Report 289

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

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By

Jerry E. Carr, Walter R. Meyer,
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U.S. Geological Survey

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ABSTRACT

This report documents the construction and calibration of four digital models for the simulation of hydrologic conditions in the Chicot and Evangeline aquifers along the Gulf Coast of Texas. The models are five-layer, finite-difference models for simulation of three-dimensional, ground-water flow.

The hydrologic properties modeled were ground-water withdrawals, aquifer transmissivity, storage coefficients of the aquifers and clay beds, effective vertical hydraulic conductivity, vertical leakage, and declines in the altitudes of the potentiometric surfaces. The models, which simulate potentiometric-surface declines, changes in storage in the clay beds, and land-surface subsidence, were calibrated by use of historic records from 1890 or 1900 to 1970, and 1890 or 1900 to 1975. The models are very sensitive to variations in aquifer transmissivity and to variations in storage in water-table aquifers; they are less sensitive to variations in storage in artesian aquifers and to variations in storage in clay beds.

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INTRODUCTION

Purpose and Scope of This Report

The freshwater aquifers along the Texas Gulf Coast (Figure 1) supply large quantities of water for municipal supply, industrial use, and irrigation. However, extensive development of these aquifers has resulted in large declines of water levels in wells, land-surface subsidence, and saltwater encroachment. The purpose of this study, conducted by the U.S. Geological Survey in cooperation with the Texas Department of Water Resources, was to develop a means for predicting declines in the altitudes of the potentiometric surfaces in the Chicot and Evangeline aquifers for various conditions of pumping. Because of the complexity of the hydrologic system, digital-computer models were used to simulate the declines that would result from given pumping stresses. This report discusses the hydrologic data needed to construct and calibrate the models. It also presents maps showing the observed and simulated declines in the altitudes of the potentiometric surfaces and the observed and simulated subsidence of the land surface.

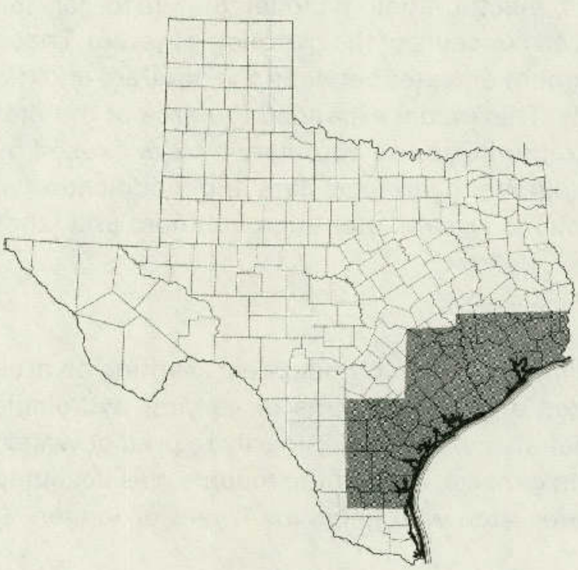


Figure 1.—Location and Extent of the Study Area

The Texas Department of Water Resources makes copies of the model and documentation available through the Texas Natural Resources Information System. Please contact the Texas Natural Resources Information System, P.O. Box 13087, Austin, Texas 78711, telephone 1-(512)-475-3321.

The study area was divided into four subregions—eastern, Houston, central, and southern. A digital-computer model was constructed and calibrated for each subregion. The coastal area was arbitrarily divided into a northern and southern region for presentation of the maps within the report. These maps show the approximate altitude of the base of the Chicot and Evangeline aquifers, the estimated transmissivities and storage coefficients of the aquifers, and the thickness of the clay beds. The modeling procedure consisted of selecting an existing computer program and modifying it to conceptually represent the hydrologic system. For each of the subregions, a generalized model (minimodel) was constructed and calibrated before constructing and calibrating a detailed model (maximodel).

For the purposes of this report, only a brief discussion of the hydrogeology is presented. For additional information on the hydrogeology of the coastal area and on the hydrologic problems related to the withdrawals of ground water, the reader is referred to the reports listed in the section "Selected References."

History of Hydrologic Modeling Along the Texas Gulf Coast

Previous hydrologic modeling along the Texas Gulf Coast was conducted for the Houston area, where the greatest amount of ground-water pumping and corresponding water-level declines have occurred. The first hydrologic model (Wood and Gabrysch, 1965) was an electric-analog model that included about 5,000 square miles (12,950 km^2) in Harris, Galveston, Brazoria, Fort Bend, Austin, Waller, Montgomery, Liberty, and Chambers Counties. This model, which was constructed on the basis of data collected since 1931, was used primarily to predict water-level declines under various conditions of pumping. This first attempt to model the ground-water system was reasonably successful, but the usefulness of the model was limited because the simulations required that the aquifers be operated independently and the results of pumping in the western part of the area could not be simulated.

The second model (Jorgensen, 1975) was an electric-analog model that incorporated additional hydrologic data and reflected more advanced concepts of the hydrologic system. These concepts included consideration of the vertical movement of water between the aquifers and the allowance for water to be derived from the clay beds. This model expanded the area of the first model to about 9,100 square miles (23,570 km^2) to minimize the boundary effects caused by long-term pumping. Jorgensen (1975) noted that additional hydrologic data and modification of the model would be needed for studies of such problems as saltwater encroachment and land-surface subsidence.

The third model (Meyer and Carr, 1979) was a digital-computer model, representing an area of 27,000 square miles (69,930 km^2), that provided an easier means of varying hydrologic properties during the calibration process. This model also was used primarily to predict water-level declines under various conditions of pumping. In general, each of the models was designed to simulate the effects of steady withdrawals of water from well fields for 1 year or longer.

Metric Conversions

Metric equivalents of "inch-pound" units of measurement are given in parentheses in the text. The "inch-pound" units may be converted to metric units by the following conversion factors:

From	Multipy by	To obtain
foot	0.3048	meter (m)
foot $^{-1}$	3.2802	meter $^{-1}$ (m^{-1})
foot per day (ft/d)	0.3048	meter per day (m/d)
foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
mile	1.609	kilometer (km)
million gallons per day	0.04381	cubic meter per second
square mile	2.590	square kilometer (km^2)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "mean sea level,"

HYDROGEOLOGY OF THE TEXAS GULF COAST

The hydrogeologic units are the Chicot aquifer, Evangeline aquifer, and the Burkeville confining layer (Figures 2 and 3). These units are composed of sedimentary deposits of gravel, sand, silt, and clay. The geologic formations, from oldest to youngest, are: the Fleming Formation and Oakville Sandstone of Miocene age; the Goliad Sand of Pliocene age; the Willis Sand, Bentley Formation, Montgomery Formation, and Beaumont Clay of Pleistocene age; and alluvium of Quaternary age. The relationship between the hydrogeologic units and the geologic formations (stratigraphic units) is given in Table 1. With exception of the alluvium and the Goliad Sand, the formations crop out in belts that are nearly parallel to the shoreline of the Gulf of Mexico. The Goliad Sand is overlapped by younger formations east of the Brazos River and is not exposed at the surface in the coastal area. The younger formations crop out nearer the Gulf and the older ones farther inland. All formations thicken downdip towards the Gulf of Mexico so that the older formations dip more steeply than the younger ones. Locally, the occurrence of salt domes, faults, and folds may cause reversals of the regional dip and thickening or thinning of the formations.

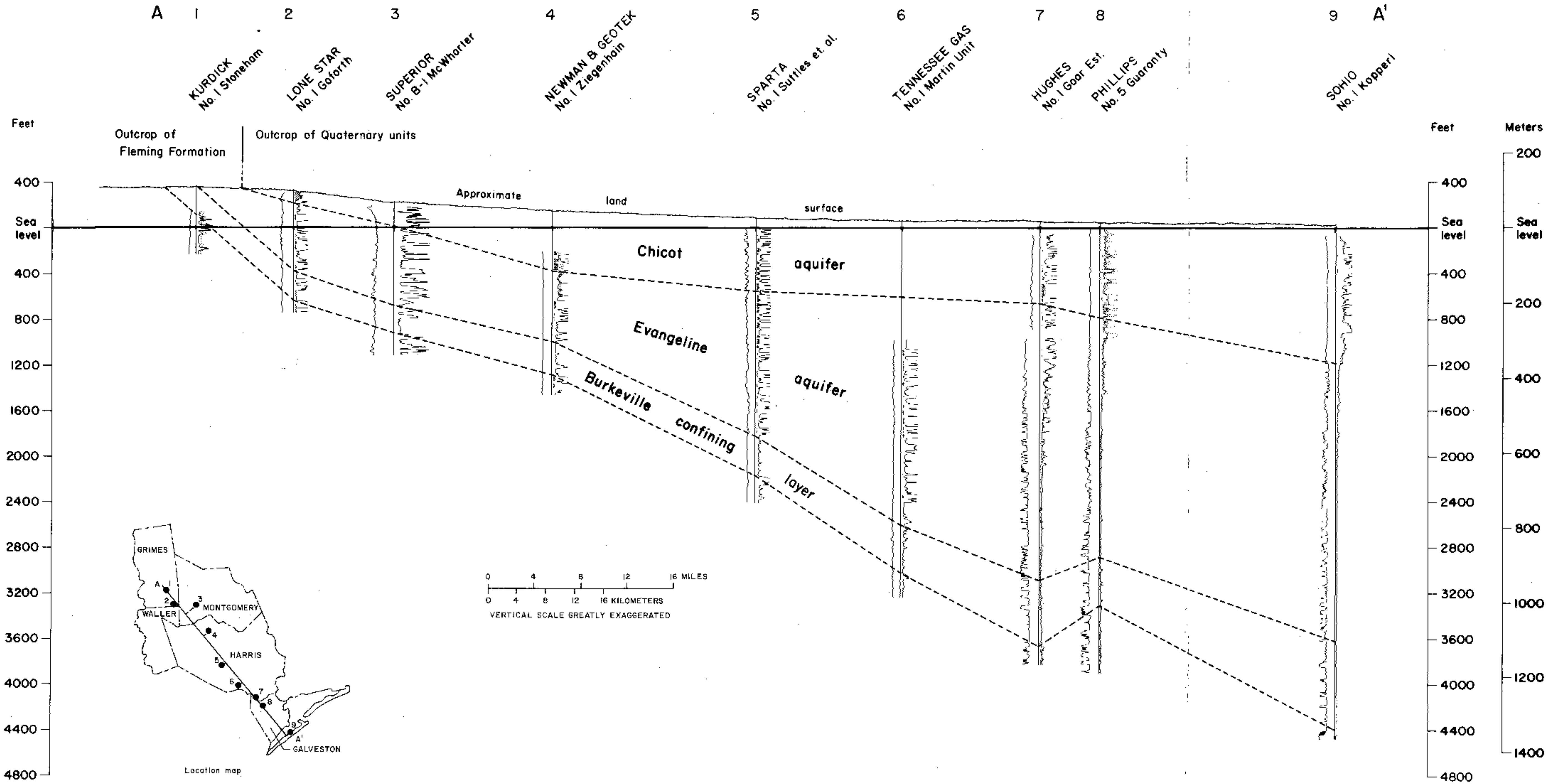


Figure 2
Hydrogeologic Section in Northern Region

Modified from Baker, 1978

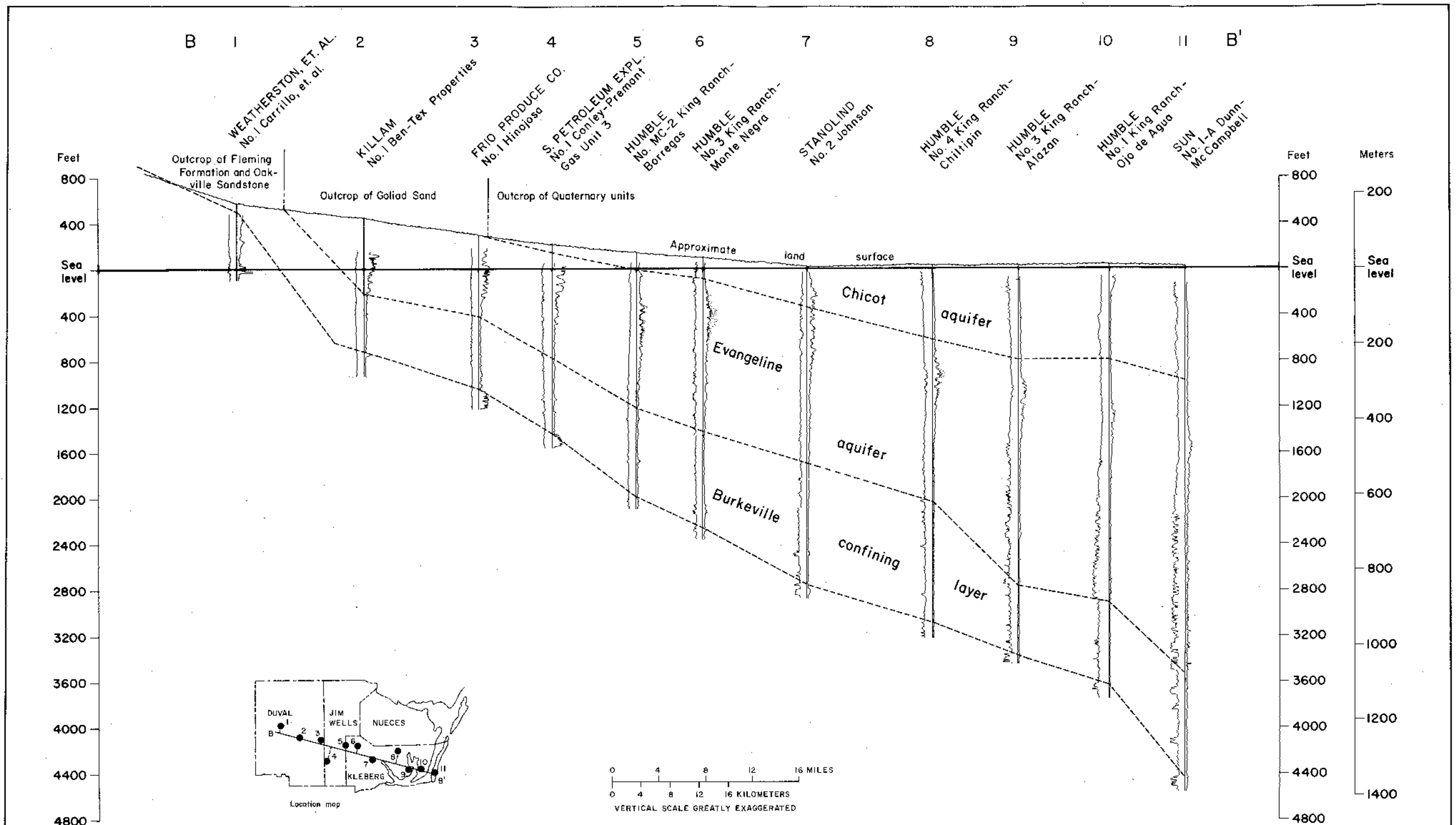


Figure 3
Hydrogeologic Section in Southern Region

Modified from Baker, 1978

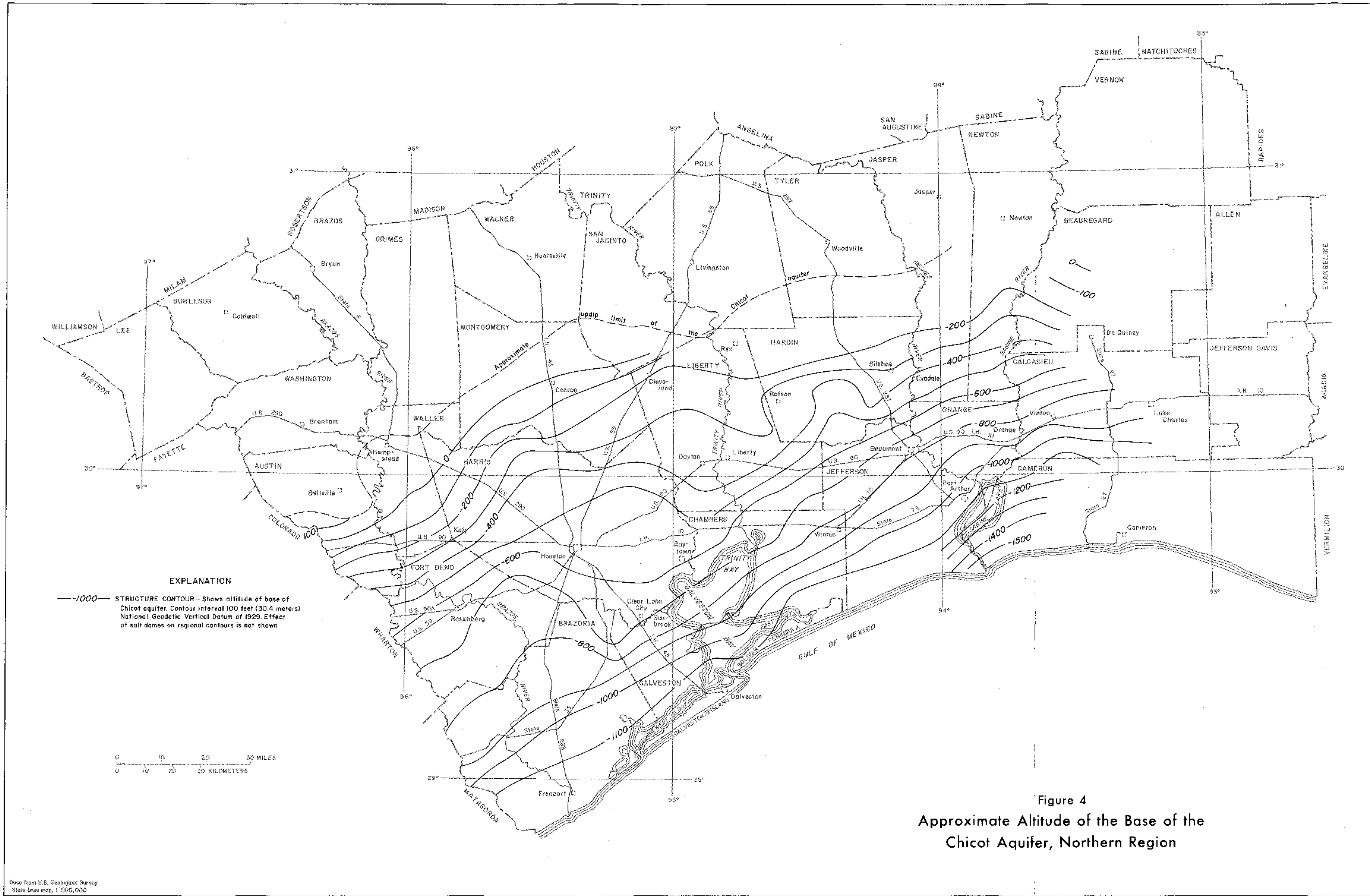


Figure 4
Approximate Altitude of the Base of the Chicot Aquifer, Northern Region

Table 1.--Geologic and Hydrologic Units Used in This Report and in Recent Reports on Nearby Areas

Geologic classification			Hydrologic units						
System	Series	Stratigraphic unit	Houston district (Lang, Winslow, and White, 1950)		Houston district (Wood and Gabrysch, 1965)	Texas-Louisiana (Turcan, Wesselman, and Kilburn, 1966)	Houston district (Jorgensen, 1975)		This report	
Quaternary	Holocene	Quaternary alluvium	Alluvial deposits		Confining layer and Alta Loma Sand of Rose (1943)	Chicot aquifer	Chicot aquifer	Upper unit	Chicot aquifer	Upper unit
	Pleistocene	Beaumont Clay	Beaumont Clay							
		Montgomery Formation		"Alta Loma Sand"				Lower unit		Lower unit
		Bentley Formation								
		Willis Sand	Zone 7							
			Zone 6							
Tertiary	Pliocene	Goliad Sand	Zone 5		Heavily pumped layer	Evangeline aquifer	Evangeline aquifer		Evangeline aquifer	
			Zone 4							
			Zone 3							
	Miocene	Fleming Formation	Zone 2		Zone 2	Burkeville confining layer	Burkeville confining layer		Burkeville confining layer	
		Oakville Sandstone	Zone 1			Jasper aquifer	Jasper aquifer			

Chicot Aquifer

The Chicot aquifer is composed of the Willis Sand, Bentley Formation, Montgomery Formation, Beaumont Clay, and Quaternary alluvium. The Chicot includes all deposits from the land surface to the top of the Evangeline aquifer. The altitude of the base of the Chicot aquifer is shown in Figures 4 and 5.

In much of the coastal area, the Chicot aquifer consists of discontinuous layers of sand and clay of about equal total thickness. However, in some parts of the coastal area (mainly within the Houston area), the aquifer can be separated into an upper and lower unit (Jorgensen, 1975). The upper unit can be defined where the altitude of its potentiometric surface differs from the altitude of the potentiometric surface in the lower unit. If the upper unit of the Chicot aquifer cannot be defined, the aquifer is said to be undifferentiated. The aquifer is under water-table conditions in its updip part, becoming confined in the downdip direction. Throughout most of Galveston County and southeast Harris County, the basal part of the Chicot aquifer is formed by a massive sand section that has a relatively high hydraulic conductivity. This sand unit, which is heavily pumped in some places, is known locally as the Alta Loma Sand (Alta Loma Sand of Rose, 1943).

Evangeline Aquifer

The Evangeline aquifer, which consists mostly of discontinuous layers of sand and clay of about equal total thickness, is composed of the Goliad Sand and the uppermost part of the Fleming Formation. The altitude of the base of the Evangeline aquifer is shown in Figures 6 and 7. Because the Chicot and Evangeline aquifers are geologically similar, the basis for separating them is primarily a difference in hydraulic conductivity, which in part causes the difference in the altitudes of the potentiometric surfaces in the two aquifers. The aquifer is under water-table conditions in its updip part, becoming confined in the downdip direction.

Burkeville Confining Layer

The Burkeville confining layer, which is composed of the upper part of the Fleming Formation, consists mainly of clay but contains some layers of sand. The Burkeville, which underlies the Evangeline aquifer, restricts the flow of water except in areas where it is pierced by salt domes and in areas where it contains a high percentage of sand.

DESCRIPTION OF THE DIGITAL MODELS

The conceptual model (Figure 8) for the four modeled subregions (Figure 9) consists of five layers. In ascending order, layer 1 is equivalent to the total thickness of the sand beds in the Evangeline aquifer; layer 2 is equivalent to the clay thickness between the centerline of the Chicot aquifer and the centerline of the Evangeline aquifer; layer 3 is equivalent to the Alta Loma Sand of Rose (1943) where present, otherwise it is equivalent to the total thickness of the sand beds in the Chicot aquifer; layer 4 is equivalent to the clay thickness between the land surface and the centerline of the Chicot aquifer; and layer 5 is used as an upper boundary to simulate recharge to

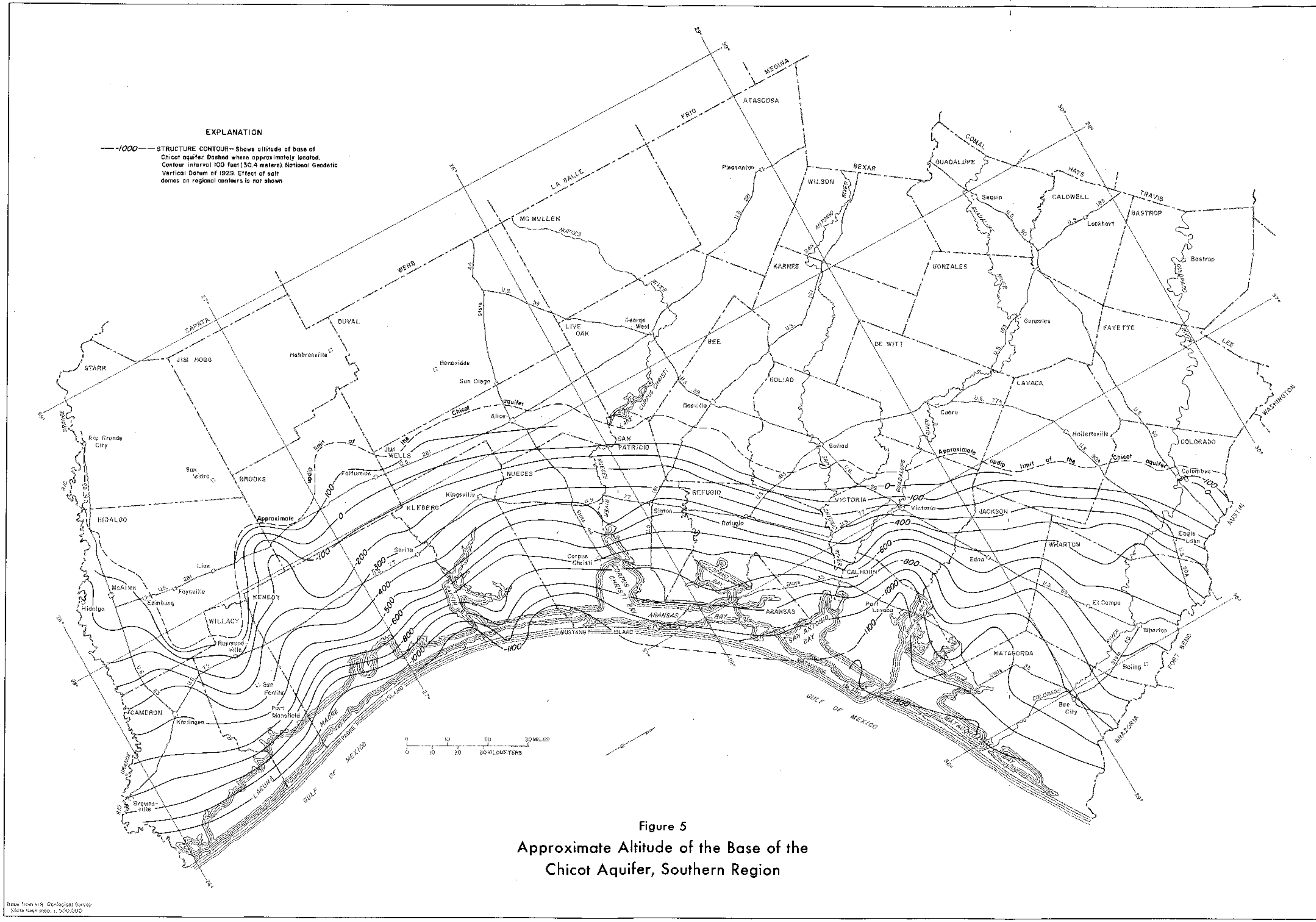


Figure 5
Approximate Altitude of the Base of the Chicot Aquifer, Southern Region

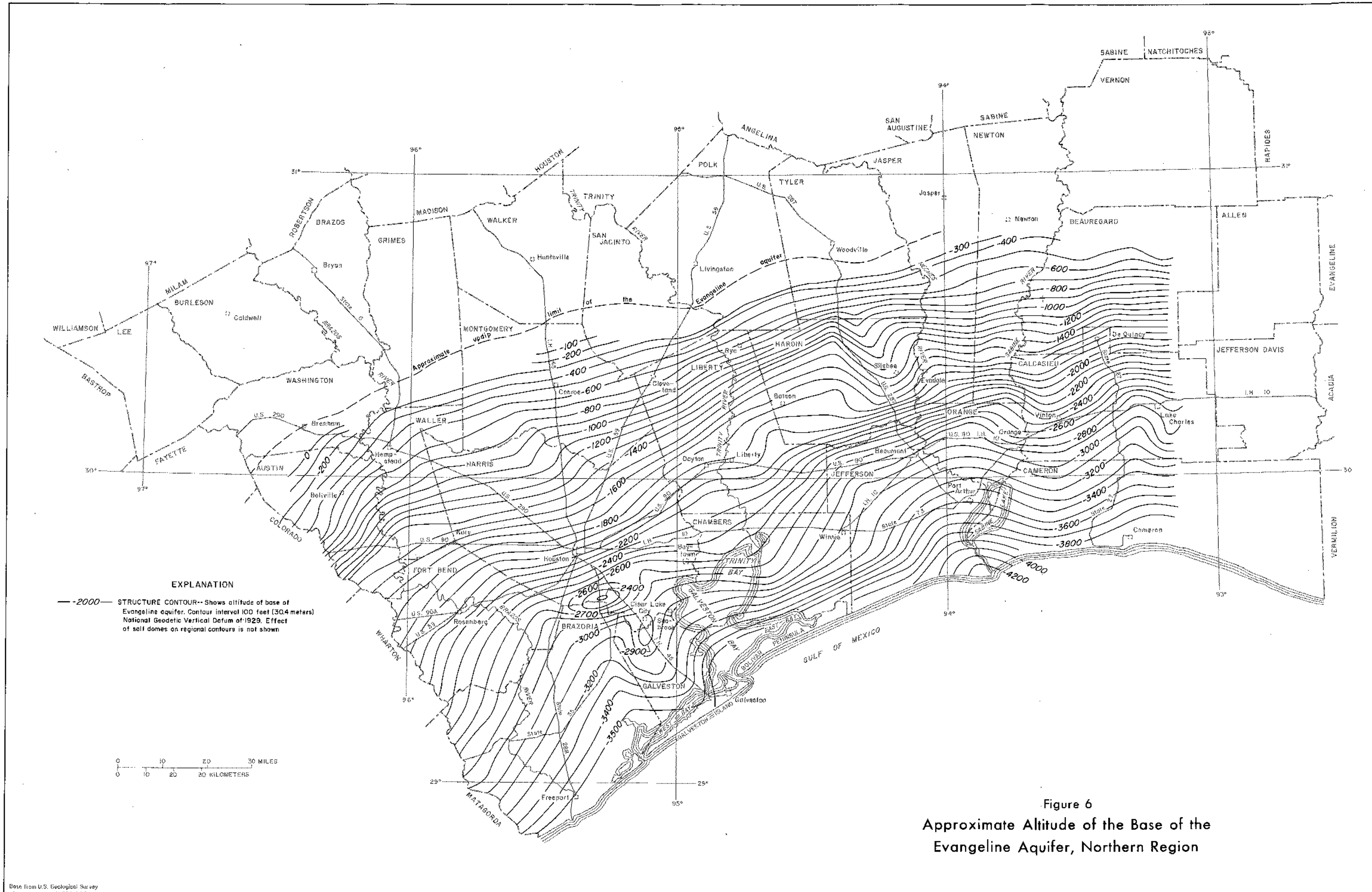


Figure 6

Approximate Altitude of the Base of the Evangeline Aquifer, Northern Region

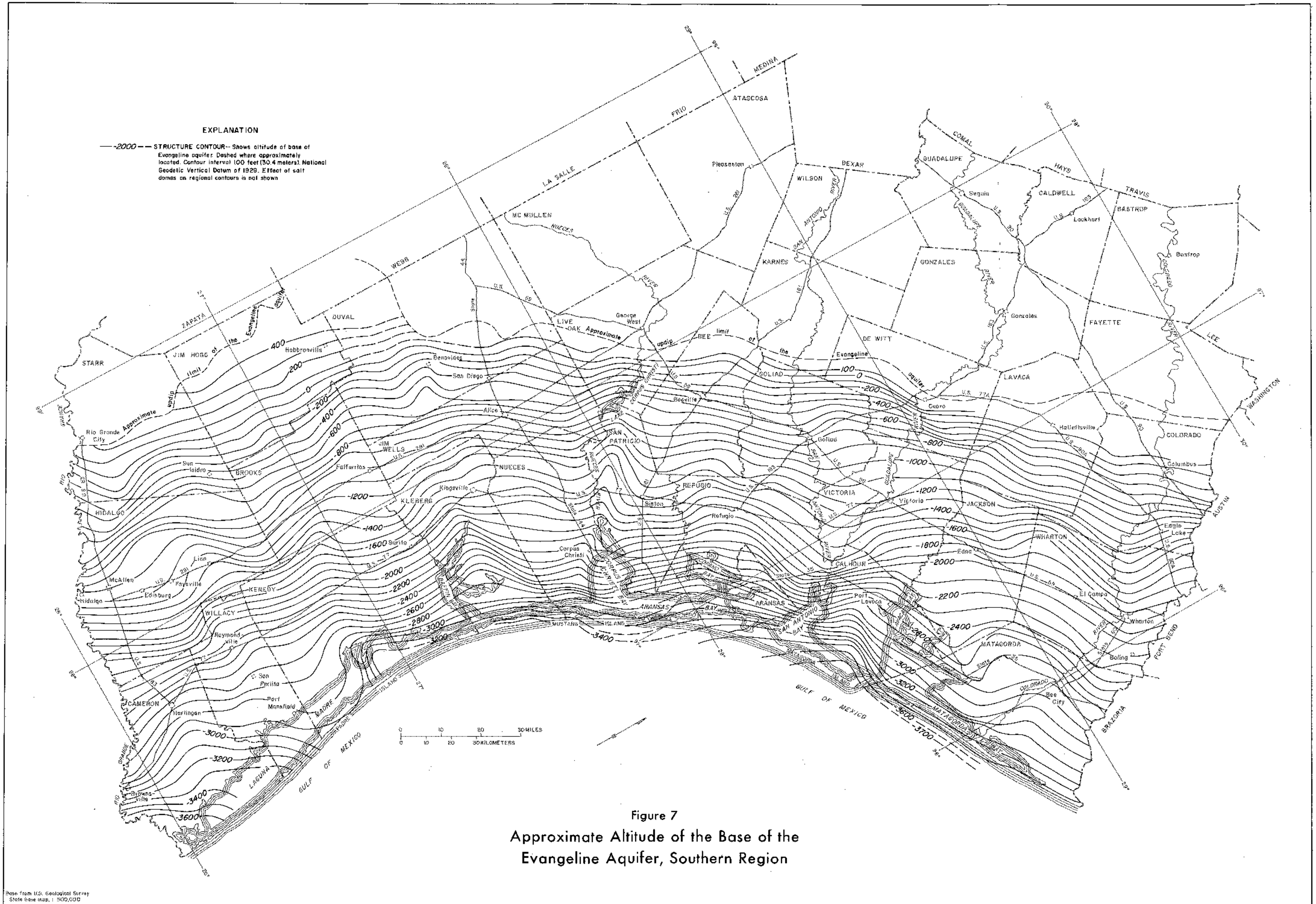


Figure 7
Approximate Altitude of the Base of the Evangeline Aquifer, Southern Region

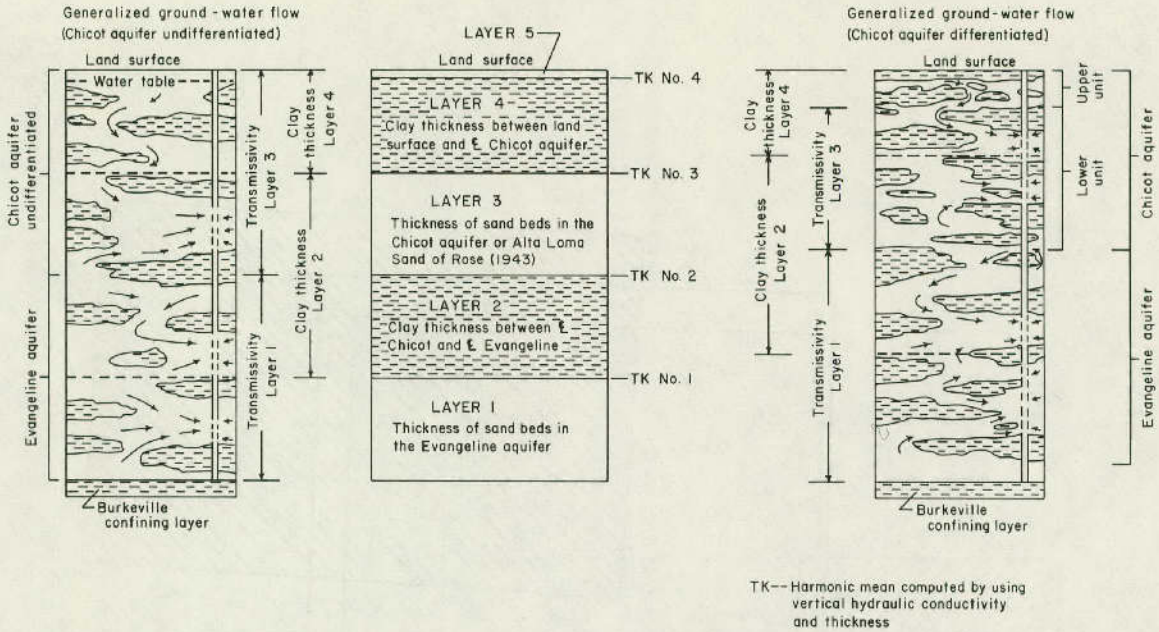


Figure 8.—Conceptual Model of the Ground-Water Hydrology of the Texas Gulf Coast

the system from vertical leakage. Within the model, clay thickness intervals are divided at aquifer centerlines to support the concept that the upper clays (layer 4) mostly control the vertical flow to the Chicot sands (layer 3), and that the clays (layer 2) from the centerline of the Chicot aquifer to the centerline of the Evangeline aquifer mostly control the vertical flow between the two aquifers.

The Burkeville confining layer (base of model) is assumed for modeling purposes to form a barrier that allows only a negligible flow of water. Salt domes, which occur throughout the study area, were not considered in the construction of the models because they have only a localized effect on ground-water conditions. In most areas, the domes do not pierce the Chicot or Evangeline aquifers.

Selection of horizontal boundaries for the models was somewhat arbitrary because the Chicot and Evangeline aquifers form an extensive and continuous hydrologic system along the Texas Gulf Coast. The no-flow boundaries selected were primarily determined by the areal extent required to minimize the effects of pumping along the boundaries and to eliminate the necessity of having flux boundaries.

The digital models used in this study are finite-difference models as modified from Trescott (1975) for simulation of three-dimensional ground-water flow; the models converge to a solution rapidly because all equations are solved simultaneously rather than sequentially as in the quasi three-dimensional model of Bredehoeft and Pinder (1970). The iterative numerical technique used to solve the set of simultaneous finite-difference equations is the strongly implicit procedure originally described by Stone (1968) for problems in two dimensions. Wienstein, Stone, and Kwan (1969) later extended the technique to three dimensions.

The model developed by Trescott (1975) was modified by J. E. Carr (Meyer and Carr, 1979) to include methods to increase or decrease the values of storage in the clay layers, at a head that is equivalent to preconsolidation stress, to simulate land-surface subsidence. This reference head is arbitrarily referred to as "critical head." Different storage coefficients, which are head depen-

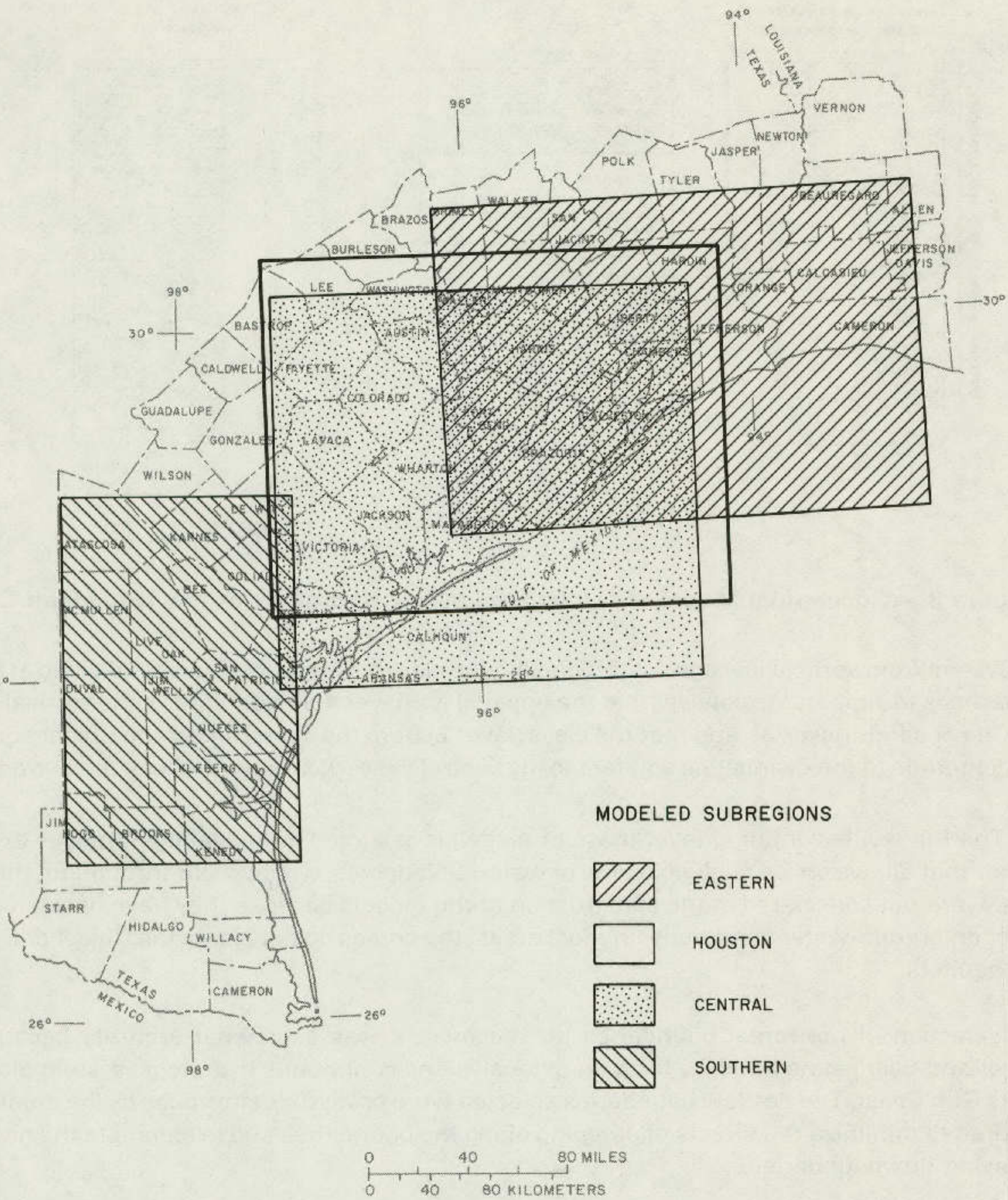


Figure 9.—Index Map of Modeled Subregions

dent, are used for elastic and inelastic compression. In addition, the modifications include accumulators for the quantities of water derived from clays in layers 2 and 4.

HYDROLOGIC PROPERTIES MODELED

Ground-Water Withdrawals

Ground-water withdrawals (Figures 10-11) were grouped into four pumping periods for report presentation. For model simulation, the Houston subregion consisted of seven pumping

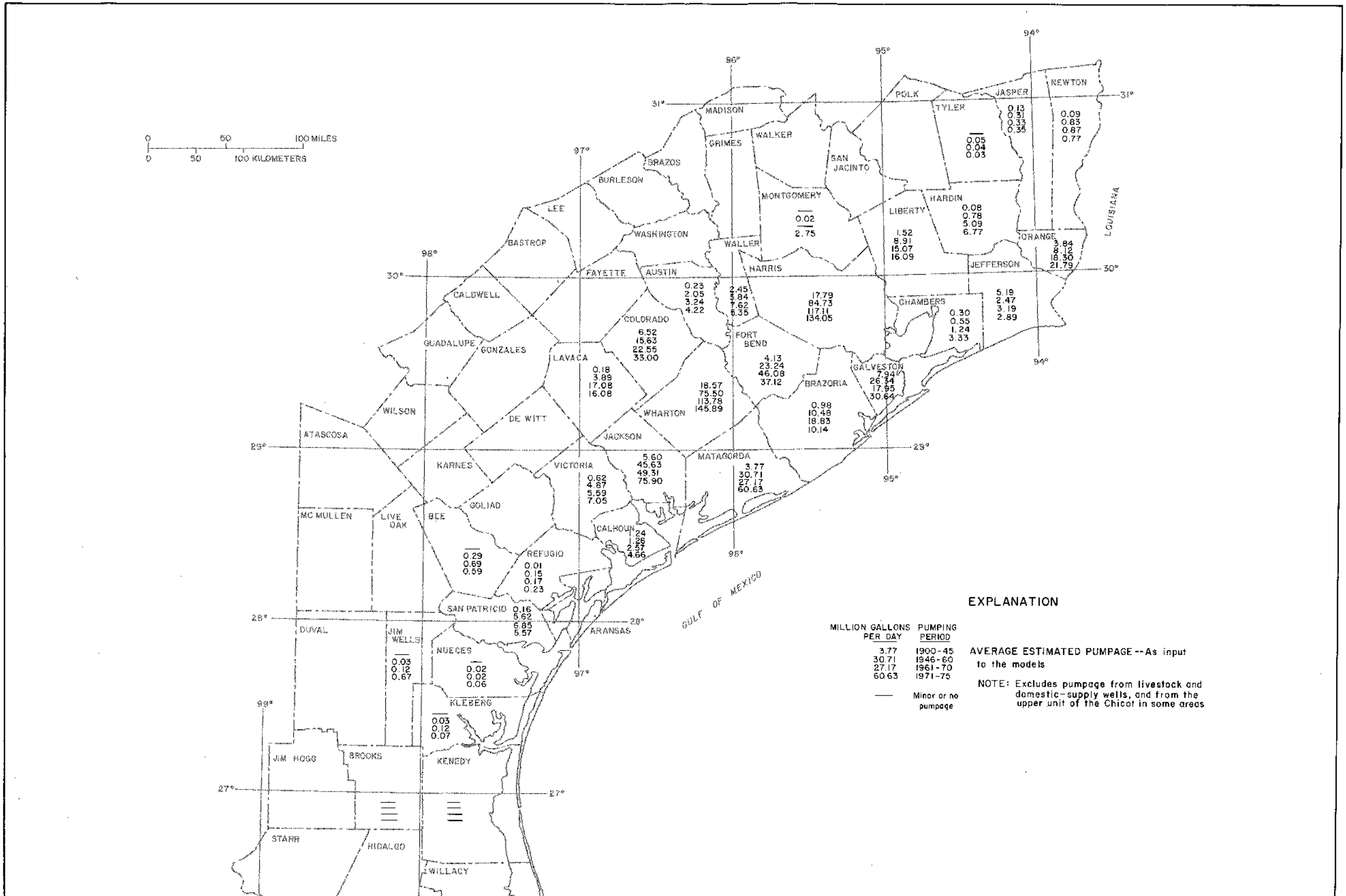


Figure 10

Estimated Withdrawals of Ground Water, by County, From the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated

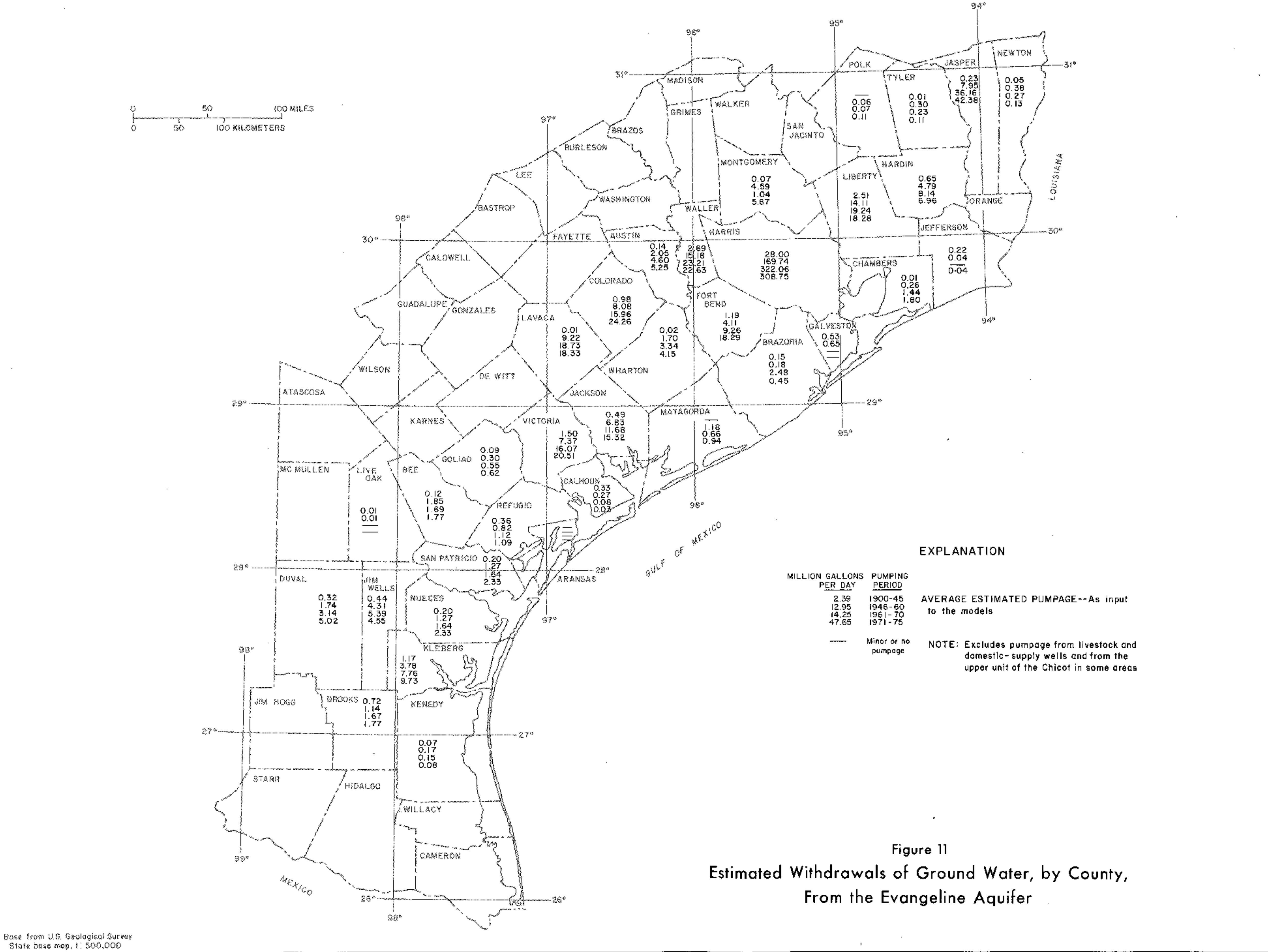


Figure 11

Estimated Withdrawals of Ground Water, by County, From the Evangeline Aquifer

periods. The distribution of withdrawals by aquifer was based on the proportion of well screens in each aquifer. Withdrawals from the upper unit of the Chicot aquifer were not modeled because withdrawals are minor in most areas.

Transmissivities

Estimates of transmissivity were originally determined from aquifer-test data by using either the Theis (1935) equation or the modified Hantush (1960) equation as outlined by Lohman (1972, p. 15-19, p. 32-34). Distribution of the estimated transmissivity was then made by multiplying the sand thickness of the aquifer at a given location by the average hydraulic conductivity as determined from the estimates of transmissivity for a given area. It should be noted that because of violations of the assumptions used by the analytical equations, the transmissivities as determined from aquifer-test data are only approximations. Therefore, the transmissivities were used to define a reasonable range of values to be tested in the models.

The areal distributions of the transmissivities of the Chicot and Evangeline aquifers that were refined through model calibrations are shown in Figures 12-15. The transmissivity of the Chicot aquifer ranged from about 3,000 ft^2/d (279 m^2/d) to about 50,000 ft^2/d (4,645 m^2/d). The transmissivity of the Evangeline aquifer ranged from about 3,000 ft^2/d (279 m^2/d) to about 15,000 ft^2/d (1,394 m^2/d).

Storage Coefficients

Aquifers

Estimates of the storage coefficients of the aquifers were originally determined from aquifer-test data that were analyzed by the Theis (1935) equation or the modified Hantush (1960) equation, and multiplication of the average sand thickness of the aquifer by 1.0×10^{-6} $feet^{-1}$ (3.3×10^{-6} m^{-1}) as suggested by Lohman (1972). The areal distribution of storage coefficients that were obtained by model calibration is shown in Figures 12-15. The storage coefficient of the Chicot aquifer ranged from about 0.0004 to about 0.1; the storage coefficient of the Evangeline aquifer ranged from about 0.0005 to about 0.1. The larger values are in the outcrop areas where the aquifers are under water-table conditions; the smaller values are in the artesian zones.

Clay Beds

The storage coefficients of the clay beds are included in the models because considerable amounts of water are released from the clay beds as water is pumped from the aquifers. This release of water allows the clay beds to compact, which in turn causes subsidence of the land surface. In the Houston area, subsidence is directly proportional to the volume of water derived from the clay beds because nearly all of the subsidence is related to ground-water pumping. In other parts of the coastal area, subsidence is related to the production of oil and gas in addition to ground-water pumping.

The rate and amount of compaction of the clay beds is dependent on overburden loading, hydraulic conductivity of the clays, previous compaction, length of the drainage path, and charac-

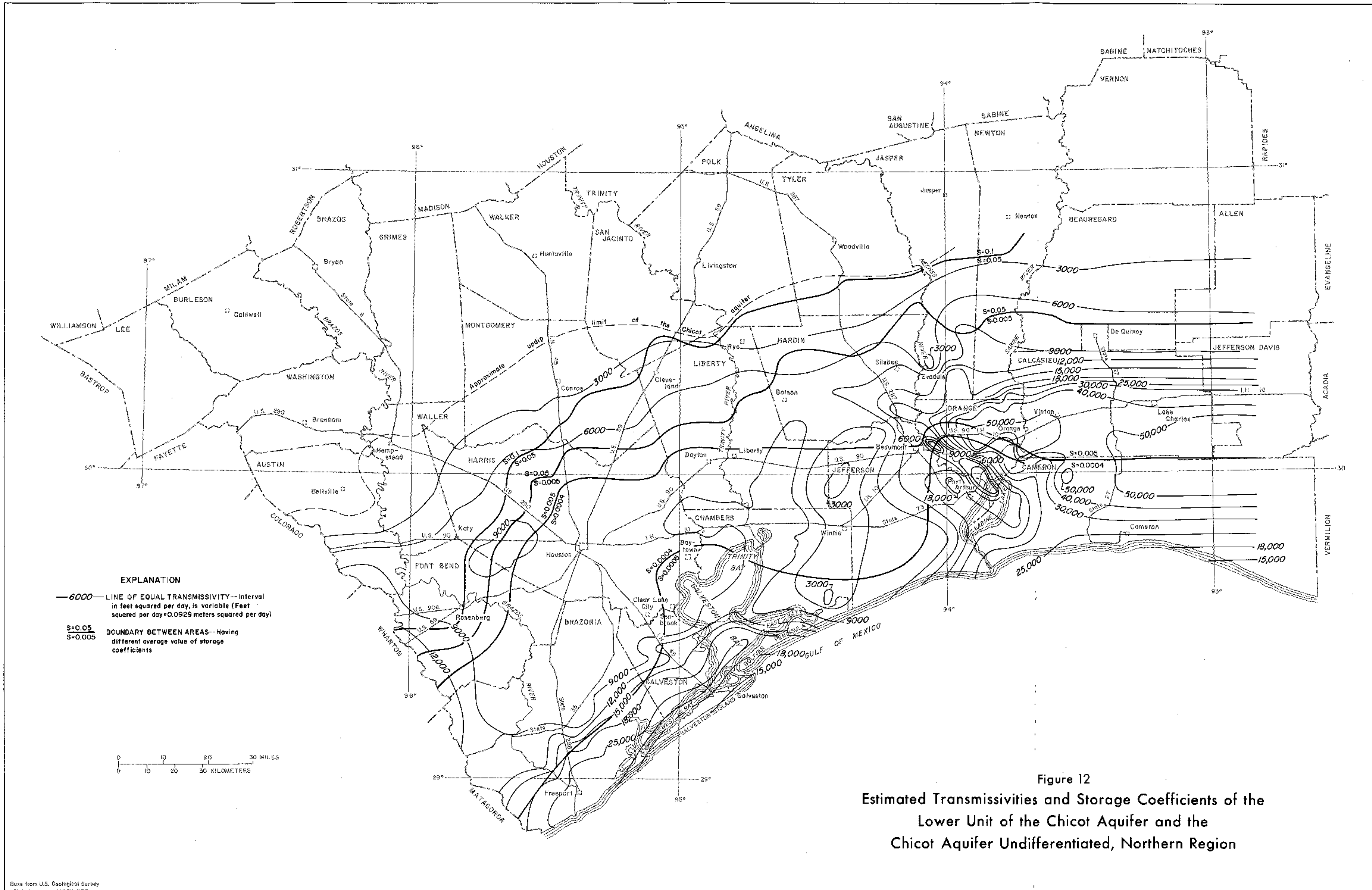


Figure 12

Estimated Transmissivities and Storage Coefficients of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Northern Region

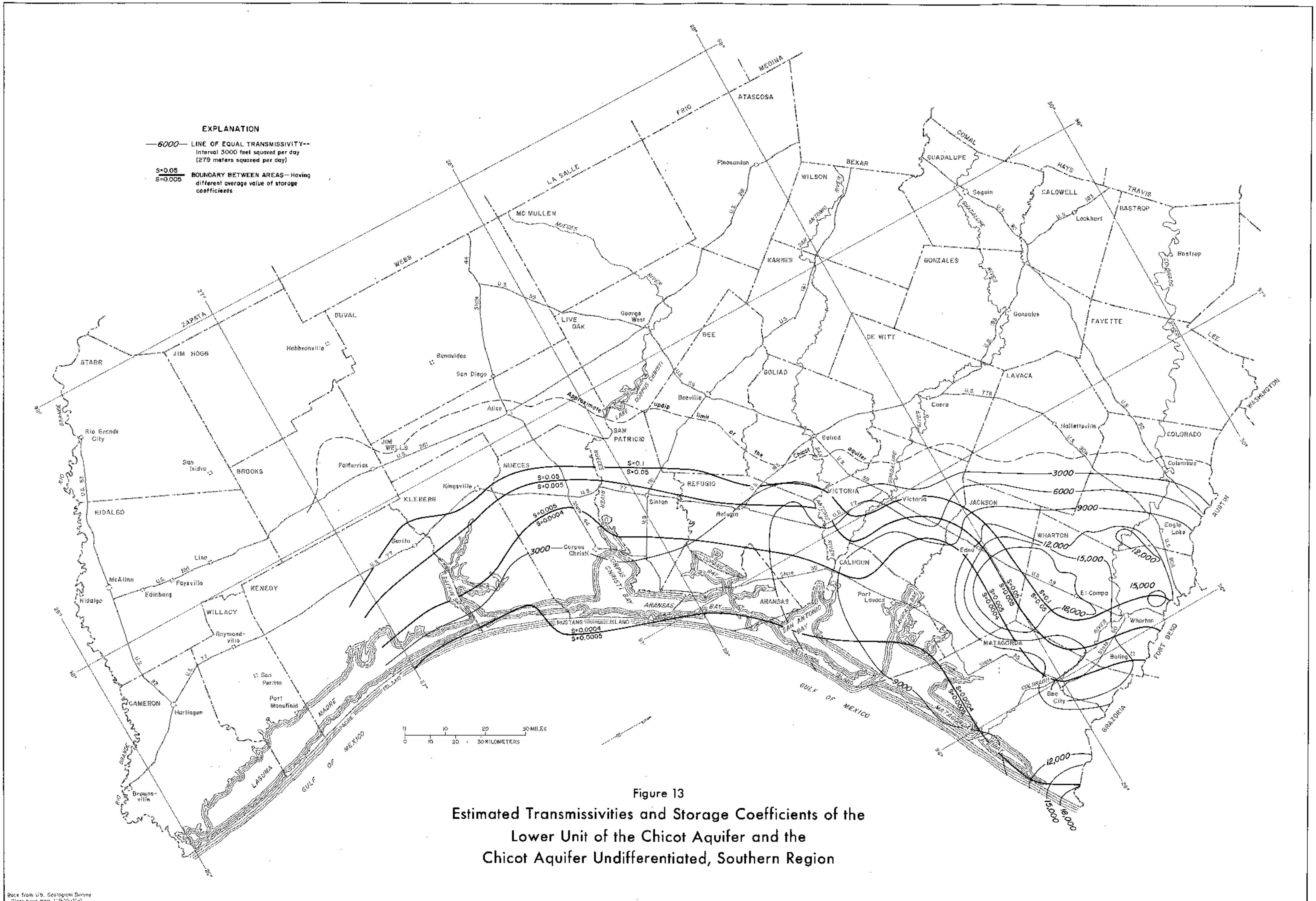


Figure 13

Estimated Transmissivities and Storage Coefficients of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Southern Region

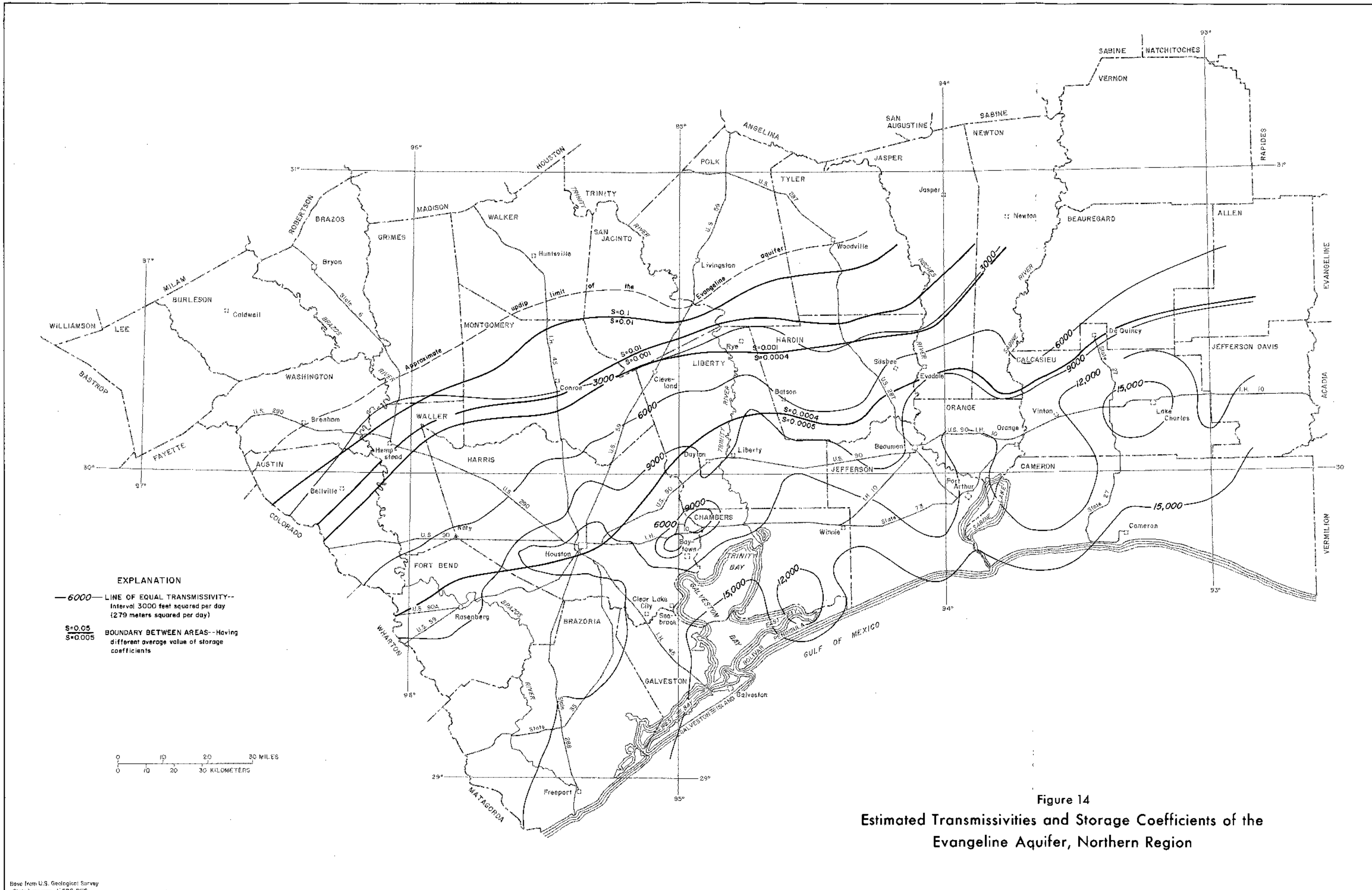


Figure 14
Estimated Transmissivities and Storage Coefficients of the Evangeline Aquifer, Northern Region

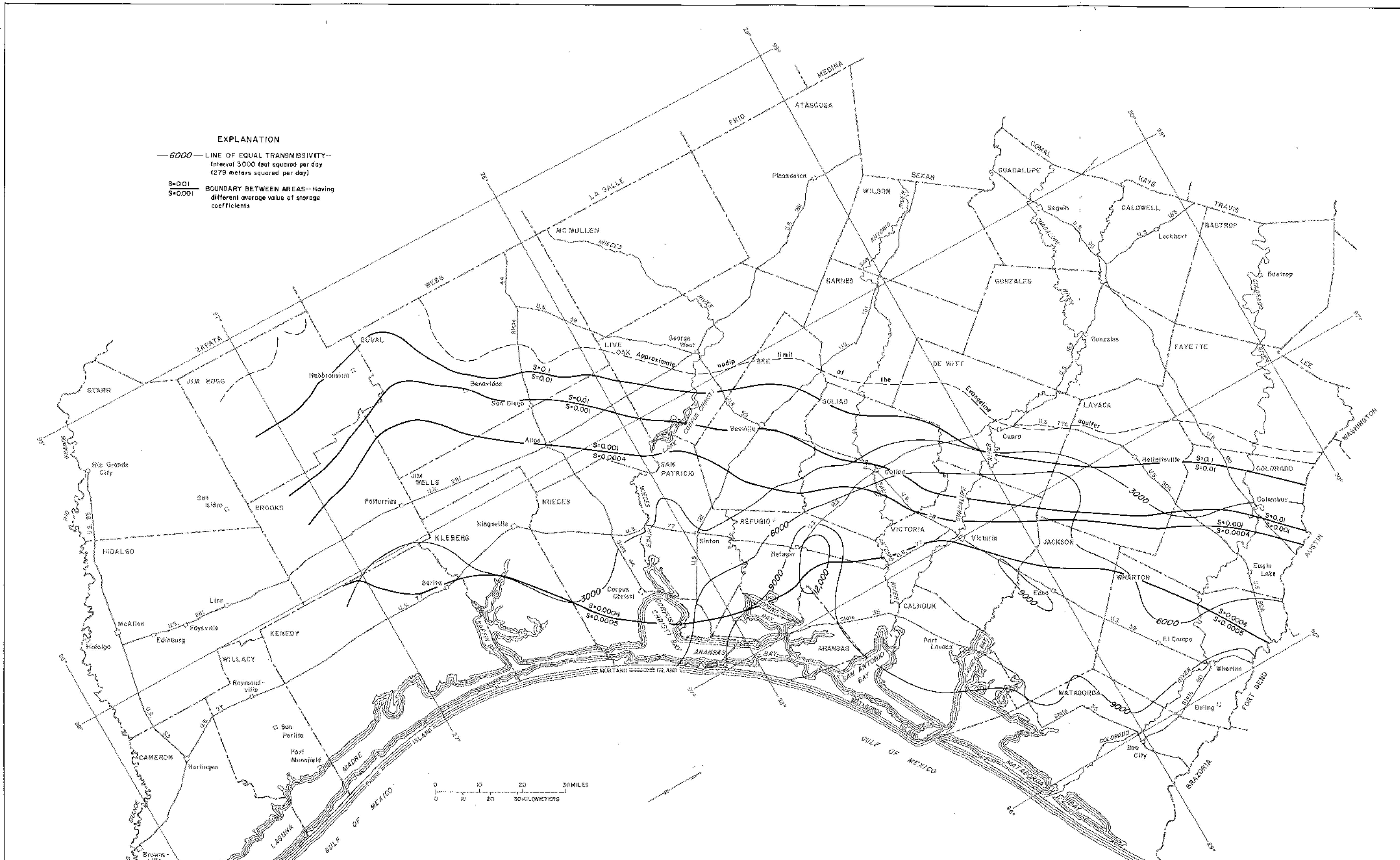


Figure 15

Estimated Transmissivities and Storage Coefficients of the Evangeline Aquifer, Southern Region

teristics of the clays. In general, clays compact more rapidly if the pressure causing compaction is greater than previous pressure or "preconsolidation load." Reported values of the "compaction ratio," which is the ratio of the volume of land-surface subsidence to the volume of water pumped, range from about 0.17 to 0.22 in the Houston area (Jorgensen, 1975, p. 49).

By relating subsidence of the land surface, clay thickness, and decrease in artesian pressure, the following method was used to derive the storage coefficients of the clay beds in the Houston area. The assumption was made that one-half of the subsidence occurred in model layer 2 and one-half occurred in layer 4. Distribution of clay-storage values for layers 2 and 4 were obtained for 1943-73 by first calculating specific unit-compaction where subsidence data were available. The specific unit-compaction for the clay in layer 4 was determined at a given node as follows:

$$\text{Specific unit-compaction in layer 4} = \frac{1/2 \text{ total subsidence for the time period}}{\text{clay thickness in layer 4} \times \text{artesian-pressure decrease in the Chicot aquifer for a given time period}} \qquad (1)$$

The specific unit-compaction for the clay in layer 2 was determined in a similar manner by using the clay thickness in layer 2 and the artesian-pressure decrease in the Evangeline aquifer. The two specific unit-compaction values were then averaged to compute a mean specific unit-compaction for layers 2 and 4. The mean value for each layer was then multiplied by the thickness of clay (Figures 16-19) at each node to obtain the storage coefficients for each layer.

Specific unit-compaction values are an approximation of specific storage if the resulting compaction approximates the ultimate compaction expected from an applied stress. The mean specific unit-compaction values determined for the model of the Houston subregion for 1943-73 are 1.0×10^{-4} feet^{-1} (3.2×10^{-4} m^{-1}) for layer 4 and 1.8×10^{-5} feet^{-1} (5.9×10^{-5} m^{-1}) for layer 2. The inelastic storage coefficients used in the models, which were obtained as the product of the mean specific unit-compaction and the clay thickness, ranged from 5.8×10^{-3} to 5.0×10^{-2}. In comparison, the minimum inelastic storage coefficients for the clay beds, as indicated by the ratio of subsidence to water-level declines, ranged from 5×10^{-3} to 3×10^{-2} (Jorgensen, 1975, p. 44). Elastic storage coefficients used in the models for the clay beds were obtained from model calibrations.

The decision to assign one-half of the subsidence to layer 2 and one-half to layer 4 for calculating specific unit-compaction was based primarily on data from a compaction monitor at Seabrook. Data from this site indicated that about 55 percent of the subsidence resulted from compaction of the clay beds in the Chicot aquifer and about 45 percent resulted from compaction of the clay beds in the Evangeline aquifer. However, because of the lack of data to define a more accurate spatial distribution of clay storage, 50 percent of the subsidence was assigned to each unit on a regional basis. The error resulting from this assumption is minimized because even though the specific unit-compaction of the Evangeline aquifer usually is smaller than that of the Chicot aquifer, the clay thickness and water-level declines in the Evangeline usually are greater. Therefore, the amount of subsidence occurring within each unit tends to be approximately equal. In addition, the calibration procedure indicated that the models are only moderately sensitive to storage in clay beds, which would further minimize the error of this assumption.

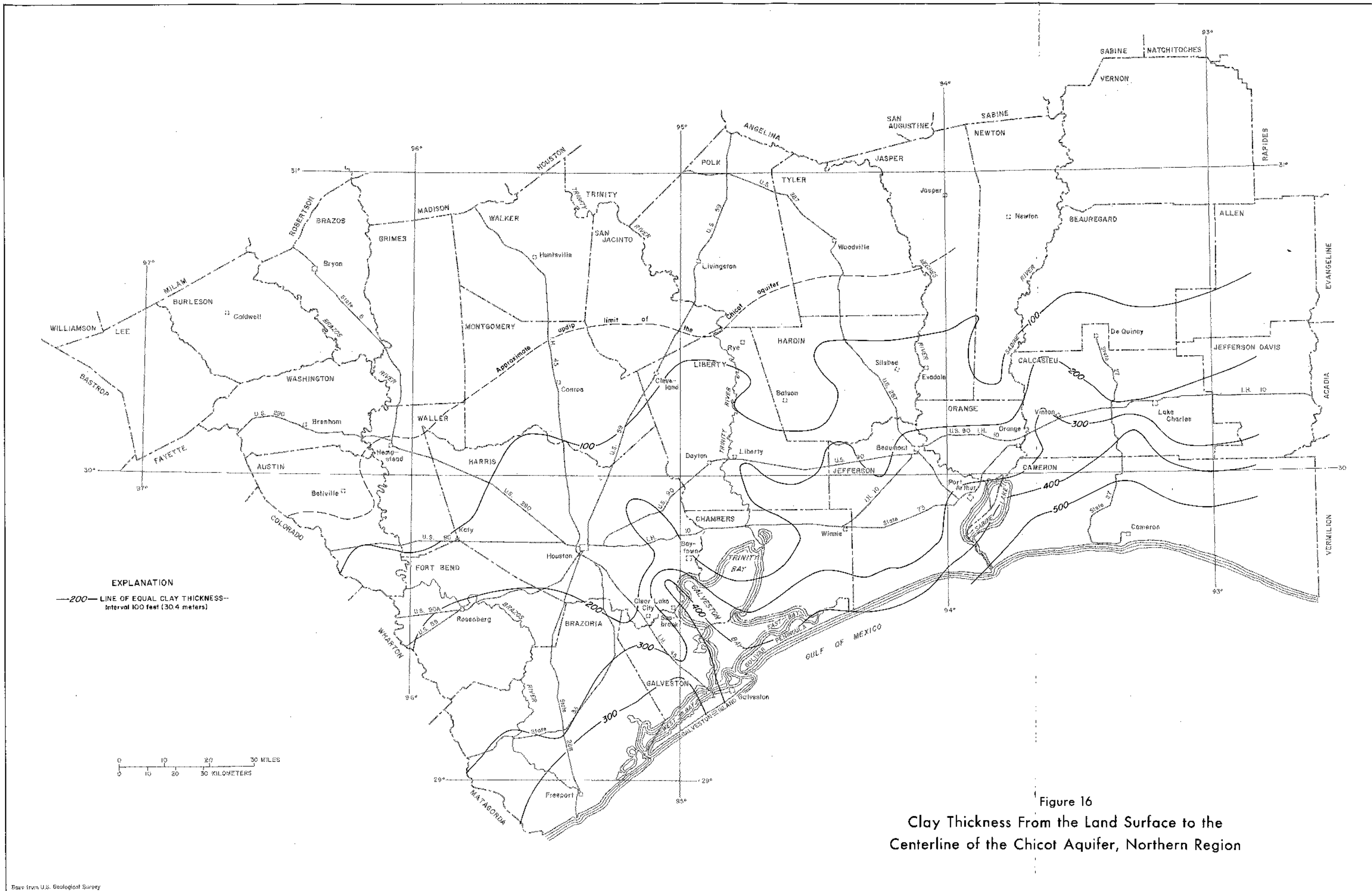


Figure 16

Clay Thickness From the Land Surface to the Centerline of the Chicot Aquifer, Northern Region

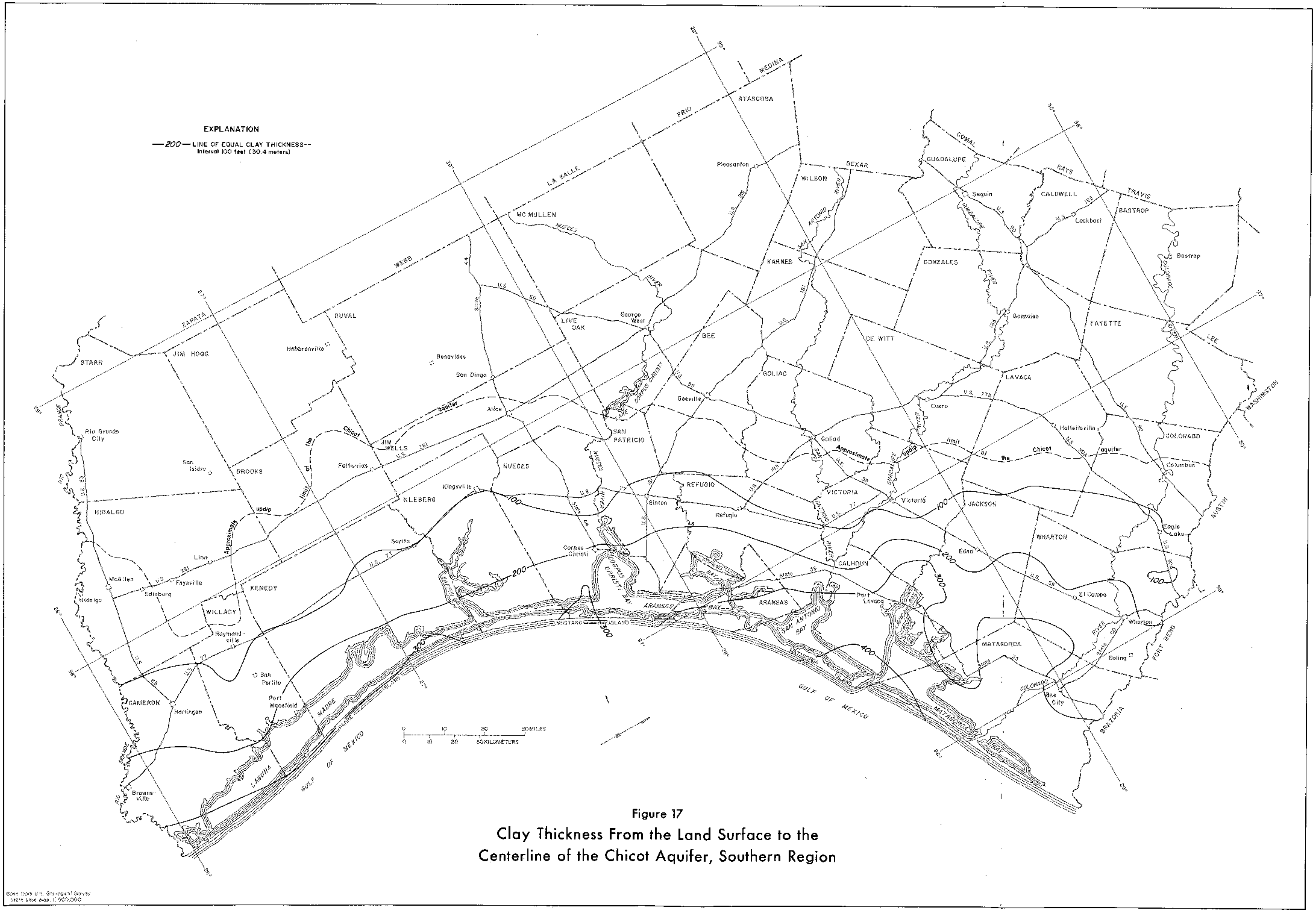


Figure 17

Clay Thickness From the Land Surface to the Centerline of the Chicot Aquifer, Southern Region

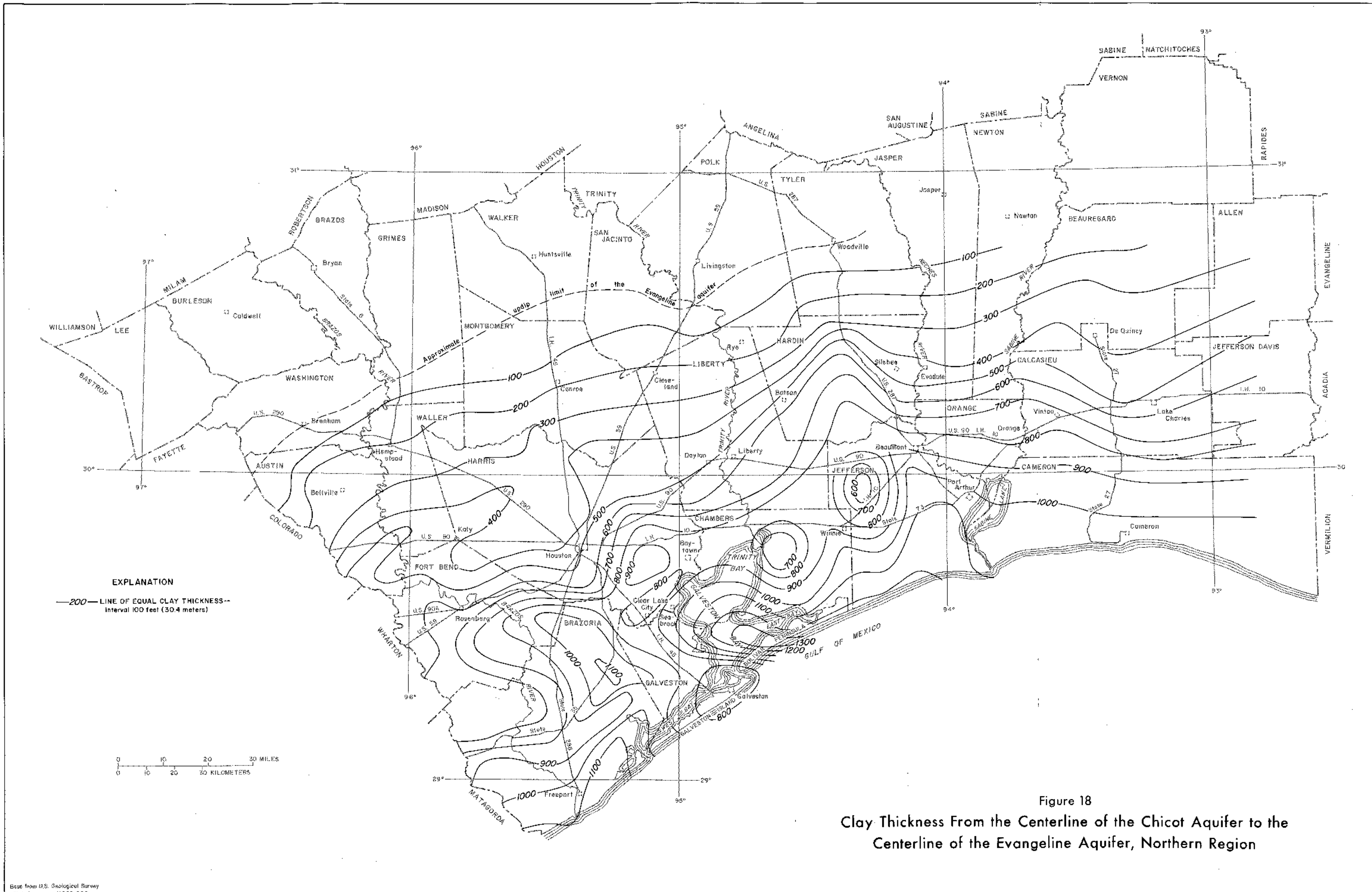


Figure 18

Clay Thickness From the Centerline of the Chicot Aquifer to the Centerline of the Evangeline Aquifer, Northern Region

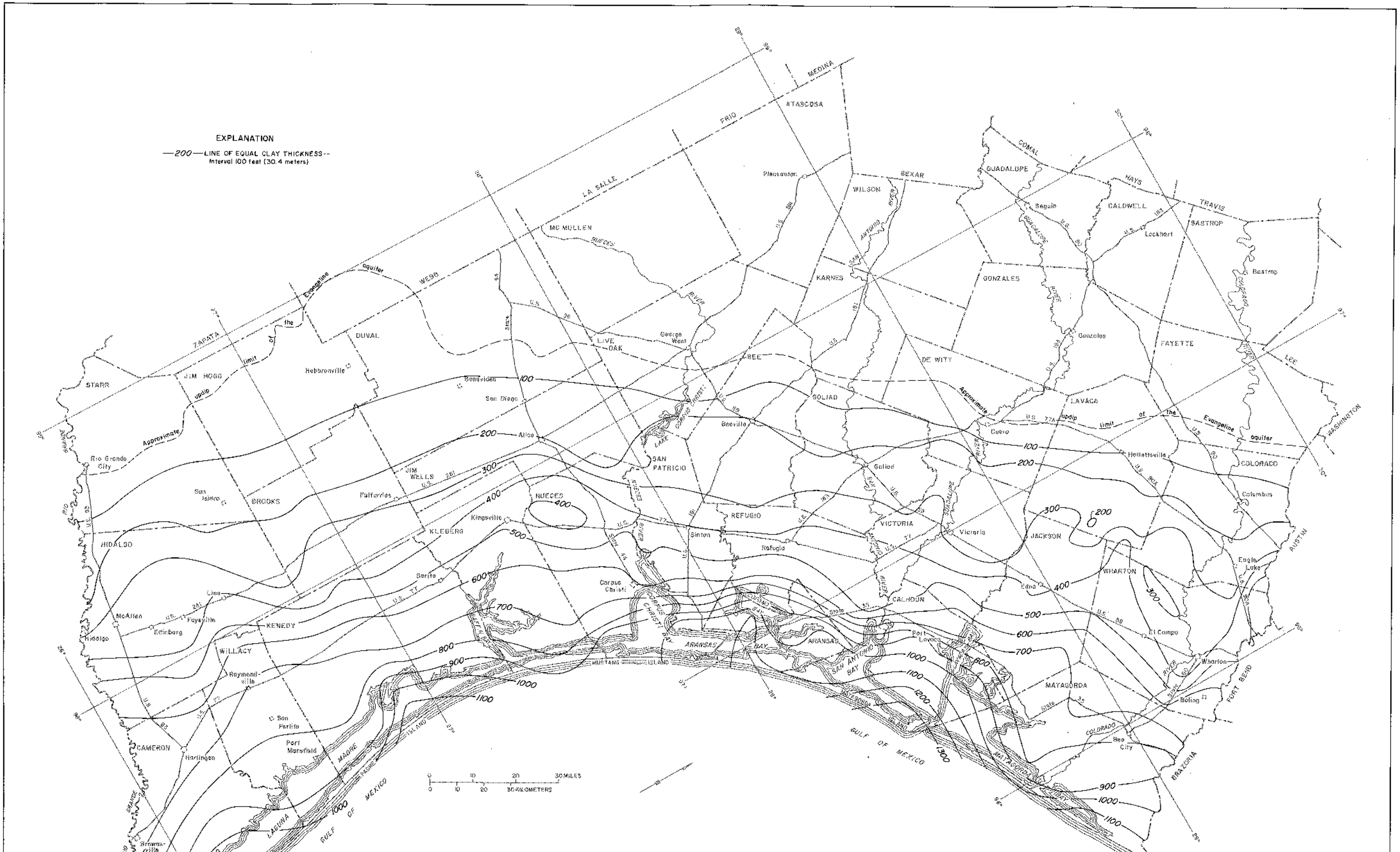


Figure 19

Clay Thickness From the Centerline of the Chicot Aquifer to the Centerline of the Evangeline Aquifer, Southern Region

The storage coefficients of the clay beds were used in the model to represent approximately the elastic response for a stress that is less than the preconsolidation loading and to represent approximately the inelastic response for a stress exceeding the preconsolidation loading. These storage coefficients, or slightly modified coefficients, were used later in the other modeled subregions.

A preconsolidation-stress variable (critical head) is used in the models to control the initial change in storage in clay beds at any given node as a function of head decline. This variable represents the maximum antecedent effective stress to which a deposit has been subjected and the stress that it can withstand without undergoing permanent deformation. Stress changes less than the preconsolidation stress produce elastic deformations of small magnitude. Within this range, the clay beds have smaller storage coefficients than if the preconsolidation stress is exceeded.

The preconsolidation stress approximates the maximum effective stress to which deposits within the study area have been subjected prior to ground-water development. This preconsolidation stress, as determined by calibration of the model of the Houston subregion, is 70 feet (21 m), which means that 70 feet (21 m) of head decline must occur at a node before the model converts to an inelastic storage value. However, the lowest head value computed at a node is retained and becomes the control for changes in storage in clay beds after the preconsolidation stress is reached. The preconsolidation stress of 70 feet (21 m) was assumed to be applicable in the models of the other subregions.

The maximum effective stress to which the clay deposits at a node have been subjected is represented by the lowest head value. After the initial change in head at a node, storage in clay beds is allowed to return to preconsolidation values when the computed head rises above the lowest head value retained. If the head declines below the lowest head value retained, storage is again changed to the consolidation value for that node.

The quantity of water that was derived from storage in the clay beds was computed by the models and summarized as a total contribution from the clay beds. The volume per model node was obtained by multiplying the water-level decline, in feet, by the apparent storage coefficient and by the area of the node, in square feet. The volume of water that originated in the clay beds ranged from 16 to 31 percent of the water pumped in the model simulations.

Effective Vertical Hydraulic Conductivity and Vertical Leakage

The effective vertical hydraulic conductivity of the aquifers is controlled primarily by the clay beds that occur within the vertical sequence of sand beds. By using three different clay layers, Jorgensen (1975, p. 54) estimated that the effective vertical hydraulic conductivity ranges from as little as 10^{-7} ft/d (0.3×10^{-7} m/d) to as much as 1 ft/d (0.3 m/d). Because of the large differences in the estimated effective vertical hydraulic conductivity, the values used in the models were determined by model calibration.

Effective vertical hydraulic conductivity as determined by calibration of the models ranged from 9.2×10^{-5} to 2.3×10^{-4} ft/d (2.8×10^{-5} to 0.7×10^{-5} m/d). The effective vertical hydraulic conductivity from the land surface to the centerline of the Chicot aquifer ranged from 3.2×10^{-5} to 2.3×10^{-4} ft/d (0.98×10^{-6} to 0.7×10^{-5} m/d). The effective vertical hydraulic conductivity from the centerline of the Chicot aquifer to the centerline of the Evangeline aquifer ranged from 9.2×10^{-5} to 4.6×10^{-3} ft/d (2.8×10^{-5} to 1.4×10^{-3} m/d).

Vertical leakage from the uppermost layer ranged from 21 to 47 percent of the amount of water pumped in the model simulations. The maximum vertical leakage per square mile ranged from 0.24 to 4.3 in/yr (0.61 to 10.9 cm/yr) at the end of 1975.

Declines in the Altitudes of the Potentiometric Surfaces

Maps showing declines in the altitudes of the potentiometric surfaces were constructed for the lower unit of the Chicot aquifer, the Chicot aquifer undifferentiated, and the Evangeline aquifer. Maps for the Houston subregion were constructed for 1890-1970 and 1890-1975. Maps for the other subregions were constructed for 1900-1970 and 1900-1975.

The maps were constructed to show the approximate altitude of the potentiometric surface at the centerline of the aquifer. However, it should be noted that wells screened at different depths in an anisotropic aquifer will probably have different depths to water, even if the wells are within a few feet of each other. Most single-screened wells in an area will have depths to water of about plus or minus 10 feet (3 m) of the depth used to construct the maps showing the declines in the altitudes of the potentiometric surfaces.

CALIBRATION AND SENSITIVITY OF THE MODELS

The models were calibrated by simulating the declines in the altitude of the potentiometric surfaces and comparing the simulated declines to the declines obtained from historic measurements for all models from 1890 or 1900 to 1970 except the Houston model, which was calibrated from 1890 or 1900 to 1975. Where the comparison of the observed declines and the simulated declines was poor, the hydrologic properties were modified and the models were tested again. This procedure was continued until the models satisfactorily simulated the observed declines. The grid patterns of the models, the observed and simulated declines in the altitude of the potentiometric surfaces, and the observed and simulated subsidence of the land surface are shown as follows:

Eastern-subregion model — Figures 20-25
Houston-subregion model — Figures 26-31
Central-subregion model — Figures 32-37
Southern-subregion model — Figures 38-43

For each of the subregions, the models were calibrated on "minimodels" (grids not shown). Each minimodel grid was composed of about one-half or less of the number of nodes that were used in the maximodel grids. Programs were written to transfer data from the maximodels to the minimodels. Results are shown from the maximodel runs in this report. The use of the "minimodels" permitted a number of relatively inexpensive computations to be used in calibrating the models. The calibrations indicated that the models were very sensitive to variations in storage in water-table aquifers and transmissivity. They are less sensitive to variations in storage in artesian aquifers and to variations in storage in clay beds. Previous testing of the model of the Houston area (Meyer and Carr, 1979) with a constant-head boundary showed that the boundary effects were minimal within short distances of the boundaries.

Some important relationships that were indicated by the calibration procedure are:

1. A large part of the Chicot aquifer in the updip section is under water-table conditions.

2. Vertical leakage of water, exclusive of irrigation returns, from the land surface to the lower part of the Chicot aquifer is an important part of the hydrologic system; however, this decreases in importance in the southern subregion.

3. Transmissivity values as determined by model calibration are about 70 to 80 percent of the value obtained by the Theis equation alone.

4. Verification was made of the interpretation by Jorgensen (1975) that in the Katy area, large amounts of water are exchanged between aquifers through irrigation wells and other wells that are open to more than one aquifer; and as much as 30 percent of the water pumped for irrigation returns to the Chicot aquifer in this area.

LIMITATIONS ON USE OF THE MODELS

The values of the hydrologic properties modeled are rational values for the hydrologic system; however, further investigations and the acquisition of additional data will allow more accurate determination of these values. The models were designed to simulate the effects of withdrawals of water from a well field for periods of 1 year or longer; the models were not designed to simulate the effects of one well pumping for a short period of time. The models were not designed to predict land-surface subsidence accurately; although the simulation of clay compaction was included. For a more accurate simulation of subsidence, more detailed data on local areas will be needed.

DATA NEEDED FOR IMPROVEMENT OF THE MODELS

The hydrologic data that are most needed to improve the models are: (1) Water-level data from observation wells that are screened in only one water-bearing unit; (2) additional data on the quantity of water pumped for irrigation; (3) more accurate determination of storage coefficients for the clay beds in each aquifer; (4) data to determine compaction coefficients for areas outside the Houston area; and (5) more detailed information on the thickness of the clay beds.

SUMMARY

The Texas Gulf Coast has two major aquifers above the Burkeville confining layer, the Chicot and the Evangeline. Both aquifers consist of alternating layers of sand and clay that dip gently towards the Gulf of Mexico. The Chicot aquifer is the uppermost one and in some places along the coast, mainly in the Houston area, it can be separated into an upper and a lower unit. The upper unit, which is not an important source of water along most of the Texas Gulf Coast, can be separated from the lower unit by differences in hydraulic head. Where the units cannot be separated, the aquifer is said to be undifferentiated. The Evangeline aquifer underlies the Chicot aquifer and also can be separated from it by a difference in head.

Large withdrawals of ground water along the coast have resulted in major cones of depression in the potentiometric surface in the lower unit of the Chicot aquifer and the Evangeline aquifer. Withdrawals of ground water have also resulted in land-surface subsidence along the coast of as much as 8.5 feet (2.6 m) within the Houston area.

Digital-computer models were constructed to study the hydrology of the coastal area and to simulate the decline in the altitude of the potentiometric surfaces. The models were verified, where possible, for declines in the altitude of the potentiometric surface of both aquifers from 1890 to 1975 for the Houston subregion and from 1900 to 1970 for all other subregions. In addition, all models also were verified for the volume of water derived from clay compaction where possible. The models are very sensitive to variations in aquifer transmissivity and in storage in water-table aquifers; they are less sensitive to variations in storage in artesian aquifers and in clay beds.

The model results indicate that a large part of the Chicot aquifer in the updip section is under water-table conditions, that vertical leakage is an important part of the hydrologic system, and that transmissivity values as determined by model calibration are about 70 to 80 percent of those obtained by the Theis equation alone.

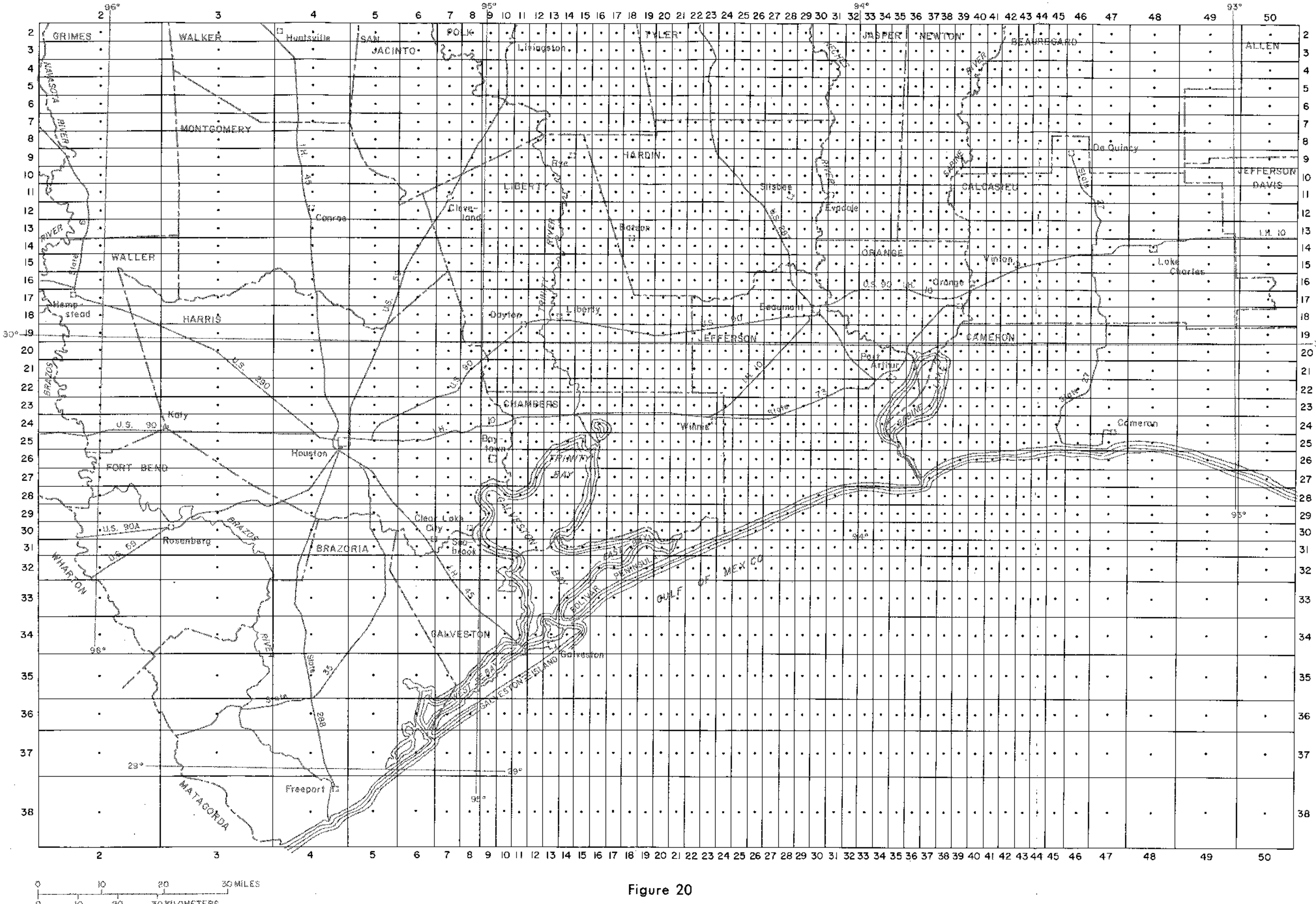


Figure 20

Boundaries and Grid Pattern of the Eastern-Subregion Model

Base from U.S. Geological Survey
State base map, 1:500,000

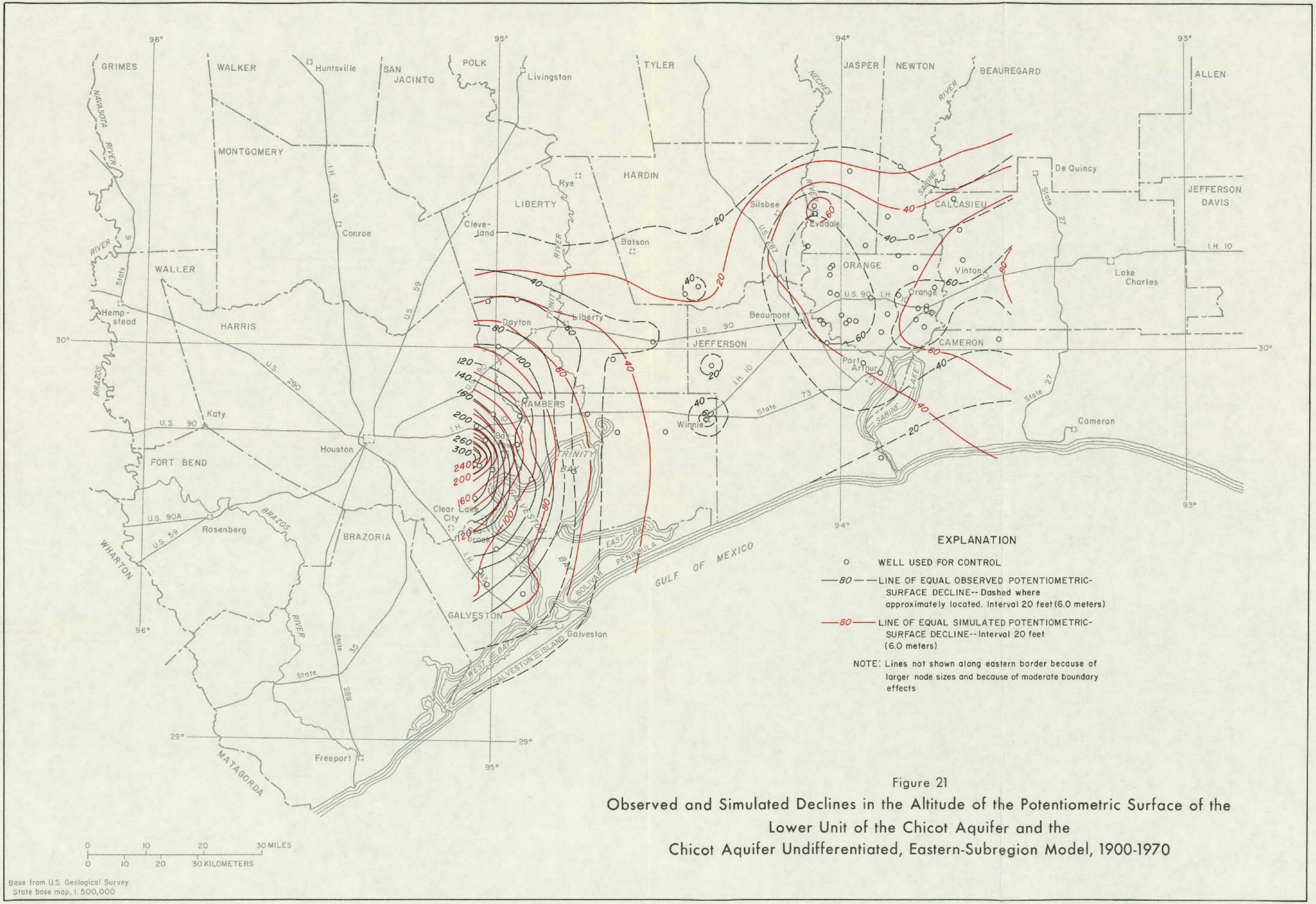


Figure 21

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Eastern-Subregion Model, 1900-1970

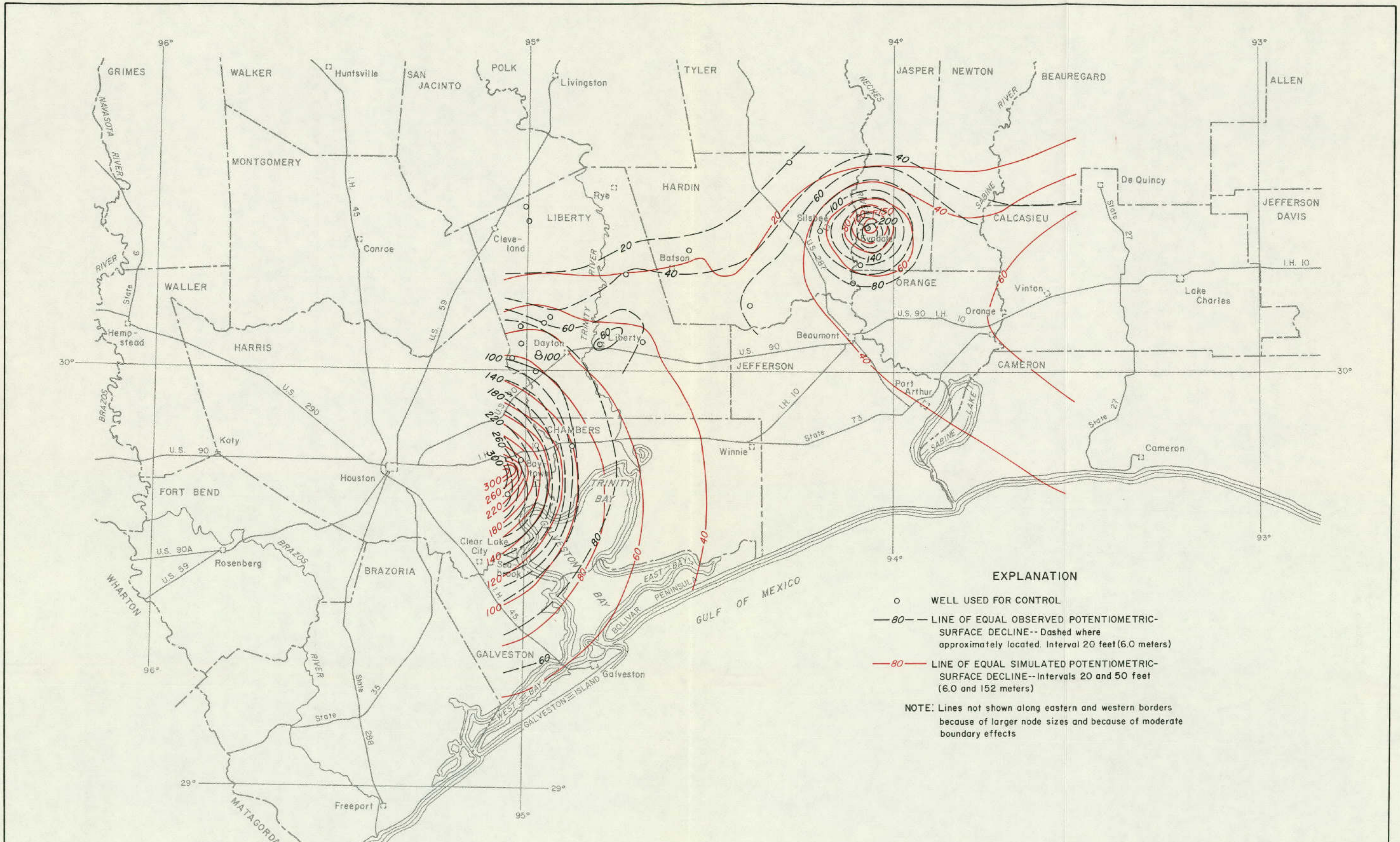


Figure 22

Observed and Simulated Declines in the Potentiometric Surface of the Evangeline Aquifer, Eastern-Subregion Model, 1900-1970

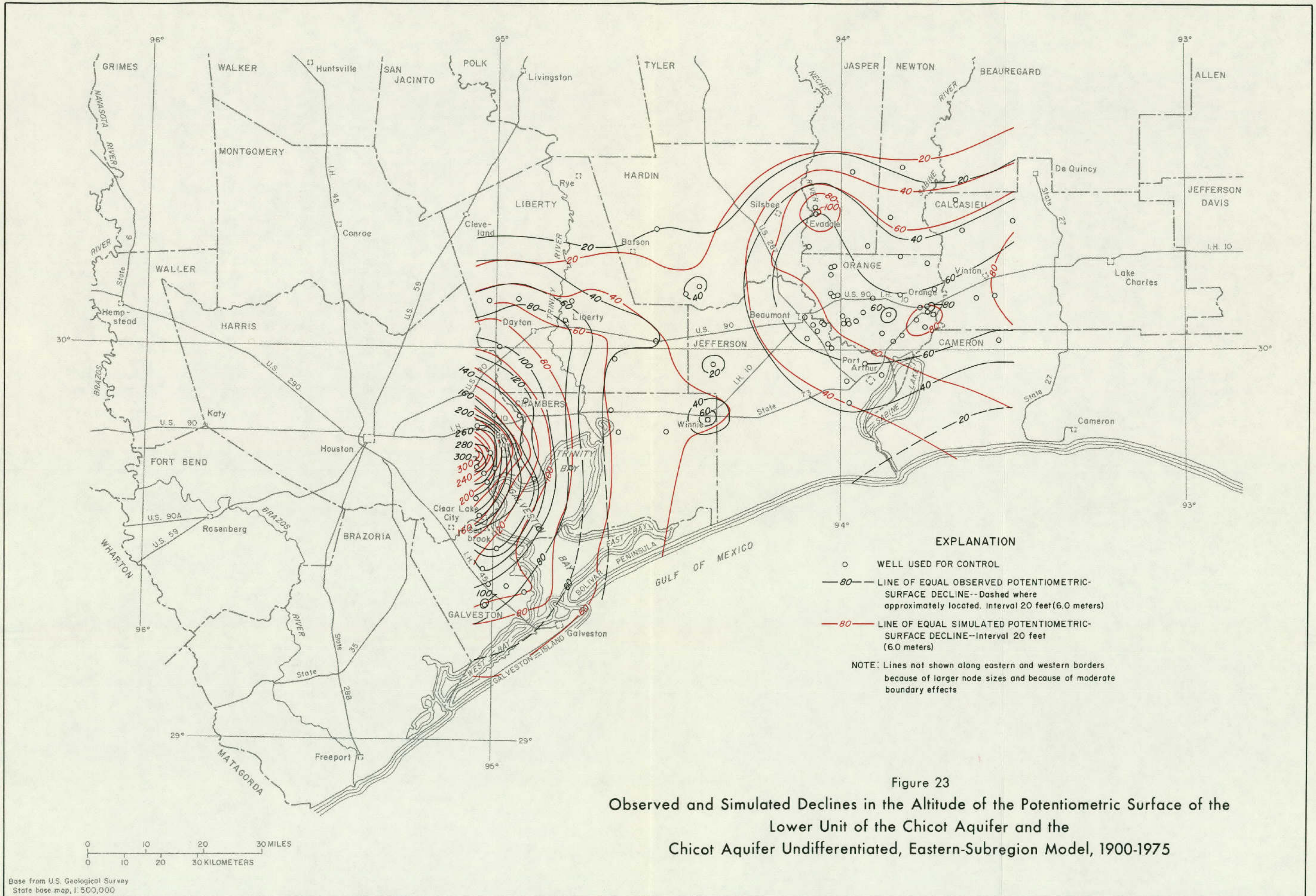


Figure 23

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Eastern-Subregion Model, 1900-1975

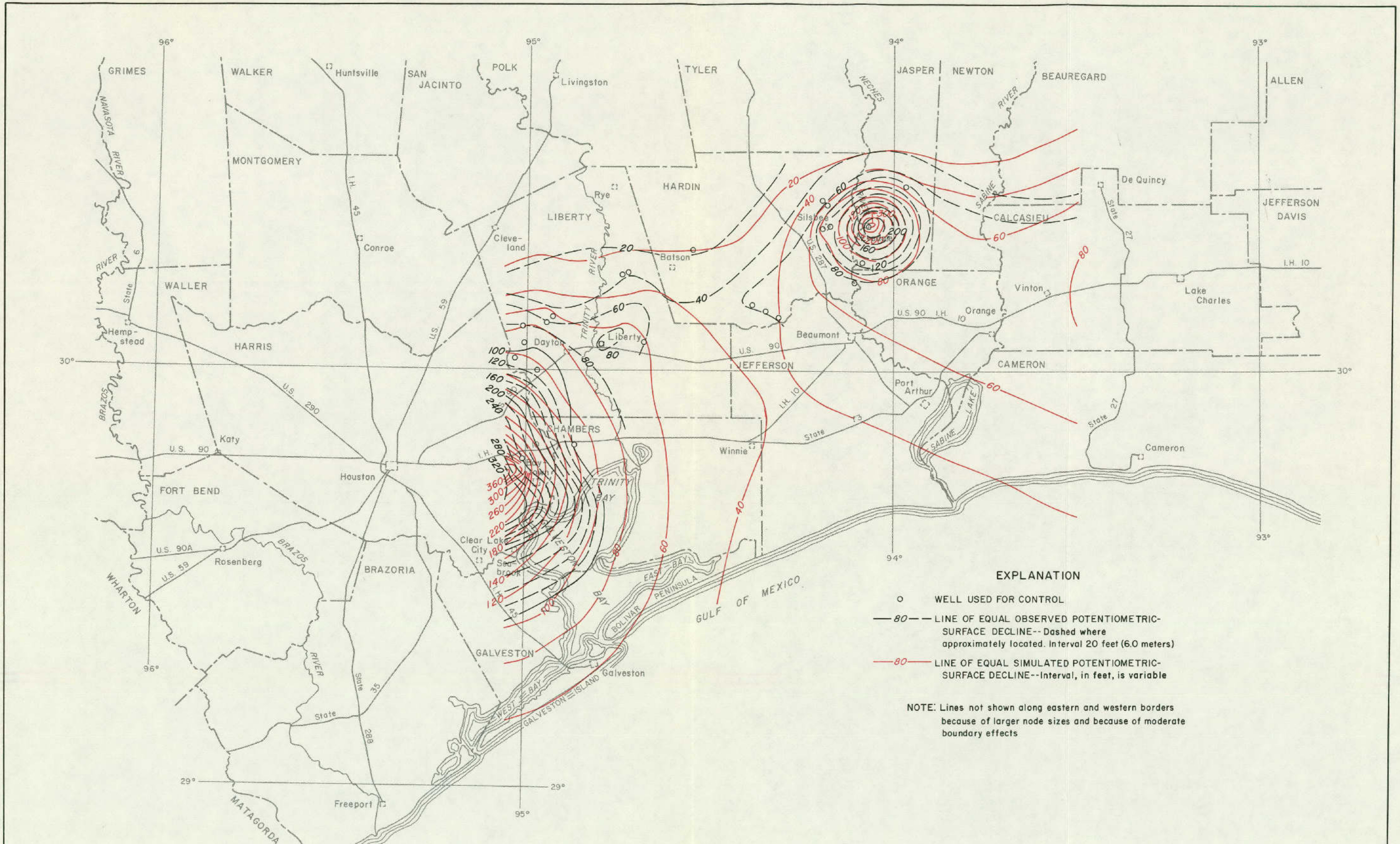


Figure 24

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Evangeline Aquifer, Eastern-Subregion Model, 1900-1975

0 10 20 30 MILES

0 10 20 30 KILOMETERS

Base from U.S. Geological Survey
State base map, 1:500,000

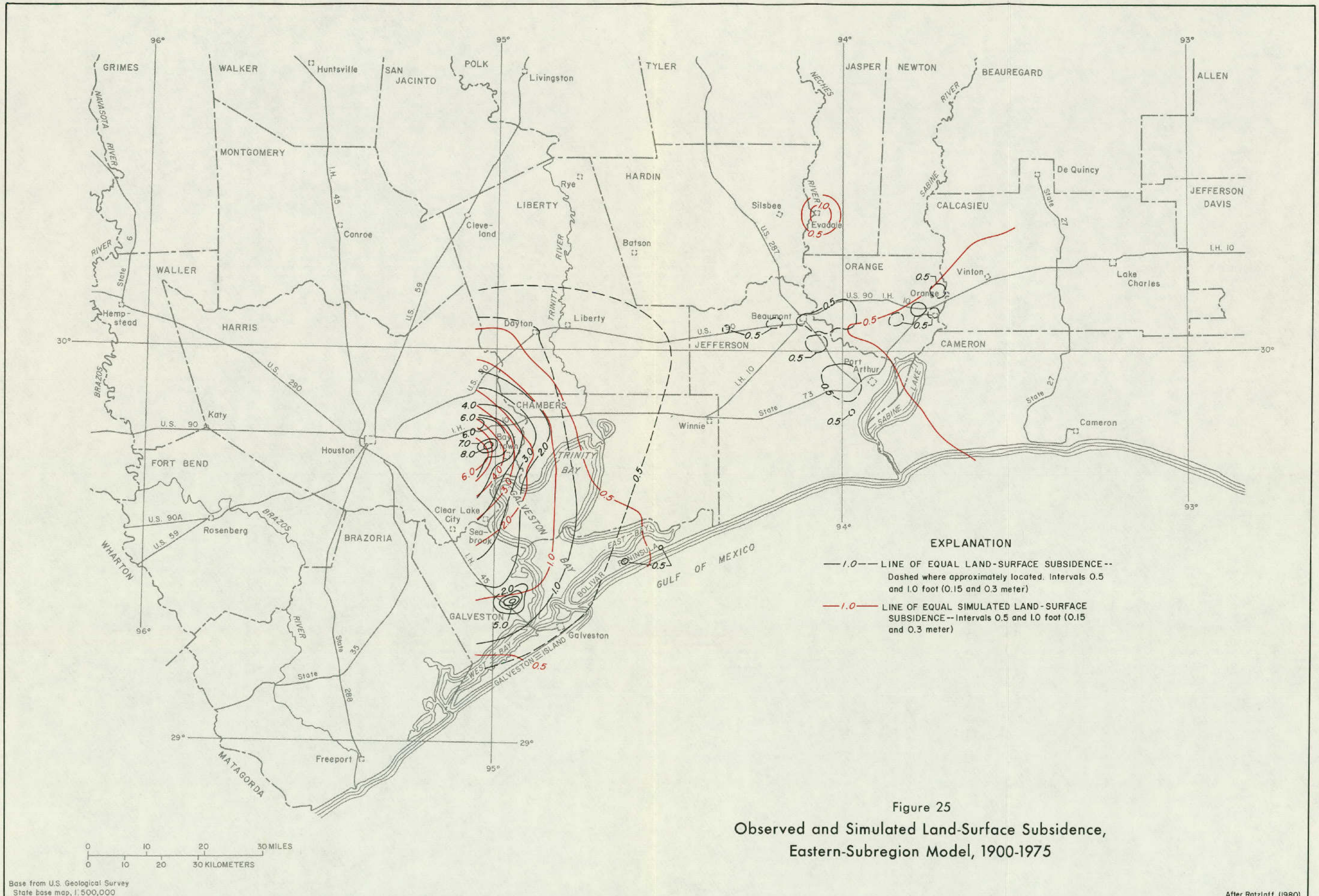


Figure 25

Observed and Simulated Land-Surface Subsidence, Eastern-Subregion Model, 1900-1975

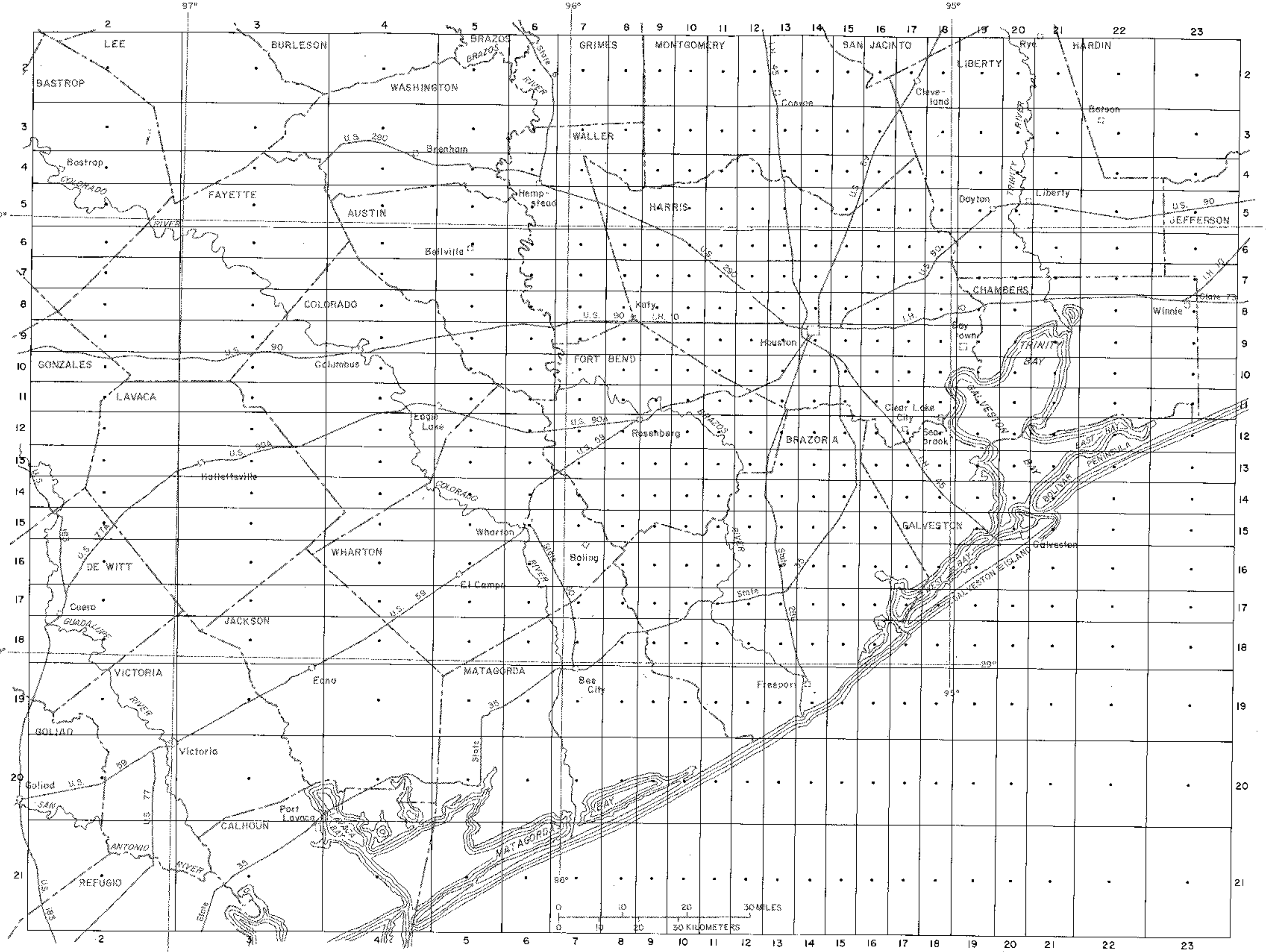


Figure 26

Boundaries and Grid Pattern of the Houston-Subregion Model

Base from U.S. Geological Survey
State base map, 1:500,000

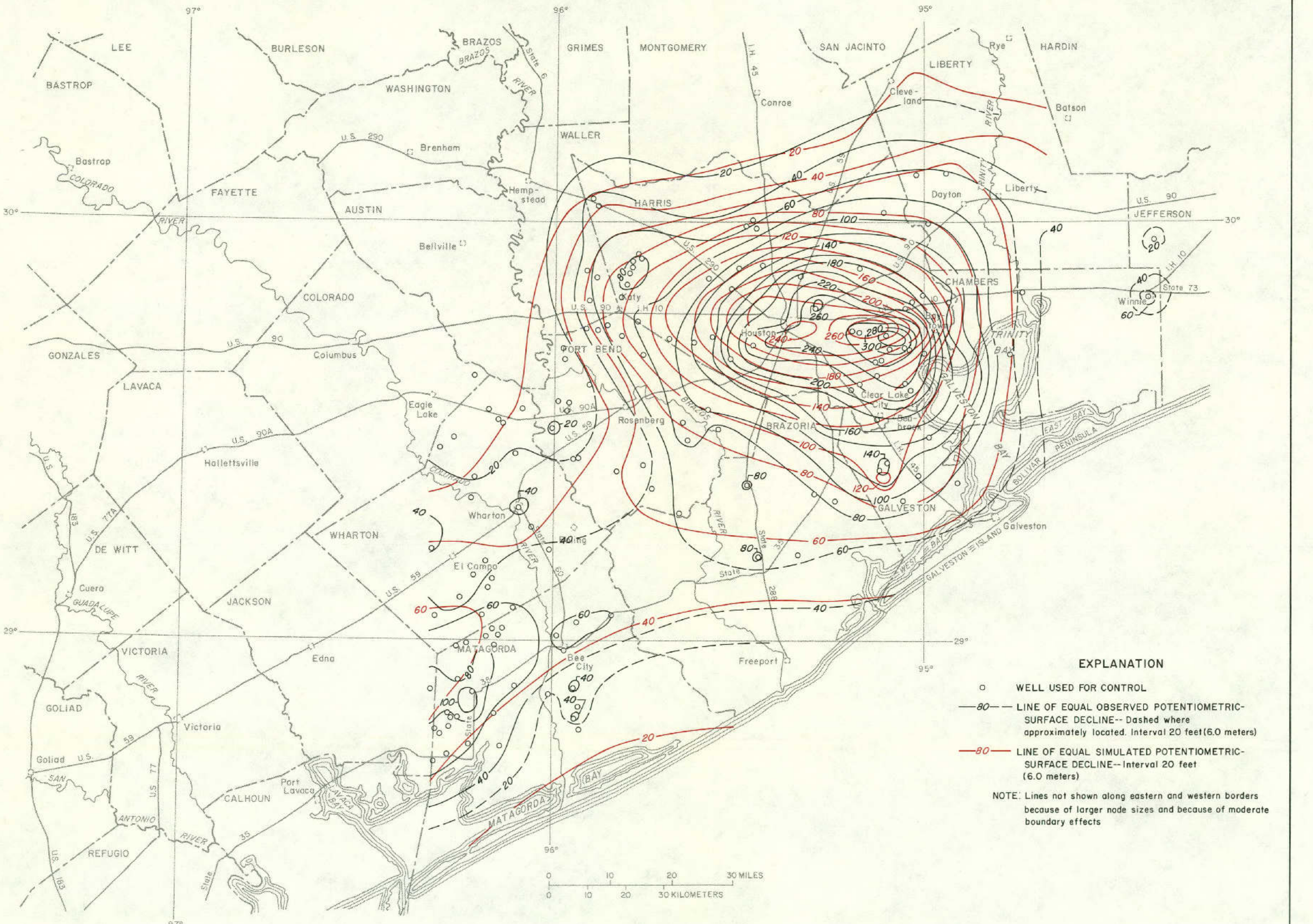


Figure 27

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Houston-Subregion Model, 1890-1970

Base from U.S. Geological Survey State base map, 1:500,000

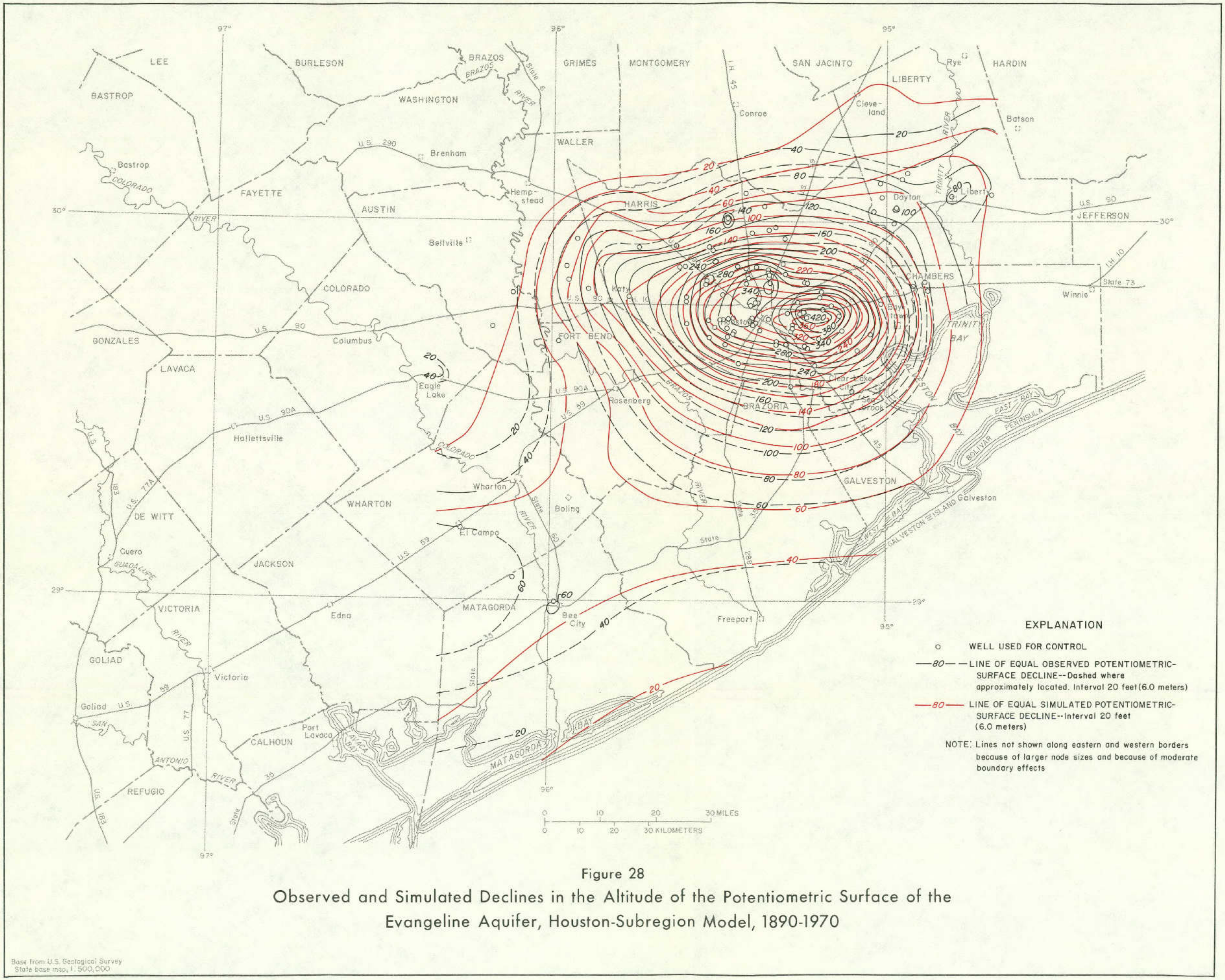


Figure 28
Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Evangeline Aquifer, Houston-Subregion Model, 1890-1970

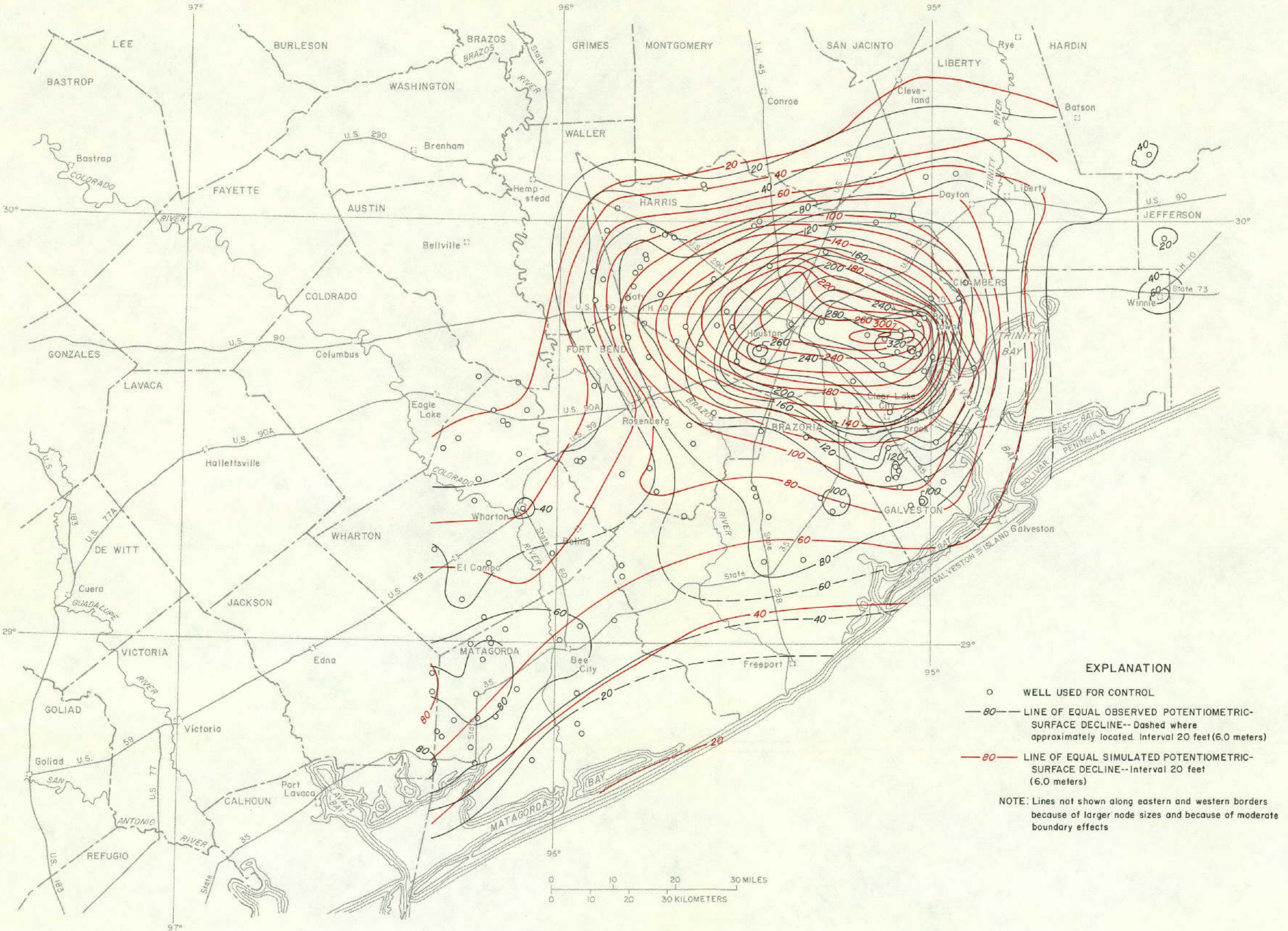


Figure 29

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Houston-Subregion Model, 1890-1975

Base from U.S. Geological Survey
State base map, 1:500,000

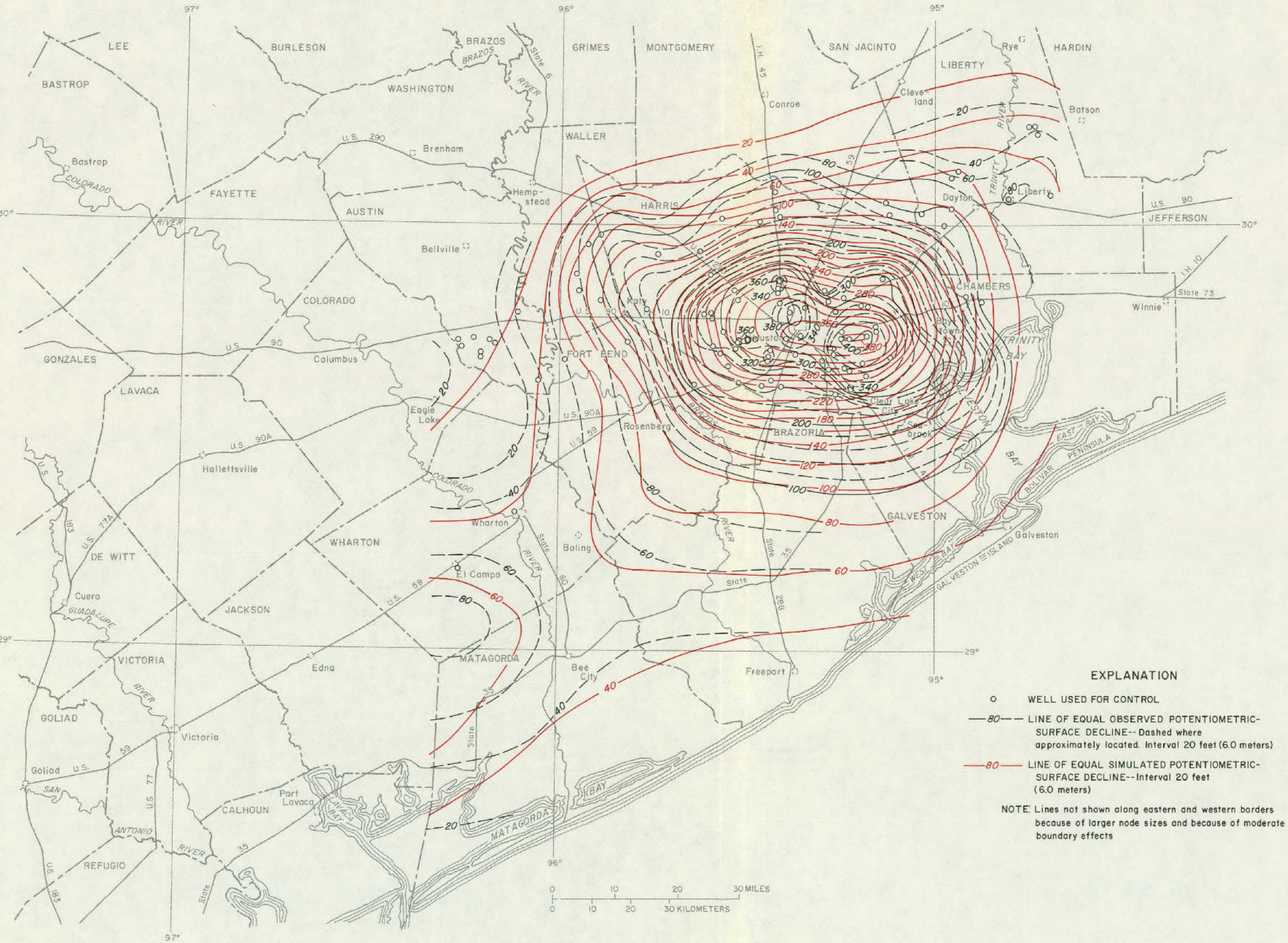


Figure 30

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Evangeline Aquifer, Houston-Subregion Model, 1890-1973

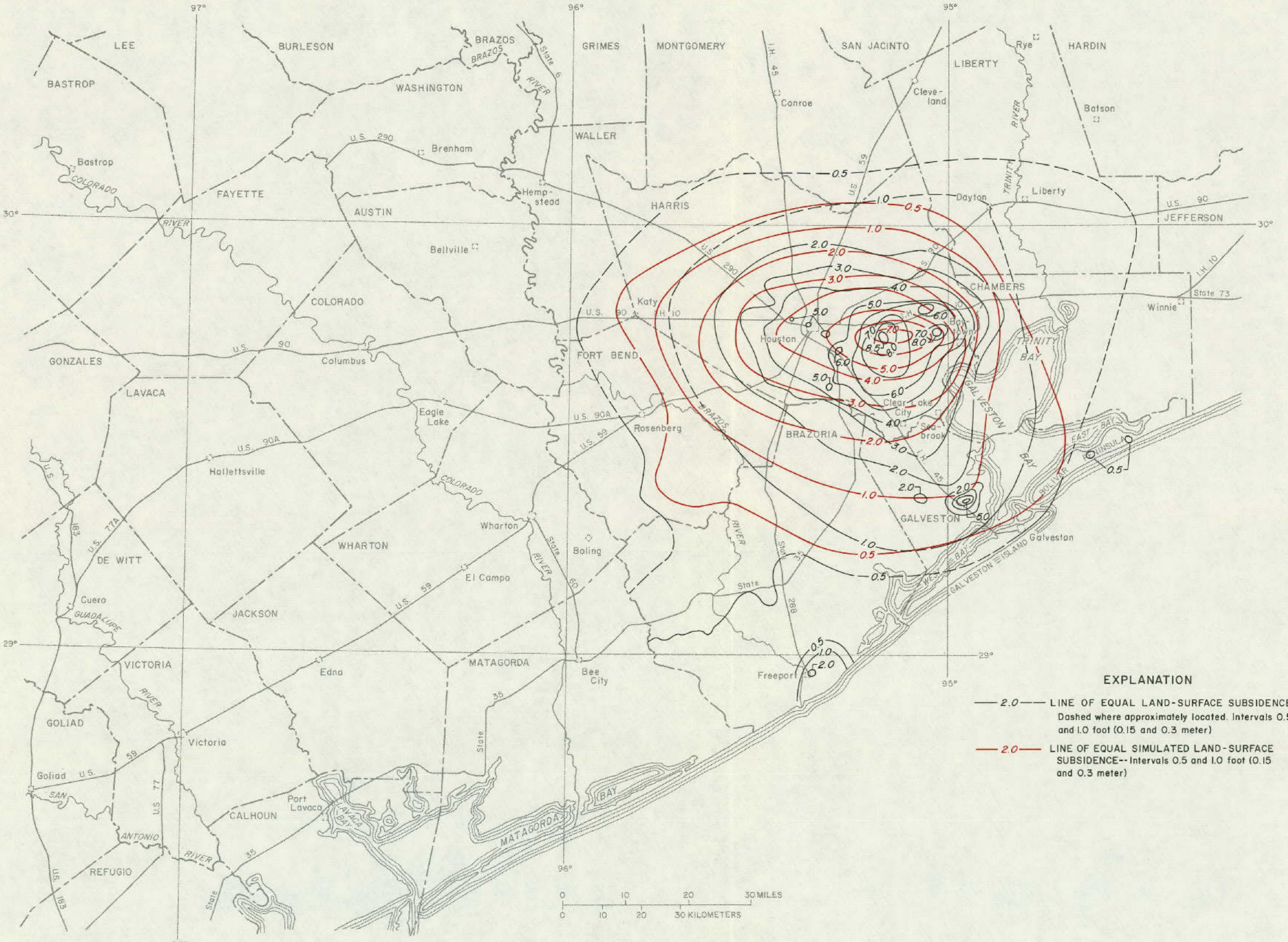


Figure 31

Observed and Simulated Land-Surface Subsidence, Houston-Subregion Model, 1890-1973

Base from U.S. Geological Survey State base map, 1:500,000

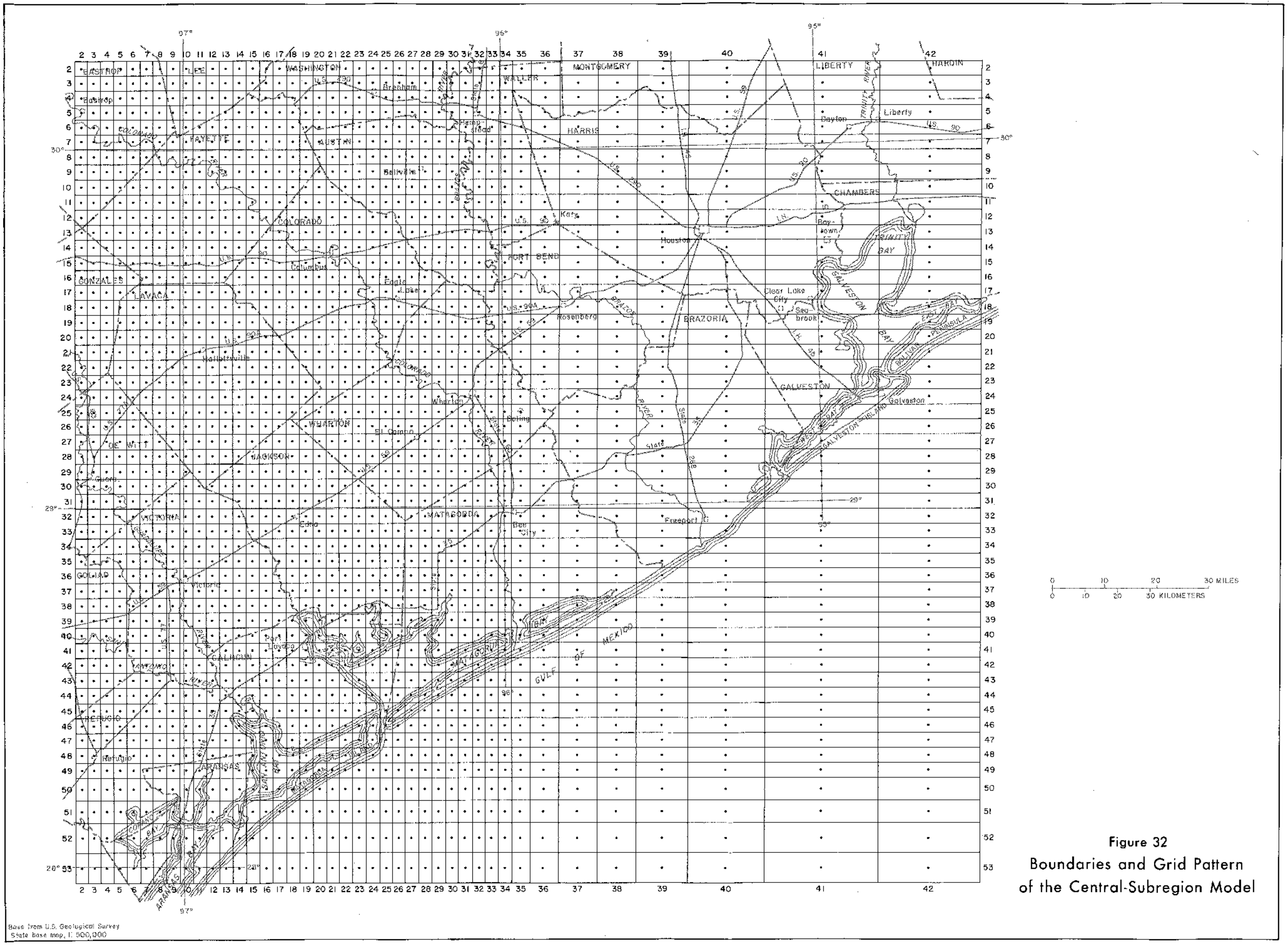


Figure 32
Boundaries and Grid Pattern of the Central-Subregion Model

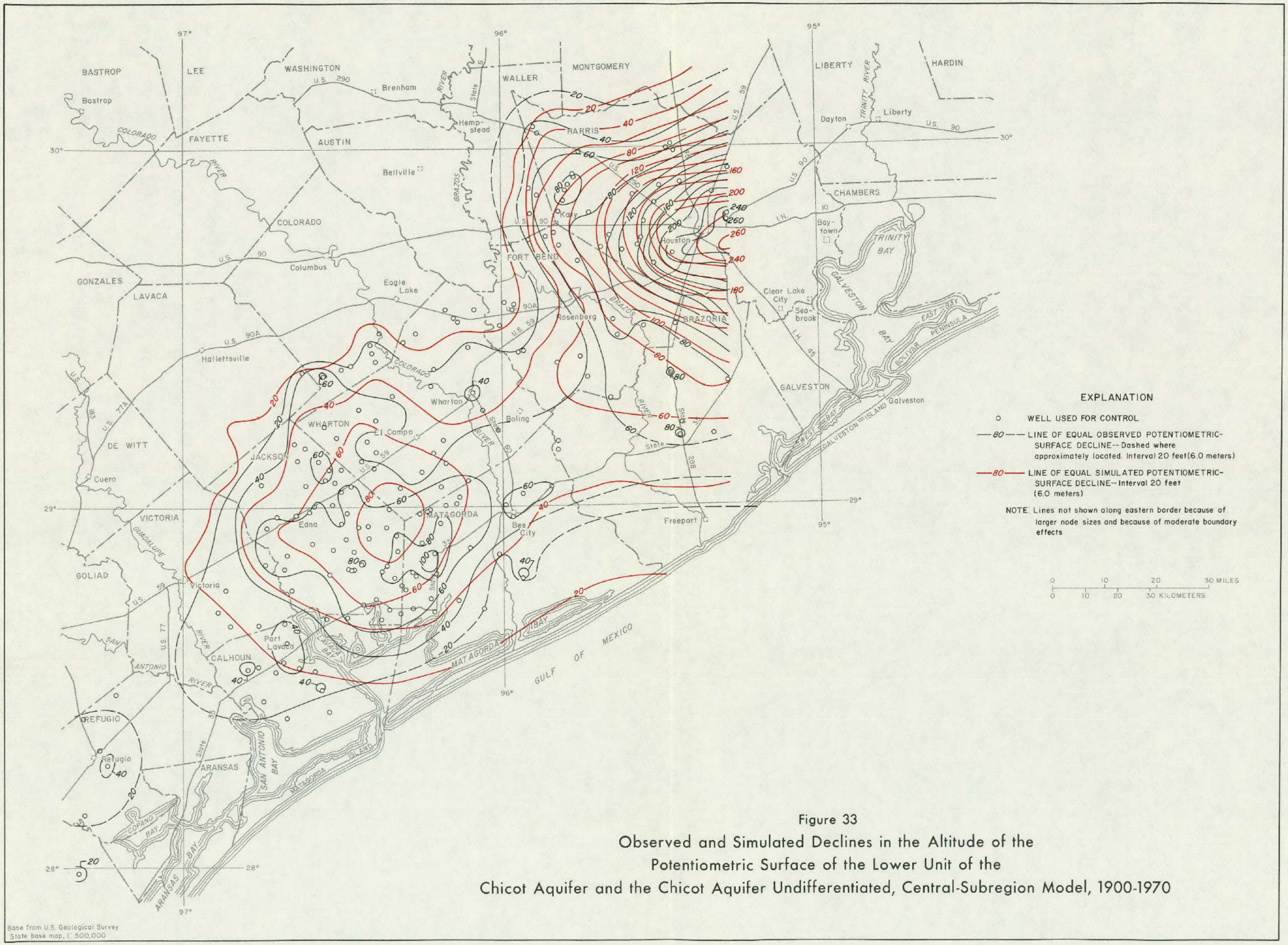


Figure 33

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Central-Subregion Model, 1900-1970

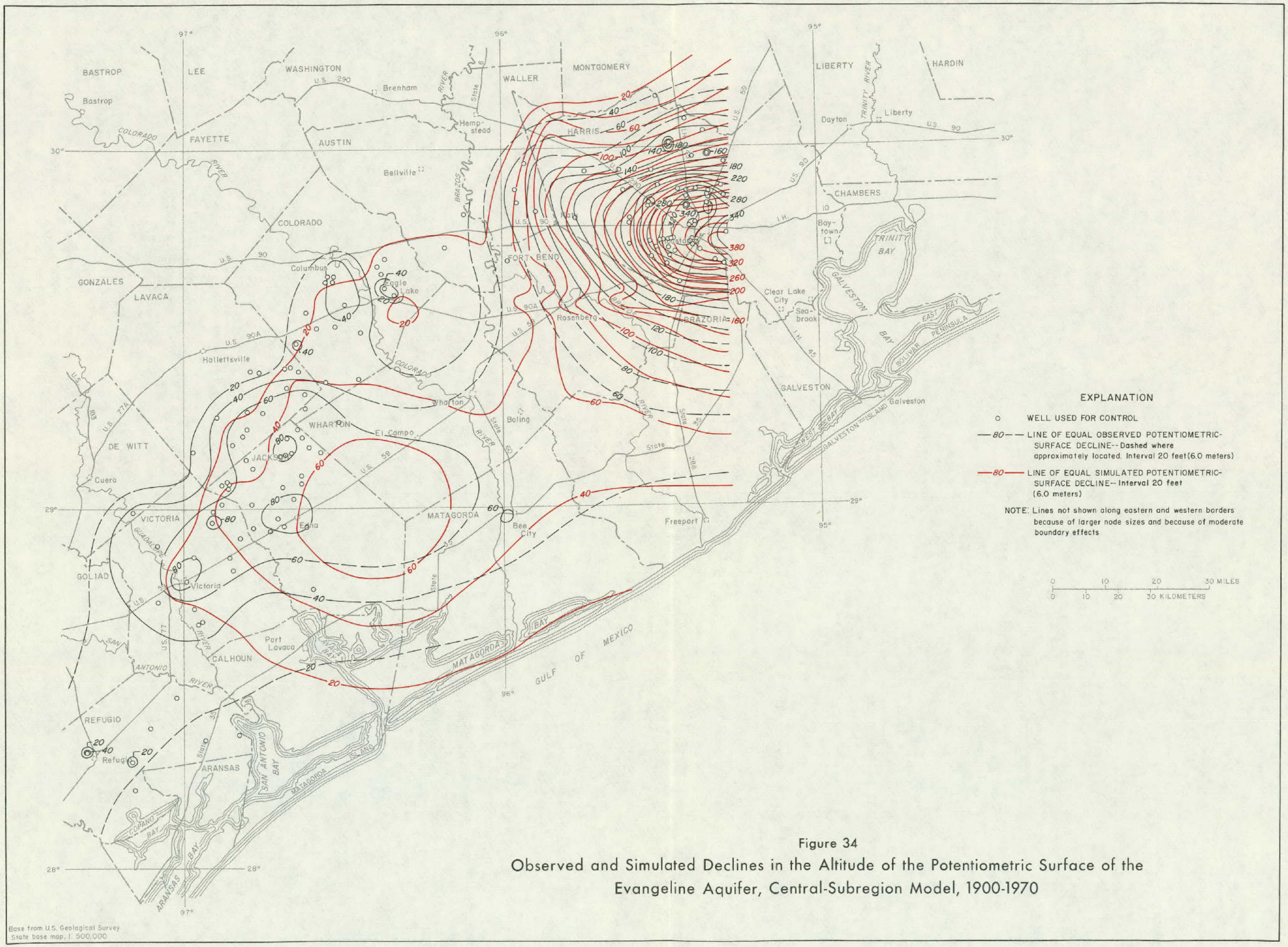


Figure 34

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Evangeline Aquifer, Central-Subregion Model, 1900-1970

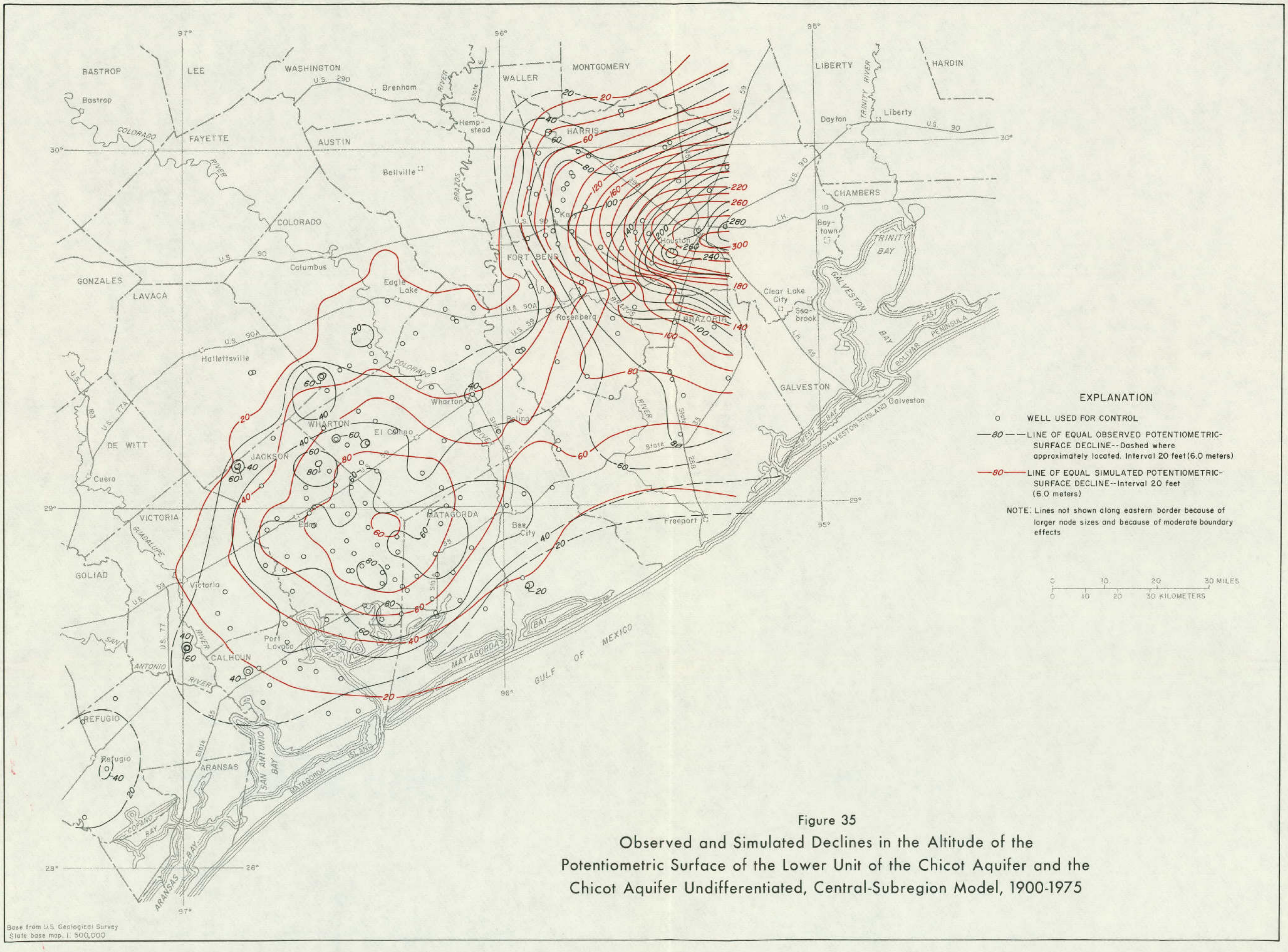


Figure 35

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Lower Unit of the Chicot Aquifer and the Chicot Aquifer Undifferentiated, Central-Subregion Model, 1900-1975

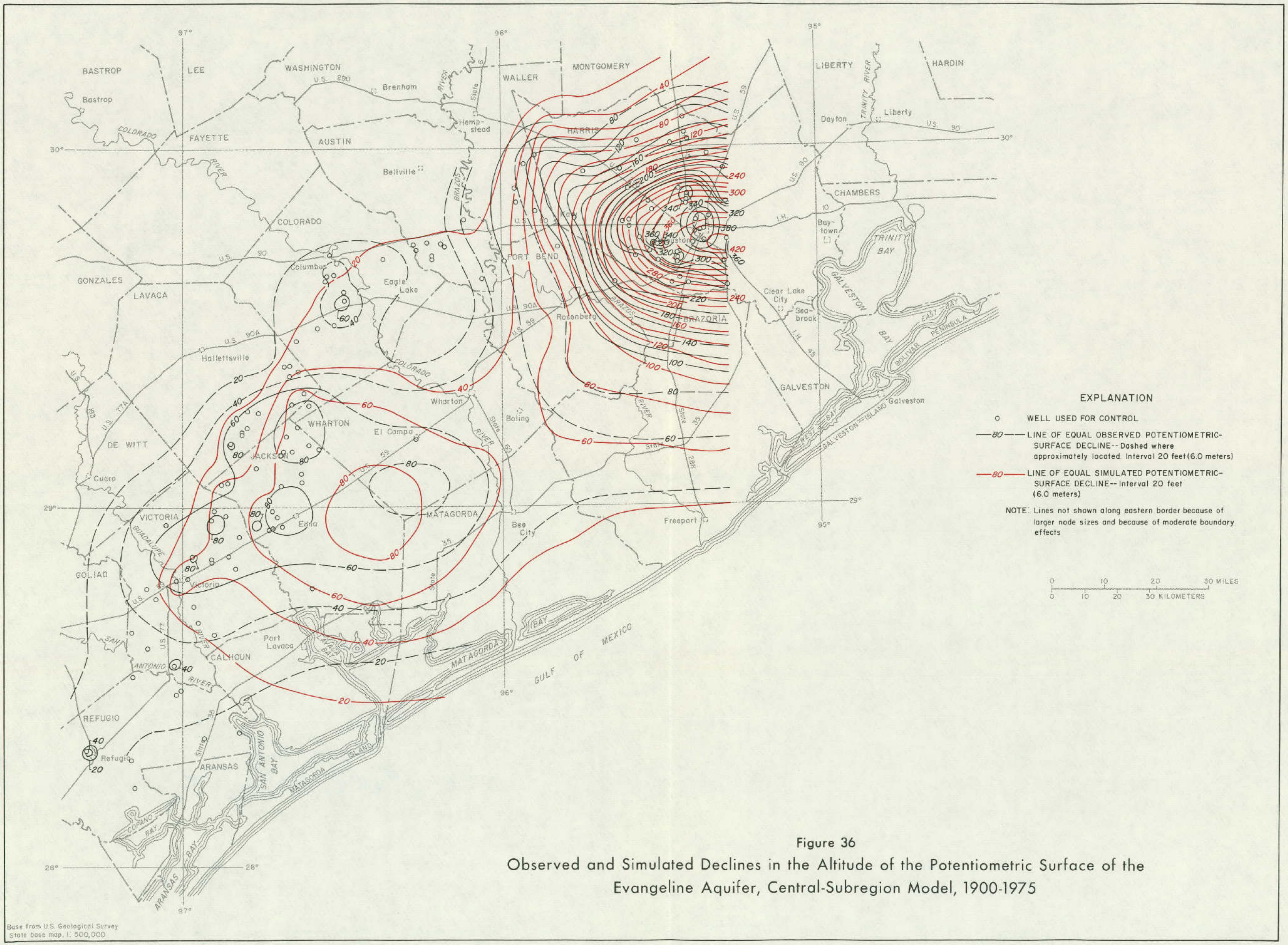


Figure 36

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Evangeline Aquifer, Central-Subregion Model, 1900-1975

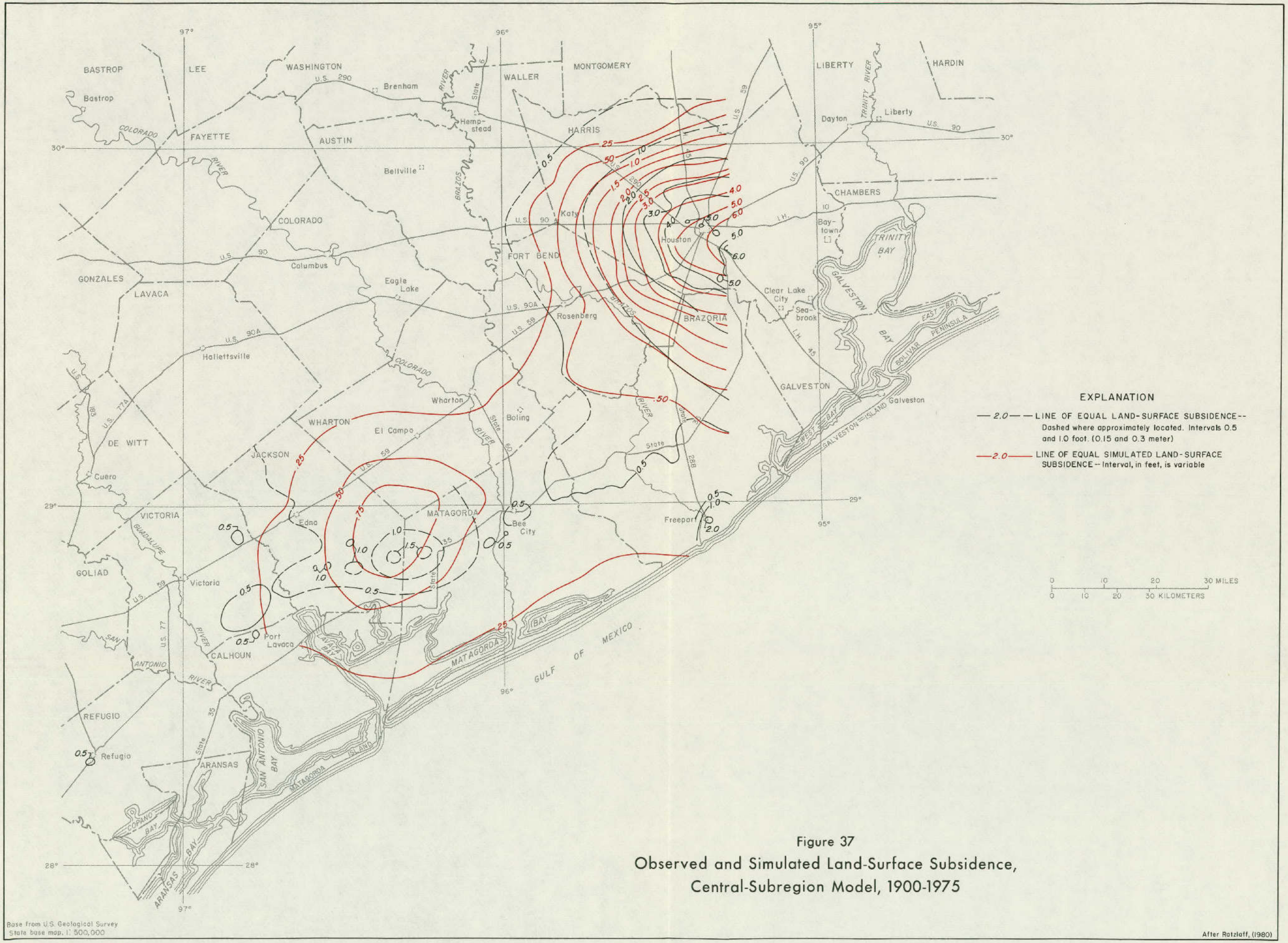


Figure 37

Observed and Simulated Land-Surface Subsidence, Central-Subregion Model, 1900-1975

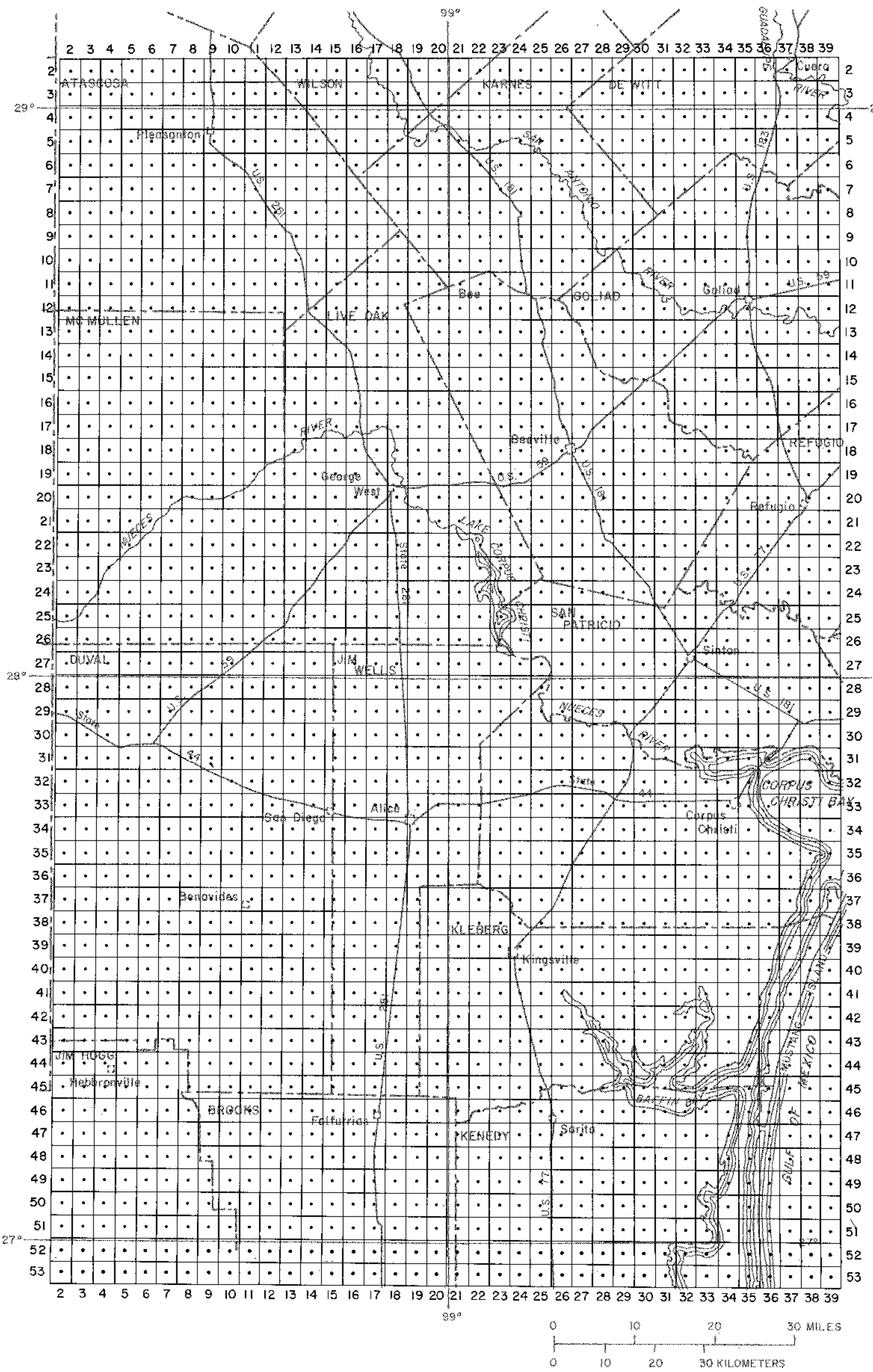


Figure 38

Boundaries and Grid Pattern of the Southern-Subregion Model

Base from U.S. Geological Survey
State base map, 1:500,000

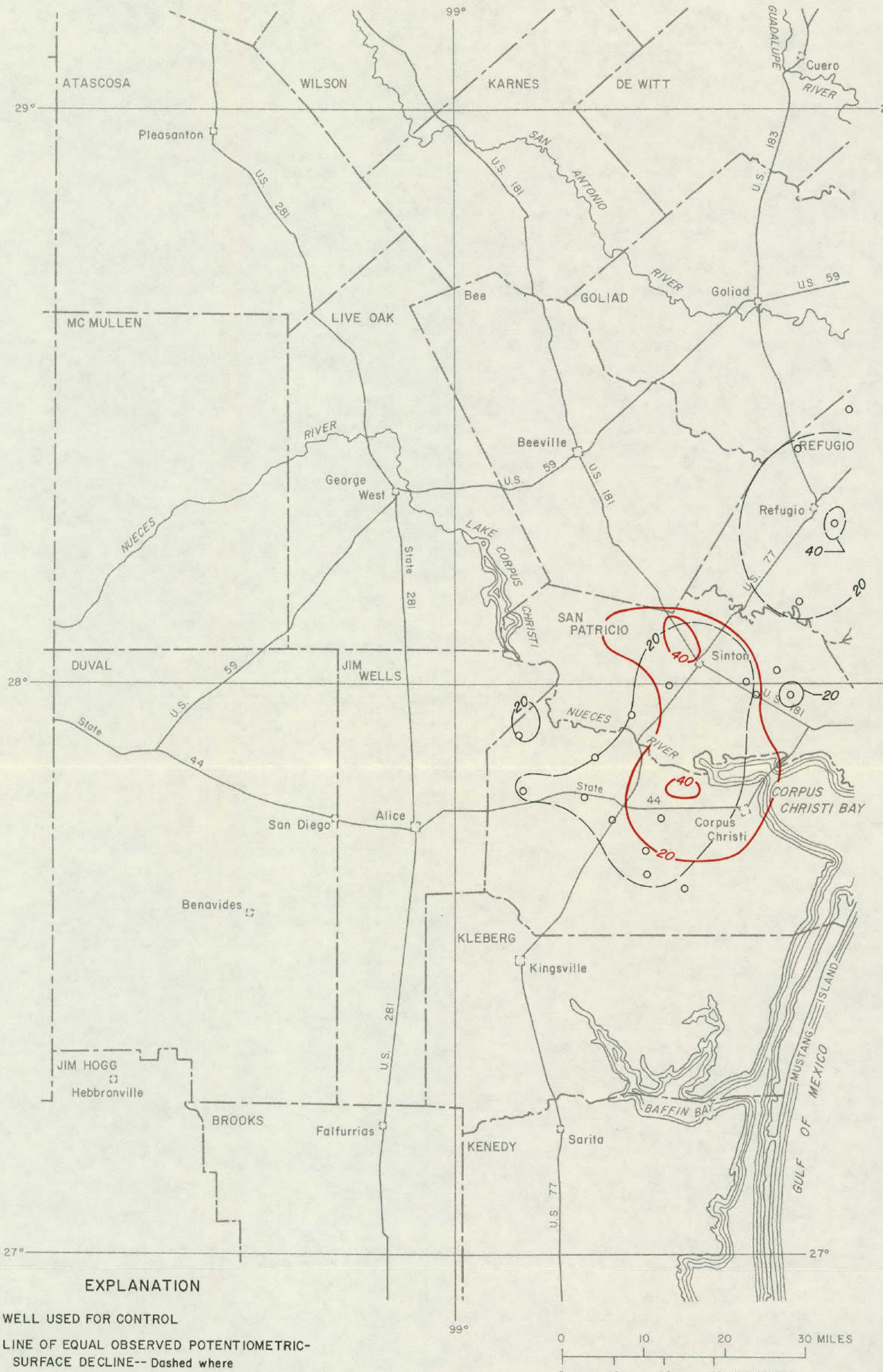


Figure 39

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Chicot Aquifer Undifferentiated, Southern-Subregion Model, 1900-1970

Base from U.S. Geological Survey
State base map, 1:500,000

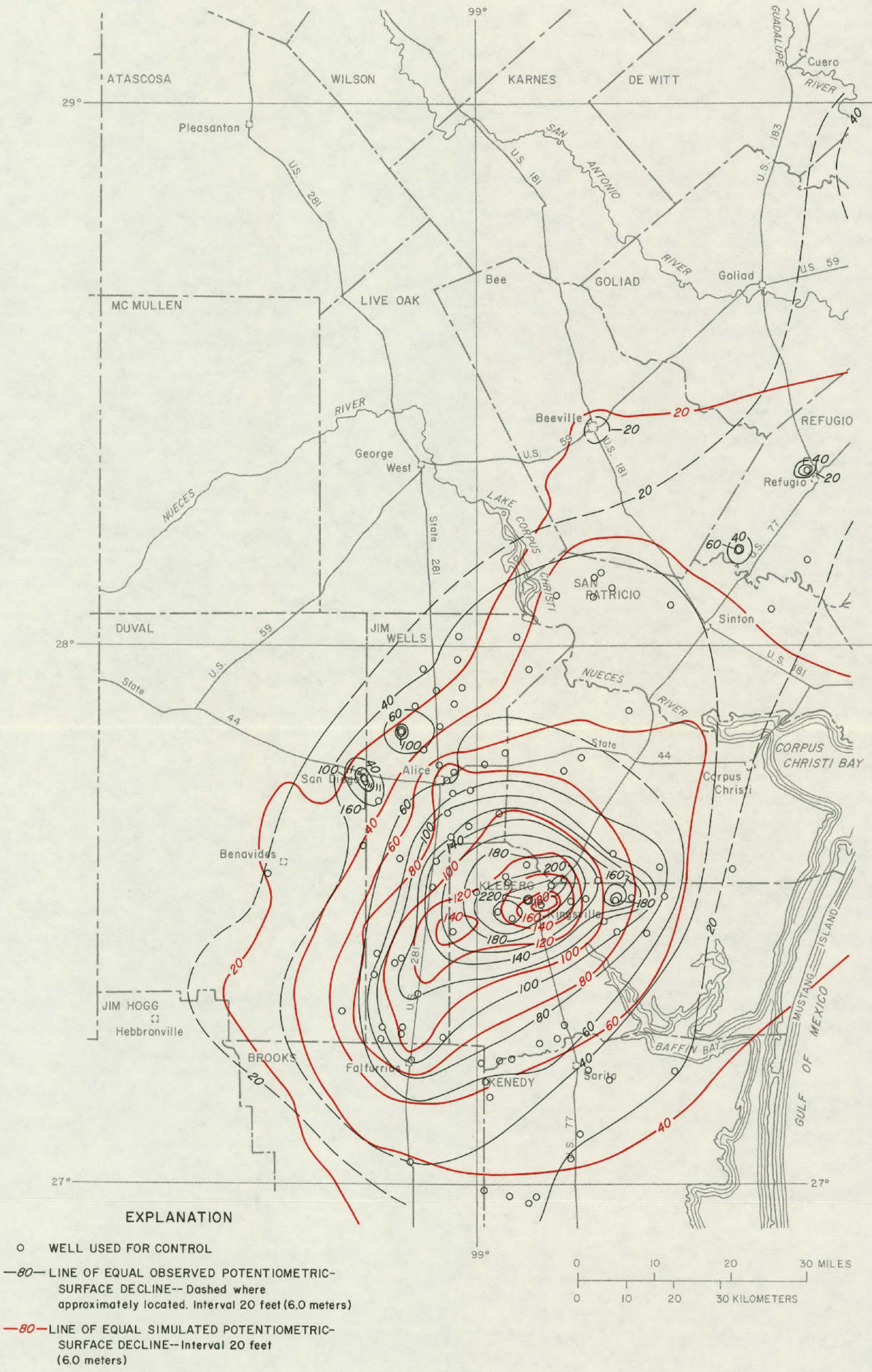


Figure 40

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Evangeline Aquifer, Southern-Subregion Model, 1900-1970

Base from U.S. Geological Survey State base map, 1:500,000

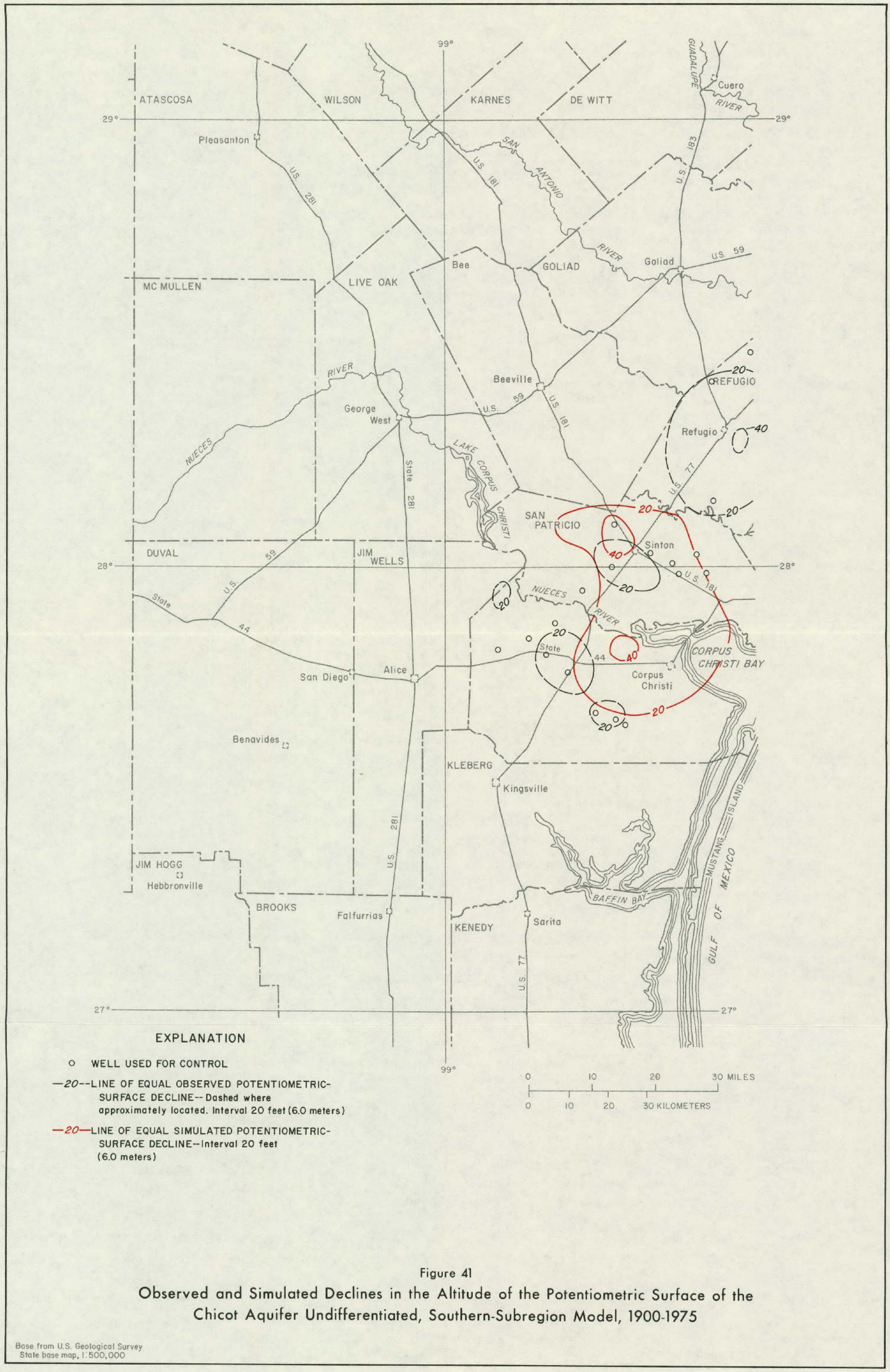


Figure 41

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Chicot Aquifer Undifferentiated, Southern-Subregion Model, 1900-1975

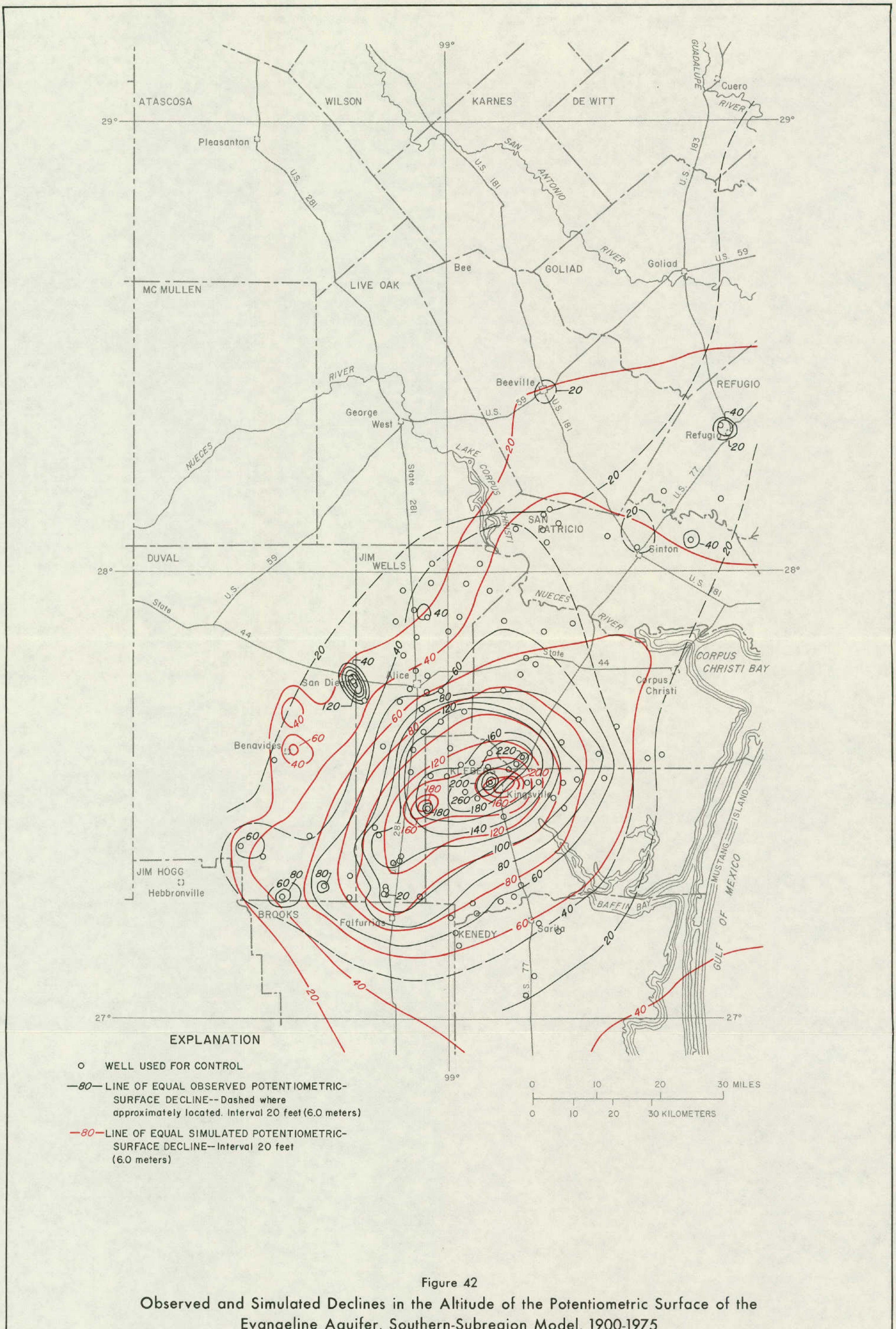
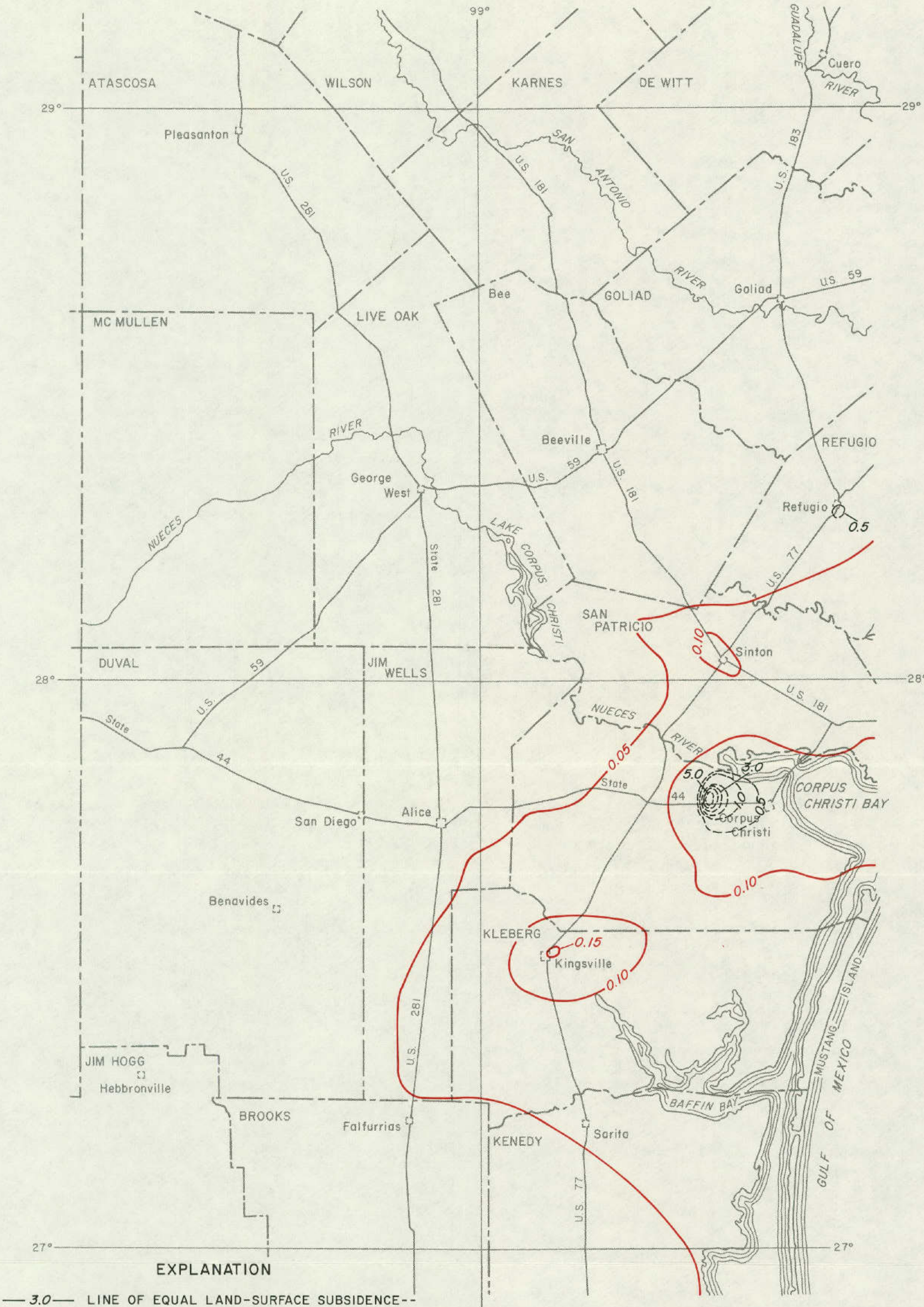


Figure 42

Observed and Simulated Declines in the Altitude of the Potentiometric Surface of the Evangeline Aquifer, Southern-Subregion Model, 1900-1975



EXPLANATION

—3.0— LINE OF EQUAL LAND-SURFACE SUBSIDENCE-- Dashed where approximately located. Interval 0.5 and 1.0 foot (0.15 and 0.3 meter)

—0.10— LINE OF EQUAL SIMULATED LAND-SURFACE SUBSIDENCE--Interval 0.05 foot (0.015 meter)

NOTE: Lines of equal subsidence are based on all data available for the period between 1918-51 and 1942-75

Figure 43

Observed and Simulated Land-Surface Subsidence, Southern-Subregion Model, 1900-1975

Base from U.S. Geological Survey State base map, 1:500,000

After Ratzlaff, (1980)

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