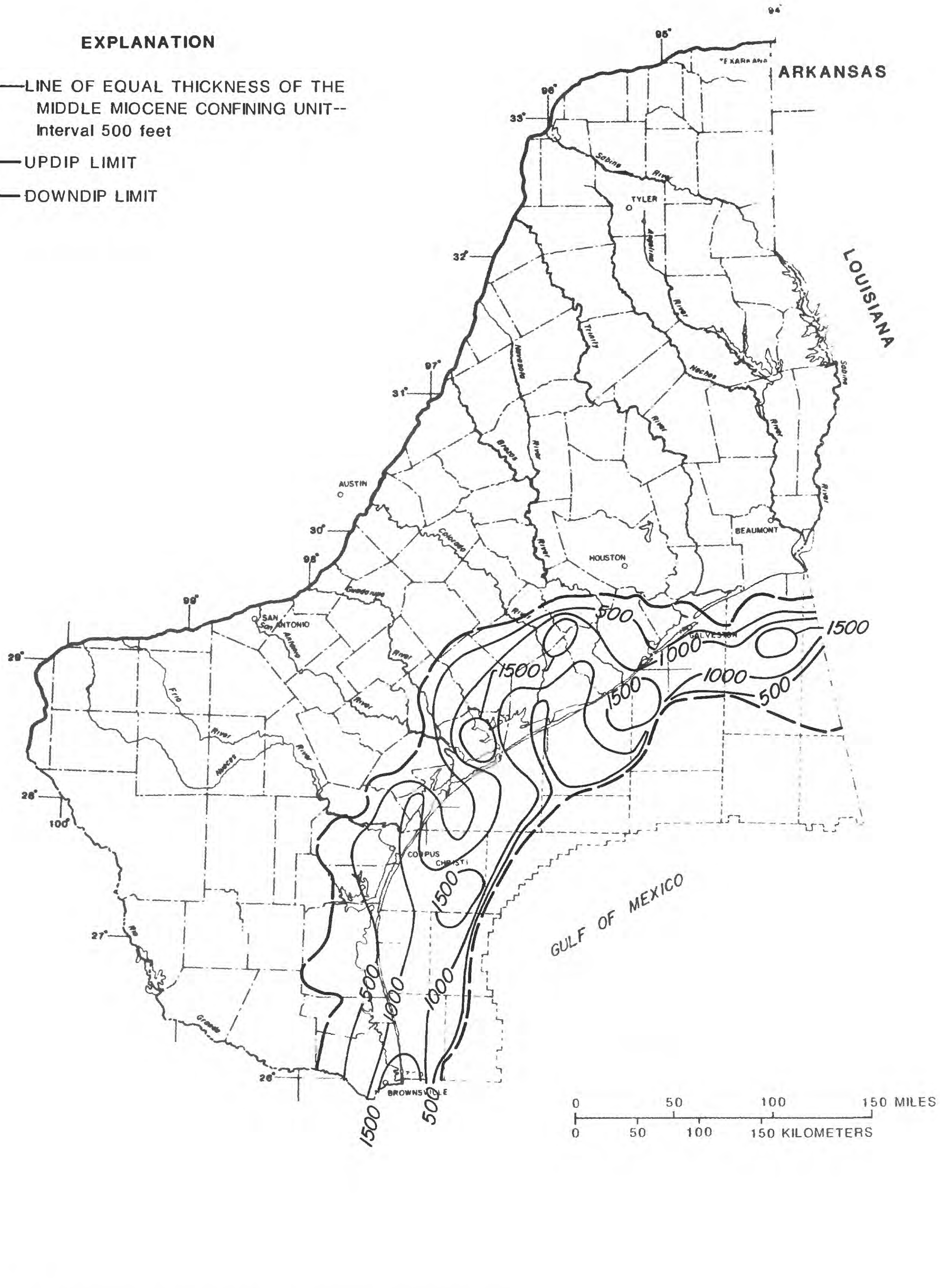


Figure 35.--Thickness of the middle Miocene confining unit.

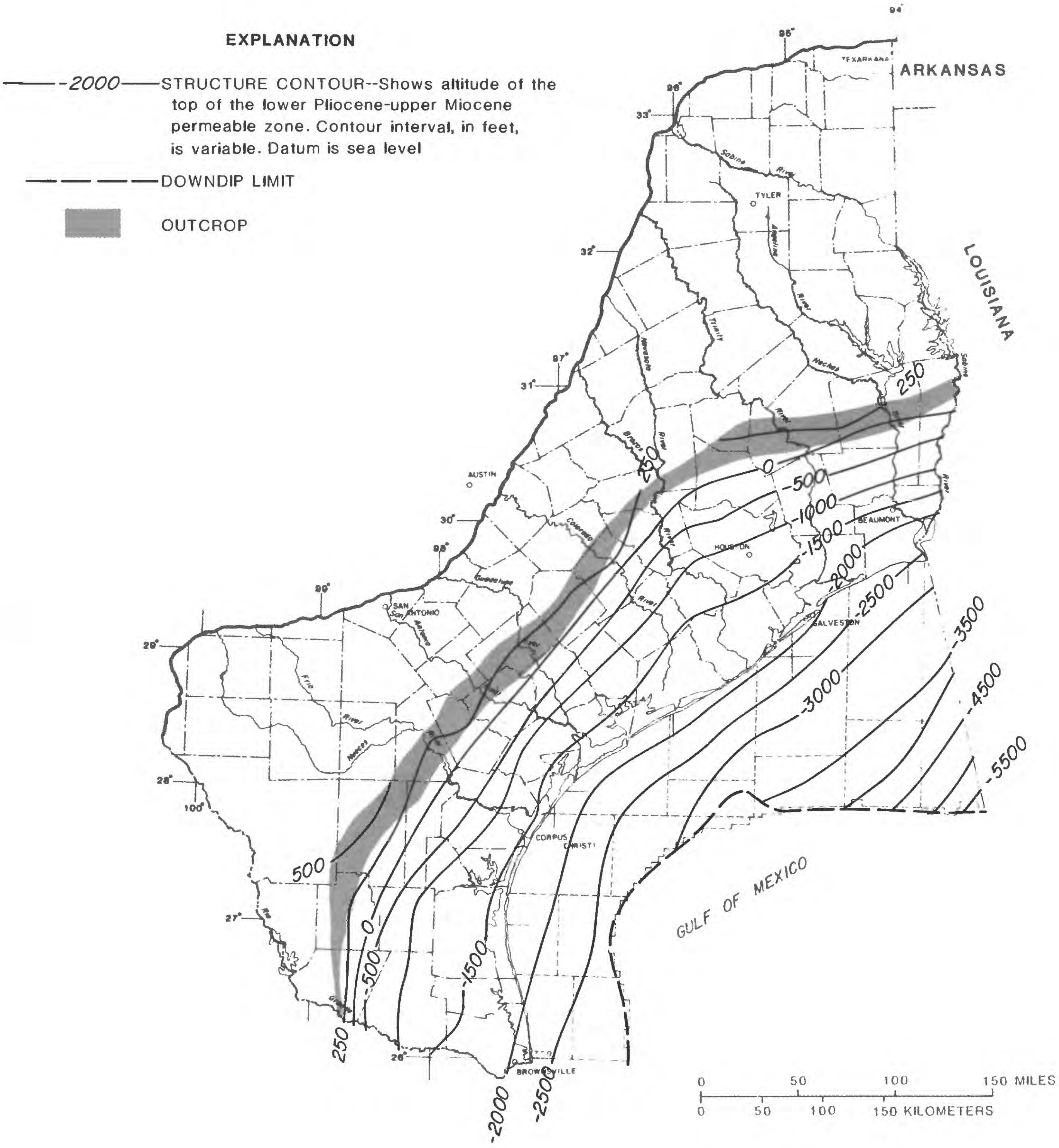


Figure 36.--Altitude of the top of the lower Pliocene-upper Miocene permeable zone.

EXPLANATION

——*2000*——LINE OF EQUAL THICKNESS OF THE LOWER PLIOCENE-UPPER MIOCENE PERMEABLE ZONE--Intervals 500 and 1,000 feet

— — — —DOWNDIP LIMIT

OUTCROP

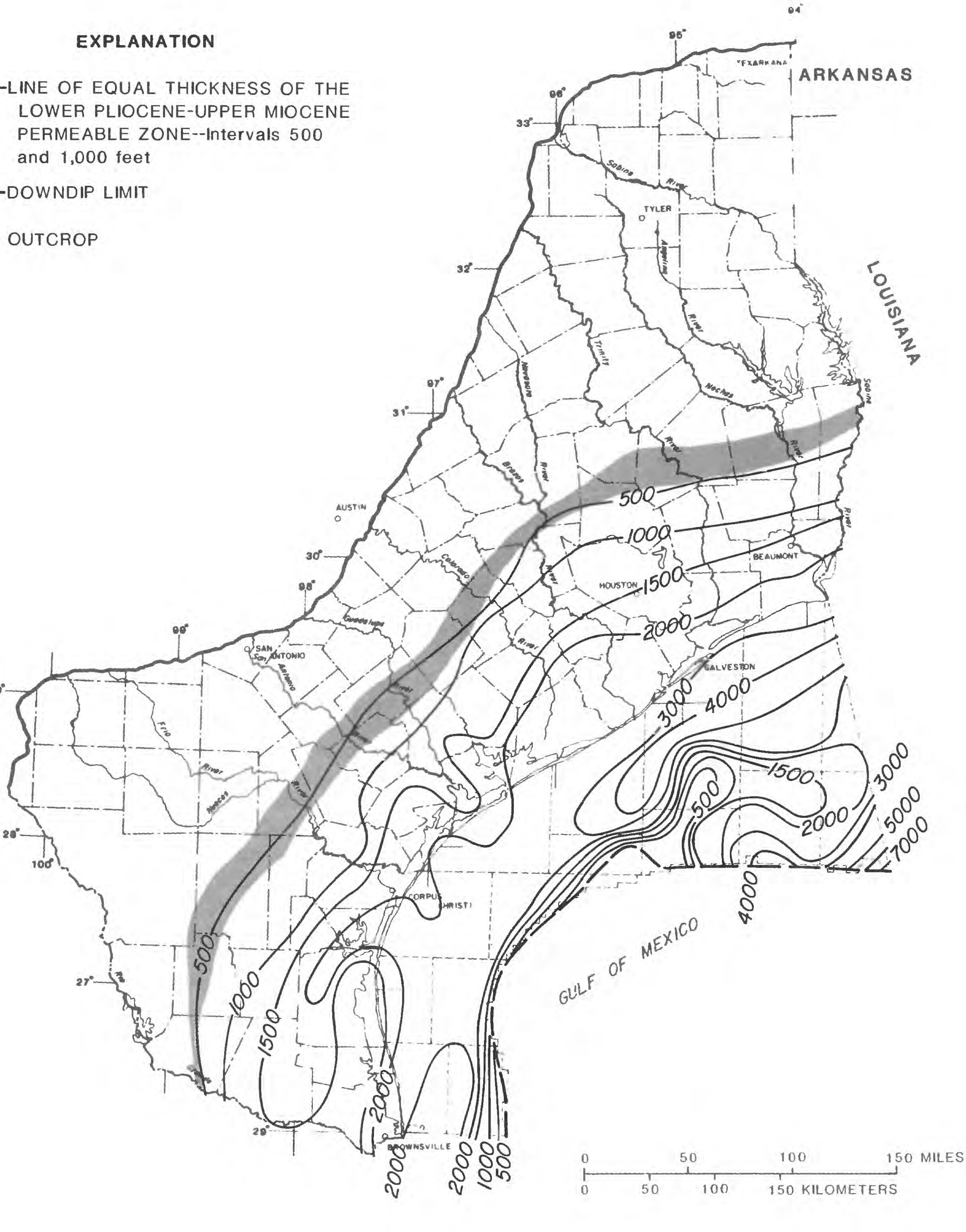


Figure 37.--Thickness of the lower Pliocene-upper Miocene permeable zone.

EXPLANATION

——-600—— STRUCTURE CONTOUR--Shows altitude of the top of the lower Pleistocene-upper Pliocene permeable zone. Contour interval, in feet, is variable. Datum is sea level

— — — — DOWNDIP LIMIT

OUTCROP

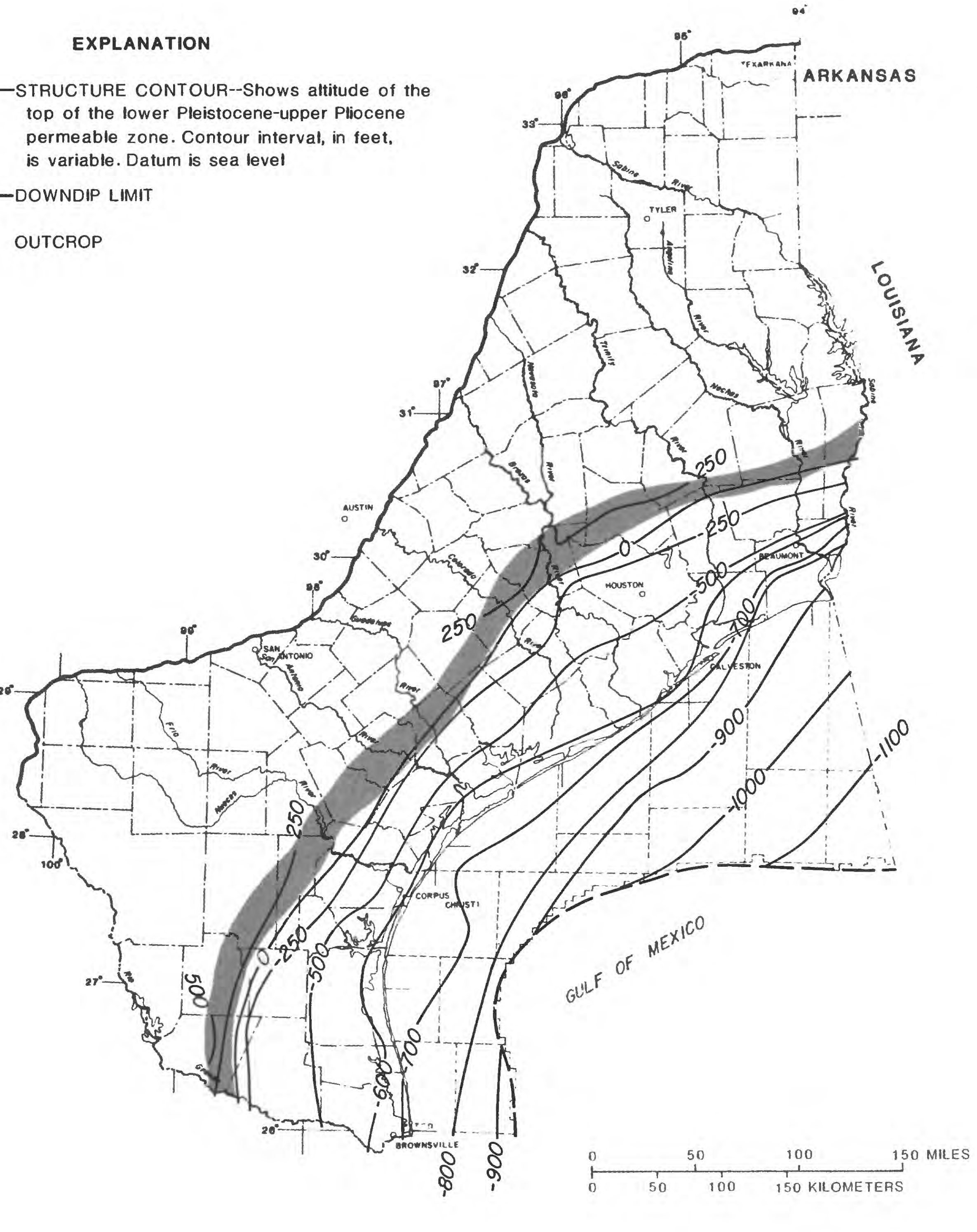


Figure 38.--Altitude of the top of the lower Pleistocene-upper Pliocene permeable zone.

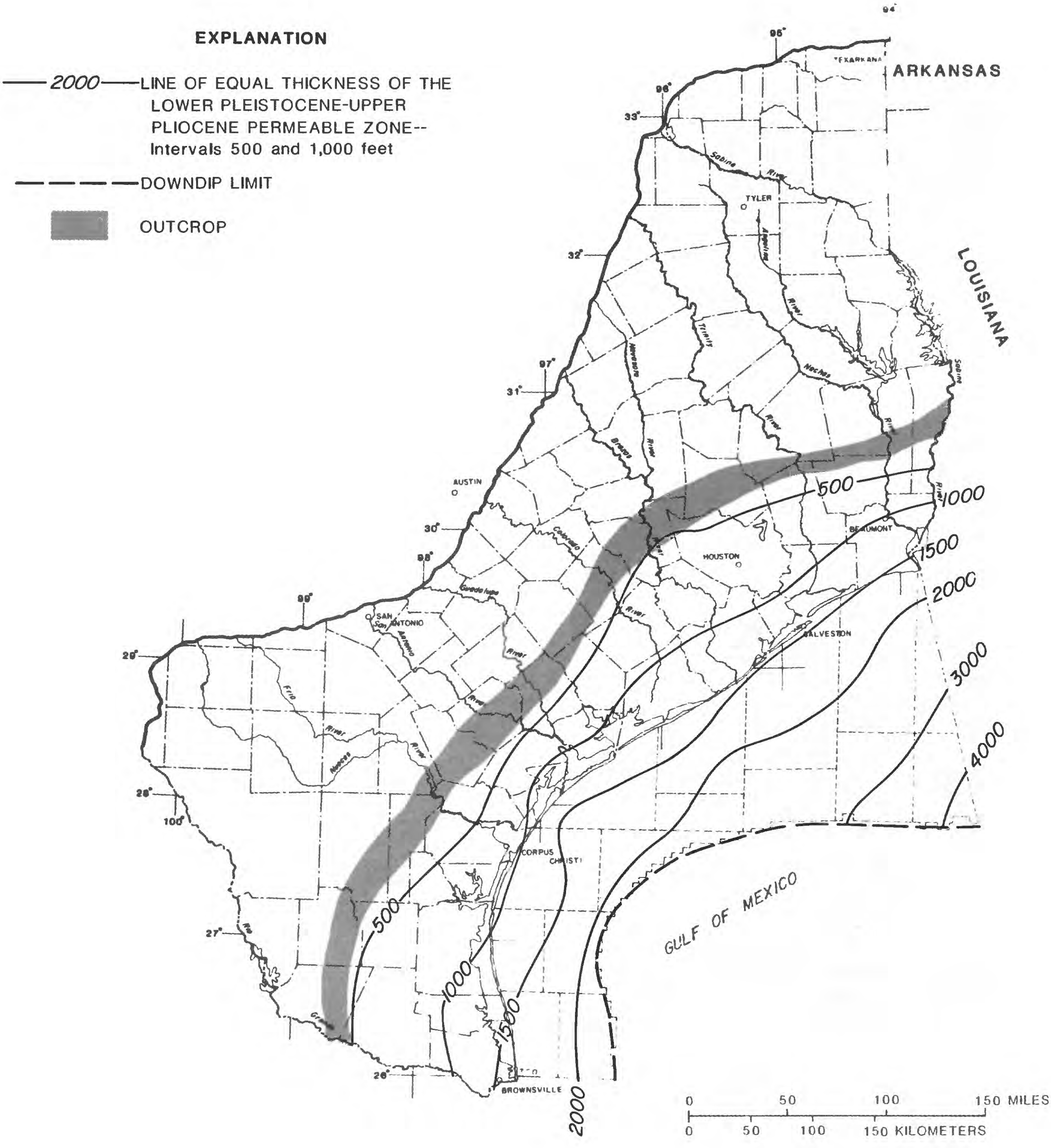


Figure 39.--Thickness of the lower Pleistocene-upper Pliocene permeable zone.

Holocene-upper Pleistocene Permeable Zone

The Holocene-upper Pleistocene permeable zone is the uppermost hydrogeologic unit in the coastal lowlands aquifer system. It overlies the lower Pleistocene-upper Pliocene permeable zone, and its top is land surface onshore and sea bottom in the Gulf of Mexico. The unit consists of Holocene and upper Pleistocene sands and clays (table 2). Locally, the unit may include Holocene alluvial deposits.

Since it is the surficial unit, the permeable zone has the largest outcrop area of all units in the Texas Gulf Coast aquifer systems (fig. 6). The altitude of the top of the unit ranges from about 350 ft above sea level in the west to more than 800 ft below sea level in downdip areas in the Gulf (fig. 40). Thickness of the unit ranges from 0 at the updip limit to more than 900 ft offshore in the east (fig. 41).

HYDRAULIC PROPERTIES AND WATER QUALITY

Important properties that govern rates of flow within and between hydrogeologic units are the horizontal and vertical hydraulic conductivities.

Horizontal Hydraulic Conductivity

Because of its capability of simulating flow in aquifers having water of varying density, the digital model requires that aquifer hydraulic conductivity and aquifer thickness be entered separately. Hydraulic conductivity for each aquifer and permeable zone in the Gulf Coast aquifer systems was estimated by analyzing and averaging hundreds of aquifer tests and specific-capacity data (A.K. Williamson and J.S. Weiss, U.S. Geological Survey, written commun., 1986). The estimates of hydraulic conductivities were derived from wells that were open only to the sand portions of an aquifer, as well as from wells open to both sand and clay portions.

No attempt was made to adjust hydraulic conductivity for variations in temperature and salinity, both of which generally increase with depth. According to A.K. Williamson (U.S. Geological Survey, written commun., 1986), a decrease in viscosity due to an increase in temperature tends to be offset by an increase in viscosity due to an increase in salinity. Whatever net effect remains is within the limits of accuracy of the estimate of hydraulic conductivity.

Hydraulic conductivity values for all aquifers and permeable zones are shown in table 3. They range from 15 cubic feet per square foot per day (reduced to ft/d) for the middle Wilcox aquifer to 170 ft/d for the Holocene-upper Pleistocene permeable zone. (Horizontal flow in confining units is considered insignificant; thus, horizontal hydraulic conductivity values are not applicable.)

Transmissivity, the hydraulic property of an aquifer that defines its potential to transmit water, is the product of hydraulic conductivity and aquifer thickness. The thickness of each aquifer and permeable zone that was described in detail in the preceding section is the total layer thickness,

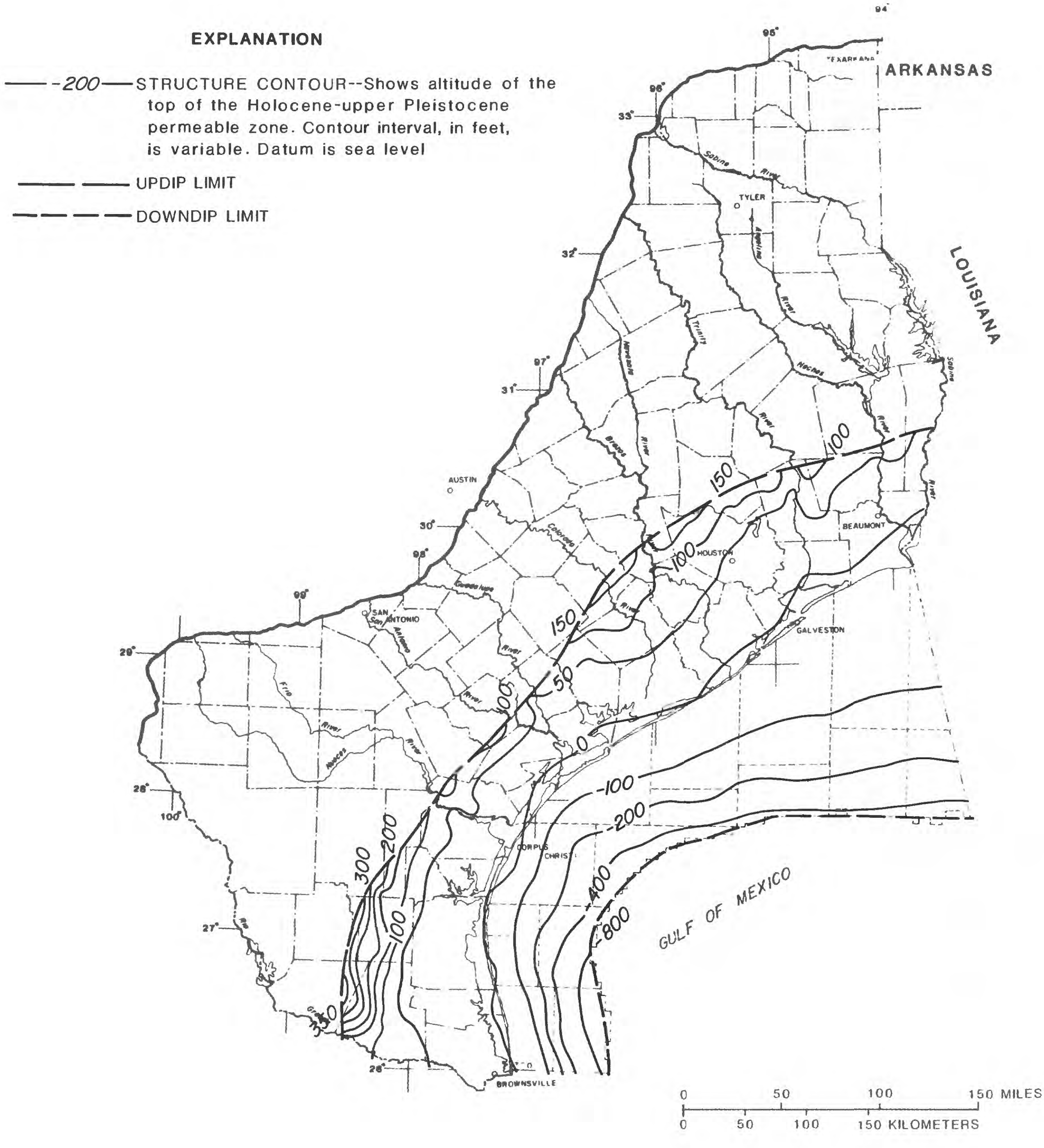


Figure 40.--Altitude of the top of the Holocene-upper Pleistocene permeable zone.

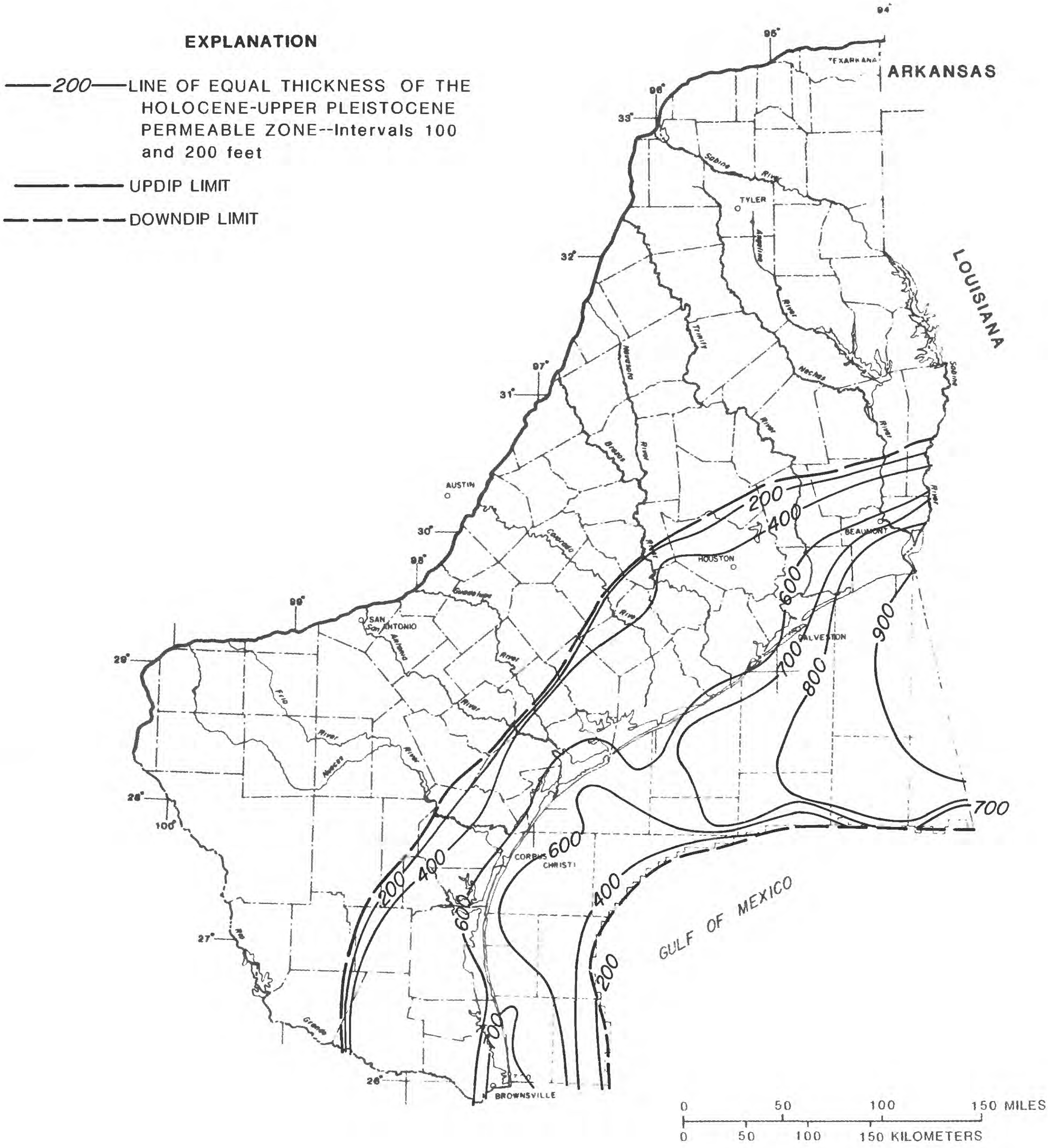


Figure 41.--Thickness of the Holocene-upper Pleistocene permeable zone.

Table 3.--Horizontal hydraulic conductivities and sand ratios of aquifer systems

Aquifer, permeable zone, and confining unit	Horizontal hydraulic conductivity (feet per day)	Sand ratio 1/			
		Maximum	Minimum	Mean	Standard deviation
Holocene-upper Pleistocene permeable zone	170	0.99	2/ 0.02	0.37	0.28
Lower Pleistocene-upper Pliocene permeable zone	20	.99	2/ .02	.34	.23
Lower Pliocene-upper Miocene permeable area	60	.99	2/ .03	.33	.16
Middle Miocene confining unit	--	.41	.00	.08	.05
Middle Miocene permeable zone	80	.88	2/ .02	.36	.17
Lower Miocene-upper Oligocene confining unit	--	.21	.00	.05	.04
Lower Miocene-upper Oligocene permeable zone	60	.99	.07	.42	.15
Vicksburg-Jackson confining unit	--	.32	.00	.03	.04
Upper Claiborne aquifer	50	.98	.16	.48	.15
Middle Claiborne confining unit	--	.26	.00	.02	.03
Middle Claiborne aquifer	55	.99	.16	.56	.20
Lower Claiborne confining unit	--	.41	.00	.04	.06
Lower Claiborne-upper Wilcox aquifer	40	.99	.18	.85	.12
Middle Wilcox aquifer	15	.97	.10	.55	.13

1/ Grid-block values
2/ Some original sand ratios were decreased during model calibration

including a significant amount of interbedded clays. It is assumed that the clays do not contribute to the transmissive property of an aquifer or permeable zone; thus, only the sand part of the layer thickness was used to compute transmissivity. In the electric-log interpretation in figure 4, the aquifer has a total thickness of 327 ft of which the cumulative sand thickness is 250 ft, or 76 percent. Thus, the transmissivity at this point is:

transmissivity = hydraulic conductivity x 0.76 x 327 ft.

The sand ratios were determined for aquifers, permeable zones, and confining units from borehole geophysical logs. Interpolation between data points provided sand ratios for model grid blocks. Statistical summaries of model grid-block values of sand ratios for aquifers, permeable zones, and confining units are shown in table 3. Maximum sand ratios for all aquifers and permeable zones range from 0.88 to 0.99, minimum ratios range from 0.02 to 0.18, and means range from 0.33 to 0.85. In contrast, maximum sand ratios for the confining units range from 0.21 to 0.41, minimum ratios are zero, and means range from 0.02 to 0.08. The sand ratios in table 3 reflect some downward adjustment of original values in the uppermost four permeable zones resulting from model calibration (to be discussed later).

Vertical Hydraulic Conductivity

Little confidence is placed in the determination of vertical hydraulic conductivity by field methods or by laboratory testing, especially for regional values of the property. The vertical hydraulic conductivity values in table 4 were derived through the calibration of a digital ground-water flow model, wherein flow across a confining unit is the product of the vertical hydraulic-head gradient, the area of the grid block, and the effective leakance. The vertical hydraulic conductivity of a unit divided by the unit's thickness is called leakance. Effective leakance is the harmonic mean of the leakances of the confining unit, the underlying aquifer, and the overlying aquifer.

Table 4 shows that vertical hydraulic conductivities of the aquifers and permeable zones are generally a few orders of magnitude less than the horizontal hydraulic conductivities of the aquifers and permeable zones (table 3). This is called anisotropy. The ratios of horizontal to vertical hydraulic conductivities range from 5,500 for the middle Claiborne aquifer to 600,000 for the lower Pliocene-upper Miocene permeable zone. Vertical conductivities of confining units are generally one or two orders of magnitude less than those of the aquifers and permeable zones. Vertical hydraulic conductivities range from 1×10^{-5} ft/d for a confining unit to 1×10^{-2} ft/d for four aquifers and permeable zones (table 4).

In the electric-log interpretation in figure 4, the confining unit has a total thickness of 330 ft of which the cumulative interbedded sand thickness is 85 ft, or 26 percent. The interbedded sands have relatively less resistance to vertical flow than do the clays. A formula was developed by the GCRASA staff (written commun., 1985) to increase vertical hydraulic conductivity as a function of sand percent. "CLAY" (table 4) is a factor that is used to increase the estimate of vertical hydraulic conductivity based on

Table 4.--Vertical hydraulic conductivities of aquifer systems and adjustment factors

Aquifer, permeable zone, and confining unit	Vertical hydraulic conductivity (foot per day)	Clay = $(\frac{1}{1 - \text{sand ratio}})$ 1/ Mean	Standard deviation
Holocene-upper Pliestocene permeable zone	1×10^{-2}	3.32	9.92
Lower Pleistocene-upper Pliocene permeable zone	1×10^{-3}	2.08	4.77
Lower Pliocene-upper Miocene permeable zone	1×10^{-4}	1.89	2.86
Middle Miocene confining unit	1×10^{-4}	1.09	.07
Middle Miocene permeable zone	1×10^{-3}	1.41	.93
Lower Miocene-upper Oligocene confining unit	1×10^{-4}	1.05	.05
Lower Miocene-upper Oligocene permeable area	1×10^{-3}	2.05	3.09
Vicksburg-Jackson confining unit	1×10^{-5}	1.03	.05
Upper Claiborne aquifer	1×10^{-2}	2.28	2.30
Middle Claiborne confining unit	1×10^{-4}	1.02	.04
Middle Claiborne aquifer	1×10^{-2}	4.47	9.74
Lower Claiborne confining unit	1×10^{-4}	1.04	.07
Lower Claiborne-upper Wilcox aquifer	1×10^{-2}	23.88	31.83
Middle Wilcox aquifer	1×10^{-3}	2.46	1.13

1/ Grid-block values

the interbedded sand. Thus, leakance at this point is:

leakance = (vertical hydraulic conductivity x CLAY) / 330 ft ,
where CLAY = 1 / (1-0.26) = 1.35.

Another way to view this adjustment is to say that the sand thickness is subtracted from the total thickness before it is divided into the hydraulic conductivity to compute leakance. Thus, leakance for both the confining units and aquifers is allowed to vary areally as a function of sand percent assigned to the model grid blocks. Means of the CLAY factors for the confining units range from 1.02 to 1.09 (table 4); those for the aquifers and permeable zones range from about 1.4 to 24.0.

Water Density

The density of water in the aquifers and permeable zones was calculated by using a linear relationship between density and dissolved-solids concentration (J.S. Weiss, U.S. Geological Survey, written commum., 1985). No corrections were made for the effects of temperature and pressure variations. Dissolved-solids concentrations were estimated from water resistivities calculated from the spontaneous potential curve of electric logs (Weiss, 1986). The method is valid for dissolved-solids concentrations greater than about 10,000 mg/L. Dissolved-solids concentrations (and thus densities) for less saline waters were determined by chemical analyses.

Dissolved-solids concentrations and densities generally increase with decreasing sand percentages in a downdip, Gulfward direction. The estimated densities of the water range from a minimum of 1.0 g/cm^3 (gram per cubic centimeter) where freshwater occurs, to a maximum of 1.171 g/cm^3 where concentrated brines (dissolved-solids concentration of 240,000 mg/L) occur in parts of the lower Pliocene-upper Miocene permeable zone (table 5). The density of water in confining units is assumed to be the same as in the subjacent aquifers and permeable zones. The mean density as shown in table 5 ranges from 1.004 g/cm^3 for the Holocene-upper Pleistocene permeable zone to 1.037 g/cm^3 for the middle Miocene permeable zone.

Freshwater-Saltwater Delineation

For this report, fresh, slightly saline, saline water, and brine are defined as having dissolved-solids concentrations of 0-1,000, 1,000-3,000, 3,000-100,000, and more than 100,000 mg/L, respectively. Water in the coastal uplands and coastal lowlands aquifer systems ranges from fresh to brine. Water with dissolved-solids concentrations greater than 3,000 mg/L is delineated for hydrogeologic units in section view in figures 7-9 and areally in figures 42 through 49. The delineation is made from a plot of grid-block values of dissolved-solids concentrations; thus, the values are mean values, and point values within a particular block could vary over some range. A dissolved-solids concentration of 3,000 mg/L was chosen for two major reasons: 1) the value represents a convenient break between water that is generally withdrawn for man's use and that which is not; 2) 3,000 mg/L is a useful criterion chosen for planning purposes by various State agencies.

Table 5.--Summary of estimated densities of water in the hydrogeologic units

Aquifer, permeable zone, and confining unit	Water density 1/ (grams per cubic centimeter) at atmospheric pressure, 20 °C		
	Maximum	Minimum	Mean
Holocene-upper Pleistocene permeable zone	1.037	1.000	1.004
Lower Pleistocene-upper Pliocene permeable zone	1.091	1.000	1.018
Lower Pliocene-upper Miocene permeable zone	1.171	1.000	1.033
Middle Miocene confining unit	1.146	1.000	1.037
Middle Miocene permeable zone	1.146	1.000	1.037
Lower Miocene-upper Oligocene confining unit	1.104	1.000	1.033
Lower Miocene-upper Oligocene permeable zone	1.104	1.000	1.033
Vicksburg-Jackson confining unit	1.076	1.000	1.020
Upper Claiborne aquifer	1.076	1.000	1.020
Middle Claiborne confining unit	1.066	1.000	1.013
Middle Claiborne aquifer	1.066	1.000	1.013
Lower Claiborne confining unit	1.079	1.000	1.006
Lower Claiborne-upper Wilcox aquifer	1.079	1.000	1.006
Middle Wilcox aquifer	1.075	1.000	1.016

1/ Grid-block values

Dissolved-solids concentrations generally increase with depth and in a downdip, Gulfward direction. Water with dissolved-solids concentrations less than 3,000 mg/L occurs in outcrop areas and extends downdip some distance before becoming more saline (figs. 7-9, 45-53). There is some variability in the distribution of freshwater and saltwater in the various aquifers. The quality of water is greatly affected by aquifer and confining-unit hydraulic conductivities and vertical and lateral hydraulic gradients. Of special note are the two aquifers that lie above and below the thick and effective Vicksburg-Jackson confining unit (figs. 48 and 49). The areas of these aquifers that have water with less than 3,000 mg/L dissolved solids are relatively small. Also, all aquifers of middle Claiborne or younger age have slightly saline water in some or all of their outcrop areas in and near the Rio Grande valley (figs. 6, 47-53). Speculation as to the source of the salinity includes low permeability of the aquifers and permeable zones in this area and a consequent incomplete flushing by freshwater.

PREDEVELOPMENT FLOW SYSTEM

This report deals only with the predevelopment flow system; the effects of man's development, such as ground-water withdrawals and the lowering of potentiometric surfaces, are not considered.

Conceptual Model

Water in the Texas Gulf Coast aquifer systems generally originates as precipitation that falls on the outcrops of the various hydrogeologic units. Much of the precipitation quickly runs into streams that drain into the Gulf of Mexico. A substantial amount of precipitation is returned to the atmosphere by evaporation and by plant transpiration. A small amount of the precipitation, on the order of a few inches per year, reaches the water table by downward percolation in topographically high parts of the outcrops. After reaching the water table, most of the water moves downgradient and is discharged in topographically low areas, still in the outcrop, in the form of evapotranspiration, seepage, and stream base flow. A smaller, but significant part of the water flows slowly downdip between overlying and underlying units until vertical head gradients cause upward or downward leakage into adjacent units.

A variation of the above conceptual model occurs in the southwestern part of the study area. Westward from a line through Corpus Christi and San Antonio, average annual precipitation ranges from about 30 to about 21 in. In this semiarid area, many of the streams are intermittent, and flow that does occur is often a source of recharge to the aquifers. Although ground-water discharges, such as springs, seeps, and stream baseflows are generally not visible, it is probable that a small, net ground-water discharge occurs in topographically low areas. The discharge is by evapotranspiration, with transpiration by phreatophytes, such as live oaks, pecans, salt cedars and mesquite, having a major role.

Digital Model

A numerical model developed by Kuiper (1985) was used to simulate the ground-water flow system in the study area. The model simulates variable-density ground-water flow in three dimensions. The ground-water density is variable in space, but is assumed to be constant in time. Horizontal and vertical flow is computed for aquifers and permeable zones, and vertical flow is computed for confining units. The model utilizes an integrated finite-difference grid, wherein the six-sided grid elements are rectangular when viewed from the vertical direction. The sides of the elements are vertical planes, but their top and bottom surfaces follow the curvature of the hydrogeologic units in the modeled area (Kuiper, 1985). The model has several solution methods for solving the approximating flow equations. The preconditioned conjugate gradient (PCG) method was selected because of its computational efficiency and thus because it saves valuable computer time. A technical explanation and discussion of the PCG method is in Kuiper (1981, 1985). See Kuiper (1985) for a complete documentation of the model, including detailed instructions for the use of the computer program.

Model Grid and Boundary Conditions

As explained in the "Method of Investigation" section of the "Introduction", hydrologic data are adapted for use in the model by a process known as discretization. For this purpose, a finite-difference grid was constructed (fig. 42). The grid consists of 106 rows and 77 columns. The rows and columns are uniformly spaced 5 mi apart; thus each grid element, or grid block, has an area of 25 mi^2. There are 15 layers representing a constant-head water table and 14 hydrogeologic units; the latter consist of 4 aquifers, 5 permeable zones, and 5 confining units. The modeled area extends beyond the study area to include parts of Louisiana and Mexico (fig. 42). The total extent of the modeled area is 149,000 mi^2.

The modeled area is bounded from below and on all four sides by a no-flow boundary. The eastern boundary is a row of the GCRASA regional grid selected to include the aquifer systems in Texas. The landward boundary represents the updip extent of the aquifer systems. The western and Gulfward boundaries are located where hydrologic data become sparse to nonexistent. The aquifer systems are bounded from below by the impermeable Midway confining unit or by the top of the geopressured zone. It is assumed that abnormally high pressures in the geopressured zone preclude the possibility of significant flow out of this zone. Finally, the top layer of grid blocks is a constant-head boundary that represents the water levels in the uppermost 100 ft of the exposed portions of the units. A perspective of the total system boundaries and individual layer boundaries is given in figure 43.

A ground-water flow model was constructed to identify areas of recharge and discharge within the aquifer systems, and to estimate rates of flow. Figure 43 shows a generalized section of the conceptual model of the aquifer systems, and how the component parts of the systems are represented in the digital model. Five types of boundary conditions are shown for the model: 1) the constant-head layer represents the water table in the outcrop area which is the driving force for the flow system; 2) the left edge of each layer is a no-flow boundary which represents the updip pinching-out of the units; 3)

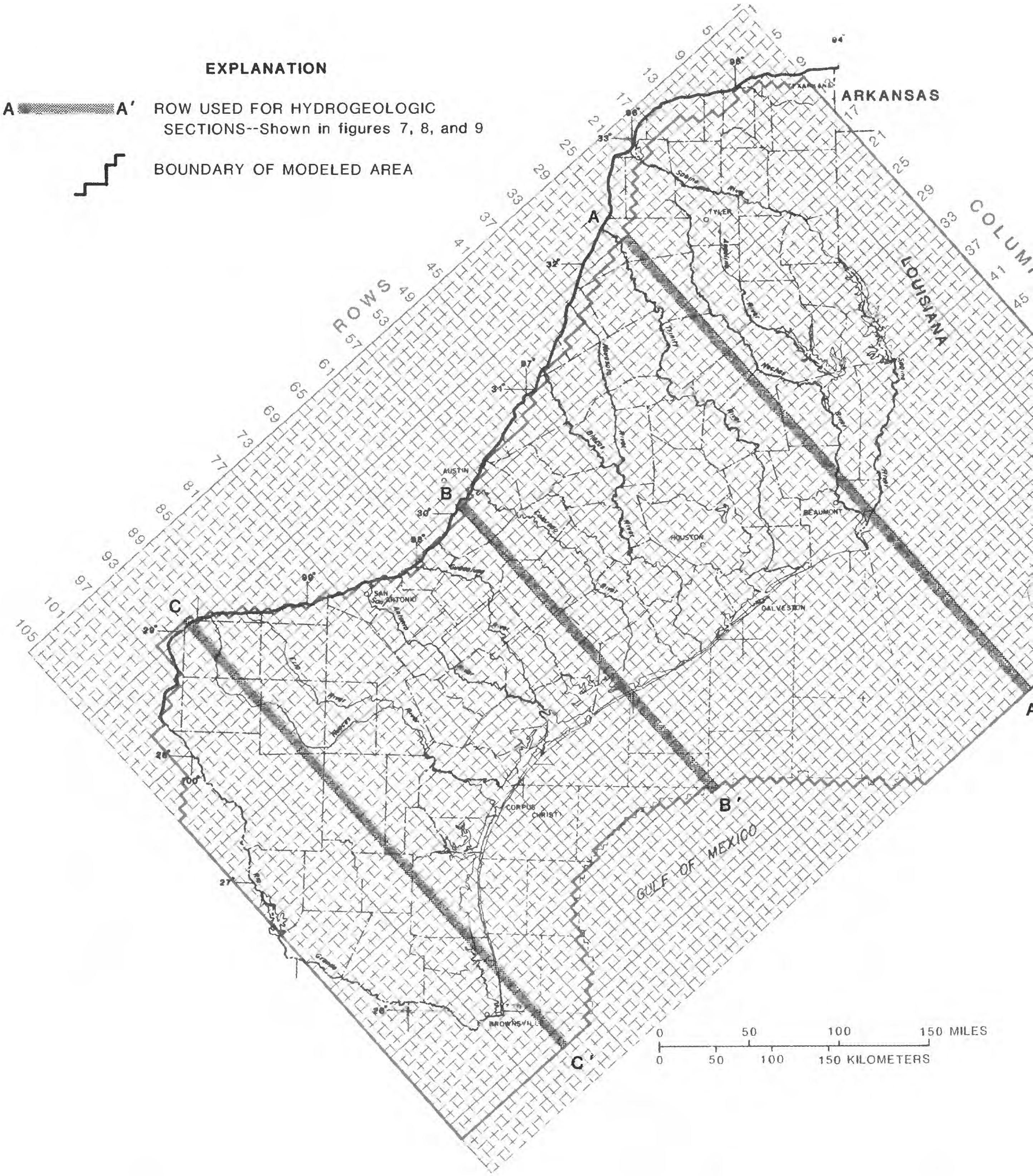


Figure 42.--Finite-difference grid superimposed on modeled area and study area.

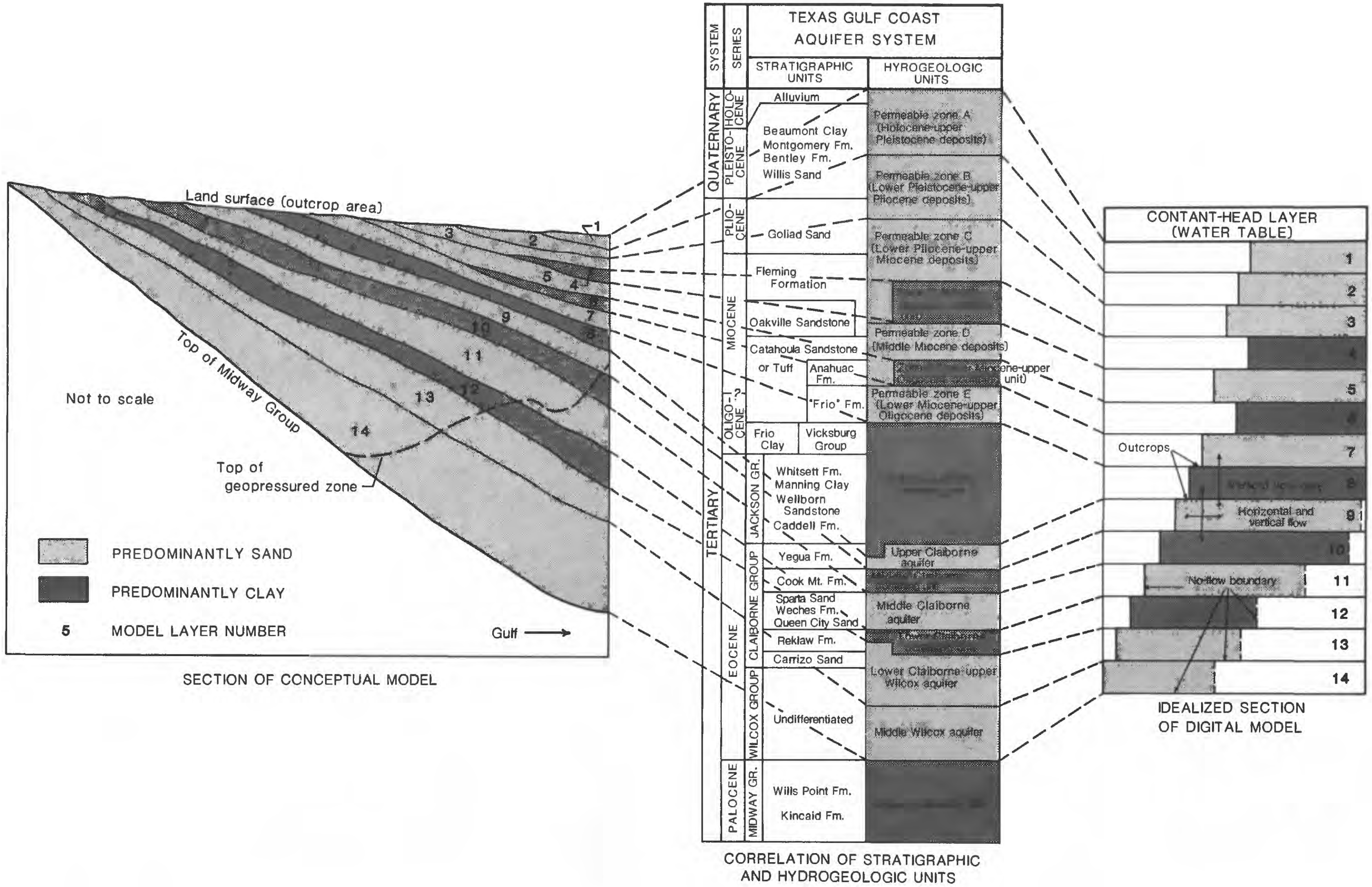


Figure 43.--Conceptual model of aquifer systems and generalized representation in the digital model

3) the right edge of each layer is a no-flow boundary where the top of the geopressured zone eliminates flow in the aquifer, or where the uppermost layers are truncated in the Gulf; 4) the bottom of a layer is a no-flow boundary where the unit is underlain by the top of the geopressured zone; and 5) the bottom of a layer is a no-flow boundary where the unit is underlain by the Midway confining unit rather than the top of the geopressured zone. Figure 43 also shows that the model computes vertical and horizontal flow for layers representing aquifers and permeable zones, but only vertical flow across confining units.

The altitude of the water table that functions as a constant-head boundary is shown in figure 44. It was constructed by interpolating between average water-table values for the 25-mi^2 grid blocks. The water-table values were estimated as follows (GCRASA staff, written commun., 1985): It was determined that most of the variation in water-table altitude is a function of the variation in land-surface altitudes. Many more detailed data are available for land-surface altitudes in comparison to water-table altitudes as determined from wells. A multiple linear regression of depth to water as a function of land-surface altitude and well depth (for wells less than 100 ft deep) was calculated, yielding the following equation: water-table altitude = 0.9585 x land-surface altitude. This equation was used to estimate water-table altitudes for the area.

The highest water table is in the northwest in Uvalde County and in eastern Webb County where the altitude exceeds 800 ft above sea level. The water table is generally less than 500 ft above sea level in the eastern and central areas. In the Gulf, the water table was assigned a positive value that is close to sea level. Onshore, the water-table layer was assigned a freshwater density of 1.0 g/cm^3 and a thickness of 1 ft; in the Gulf, the layer was assigned a seawater density of 1.025 g/cm^3 and a thickness equal to that of the ocean depth.

Hydrologic Data and Calibration

Each hydrogeologic unit, or model layer, has certain associated properties, such as thickness and hydraulic conductivity. These properties are entered into the model in the form of arrays, where an array contains data for each grid block in a particular model layer. The number of required arrays ranges from 1, for example the altitude of the bottom of the aquifer systems, to 15 which include data for the 4 aquifer layers, 5 permeable-zone layers, 5 confining-unit layers, and the water-table layer. Each array has a multiplier that permits flexibility in the format of the array data. The following table is a summary of the hydrologic data used in the ground-water flow model:

Element	Array multiplier	Number of arrays	Remarks
Water table	1.0	1	Constant-head layer
Initial heads	1.0	9	Heads not required for confining units
Bottom altitude of systems	1.0	1	--

EXPLANATION

——*400*——WATER-TABLE CONTOUR--Shows altitude of water table in outcrop area of the Texas Gulf Coast aquifer system. Contour intervals 25 feet (near coast) and 50 feet. Datum is sea level

— — —UPDIP LIMIT

— — — —DOWNDIP LIMIT

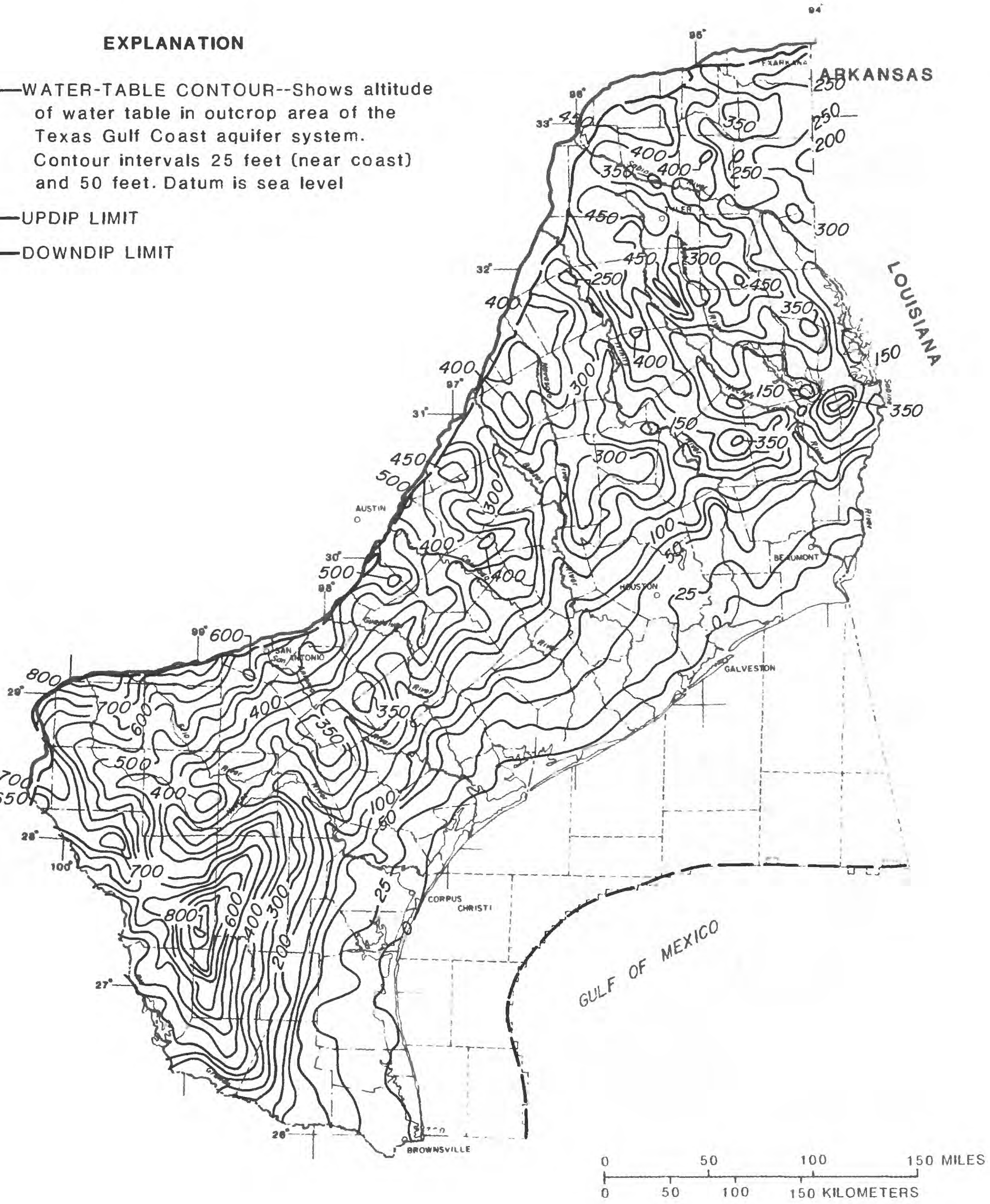


Figure 44.--Estimated altitude of the water table for the model constant-head boundary.

Element	Array multiplier	Number of arrays	Remarks
Density	0.000714	15	Multiplier converts value of dissolved solids to density
Thickness	1.0	15	--
Storage	0.0	10	Zero for steady-state simulations
Horizontal hydraulic conductivity	see table 3	10	Uniform value for water-table layer = 1.0 ft/d
Vertical hydraulic conductivity	see table 4	15	Uniform value for water-table layer = 1×10^{-5} ft/d
Pumpage	0.0	10	Set to zero for predevelopment

The above hydrologic data are generally initial estimates based upon existing geologic and hydrologic information, except for the vertical hydraulic conductivity values. Initial estimates of the vertical hydraulic conductivities were adjusted during the calibration of a larger, regional model of the entire GCRASA area. Grid spacing of the larger model was 30 mi and the blocks were spaced uniformly 30 mi apart. Calibration was accomplished by application of a parameter-estimation technique (L.K. Kuiper, U.S. Geological Survey, written commun., 1986), whereby the vertical hydraulic conductivities are changed until the differences between computed and measured aquifer heads are minimized.

The calibration resulted in a substantial increase of vertical hydraulic conductivities from initial estimates. The vertical hydraulic conductivity values determined by calibration are shown in table 4. Use of the vertical hydraulic conductivity values in the Texas Gulf Coast model resulted in a reasonably good comparison between computed and measured heads. However, some of the largest recharge rates in the model, as much as 10 in./yr in some grid blocks, were simulated for the uppermost four permeable zones in the southwest, from about Corpus Christi to the Rio Grande. Because this part of the study area has the least rainfall (fig. 3), it probably has less recharge. Less recharge can be simulated by the model by decreasing vertical and horizontal hydraulic conductivities in the appropriate layers. Justification for such decreases can be found in the literature. Wood (1956), in a study of the coastal lowlands permeable zones from Mexico to Louisiana, reported that the sediments in the southwestern part of the region are finer grained and less permeable than those in the northeastern part.

The calibration was modified in the area southwest of row 76 (fig. 42) by decreasing grid-block values of sand ratios and CLAY factors as follows:

	Property	
Layer 1/	Sand ratio	CLAY
5	Original/2	Original/10
3	Original/2	(no change)
2	Original/4	Original/10

Cont.

Property		
1	Original/4	Original/10

1/ See figure 43.

The modified calibration caused significant decreases in recharge and discharge rates, but no substantial difference in overall residual errors (computed heads minus measured heads).

Maps of the measured and simulated potentiometric surfaces of the aquifers are shown in figures 45-53. Water-level data were obtained from the files of the Texas Department of Water Resources and the U.S. Geological Survey, and from published and unpublished reports and maps. The measurements that were used to construct the maps were largely from the early 1900's to reflect predevelopment conditions; they were supplemented by more recent measurements in areas where water-level data were sparse and evidence indicated no significant effects of pumpage. Water-level measurements were available only in areas where the aquifers contained fresh or slightly saline water; thus they are not affected by density variations.

Potentiometric contours were drawn only where measurements provided a sufficient number of data points. Large variations were observed in plots of the measured water levels across short lateral distances. These were believed due to the different depths of penetration by the wells in the vertically anisotropic aquifers. Measurements made in fully penetrating wells are mean water levels for the aquifer; however, those measurements are generally not available because such wells are rare where the aquifers may be several hundreds of feet thick. For the evaluation, water levels from the deeper and shallower wells were averaged, and more weight was given to water levels from wells that were open to the middle parts of the aquifers. From the contour maps, average head values for each 25-mi^2 grid block were determined to compare with simulated heads.

Analysis of Calibration Residuals

The differences between simulated aquifer water levels and measured water levels are often referred to as residual errors, or simply residuals. Analysis of the magnitude and distribution of the residuals provides an assessment of the reasonableness and accuracy of the model calibration. Two forms of analysis are: 1) graphical, and 2) statistical. Graphical analyses are presented in figures 45-53, where simulated potentiometric surface contours are shown together with potentiometric surface contours based on measured water levels. The two sets of contours coexist only in the freshwater or slightly saline water zones where measured water levels were available. Simulated water levels in saline water and brine water areas are discussed in a later section of the report that deals with ground-water flow.

The illustrations supplement statistical analyses by displaying the areal distribution of residuals and the general directions of ground-water flow. The following conclusions about the relation between simulated and measured potentiometric surfaces are based on examination of figures 45-53: 1) the

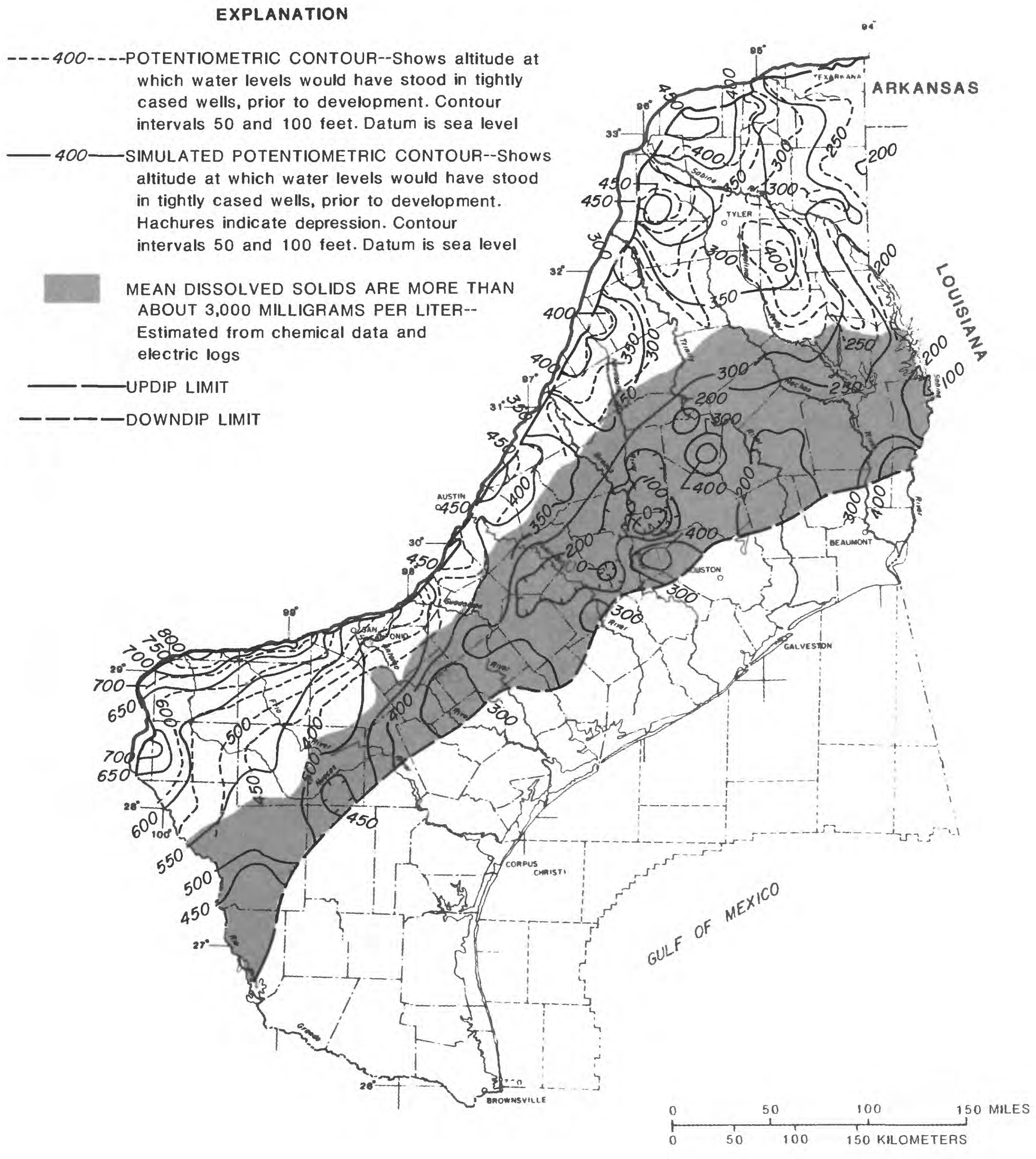


Figure 45.--Measured and simulated potentiometric surfaces of the middle Wilcox aquifer.

EXPLANATION

----*400*--- POTENTIOMETRIC CONTOUR--Shows altitude at which water levels would have stood in tightly cased wells, prior to development. Contour interval 50 feet. Datum is sea level

——*400*—— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude at which water levels would have stood in tightly cased wells, prior to development. Hachures indicate depression. Contour interval 50 feet. Datum is sea level

MEAN DISSOLVED SOLIDS ARE MORE THAN ABOUT 3,000 MILLIGRAMS PER LITER--Estimated from chemical data and electric logs

——— UPDIP LIMIT

— — — DOWNDIP LIMIT

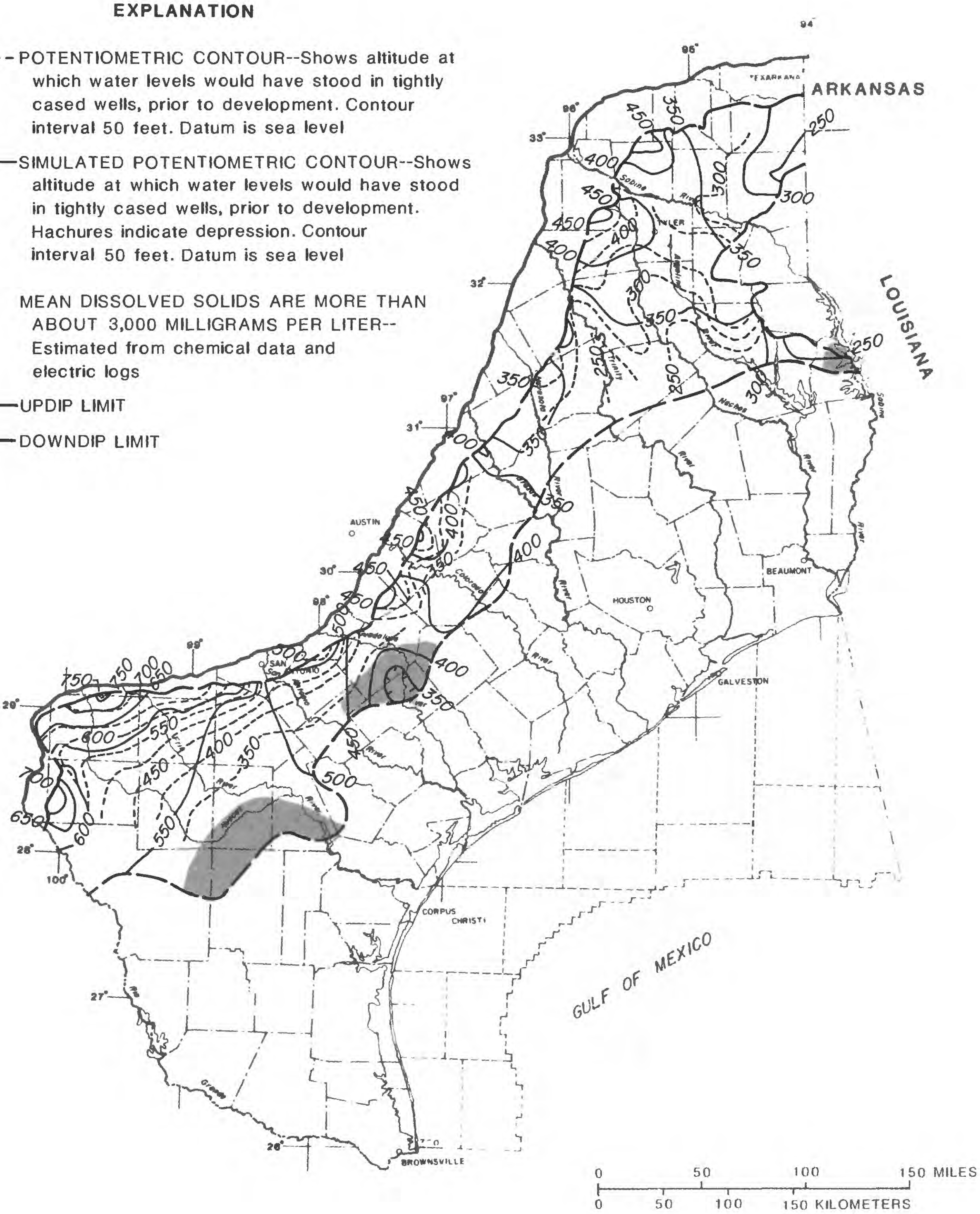


Figure 46.--Measured and simulated potentiometric surfaces of the lower Claiborne-upper Wilcox aquifer.

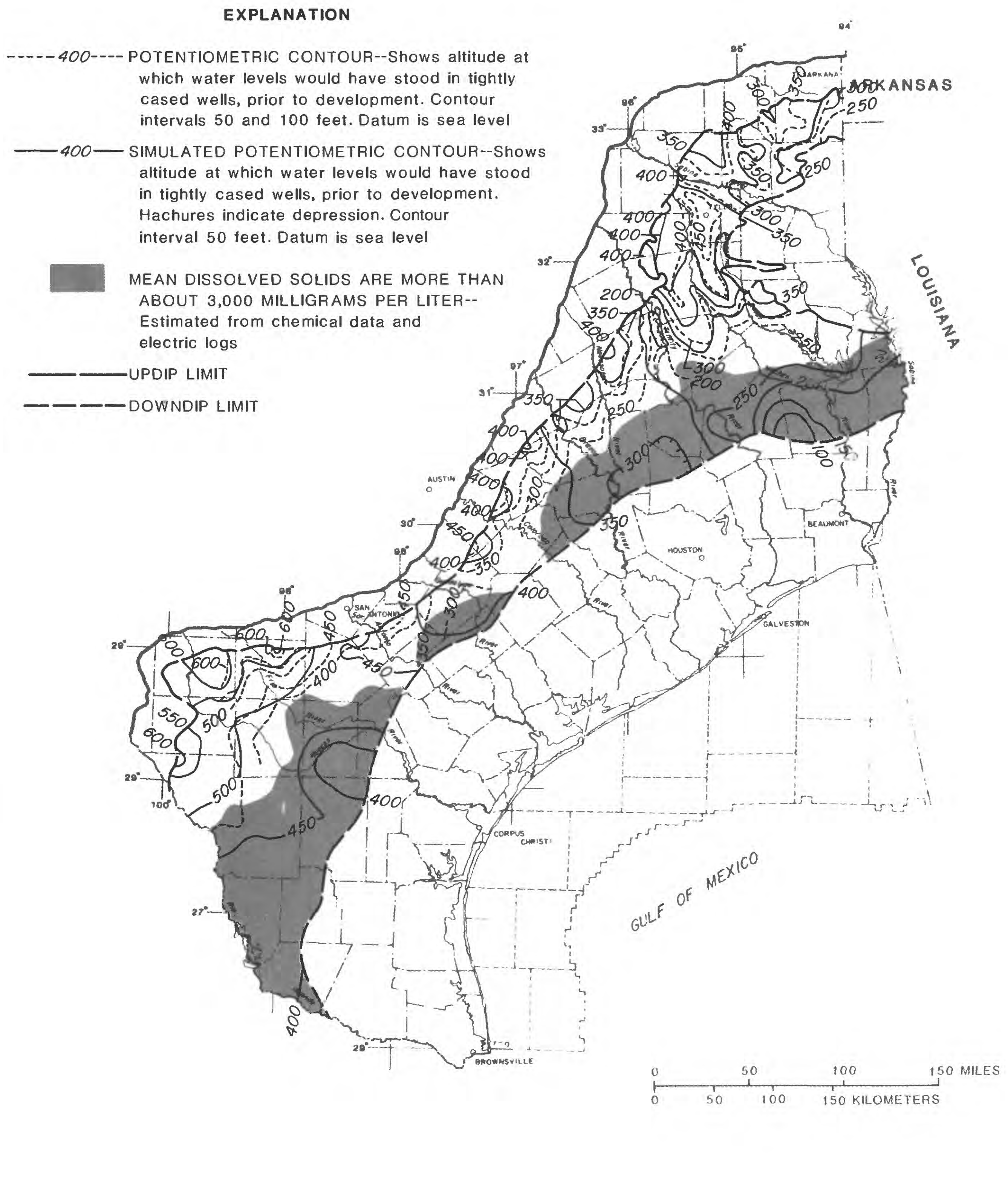


Figure 47.--Measured and simulated potentiometric surfaces of the middle Claiborne aquifer.

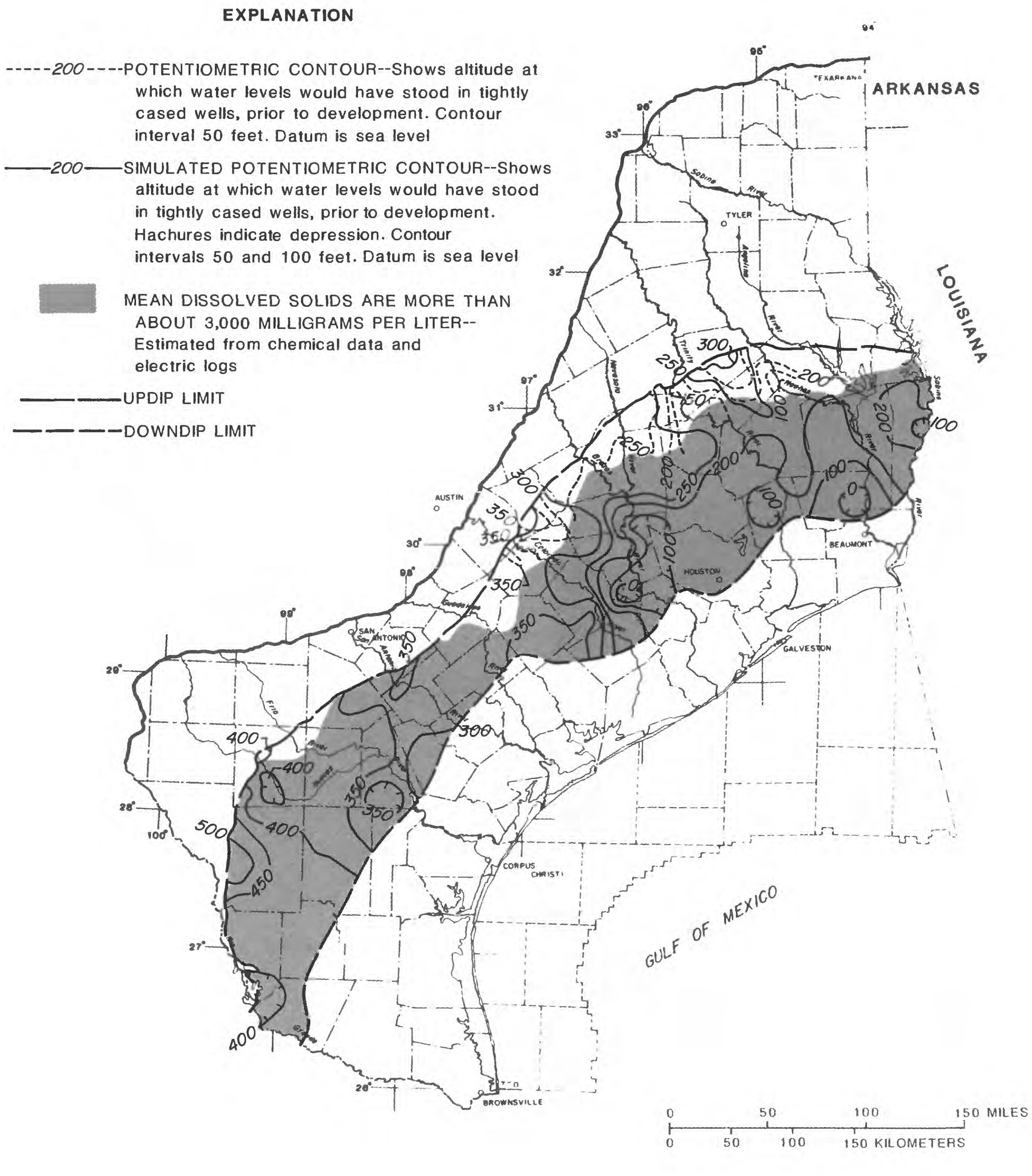


Figure 48.--Measured and simulated potentiometric surfaces of the upper Claiborne aquifer.

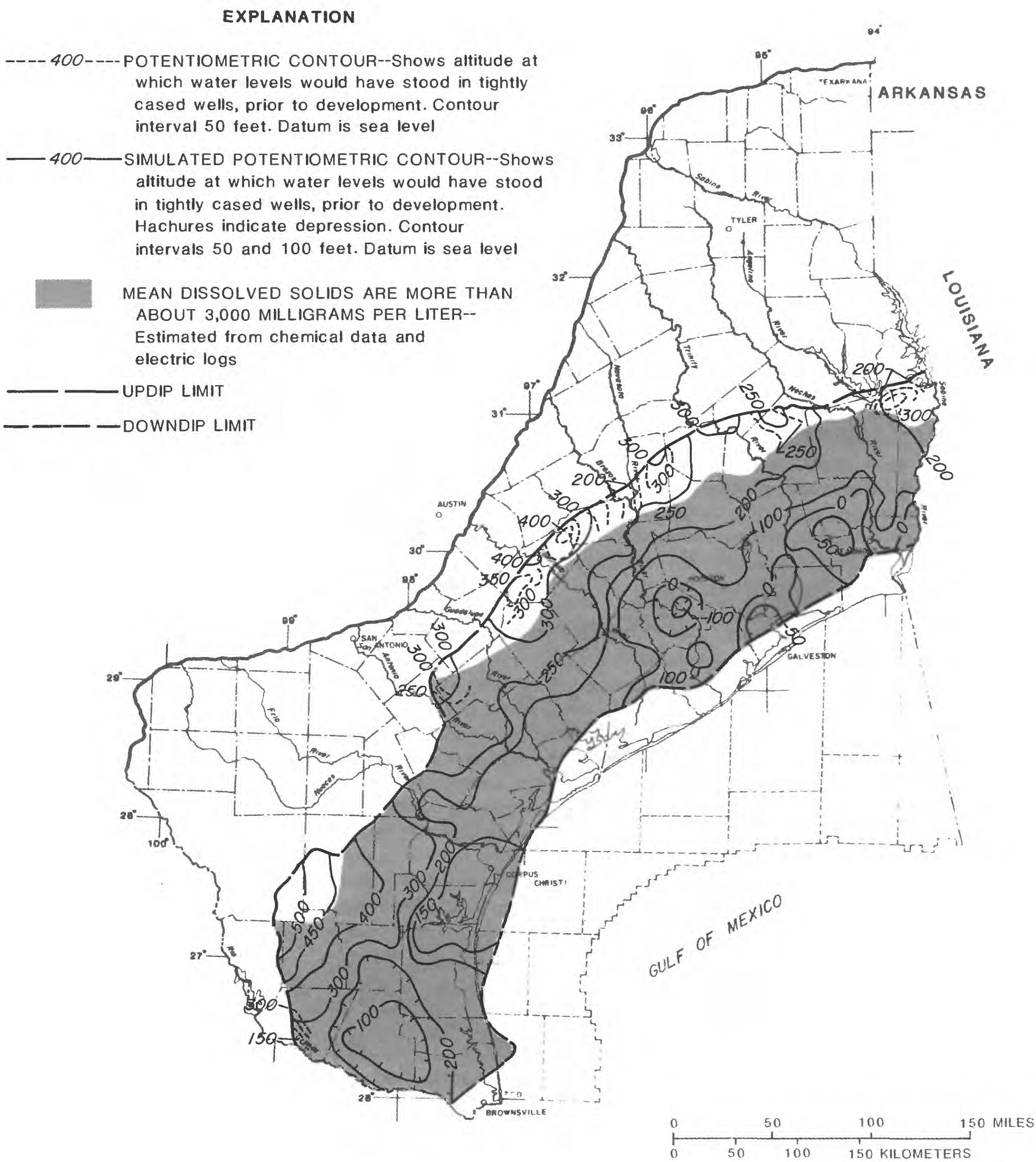


Figure 49.--Measured and simulated potentiometric surfaces of the lower Miocene-upper Oligocene permeable zone.

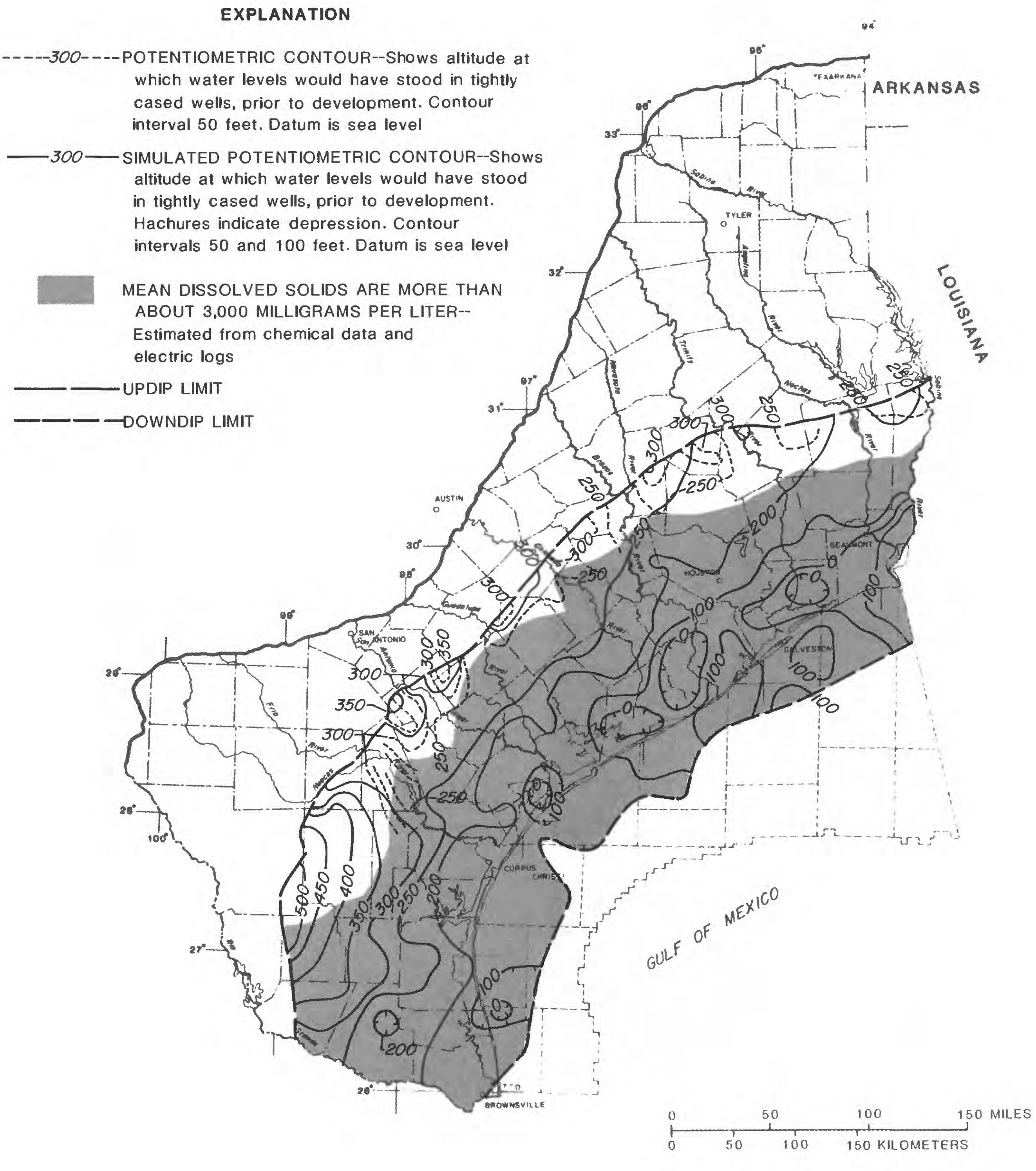


Figure 50.--Measured and simulated potentiometric surfaces of the middle Miocene permeable zone.

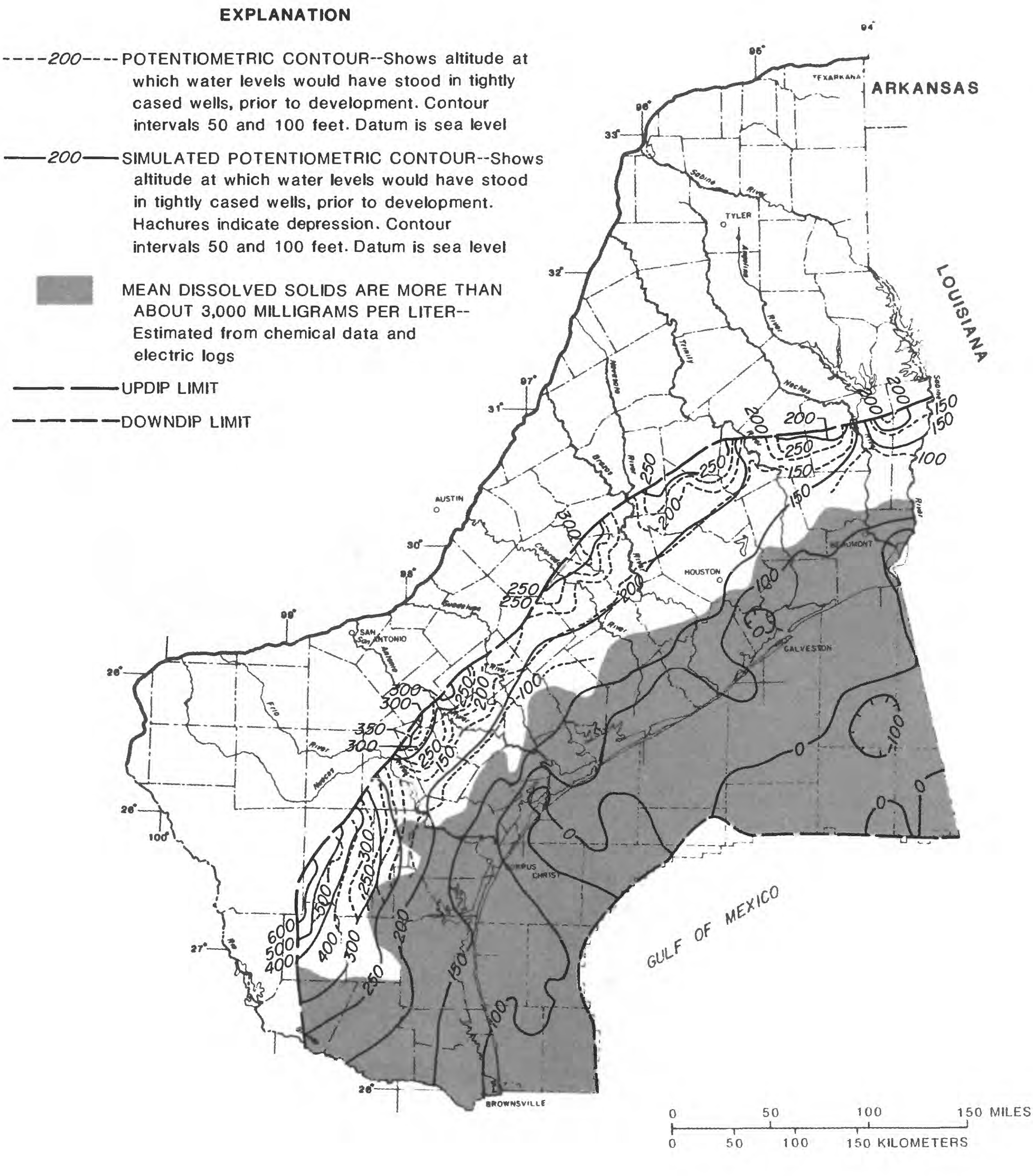


Figure 51.--Measured and simulated potentiometric surfaces of the lower Pliocene-upper Miocene permeable zone.

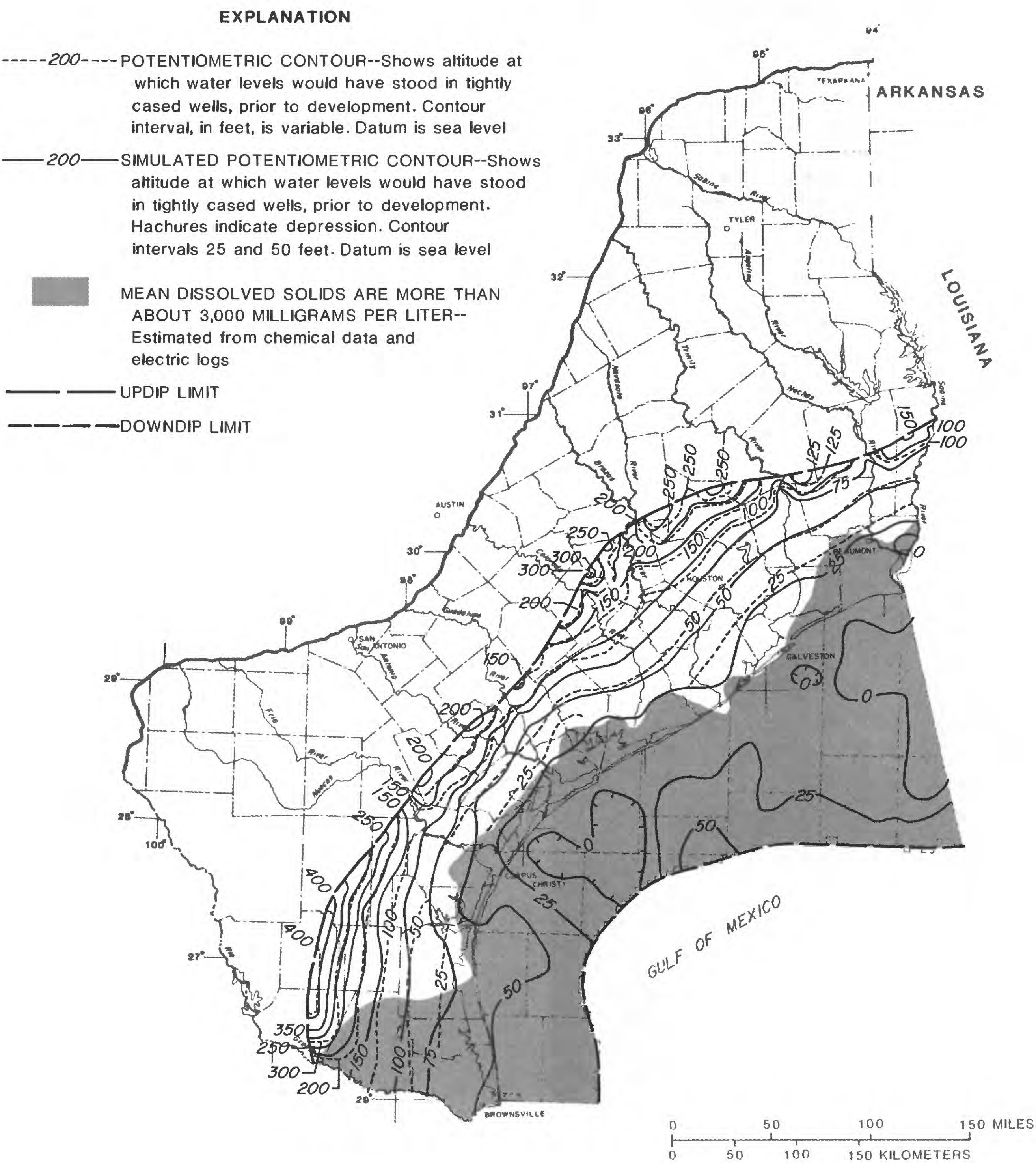


Figure 52.--Measured and simulated potentiometric surfaces of the lower Pleistocene-upper Pliocene permeable zone.

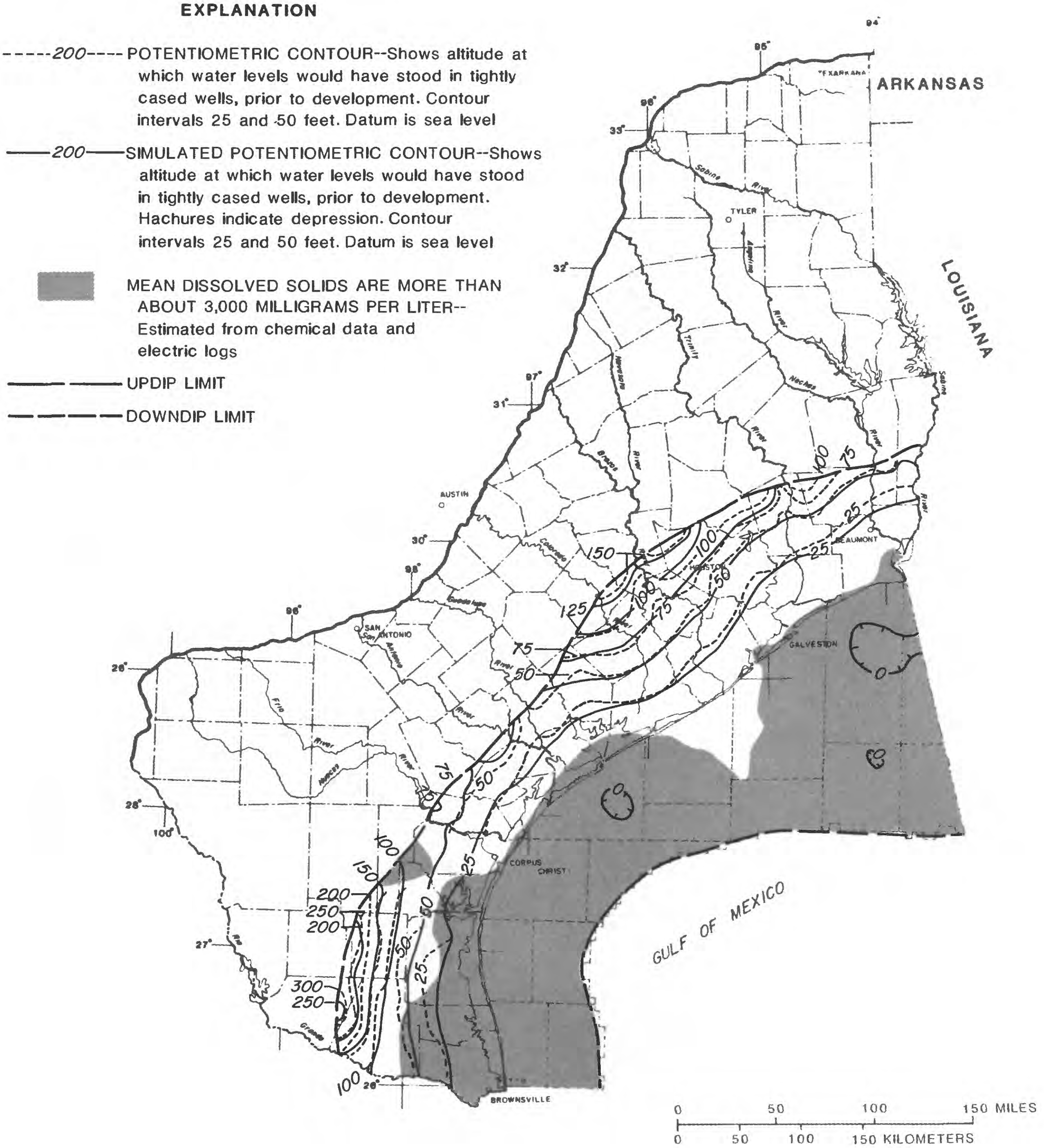


Figure 53.--Measured and simulated potentiometric surfaces of the Holocene-upper Pleistocene permeable zone.

general direction of ground-water flow in nearly all aquifers is reasonably well simulated; 2) simulated water levels approximate measured water levels in the outcrop areas better than in downdip areas; 3) residuals in downdip areas tend to be positive (simulated water levels are larger than measured water levels); and 4) the best agreements between simulated and measured water levels are for the uppermost two permeable zones, excluding the lower Miocene-upper Oligocene permeable zone for which only a limited comparison can be made because few measurements are available.

The good agreement between simulated and measured water levels in the outcrop areas, and particularly for the uppermost permeable zone which is exposed in its entirety, is because there is generally not a great difference in altitude between the measured mean artesian head and the water table. Because the aquifer and water table are in direct contact in the outcrop areas, with no intervening layers, vertical resistance is minimal and the constant-head water-table values are imposed on the aquifers.

A statistical analysis of the residuals is presented in table 6. Table 6 shows, for each aquifer and for the combined aquifers: 1) the number of grid blocks with measured water levels; 2) the minimum, maximum, mean, and standard deviation of the residuals; and 3) the mean of the absolute values of the residuals. Also shown are the rates of recharge and discharge in the outcrop areas; these will be referred to in the next section that deals with sensitivity analysis.

There are more than 4,500 grid blocks in the modeled area with measured water levels. The number of grid blocks with measured water levels ranges from 68 for the lower Miocene-upper Oligocene permeable zone to 991 for the middle Wilcox aquifer. Residuals range from a minimum value of -134 ft for the middle Miocene permeable zone to a maximum value of 201 ft for the lower Claiborne-upper Wilcox aquifer. The lower Claiborne-upper Wilcox aquifer has the largest residuals of all the aquifers and permeable zones, with a standard deviation of 53 ft and a mean of the absolute values of the residuals of 56 ft. The Holocene-upper Pleistocene permeable zone has the smallest residuals, with a standard deviation of 13 ft and a mean of the absolute values of the residuals of 8 ft. For the combined aquifers and permeable zones, the standard deviation is 39 ft and the mean of the absolute values of the residuals is 30 ft.

Sensitivity Analysis

The calibrated values of vertical and horizontal hydraulic conductivities are neither uniquely determined nor free from error. In order to test the sensitivity of the model to changes in the calibrated values of the hydraulic conductivities, four steady-state model runs were made with altered values of hydraulic conductivities. In the first run, the horizontal hydraulic conductivities of all aquifers and permeable zones were increased by 50 percent, and in the second run the conductivities were decreased by 50 percent. In the third run, the vertical hydraulic conductivities of all layers (water table, aquifers, permeable zones, and confining units) were increased by a factor of 10, and in the fourth run the conductivities were decreased by a factor of 10. The changes for the four runs are summarized in the following table:

Table 6.--Analysis of residuals for model calibration run

[ft, foot; ft^3/d, cubic foot per day]

Aquifer and permeable zone	Total grid blocks with measured heads	Mean of residuals (ft)	Minimum residual (ft)	Maximum residual (ft)	Standard deviation of residuals (ft)	Mean of absolute values of residuals (ft)	Total recharge (+) and discharge (-) in outcrop areas (10^6 ft^3/d)1/
All	4,537	19	-134	201	39	30	269 -269
Holocene-upper Pleistocene	638	-1	-70	31	13	8	61 -104
Lower Pleistocene-upper Pliocene	858	6	-60	66	20	15	16 -7
Lower Pliocene-upper Miocene	441	30	-129	147	45	46	19 -5
Middle Miocene	261	5	-134	141	45	36	25 -13
Lower Miocene-upper Oligocene	68	-4	-71	81	27	21	16 -8
Upper Claiborne	137	33	-29	155	39	36	22 1/ -32
Middle Claiborne	548	19	-48	136	37	31	65 1/ -65
Lower Claiborne-upper Wilcox	595	52	-59	201	53	56	27 1/ -14
Middle Wilcox	991	24	-62	150	35	33	18 -21

1/ Includes flow through outcrop of superjacent confining unit

Run	Property change
1	Horizontal Hydraulic conductivities (Kh's) of all aquifers and permeable zones = calibrated Kh's x 1.5
2	Horizontal hydraulic conductivities (Kh's) of all aquifers and permeable zones = calibrated Kh's x 0.5
3	Vertical hydraulic conductivities (Kv's) of all layers = calibrated Kv's x 10
4	Vertical hydraulic conductivities (Kv's) of all layers = calibrated Kv's x 0.1

Each change was uniform over the modeled area. When each property value was changed for a model run, all other values remained unchanged from their calibrated values.

Each sensitivity run is evaluated by: 1) showing the change in water levels resulting from changes in the conductivities for each aquifer and permeable zone in the hydrogeologic sections in figures 7-9 (model rows 27, 60, and 91); 2) statistically analyzing the new residuals for comparison with the calibration residuals; and 3) computing new rates of recharge and discharge in outcrop areas for comparison with rates from the calibrated model.

For the first sensitivity run, the horizontal hydraulic conductivities of the aquifers and permeable zones were increased by 50 percent. The changes in water levels at cross sections located along three model rows (fig. 42) are shown in figure 54. A maximum decrease in water level of 22 ft occurred in the outcrop of the middle Miocene permeable zone in row 91, and a maximum increase in water level of 17 ft occurred in the lower Pliocene-upper Miocene permeable zone at the farthest downdip point in row 91. The magnitude and pattern of water-level changes vary greatly with aquifer and with row location. However, a pattern that frequently occurs is one in which there is a decrease in water level in the outcrops and an increase in water-level downdip. In those areas where there were water level rises in the outcrop, the rises were in topographically low areas, such as the bottoms or sides of stream valleys.

The flattening of the potentiometric surfaces is accompanied by an increase in flow rates, but the increase is far less than the 50-percent increase for hydraulic conductivity. Since the flow rates increase less than 50 percent, Darcy's law implies that there would be a decrease in hydraulic gradients. This conclusion is similar to that of Baker (1986, p. 58), who performed a sensitivity analysis for a model of the Jasper aquifer using a constant recharge rate.

Although there were substantial decreases and increases in water levels in some aquifers at some locations, the statistical analysis of the new residuals (table 7) is similar to that of the calibration residuals (table 6); means and standard deviations are generally 2 ft larger. The change in recharge and discharge rates in outcrop areas ranges from no change in the lower Claiborne-upper Wilcox aquifer to a 50-percent increase in recharge for the middle Wilcox aquifer (table 7). For the combined aquifers and permeable

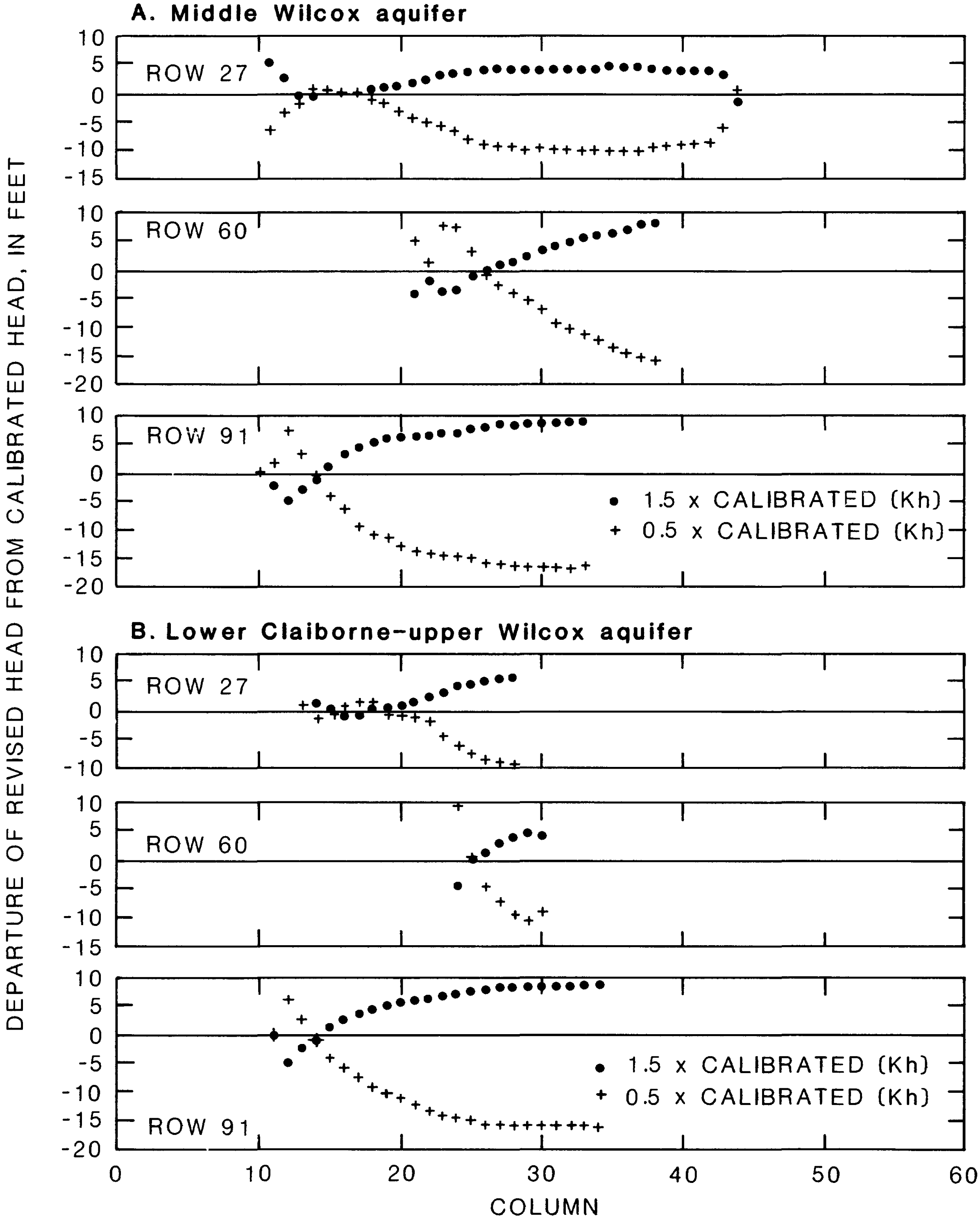
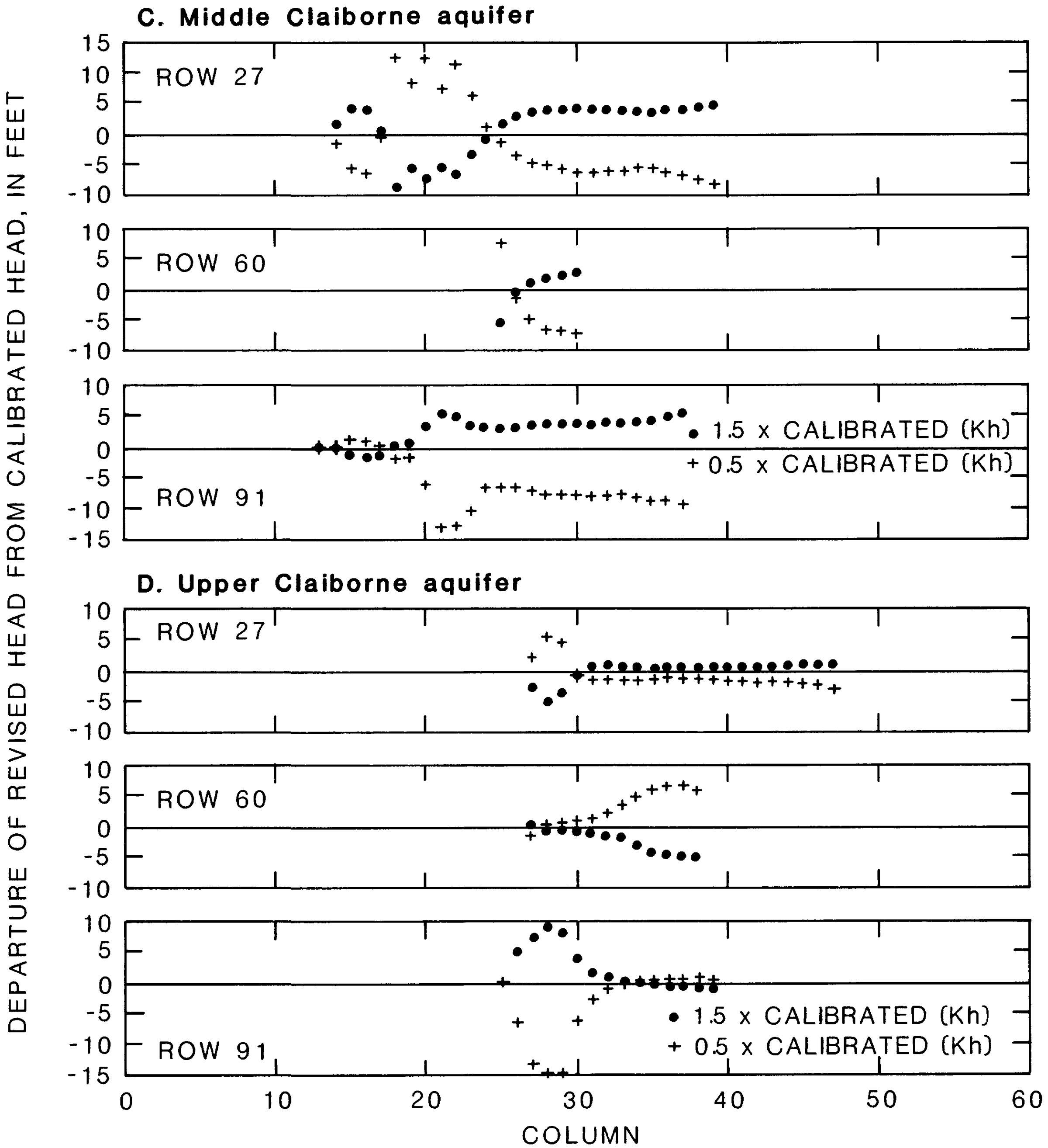


Figure 54.--Sensitivity of simulated heads to change in horizontal hydraulic conductivity (Kh) for the:



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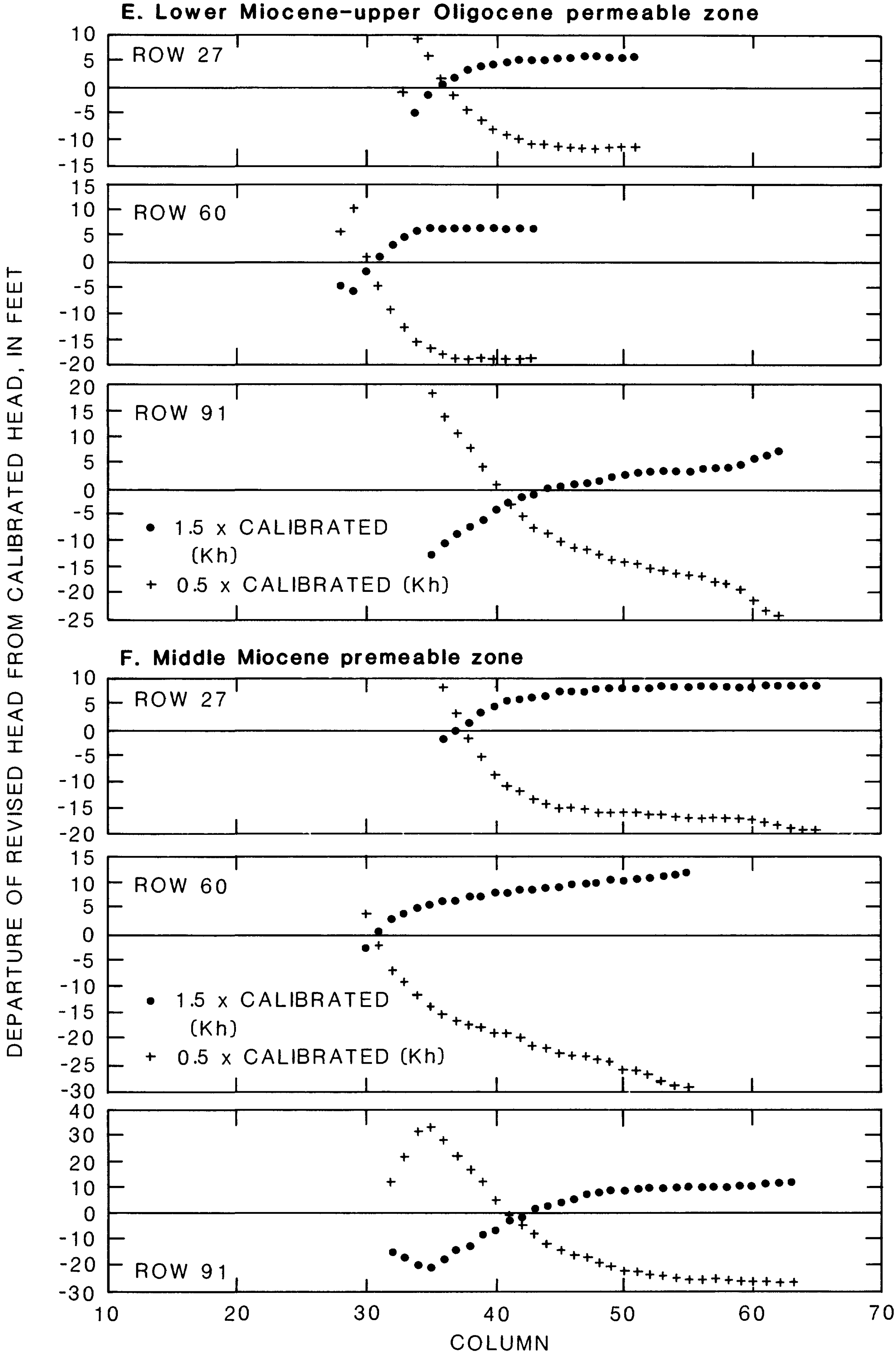
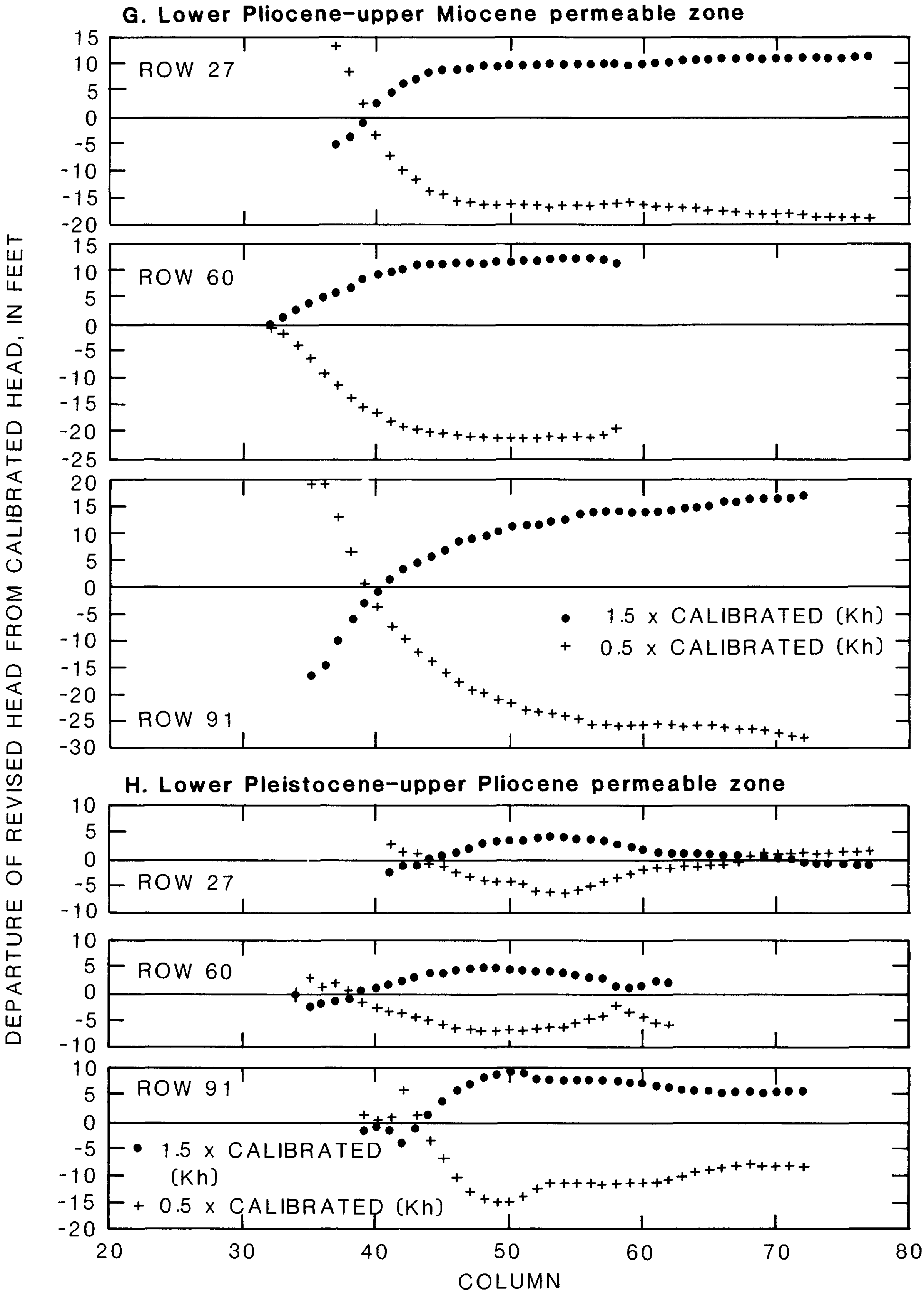


Figure 54.--Continued



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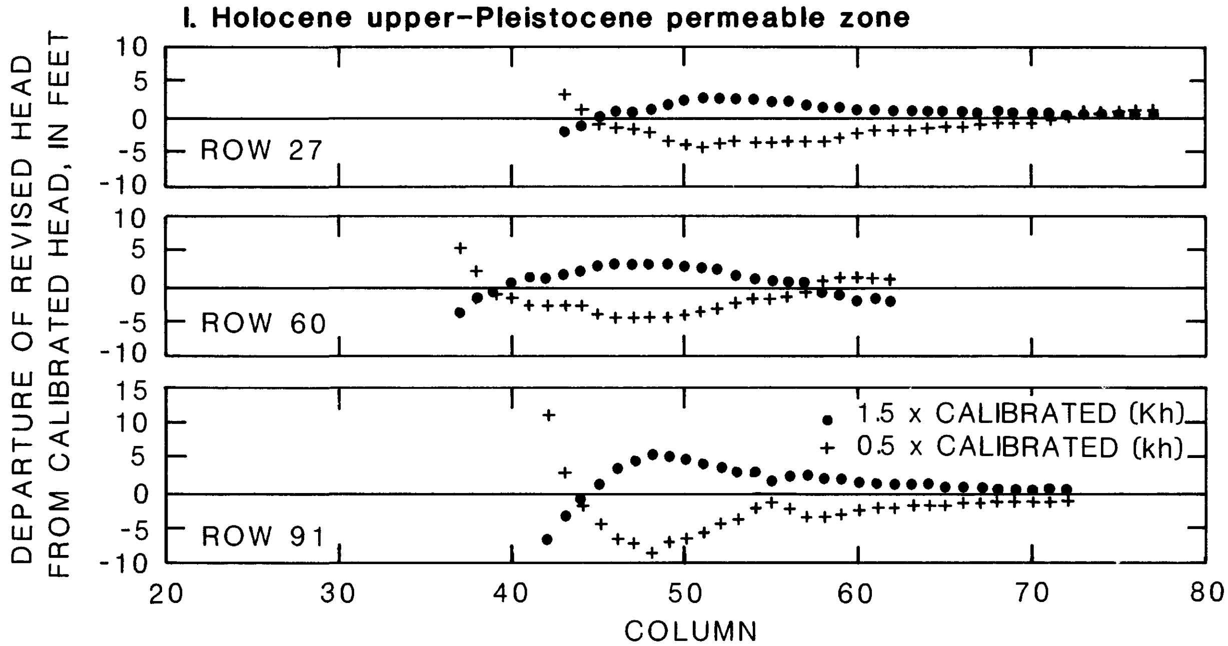


Figure 54.--Continued

Table 7.--Sensitivity of model to 50 percent increase in horizontal hydraulic conductivity of all aquifers and permeable zones

[ft, foot; ft^3/d, cubic foot per day]

Aquifer and permeable zone	Total grid blocks with measured heads	Mean of residuals (ft)	Minimum residual (ft)	Maximum residual (ft)	Standard deviation of residuals (ft)	Mean of absolute values of residuals (ft)	Total recharge (+) and discharge (-) in outcrop areas (10^6 ft^3/d)1/
All	4,537	20	-145	209	42	32	316 -316
Holocene-upper Pleistocene	638	-1	-90	36	16	10	71 -125
Lower Pleistocene-upper Pliocene	858	7	-61	74	23	17	22 -8
Lower Pliocene-upper Miocene	441	30	-145	155	49	49	23 -5
Middle Miocene	261	4	-136	143	47	37	27 -14
Lower Miocene-Upper Oligocene	68	-6	-75	78	28	23	19 -10
Upper Claiborne	137	34	-31	157	41	38	25 1/ -37
Middle Claiborne	548	20	-48	140	39	33	75 1/ -78
Lower Claiborne-upper Wilcox	595	53	-64	209	55	59	27 1/ -14
Middle Wilcox	991	24	-67	156	37	34	27 -25

1/ Includes flow through outcrop of superjacent confining unit

zones, there is a 17.5-percent increase in the rates of recharge and discharge from the calibration rates.

A 50-percent decrease in horizontal hydraulic conductivities in the second simulation resulted in the water-level change patterns in all aquifers and permeable zones being nearly mirror images of the patterns that resulted from the increase in conductivities (fig. 54). The maximum decrease in water level of 29 ft occurred in the middle Miocene permeable zone at the farthest downdip point in row 60 (fig. 54f). The maximum increase in water level of 32 ft occurred in the outcrop area of the middle Miocene permeable zone in row 91 (fig. 54f). Water-level changes along the cross sections indicate a greater sensitivity of the model to a decrease in conductivities compared to an increase. The relative sensitivity is verified by the statistical analysis given in table 8, which shows that standard deviations and means decrease to a somewhat greater extent than they increase in the first sensitivity run. The decreased residuals produced by the decreased conductivities resulted mainly from the consistent and rather large decrease in water levels in downdip areas, which compared better to the measured water levels. The decreased conductivities also produced a greater change in rates of recharge and discharge than did the increased conductivities. For the combined aquifers and permeable zones, there was a 26-percent decrease in the rates of recharge and discharge in the outcrop areas (table 8).

The vertical hydraulic conductivities of all layers, including the constant-head layer, aquifers, permeable zones, and confining units were increased tenfold for the third sensitivity run. The water-level changes along the three cross sections are shown in figure 55. As with the changed horizontal hydraulic conductivities, there is a large variation in the magnitude and pattern of the water-level changes, and also a frequently occurring pattern. Unlike the response produced by increased horizontal conductivities, increased vertical conductivities produced an increase in water levels in the outcrops and a decrease in water level downdip.

The model was considerably more sensitive to the 1,000-percent increase in vertical hydraulic conductivity than to the 50-percent increase in horizontal conductivity. The simulation resulted in a maximum decrease in water level of 128 ft in the lower Miocene-upper Oligocene permeable zone at the farthest point downdip in row 91 (fig. 55e). The maximum increase in water level was 94 ft in the outcrop area of the middle Miocene permeable zone in row 91 (fig. 55f). The statistical analysis of the residuals showed a large improvement for every aquifer and permeable zone (table 9). For the combined aquifers and permeable zones, the standard deviation of the residuals decreased to 29 ft from the calibrated value of 39 ft, and the mean of the absolute values of the residuals decreased from 30 to 23 ft. However, there were considerable increases in rates of recharge and discharge in the outcrop areas. The rate for the combined aquifers and permeable zones was 878 million ft^3/d, more than three times the calibrated rate. The rates were mapped and examined, and were found to be unrealistically large and unacceptable.

The vertical hydraulic conductivities of all layers were decreased by a factor of 10 for the fourth sensitivity simulation. Similar to the first two sensitivity simulations, the water-level change patterns tended to be mirror images of the patterns that resulted from the increase in vertical conductivities (fig. 55). The maximum decrease in water level of 147 ft

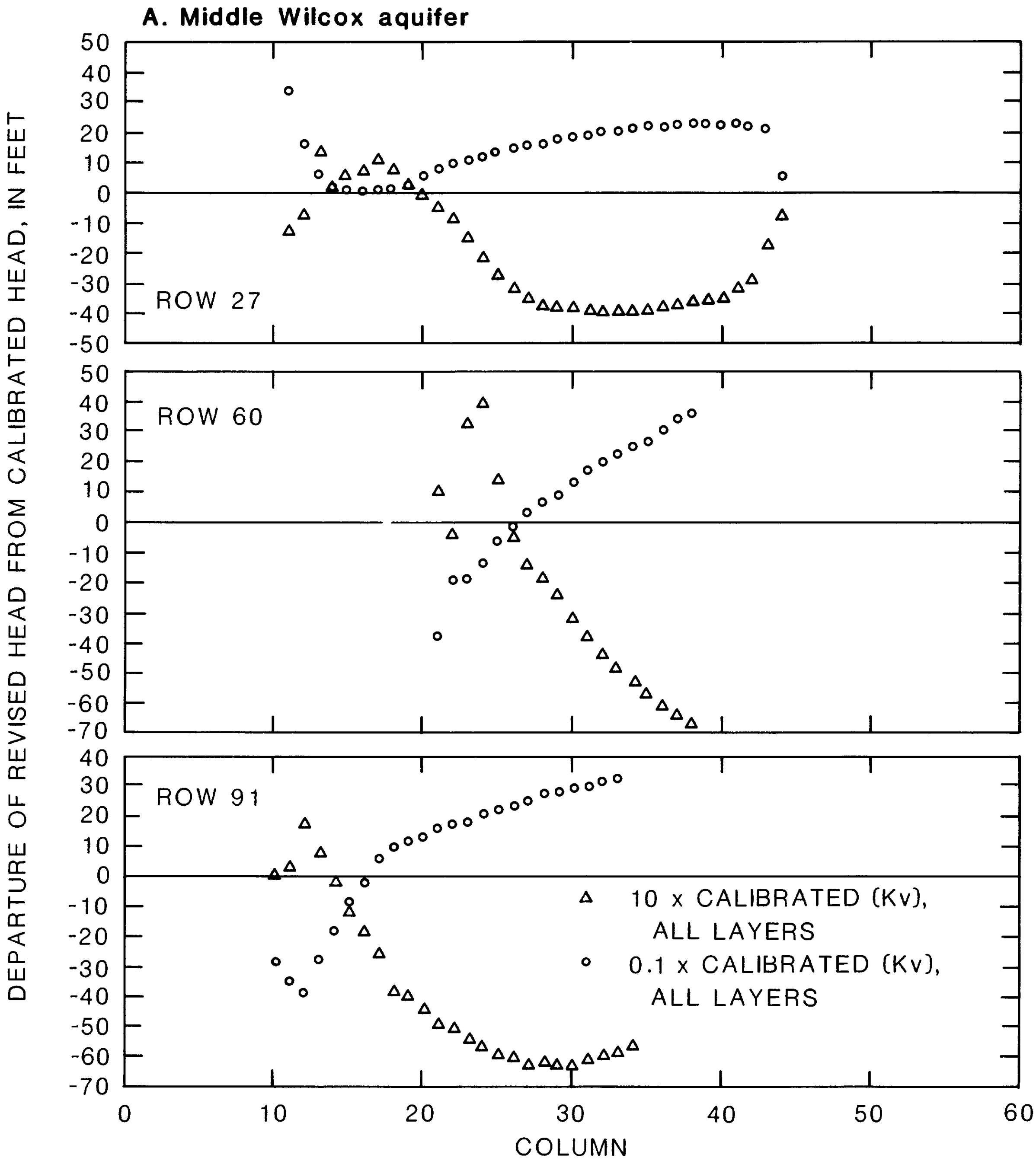
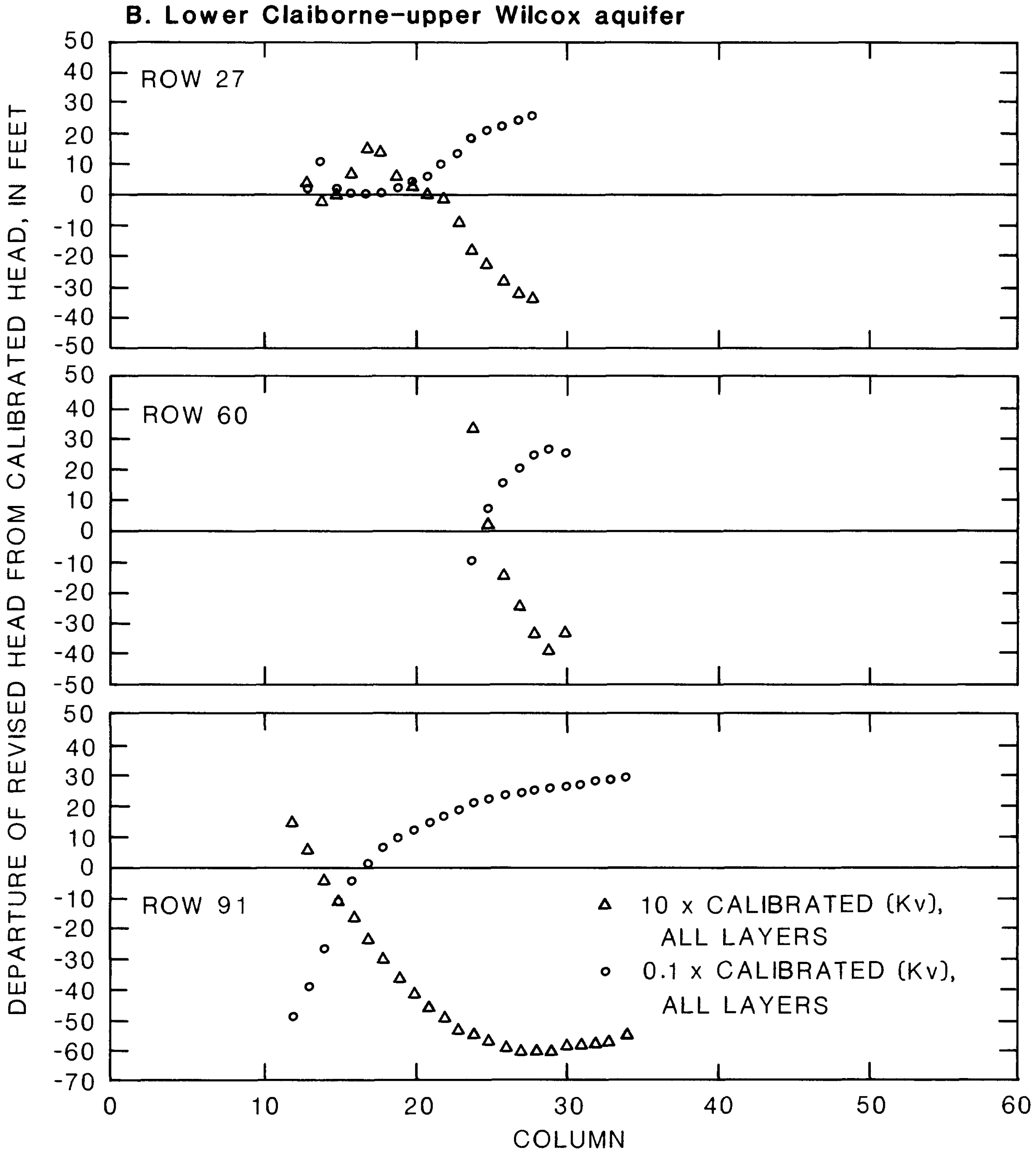


Figure 55.--Sensitivity of simulated heads to change in vertical hydraulic conductivity (Kv) for the:



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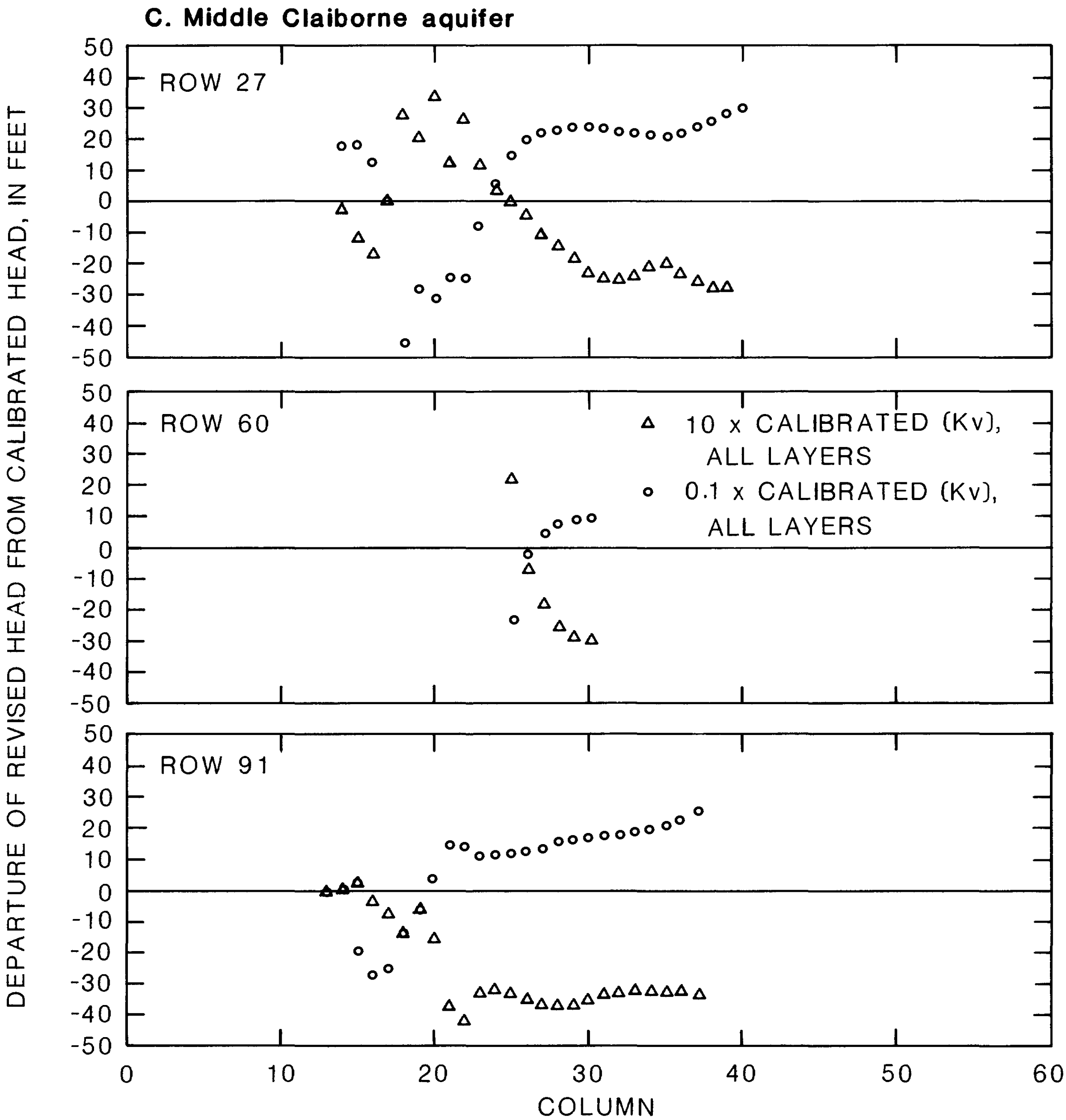

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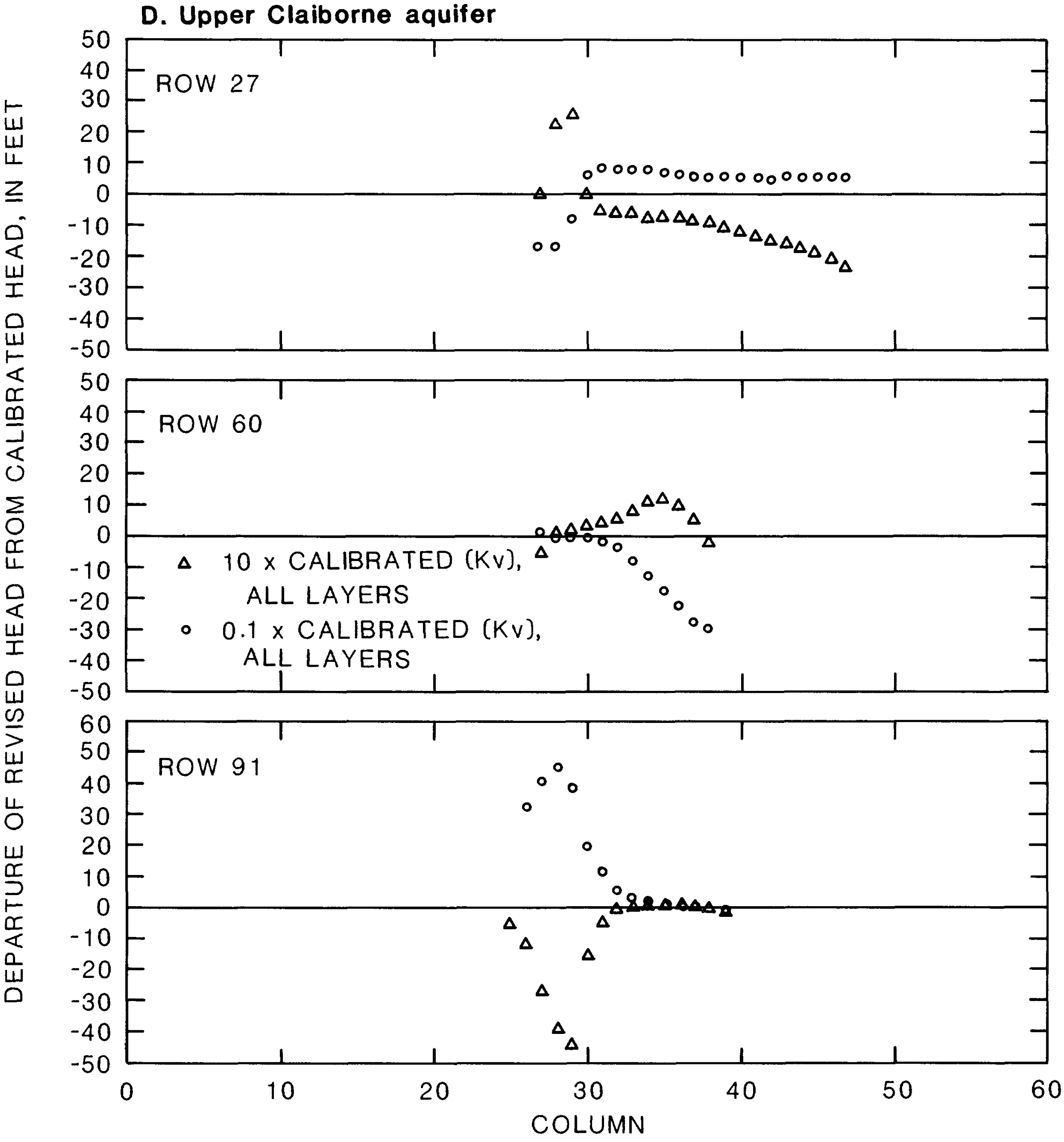

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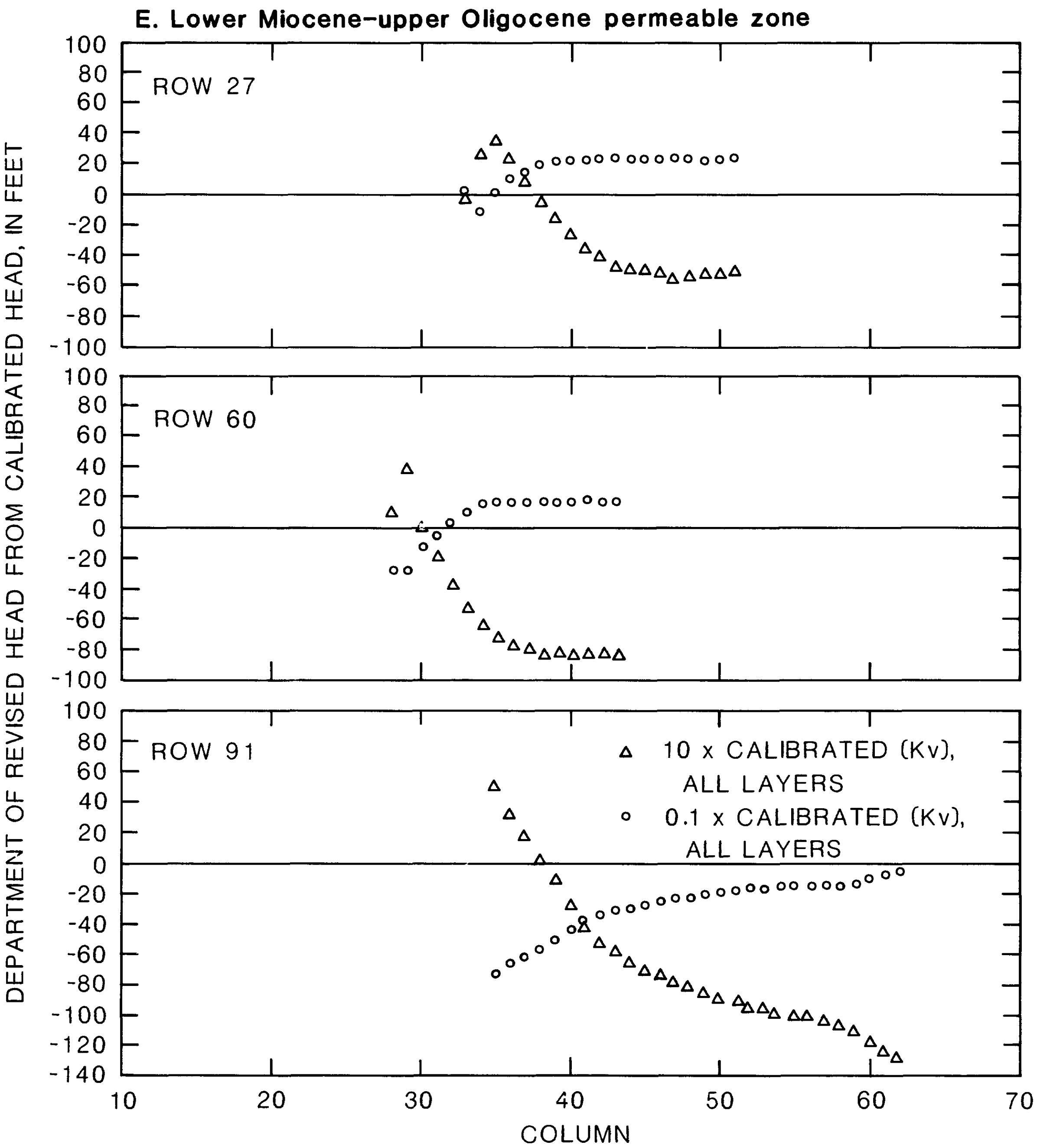

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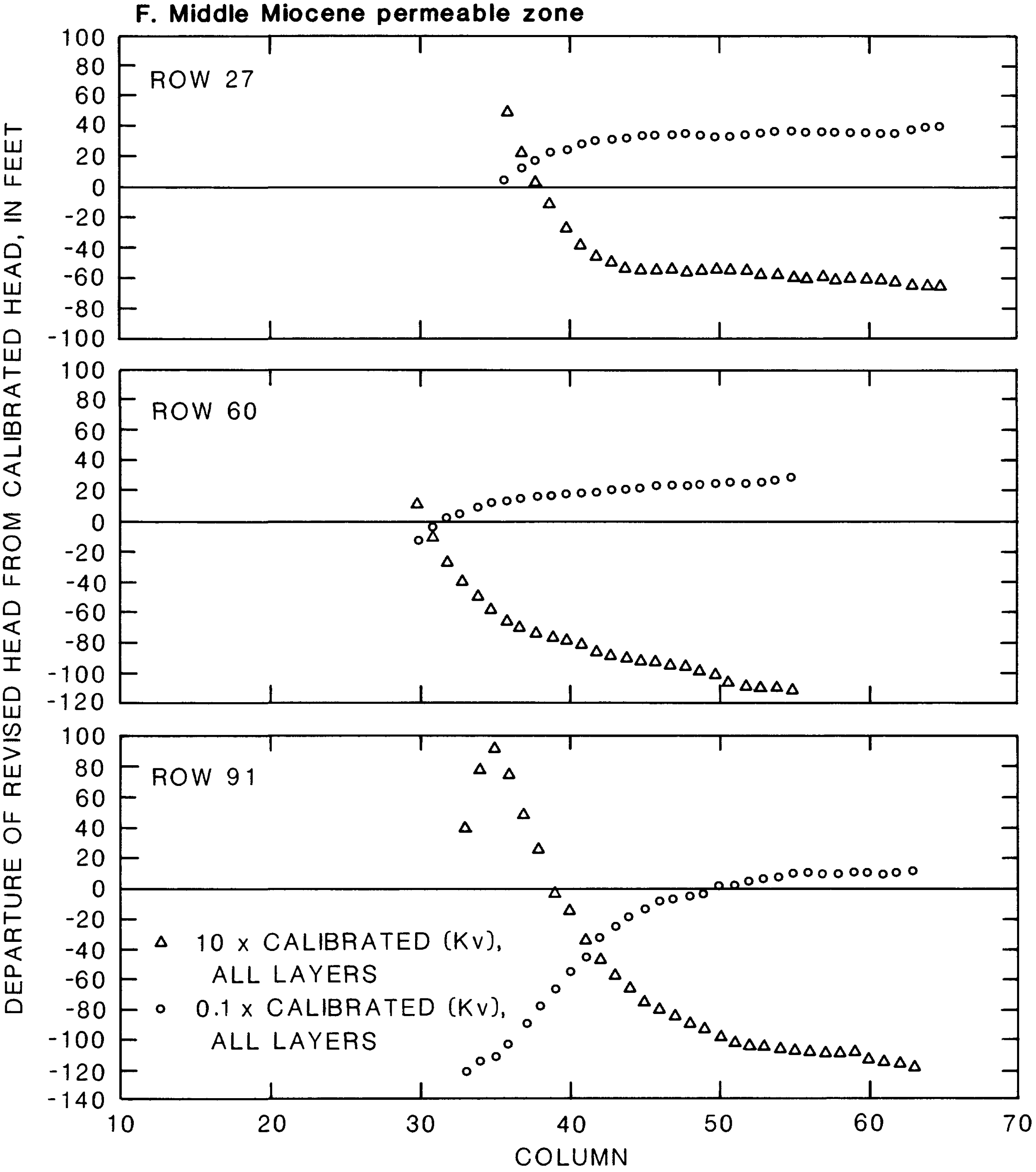

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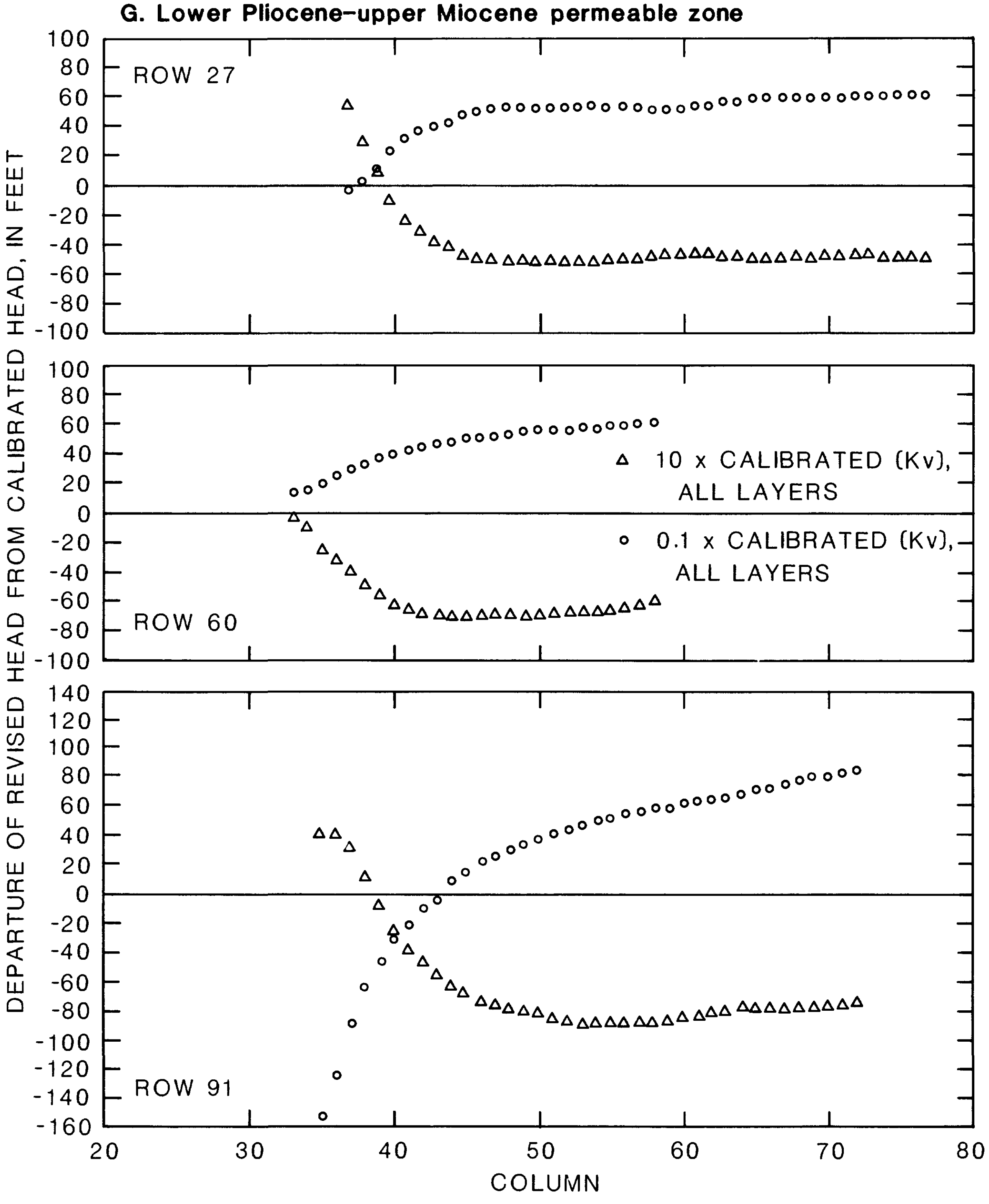

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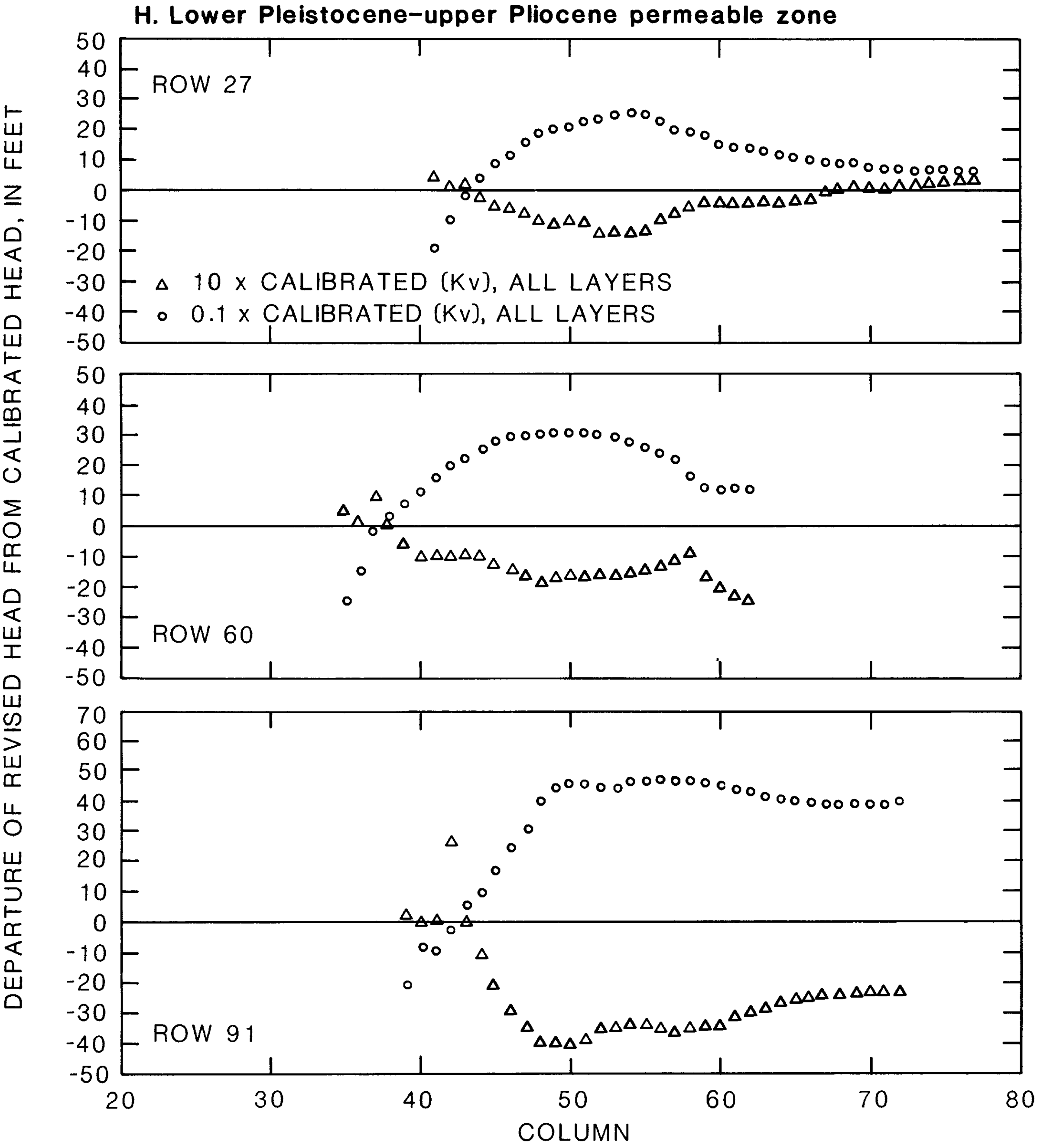

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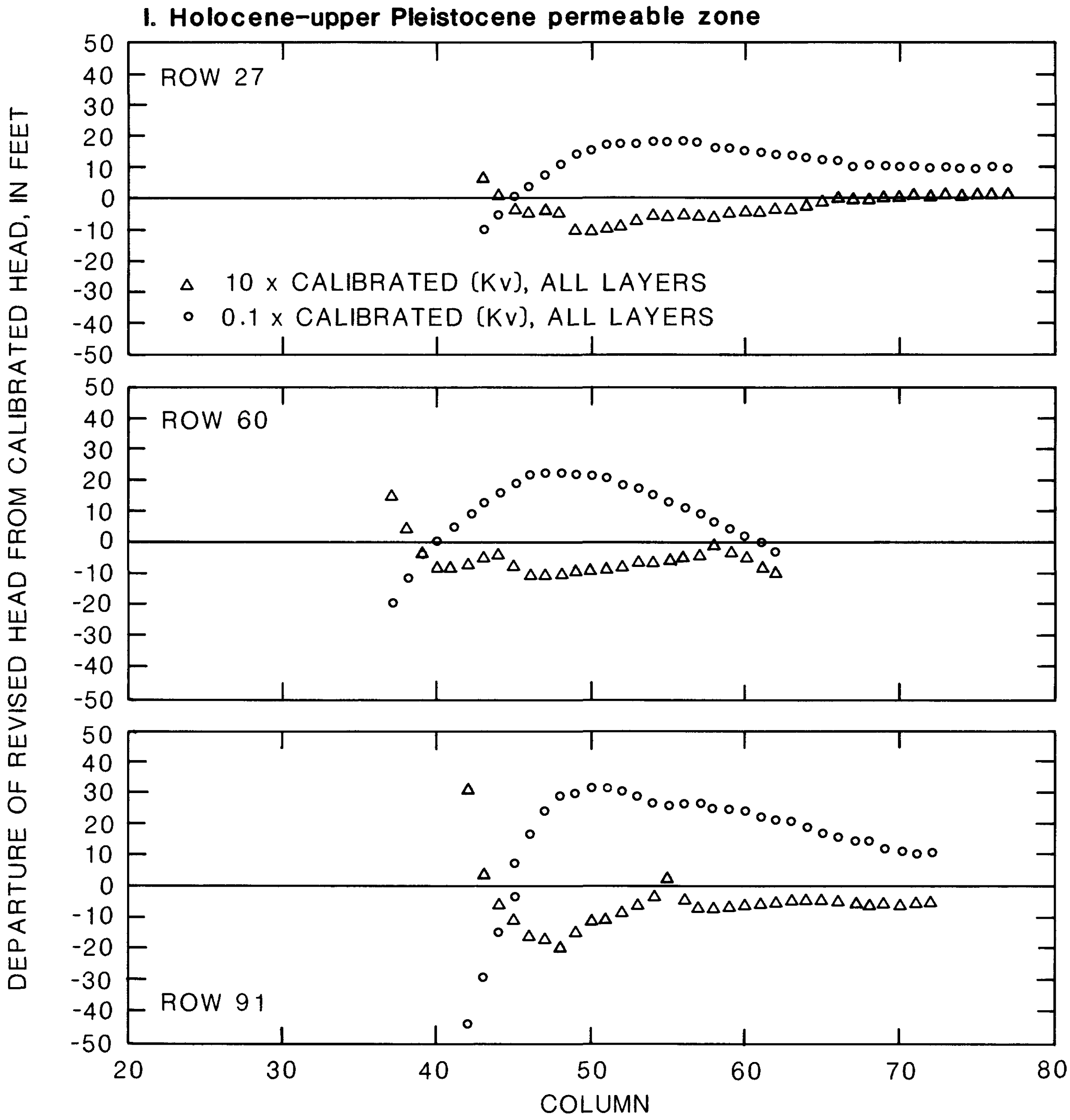


Figure 55.--Continued

Table 8.--Sensitivity of model to 50-percent decrease in horizontal hydraulic conductivity of all aquifers and permeable zones

[ft, foot; ft^3/d, cubic foot per day]

Aquifer and permeable zone	Total grid blocks with measured heads	Mean of residuals (ft)	Minimum residual (ft)	Maximum residual (ft)	Standard deviation of residuals (ft)	Mean of absolute values of residuals (ft)	Total recharge (+) and discharge (-) in outcrop areas (10^6 ft^3/d)1/
All	4,537	18	-126	184	36	27	199 -199
Holocene-upper Pleistocene	638	-1	-50	23	9	6	46 -76
Lower Pleistocene-upper Pliocene	858	5	-60	58	17	13	9 -6
Lower Pliocene-upper Miocene	441	28	-106	128	39	40	14 -4
Middle Miocene	261	5	-126	144	41	33	21 -10
Lower Miocene-Upper Oligocene	68	-1	-59	84	24	18	12 -6
Upper Claiborne	137	32	-26	152	36	35	16 1/ -23
Middle Claiborne	548	17	-50	128	34	29	49 1/ -51
Lower Claiborne-upper Wilcox	595	49	-50	184	48	53	17 1/ -9
Middle Wilcox	991	23	-65	138	33	31	15 -14

1/ Includes flow through outcrop of superjacent confining unit

Table 9.--Sensitivity of model to tenfold increase in vertical hydraulic conductivity of all model layers

[ft, foot; ft^3/d, cubic foot per day]

Aquifer and permeable zone	Total grid blocks with measured heads	Mean of residuals (ft)	Minimum residual (ft)	Maximum residual (ft)	Standard deviation of residuals (ft)	Mean of absolute values of residuals (ft)	Total recharge (+) and discharge (-) in outcrop areas (10^6 ft^3/d)1/
All	4,537	15	-84	143	29	23	878 -878
Holocene-upper Pleistocene	638	-1	-30	23	7	5	231 -347
Lower Pleistocene-upper Pliocene	858	1	-61	63	13	10	30 -34
Lower Pliocene-upper Miocene	441	20	-72	76	24	26	72 -28
Middle Miocene	261	7	-84	123	31	25	107 -54
Lower Miocene-Upper Oligocene	68	6	-37	87	21	17	40 -22
Upper Claiborne	137	30	-29	143	33	33	60 1/ -95
Middle Claiborne	548	14	-60	102	30	26	216 1/-207
Lower Claiborne-upper Wilcox	595	40	-50	136	38	44	69 1/ -38
Middle Wilcox	991	21	-73	117	31	29	53 -53

1/ Includes flow through outcrop of superjacent confining unit

occurred in the outcrop area of the lower Pliocene-upper Miocene permeable zone in row 91 (fig. 55g). The maximum increase in water level of 85 ft occurred in the lower Pliocene-upper Miocene permeable zone at the farthest point downdip in row 91 (fig. 55g). The statistical analysis in table 10 indicates that the decrease in vertical conductivities caused greater departures from calibrated water levels than did the increase in vertical conductivities. For the combined aquifers and permeable zones, the standard deviation of the residuals increased to 53 ft from the 39 ft for the calibration simulation, and the mean of the absolute values of the residuals increased to 42 ft from the calibration mean of 30 ft. Recharge and discharge rates in the outcrops were considerably reduced for each aquifer and permeable zone. For the combined aquifers and permeable zones, the rate was 59 million ft^3/d, about 22 percent of the calibration rate (table 10). The decreased vertical conductivities resulted in unrealistically small recharge rates, with maximum values of only 1 in./yr in eight grid blocks.

The model is generally sensitive to reasonable changes in hydraulic conductivities. Calibration residuals could be decreased by decreasing horizontal hydraulic conductivities or by increasing vertical hydraulic conductivities. Any such changes should be done judiciously, so that resultant recharge rates are reasonable.

The predevelopment model was not tested for sensitivity to changes in water density. Such tests are probably warranted due to the imprecise method of estimating densities, and they will be considered in future simulations that include ground-water development.

Simulated Predevelopment Flow

There are two components of flow: 1) horizontal flow within aquifers and permeable zones, and 2) vertical flow between the various model layers. Direction of horizontal flow in the aquifers and permeable zones can be ascertained from the simulated potentiometric-surface maps. In figures 45-53, simulated and measured heads in the unshaded areas and somewhat into the slightly saline water zones are considered freshwater heads. In these areas of essentially constant density, the direction of ground-water flow is from the higher to the lower potentials at right angles to the potentiometric contours. However, water-density variations significantly affect the direction of flow in the more saline water zones. Theoretical discussions describing the effect of density on ground-water flow are found in references such as Freeze and Cherry (1979), Hubbert (1969), and Lusczynski (1961).

The simulated heads in figures 45-53 are termed hydraulic heads and are defined by the following expression (Kuiper, 1985, p. 9):

$$\text{hydraulic head } H = \frac{h}{\frac{\rho}{\rho 0}} + z \quad ,$$

where: $$h = \text{pressure head} = \frac{p}{\rho 0 \; gr} \quad ,$$

Table 10.--Sensitivity of model to tenfold decrease in vertical hydraulic conductivity of all model layers

[ft, foot; ft^3/d, cubic foot per day]

Aquifer and permeable zone	Total grid blocks with measured heads	Mean of residuals (ft)	Minimum residual (ft)	Maximum residual (ft)	Standard deviation of residuals (ft)	Mean of absolute values of residuals (ft)	Total recharge (+) and discharge (-) in outcrop areas (10^6 ft^3/d)1/
All	4,537	19	-256	226	53	42	59 -59
Halacene-upper Pleistocene	638	-4	-182	49	34	23	14 -27
Lower Pleistocene-upper Pliocene	858	8	-94	110	40	31	8 -1
Lower Pliocene-upper Miocene	441	30	-256	164	65	60	5 -1
Middle Miocene	261	-1	-213	140	53	42	3 -2
Lower Miocene-Upper Oligocene	68	-11	-92	72	39	34	3 -2
Upper Claiborne	137	40	-50	167	50	48	4 1/ -6
Middle Claiborne	548	24	-75	151	49	44	11 1/ -13
Lower Claiborne-upper Wilcox	595	54	-93	226	66	66	5 1/ -2
Middle Wilcox	991	21	-105	170	45	40	6 -5

1/ Includes flow through outcrop of superjacent confining unit

z = elevation of point at bottom of well casing,
p = water pressure at bottom of well casing,
$\rho 0$ = freshwater density = $\frac{1\ g}{cm^3}$,
gr = the acceleration of gravity,
ρ = water density at bottom of well casing.

It would appear from the rather large hydraulic-head gradients in the saline zones of nearly all the aquifers and permeable zones that there is a large component of saltwater flow. In fact, analysis of the model results shows that there may or may not be significant flow in the steep-gradient areas in the saltwater regime. This seeming contradiction is explained by Lusczynski (1961), who discusses constant-density and density-dependent flow in relation to hydraulic heads, which he terms point-water heads.

Examination of the simulated horizontal flow rates shows that the largest rates are in the outcrop areas where the freshwater gradients are steepest and hydraulic conductivities tend to be larger. For the predevelopment model, it is of interest to examine the vertical flow rates more closely. Vertical flow may be divided into two regimes: 1) flow to and from the water table in the outcrop areas, and 2) flow between aquifers and confining units downdip from the outcrop areas.

Recharge and Discharge in Outcrop Areas

In the discussion of the conceptual model of the flow system, it was stated that precipitation on topographically high parts of the outcrops percolates downward to the water table, and from there most of the water moves downgradient and is discharged in topographically low parts of the outcrops. In nature, there is a mixture of vertical and lateral flow components in an aquifer or permeable zone, made more complex by the common thin clay lenses. For model simulation, the flow system is simplified so that there is a single, mean aquifer head in a grid block that interacts with the constant water-table head in the overlying grid block.

If the water-table head is higher than the aquifer head, there is downward flow, or recharge, to the aquifer across the bottom of the water-table layer. If the water-table head is lower than the aquifer head, there is discharge from the aquifer to the water table. The rate of vertical flow (Q) is computed by the following equation:

$$Q = \frac{K'}{b'} \times (H-h) \times A \qquad ,$$

where: H = water-table head,
h = aquifer head,
A = area of grid block,

$$\frac{K'}{b'} = \frac{2\ K1\ K2}{K1\ b2 + K2\ b1} = \text{harmonic mean of leakances,}$$

where: K1 = vertical hydraulic conductivity of water-table layer,
K2 = vertical hydraulic conductivity of aquifer layer,
b1 = thickness of water-table layer,
b2 = thickness of aquifer layer.

Simulated rates of recharge and discharge in outcrop areas, in in./yr, are shown in figure 56. The rates range from a minimum of about 6 in./yr of discharge to a maximum of 6 in./yr of recharge. The largest values of recharge, 4 to 6 in./yr, occur in relatively small areas in topographic highs. Areas with the greatest range of discharge rates, 4 to 6 in./yr, are also relatively small and are situated in stream valleys. Much of the recharge, particularly in areas with the greatest rates, moves laterally through relatively short distances and emerges as discharge in adjacent stream valleys (fig. 56). Areas with the greater rates of recharge and discharge are somewhat more prevalent in the east than in the west. Analysis of the simulated data shows that recharge and discharge rates beyond the Gulf coastline become progressively smaller. The average grid-block recharge rate for the area simulated is 0.74 in./yr. Because the discharge area is larger, the average grid-block discharge rate of 0.45 in./yr is smaller.

Inter-Aquifer Leakage and Summary of Vertical Flow Components

Although there is less flow in the downdip, saline parts of the aquifers and permeable zones, a significant portion of the recharge in most aquifers and permeable zones flows downdip beyond the outcrop areas. The water flows downdip in a general Gulfward direction until hydraulic pressure differences between the aquifer and overlying or underlying units cause flow vertically upward or downward. If flow is into a confining unit, it continues through into the next aquifer. After reaching another aquifer, the water may flow in any of several directions, including: 1) vertically in the same direction into another aquifer; 2) laterally, and then vertically into the original aquifer; 3) laterally, to emerge as discharge in an outcrop area; and 4) vertically, into the uppermost permeable zone to emerge as outcrop discharge.

The general result of downdip flow in each aquifer or permeable zone is a net upward flow into overlying aquifers (table 11). Table 11 summarizes the upward, downward, and net flow rates for the outcrop and downdip parts of each aquifer. The small rates of recharge and discharge in outcropping confining units are included in the rates of subjacent aquifers. The rates are for the simulated area including parts of Louisiana and Mexico.

Table 11 shows that the smallest rates of leakage (less than 1 million ft^3/d) occur between the upper Claiborne aquifer and the lower Miocene-upper Oligocene permeable zone. Flow is restricted because the thick, marine clay of the Vicksburg-Jackson confining unit separates the two units. Higher rates of leakage are characteristic of the coastal lowlands aquifer system. The maximum upward leakage, 47 million ft^3/d, is into the Holocene-upper Pleistocene permeable zone.

Total recharge in the outcrop areas is 269 million ft^3/d. The middle Claiborne aquifer receives the largest share, 65 million ft^3/d or 24 percent, closely followed by the Holocene-upper Pleistocene permeable zone which receives 61 million ft^3/d or about 23 percent. Total discharge in the outcrop

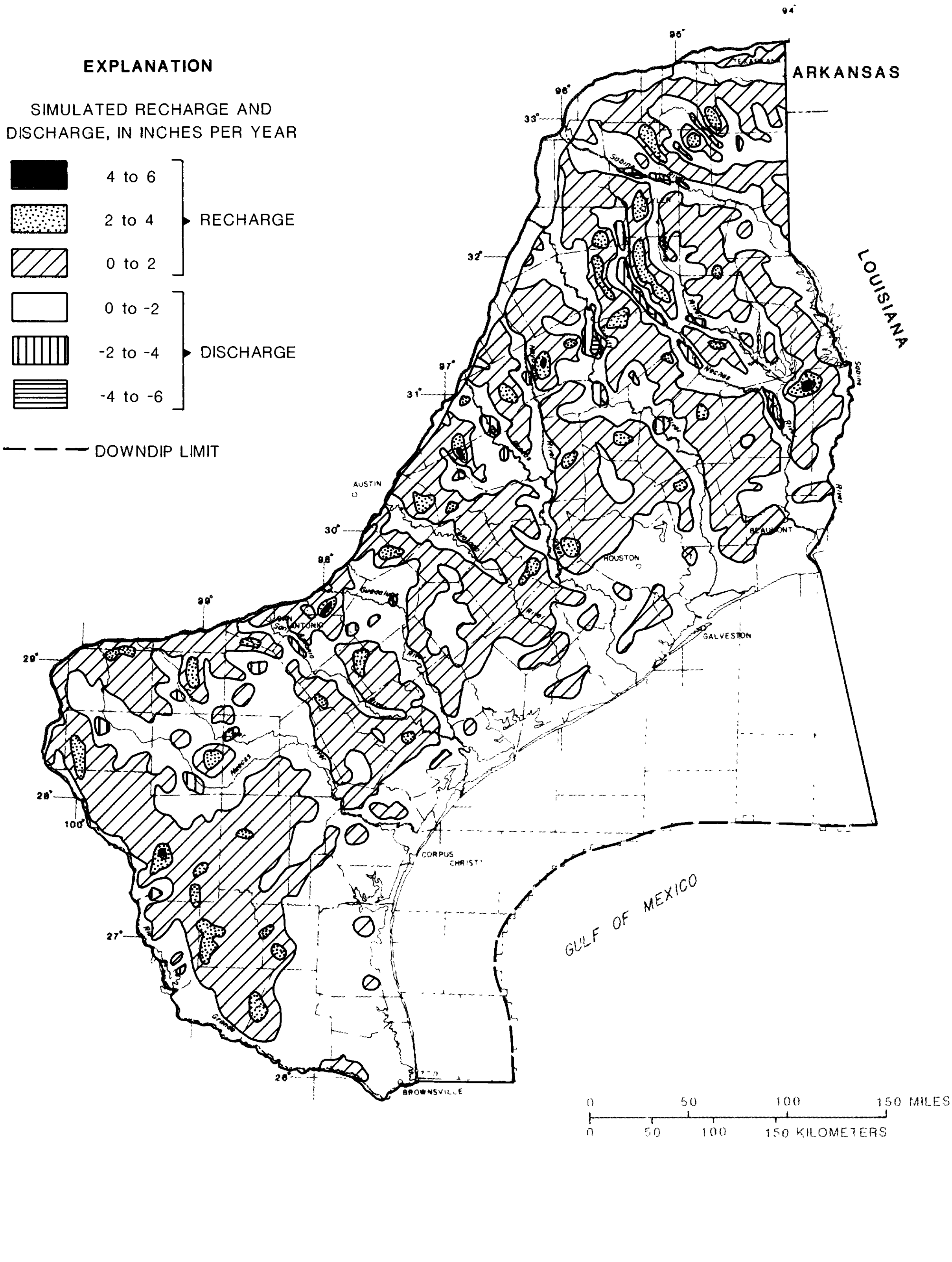


Figure 56.--Simulated recharge and discharge in the outcrop areas of aquifers, permeable zones, and confining units.

Table 11.--Simulated vertical flow rates across hydrogeologic units.

EXPLANATION

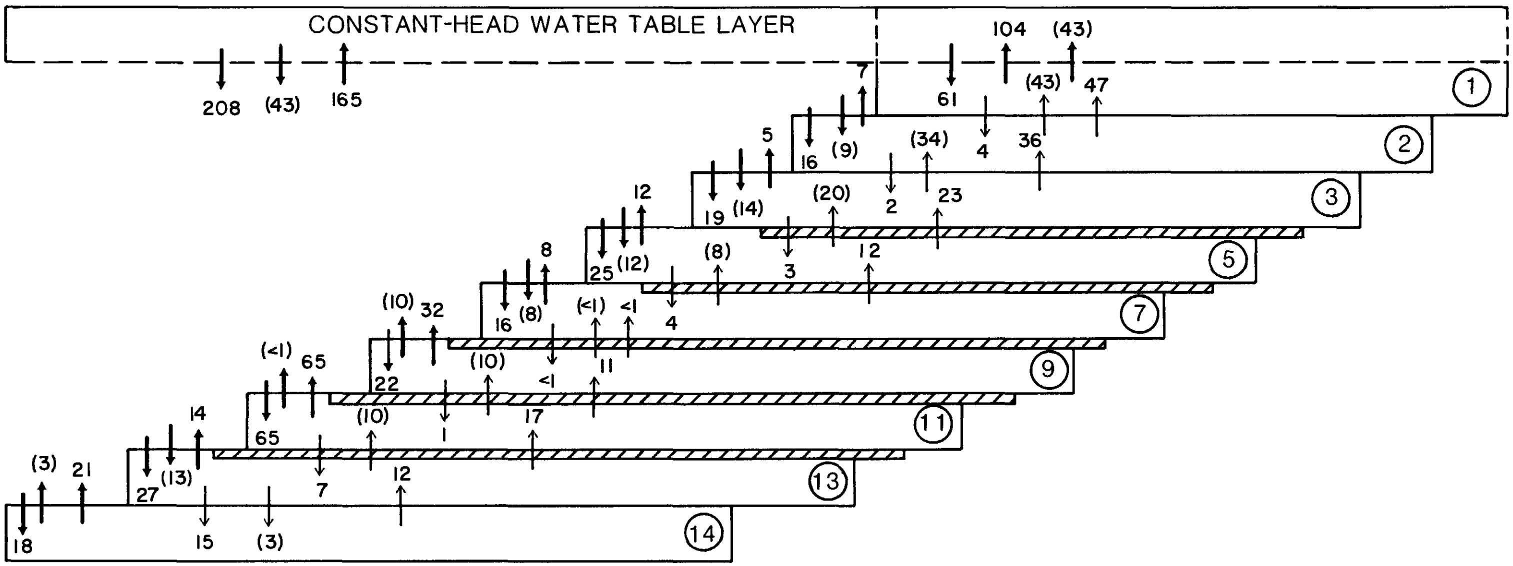
(ALL FLOWS ARE IN CUBIC FEET PER DAY ÷ 10^6)

32	Total recharge (↓) discharge (↑) in outcrop area 1/
(10)	Net recharge or discharge 1/
11	Total leakage through bottom of aquifer
(10)	Net upward (↑) or downward (↓) leakage
[hatched bar]	CONFINING UNIT
(3)	AQUIFER AND PERMEABLE ZONE IDENTIFIER

AQUIFER AND PERMEABLE ZONE:

(1)	Holocene-upper Pleistocene permeable zone
(2)	Lower Pleistocene-upper Pliocene permeable zone
(3)	Lower Pliocene-upper Miocene permeable zone
(5)	Middle Miocene permeable zone
(7)	Lower Miocene-upper Oligocene permeable zone
(9)	Upper Claiborne aquifer
(11)	Middle Claiborne aquifer
(13)	Lower Claiborne-upper Wilcox aquifer
(14)	Middle Wilcox aquifer

1/ Includes flow through superjacent confining unit where the confining unit is exposed at the surface



areas is 269 million ft^3/d. Of this, the Holocene-upper Pleistocene permeable zone discharges the most, 104 million ft^3/d or nearly 39 percent, followed by the middle Claiborne aquifer which discharges 65 million ft^3/d or 24 percent. One factor that accounts for the large rates of recharge and discharge in the middle Claiborne aquifer and Holocene-upper Pleistocene permeable zone is their relatively large outcrop areas.

SUMMARY AND CONCLUSIONS

Gulf Coastal Plain sediments as much as several thousand feet thick were subdivided into discrete aquifers, permeable zones, and confining units for construction of a multilayered digital model. The bases for selecting the number of hydrogeologic units includes practical considerations of size of the area, objectives of the model study, and computer cost limitations. Electrical-log interpretations of lithology, and vertical head differences at major pumping centers in Texas and Louisiana were used to delineate hydrologic units.

Two aquifer systems are recognized for the Texas Gulf Coast: the Texas coastal uplands aquifer system and the coastal lowlands aquifer system. The coastal uplands aquifer system consists of four aquifers and two confining units in the Wilcox and Claiborne Groups. The system is bounded from below by the practically impermeable clays of the Midway Group, or by the top of the geopressured zone. The overlying Vicksburg-Jackson confining unit separates the coastal uplands and the younger coastal lowlands aquifer systems.

The coastal lowlands aquifer system consists of five permeable zones and two confining units that range in age from Oligocene to Holocene. The hydrogeologic units were identified primarily by vertical head differences at major pumping centers in Houston, Texas, and Baton Rouge, Louisiana. The unit intervals were extrapolated to other areas by electrical-log correlations. Stratigraphic positions of the permeable zones and confining units of the coastal lowlands aquifer system differ significantly from those that have been determined for Texas in recent published reports.

Water quality in the aquifer systems varies from freshwater to brines, with dissolved solids ranging from a few hundred to more than 200,000 mg/L. A three-dimensional, variable-density digital model was developed for predevelopment, steady-state flow conditions. The area simulated extends beyond the study area to include parts of Louisiana and Mexico. No-flow boundaries were used at the updip and downdip extent of the hydrogeologic units and at the eastern and western limits. A constant-head water-table boundary provides water to and from the units in their outcrop areas.

Initial estimates of horizontal and vertical hydraulic conductivities for the model were based on available data. The vertical hydraulic conductivities were changed during the calibration process, whereby differences between simulated and measured water levels are minimized. Vertical hydraulic conductivities in the calibrated model range from 1×10^{-5} ft/d for the Vicksburg-Jackson confining unit, to 1×10^{-2} ft/d for four of the aquifers and permeable zones. Horizontal hydraulic conductivities range from 15 ft/d for the middle Wilcox aquifer to 170 ft/d for the Holocene-upper

Pleistocene permeable zone. Transmissivities and leakances vary areally in the model as a function of the percent sand.

Calibration residuals (simulated minus measured water levels) were analyzed graphically and statistically. The residuals are smaller in the outcrop areas, and there is a strong tendency for simulated to exceed measured water levels in downdip areas. For the combined aquifers and permeable zones, a total of more than 4,500 grid blocks contain measured water-level values. Largest residuals are for the lower Claiborne-upper Wilcox aquifer, with a standard deviation of 53 ft and a mean of the absolute values of the residuals of 56 ft. Smallest residuals are for the Holocene-upper Pleistocene permeable zone, with a standard deviation of 13 ft and an absolute mean of 8 ft. For the combined aquifers and permeable zones, the standard deviation is 39 ft and the absolute mean is 30 ft.

The model was tested for sensitivity to changes in horizontal hydraulic conductivities by both increasing and decreasing conductivities of all aquifers and permeable zones by 50 percent. Tests were also made for model sensitivity to changes in vertical hydraulic conductivities by increasing and by decreasing conductivities of all layers by a factor of 10. In general, the model is sensitive to the changed hydraulic conductivities. Calibration residuals could be decreased by decreasing horizontal hydraulic conductivities or by increasing vertical hydraulic conductivities. Care must be exercised in making such changes so that resultant recharge rates are reasonable.

Simulated discharge and recharge rates in the combined outcrop areas do not exceed 6 in./yr. The largest rates are in local topographically low and high areas. The average discharge rate for the outcrop areas is 0.45 in./yr, and the average recharge rate is 0.74 in./yr. Recharge and discharge rates are somewhat lower in the west than in the east. The west, in comparison to the east, has less annual precipitation and a general lack of springs and stream base flows.

A total recharge rate of 269 million ft^3/d in the outcrop areas is offset by an equal rate of discharge in the outcrops. The smallest rates of leakage downdip in the systems are across the Vicksburg-Jackson confining unit, where leakage rates are less than 1 million ft^3/d. The highest rate of leakage is 47 million ft^3/d upward into the Holocene-upper Pleistocene permeable zone.

The hydrogeologic framework has been described, and a preliminary description and analysis of aquifer, permeable zone and confining-unit hydraulic properties and water quality have been presented. Simulated rates of recharge and discharge in the outcrops and downdip leakage in the predevelopment flow system are reasonable. However, it is likely that the introduction of pumping stresses will lead to improved model calibration and a better understanding of the Texas Gulf Coast aquifer systems.

SELECTED REFERENCES

Baker, E.T., Jr., 1979, Stratigraphic and hydrogeologic framework of part of the Coastal Plain of Texas: Texas Department of Water Resources Report 236, 43 p.

-----1985, Texas Ground-water resources, in National Water Summary 1984: U.S. Geological Survey Water-Supply Paper 2275, p. 397-402.

-----1986, Hydrology of the Jasper aquifer in the southeast Texas Coastal Plain: Texas Water Development Board Report 295, 64 p.

Baker, E.T., Jr., and Wall, J.R., 1976, Summary appraisals of the Nation's ground-water resources, Texas-Gulf region: U.S. Geological Survey Professional Paper 813-F, 29 p.

Carr, J.E., Meyer, W.R., Sandeen, W.M., and McLane, I.R., 1985, Digital models for simulation of ground-water hydrology of the Chicot and Evangeline aquifers along the Gulf Coast of Texas: Texas Department of Water Resources Report 289, 101 p.

Ellisor, A.C., 1944, Anahuac Formation: American Association of Petroleum Geologists Bulletin, v. 28, no. 9, p. 1355-1375.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: New Jersey, Prentice-Hall, Inc., 604 p.

Garza, Sergio, Jones, B.D., and Baker, E.T., Jr., 1987, Potentiometric surface maps of aquifers in the Texas coastal uplands aquifer system: U.S. Geological Survey Hydrologic Investigations Atlas 704, scale 1:1,500,000.

Grubb, H.F., 1984, Planning report for the Gulf Coast Regional Aquifer-System Analysis in the Gulf of Mexico Coastal Plain, United States: U.S. Geological Survey Water-Resources Investigations Report 84-4219, 30 p.

-----1986, Gulf Coastal Plain regional aquifer-system study, in Sun, Ren Jen, ed., Regional Aquifer-System Analysis Program of the U.S. Geological Survey-Summary of Projects, 1978-1984: U.S. Geological Survey Circular 1002, p. 152-161.

Hubbert, M.K., 1969, The theory of ground-water motion and related papers: New York, Hafner Publishing Co., 310 p.

Jones, P.H., Stevens, P.R., Wesselman, J.B., and Wallace, R.H., Jr., 1976, Regional appraisal of the Wilcox Group in Texas for subsurface storage of fluid wastes: U.S. Geological Survey Open-File Report 76-394, 107 p.

Klemt, W.B., Duffin, G.L., and Elder, G.R., 1976, Ground-water resources of the Carrizo aquifer in the Winter Garden area of Texas: Texas Water Development Board Report 210, 30 p.

Kuiper, L.K., 1981, A comparison of the incomplete Cholesky-conjugate gradient method with the strongly implicit method as applied to the solution of two-dimensional groundwater flow equations: Water Resources Research, v. 17(4) p. 1082-1086.

-----1983, A numerical procedure for the solution of the steady state variable density groundwater flow equation: Water Resources Research, v. 19(1), p. 234-240.

-----1985, Documentation of a numerical code for the simulation of variable density ground-water flow in three dimensions: U.S. Geological Survey Water-Resources Investigations Report 84-4302, 24 p.

-----1986, A comparison of several methods for the solution of the inverse problem in two-dimensional steady state groundwater flow modeling: Water Resources Research, v. 22(5), p. 705-714.

Lohman, S.W., Bennett, R.R., Brown, R.H., Cooper, H.H., Jr., Drescher, W.J., Ferris, J.G., Johnson, A.I., McGuinness, C.L., Piper, A.M., Rorabaugh, M.I., Stallman, R.W., and Theis, C.V., 1972, Definition of selected ground-water terms--revisions and conceptual refinements: U.S. Geological Survey Water-Supply Paper 1988, 21 p.

Lusczynski, N.J., 1961, Head and flow of ground water of variable density: Journal of Geophysical Research, v. 66, no. 12, p. 4247-4256.

Payne, J.N., 1968, Hydrologic significance of the lithofacies of the Sparta Sand in Arkansas, Mississippi and Texas: U.S. Geological Survey Professional Paper 569-A, 17 p.

-----1970, Geohydrologic significance of lithofacies of the Cockfield Formation and of the Yegua Formation of Louisiana and Mississippi and of the Yegua Formation of Texas: U.S. Geological Survey Professional Paper 569-B, 14 p.

-----1972, Hydrologic significance of lithofacies of the Cane River Formation or equivalents of Arkansas, Louisiana, Mississippi, and Texas: U.S. Geological Survey Professional Paper 569-C, 17 p.

-----1975, Geohydrologic significance of lithofacies of the Carrizo Sand of Arkansas, Louisiana, and Texas and the Meridian Sand of Mississippi: U.S. Geological Survey Professional Paper 569-D, 11 p.

Texas Department of Water Resources, 1984, A comprehensive plan for the future, v. 1 of Water For Texas: Texas Department of Water Resources Publication Series GP-4-1, 72 p.

Weiss, J.S., 1986, Mapping dissolved-solids concentrations in highly mineralized ground water of the Gulf Coast aquifer systems using electric logs [abs.]: Geological Society of America Annual Meeting, San Antonio, Texas, 1986, Abstracts with Programs, p.784.

Weiss, J.S., and Williamson, A.K., 1985, Subdivision of thick sedimentary units into layers for simulation of ground-water flow: Ground Water, v. 23, no. 6, p. 767-774.

Wood, L.A., 1956, Availability of ground water in the Gulf Coast region of Texas: U.S. Geological Survey Open-File Report, 55 p.

Wood, L.A., Gabrysch, R.K., and Marvin, Richard, 1963, Reconnaissance investigations of the ground-water resources of the Gulf Coast region, Texas: Texas Water Commission Bulletin 6305, 114 p.