GEOHYDROLOGY AND SIMULATED EFFECTS OF WITHDRAWALS ON THE MIOCENE AQUIFER SYSTEM IN THE MISSISSIPPI GULF COAST AREA

By D.M. Sumner, B.E. Wasson, and Stephen J. Kalkhoff

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CONVERSION FACTORS AND ABBREVIATIONS

This report uses inch-pound units. The equivalent metric (International System) units may be obtained by using the following factors:

Multiply inch-pound unit	by	To obtain metric unit
mile (mi)	1.609	kilometer (km)
foot per day (ft/d)	0.3048	meter per day (m/d)
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)

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 mets of both the United States and Canada, formerly called "Mean Sea Level of 1929."

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ABSTRACT

Intense development of the Miocene aquifer system for water supplies along the Mississippi Gulf Coast has resulted in large water-level declines that have altered the ground-water flow pattern in the area. Water levels in some Miocene aquifers have declined about 2 feet per year since 1940; declines exceed 100 feet (80 feet below sea level) in large areas along the coast. Water levels in the surficial aquifer system, generally less than 20 feet below land surface, have not declined.

The Miocene and younger interbedded and lenticular sands and clays crop out in southern Mississippi and dip to the south and southwest. These sediments have large vertical variations in head and locally respond to stresses as separate aquifers.

Freshwater recharge to the Miocene aquifer system primarily is from rainfall on the surficial aquifers. The water generally moves to the south and southeast along the bedding planes toward the Mississippi Gulf Coast where the water is either withdrawn by wells, discharges to the ocean, or gradually percolates upward into overlying aquifers. Drawdowns caused by large ground-water withdrawals along the coast probably have resulted in the gradual movement of the saltwater toward the pumping centers.

In parts of the Miocene aquifer system commonly used for water supplies, the water generally is a sodium bicarbonate type. Increasing chloride concentrations in a few wells indicate that saline water is migrating into parts of all layers in the Pascagoula area. In some other areas in Pascagoula chloride concentrations are decreasing.

A quasi three-dimensional numerical model of the ground-water flow system was constructed and calibrated on the basis of both pre- and post-development conditions. The effects of an expected 1.5 percent annual increase in ground-water withdrawals during the period 1985-2005 were evaluated by the flow model. Additional water-level declines expected by the year 2005 in response to estimated pumpage are as follows: Gulfport, 135 feet in layer 4; Biloxi-Gulfport area, 100 feet in layer 5 and 50 feet in layer 3; Pascagoula area, 40 feet in layer 6 and 30 feet in layer 4. The most serious threats of saltwater encroachment occur in layers 4, 5, and 6 (the 800-, 600- and 400-foot sands) in the Pascagoula area where contamination of the southern edges of the production areas is expected to occur in less than 10 years.

INTRODUCTION

Industrial, municipal, and domestic water users along the Mississippi Gulf Coast withdraw about 60 Mgal/d (million gallons per day) from the aquifers of Miocene and Pliocene age, defined in this report as the Miocene aquifer system. Intensive development of these aquifers, primarily within a belt a few miles wide that extends along the coast from Waveland to Pascagoula (fig. 1), has significantly altered the natural flow system. In some pumping areas, ground-water levels have declined at the rate of about 2 feet per year since at least 1940. Concentrations of chloride have increased in water from a few wells; this raises the possibility of water-quality degradation by saltwater encroachment. Evaluation of the possible effects of increased usage and potential water-quality problems on ground-water development has been limited by a lack of understanding of the ground-water system. Concern for the aquifer system's ability to meet the increasing demand for water and the potential for contamination of the freshwater aquifers by saline water prompted this study of the Miocene aquifer system in southern Mississippi.

This report was prepared by the U.S. Geological Survey in cooperation with the Mississippi Department of Natural Resources, Bureau of Land and Water Resources.

Purpose and Scope

The purpose of this report is to define the geohydrology of the Miocene aquifer system of the Mississippi Gulf Coast and to quantify the effects of future withdrawals. The report describes the geohydrology of the sediments in the area as determined by field investigations and a numerical model of the Miocene aquifer system.

This investigation involved the collection of water-level, water-quality, and water-use data and the development of a geohydrologic conceptualization of the Miocene aquifer system. A numerical model of the ground-water flow system was constructed and used to evaluate the effects of anticipated increased pumping on water levels and water quality. Although the primary study area was the Mississippi Gulf Coast (fig. 1), the study was extended to consider the larger, more regional system that affects the area of concern.

Previous Investigations

The earliest geohydrologic reports that cover large parts of the study area were by Logan and Perkins (1905), Crider and Johnson (1906), Stephenson and others (1928), Brown and others (1944), and Lang and Newcome (1964). More recent geohydrologic reports that generally cover the study area are by Newcome (1971, 1975), Callahan (1975), Boswell (1979), Gandl (1982), and Colson and Boswell (1985). Other important geohydrologic reports that cover smaller parts of the study area are by Harvey and others (1965) for Jackson County, Newcome (1967a) for part of Hancock County, Newcome and others (1968) for Harrison County, Wasson (1978) for the Pascagoula area, and Brahana and Dalsin (1977) for George, Hancock, Pearl River, and Stone Counties.

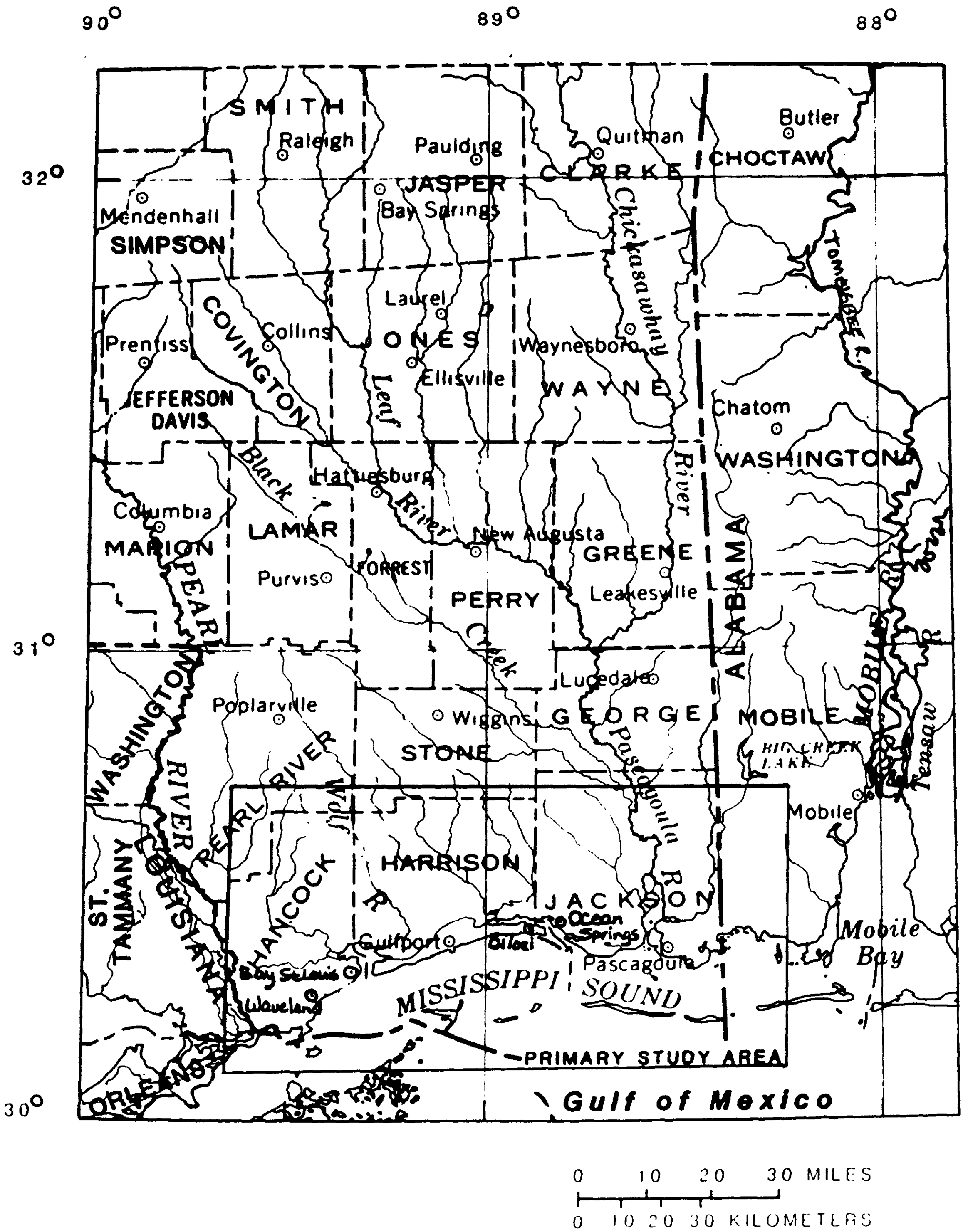


Figure 1.--Culture and drainage of the primary and secondary study areas in southeast Mississippi.

Geologic reports useful to the study were by Rainwater (1964), Williams and others (1967), and May and others (1974). Water-data reports on the coastal area include those by Shattles and others (1967), Shattles and Callahan (1970), and Callahan (1982).

In Alabama, several geohydrologic reports on the area adjoining the Mississippi study area were by Reed and McCain (1971, 1972), Newton and others (1972), Epsman and others (1983), and Moore and Raymond (1985). In southeastern Louisiana some of the geohydrologic reports useful to this study were by Rollo (1960), Howe (1962), Winslow and others (1968), Nyman and Fayard (1978), and Case (1979). Potentiometric maps for two of the principal aquifers in the area are by Martin and Whiteman (1985a, 1985b).

GEOHYDROLOGY OF THE GROUND-WATER SYSTEM

Geology

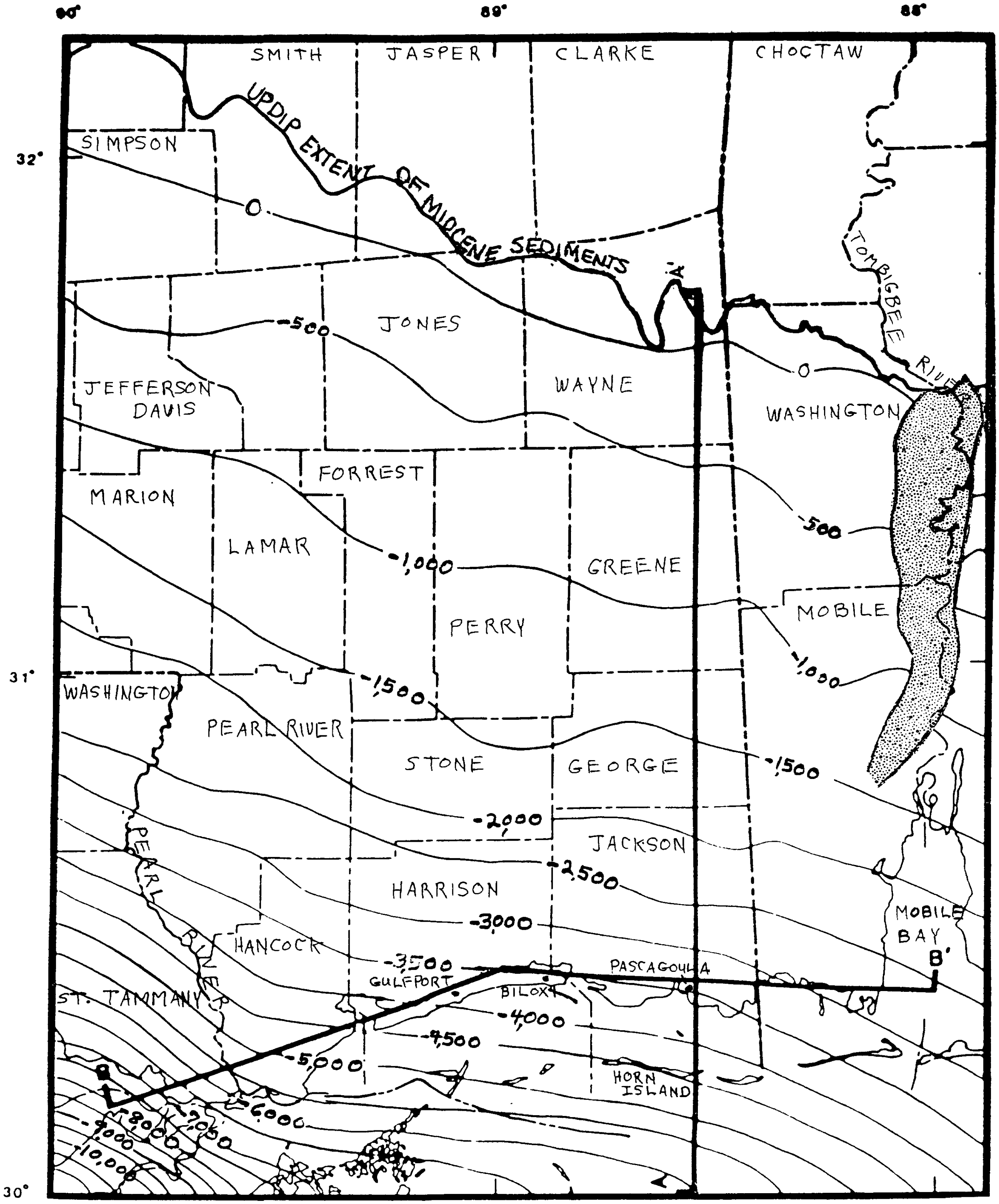
The Gulf Coast geosyncline is a dominant regional structural feature that affects the Miocene and younger sediments of coastal Mississippi. The sediments dip southwest, commonly less than 30 feet per mile at depths of less than about 2,000 feet (fig. 2), but dips increase dramatically downdip with depth, resulting in an increase in thickness of a given stratigraphic interval.

Underlying the area are several hundred feet of low permeability clay and limestone sediments in the Jackson and Vicksburg Groups of Eocene and Oligocene age (table 1).

The Miocene and Pliocene sediments consist of, in ascending order, Catahoula Sandstone, Hattiesburg Formation, Pascagoula Formation, Graham Ferry Formation, and Citronelle Formation and are commonly composed of clay, silt, sand and occasionally gravel, but may have beds of limestone at depth. The downdip sediments may be partly marine, whereas sediments near the outcrop tend to be terrestrial. The youngest and most extensive of the Pliocene and Miocene sediments is the Citronelle Formation. Over much of the area, the Citronelle ranges from 0 to 160 feet in thickness and dips at a rate of less than 10 feet per mile (Boswell, 1979). Near the coast, the Citronelle Formation dips into the subsurface and is the upper part of the Miocene aquifer system.

In contrast to older geologic (Eocene and Cretaceous) units within the Gulf Coast geosyncline, the Pliocene and Miocene sediments lack regional lithologic layering and tend to be areally discontinuous and variable in thickness. Several investigators have attempted to differentiate the Pliocene and Miocene sediments on the basis of paleontologic and lithologic evidence but have met with limited success (Newcome, 1975).

Lying unconformably above a large area of the Pliocene and Miocene sediments are Pleistocene deposits. Younger undifferentiated Pleistocene alluvium and terrace deposits at the surface range from 0 to 100 feet in thickness and dip at a rate of less than 10 feet per mile (Brown and others, 1944).



EXPLANATION

—— -1,500 —— STRUCTURE CONTOUR--shows altitude of the base of the Miocene sediments. Contour interval 500 feet. Datum is sea level

A A' CROSS SECTION TRACE

AREA OF GEOLOGIC FAULTING--structure contours not shown

Geology modified from Moore and Raymond (1985), Newcome (1975), and Howe (1962).

0 10 20 MILES
0 10 20 KILOMETERS

Figure 2.--Altitude of the base of the Miocene sediments.

Table 1.--Geologic units, major aquifers, and hydrologic layering of the Miocene aquifer system in south Mississippi

System	Series	Group	Geologic unit	Major aquifer or aquifer system	Hydrologic layers: Layer number	Hydrologic layers: Depth of base of layer at Pascagoula, in feet
Quaternary	Holocene and Pleistocene		Undifferentiated alluvium and terrace deposits	Surficial aquifer system--includes those parts of aquifers that are less than about 200 feet below land surface [Undifferentiated alluvium through Catahoula Sandstone]		
	Pleistocene		Loess			
			Terrace deposits, undifferentiated	Miocene aquifer system [Terrace deposits through Catahoula Sandstone]	8	(not present)
Tertiary	Pliocene		Citronelle Formation		7	180
					6	450
			Graham Ferry Formation		5	650
	Miocene				4	950
			Pascagoula Formation		3	1350
			Hattiesburg Formation		2	2050
			Catahoula Sandstone		1	3500
	Oligocene		Paynes Hammock Sand			
			Chickasawhay Sandstone			
		Vicksburg	Bucatunna Formation			
			Byram Formation			
			Glendon Formation			
			Marianna Formation	Oligocene aquifer system		
			Mint Spring Formation			
			Forest Hill Formation			
	Eocene	Jackson	Yazoo Clay			
			Moodys Branch Formation			
		Claiborne	Cockfield Formation	Cockfield aquifer		
			Cook Mountain Formation			
			Sparta Sand	Sparta aquifer system		
			Zilpha Clay			

Hydrologic Layering of Miocene and Younger Sediments

The Pliocene and Miocene sediments of southern Mississippi do not fit the layered geologic structure common to older sediments in the State. Sand and clay bodies in these sediments generally are lenticular and local in extent. Although regional lithologic layering may not exist, small-scale layering owing to lenticular lithology, results in greater horizontal than vertical hydraulic conductivity on the regional scale. To develop a mathematical model of the Miocene aquifer system for this study, it was necessary to divide the Pliocene and Miocene sediments into layers that are oriented with respect to this anisotropy and can reproduce the vertical head differences (fig. 3) found in the Miocene aquifer system. Premchitt and Das Gupta (1981) and Weiss and Williamson (1985) described the need for similar model layers in a similar geohydrologic environment.

Regional hydrologic layers that are oriented with respect to the anisotropic nature of the aquifer system have slopes which approximate the slope of the base of the Miocene surface, which is the youngest geologic surface that is regionally mappable (fig. 2). Because subsidence of the Gulf Coast geosyncline produced units that progressively thicken downdip, the dip at a given location increases for progressively deeper sediments (fig. 4). The altitudes of the bottoms of the well screens in a 3-mile-wide band along the coast were plotted on a cross section (figs. 2 and 5). Using the distribution of well-screen bottoms and water-level heads as an indicator of the distribution of zones within which hydraulic head is roughly uniform, hydrologic layering was estimated at Pascagoula, Miss., (fig. 3). These layer divisions were extended throughout the Miocene aquifer system in a manner consistent with principal directions of anisotropy by using the base of the Miocene and the slope ratio between the Graham Ferry-Pascagoula contact and the base of the Miocene. Figure 4 illustrates the change in slope ratio with depth of the base of the Miocene. Geologic sections by Harvey and others (1965) were used to establish the slope ratio of 1:4 in the Pascagoula area, where the altitude of the base of the Miocene is between 2,600 and 3,700 feet below sea level. This 1:4 ratio was applied to generate layering in areas where the base of the Miocene is greater than about 2,600 feet below sea level. In those areas where the base of the Miocene is less than about 2,000 feet below sea level, the slope of the sediments is relatively uniform vertically, and regional layering is assumed to parallel the base of the Miocene. An intermediate slope ratio of 1:2.5 was applied in areas where the base of the Miocene is greater than 2,000 but less than 2,600 feet below sea level. To account for changes in layer slope in the vertical in areas where the base of the Miocene is greater than 2,000 feet below sea level, the slope ratio of individual layers was determined by linear interpolation between the 1:1 ratio at the base of the Miocene and the 1:4 or 1:2.5 ratios at the Graham Ferry-Pascagoula contact.

Eight hydrologic layers (fig. 5) were judged to best fit the existing well data on the coast. Layers 1 and 2 near the base of the Miocene sediments are penetrated by only a few wells along the coast, and because of the lack of existing head data were defined as thicker

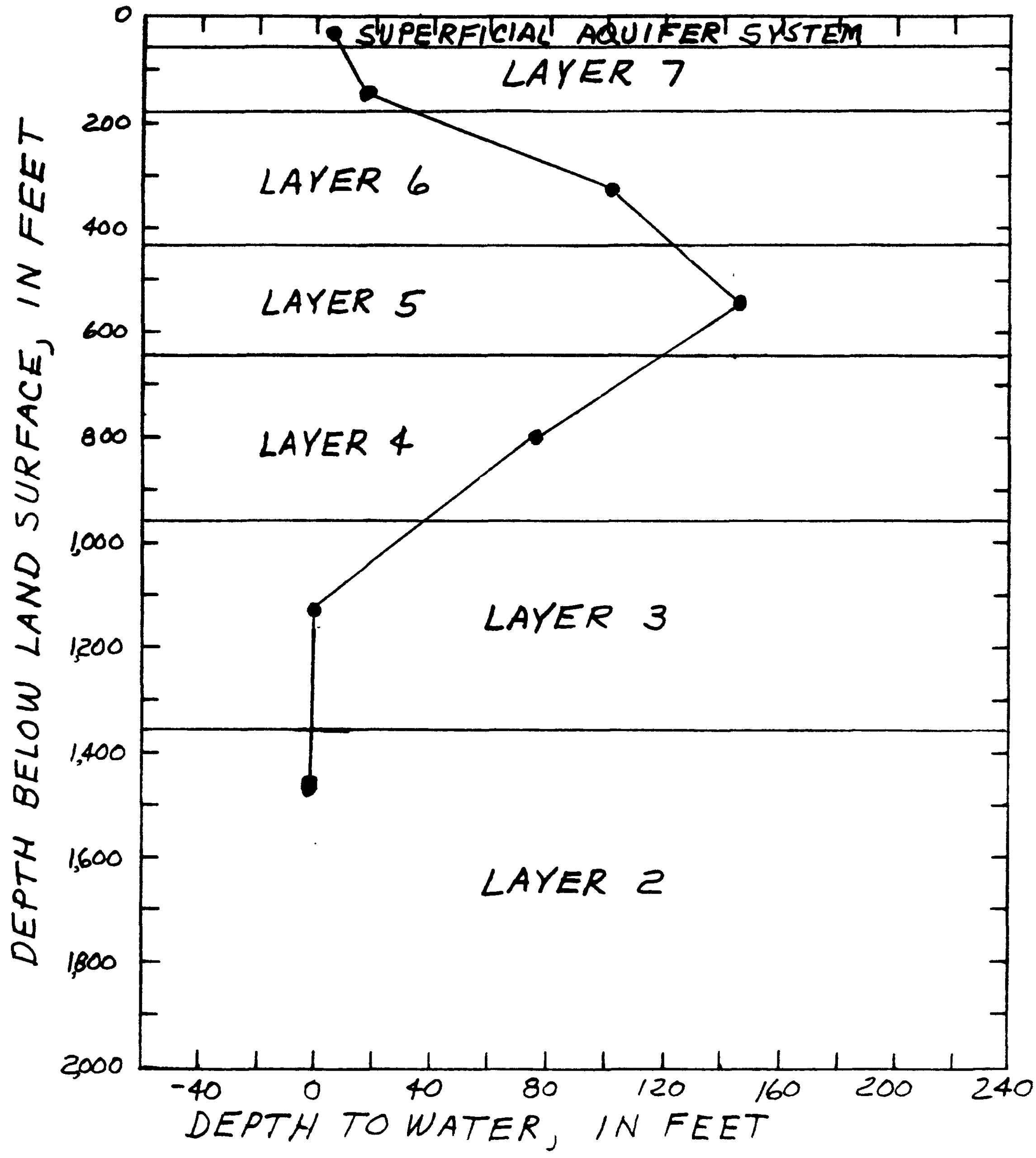


Figure 3.--General relations of water-level depth in selected wells in 1985 to the various model layers in the Pascagoula area.

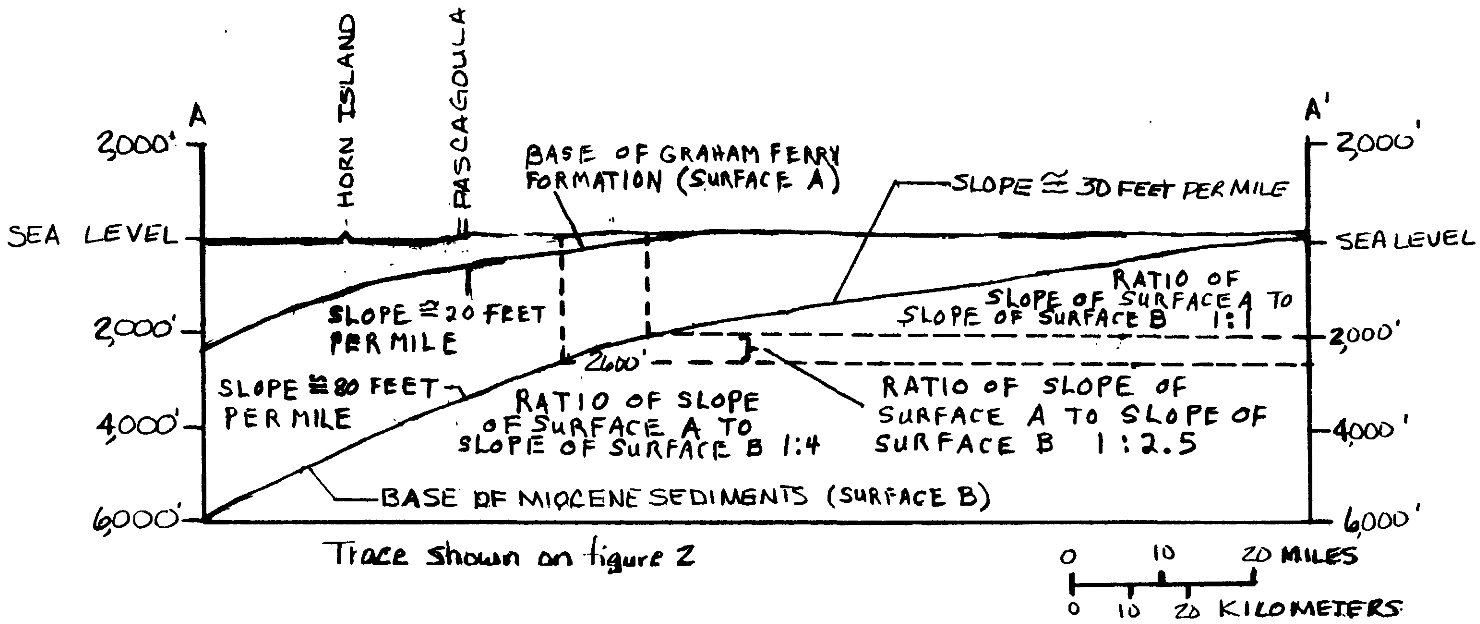
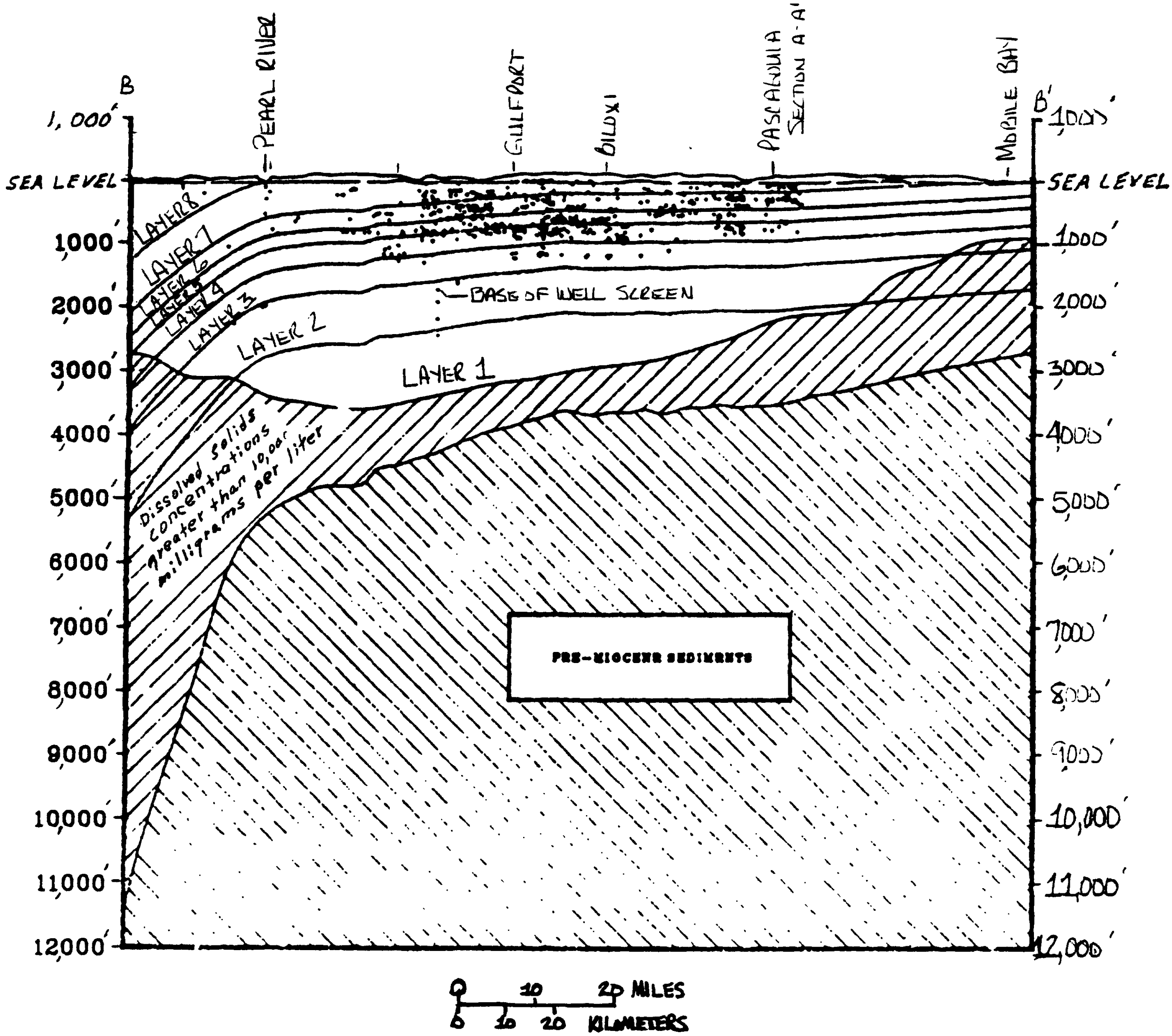


Figure 4.--Diagrammatic section A-A' through Pascagoula showing the ratio of the slopes between the Graham Ferry-Pascagoula contact and the base of the Miocene sediments.



VERTICAL SCALE GREATLY EXAGGERATED
TRACE SHOWN ON FIGURE 2

Figure 5.--Geohydrologic section B-B' along the Mississippi Gulf Coast showing scheme for layering the Miocene and younger sediments.

layers. Layers 3 through 7 were relatively thin and contained almost all of the existing wells. The lack of wells in the deeper sand beds along the coast allowed gross resolution in the older sediments, whereas the main production zone required considerably more resolution. Layer 8 existed only in the western end of the cross section along the coast and was relatively undeveloped.

The base of the surficial aquifer system is assumed to include those parts of the ground-water system that are affected by precipitation, evapotranspiration, and stream stage, and is considered to be the top of the Miocene aquifer system. The base of the surficial aquifer system onshore is estimated in this study to be 50 feet below the potentiometric surface (fig. 6) of the unit. Offshore, the upper boundary of the flow system is the floor of the Gulf of Mexico. Configurations of the tops of the layers and the subcrop of each layer have been mathematically generated (fig. 7). The relations of these layers to local aquifer designations of previous investigators have been summarized in table 1.

This hydrologic layering scheme is based primarily on the present (1985) potentiometric head distribution along the Mississippi Gulf Coast. Extensive development of the deeper, thicker layers could require a revision of the layering scheme to maintain sufficient vertical resolution.

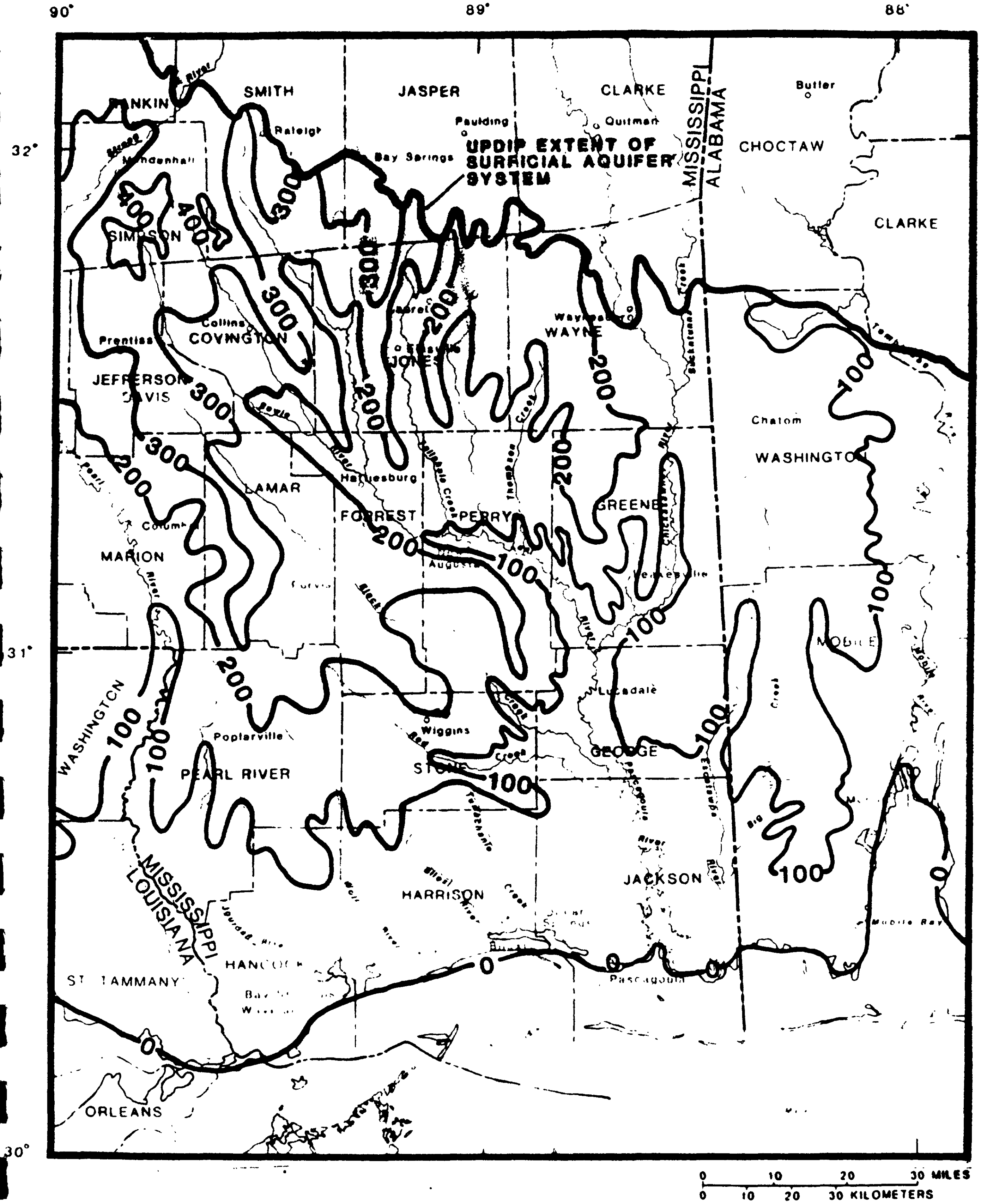
Ground-water Flow

Recharge

The source of nearly all recharge to the Miocene aquifer system is precipitation on the surface of the surficial aquifer system (table 1), which includes most of the Citronelle aquifer, all terrace and alluvial aquifers, and the shallowest parts of Miocene beds in the outcrop areas. Although south Mississippi receives nearly 60 inches of rain annually and several inches may percolate into the surficial aquifer system in some areas, most of this recharge flows relatively short distances to surface-water drains. The amount of recharge to the deeper Miocene aquifer system from the surficial aquifer probably is less than 1 inch (Angel Martin, Jr., U.S. Geological Survey, oral commun., 1987).

The potentiometric map of the surficial aquifer system (fig. 6) indicates that the direction of ground-water flow generally is from areas of recharge of the surficial aquifer system to the streams and to the gulf. The potentiometric surface of the surficial aquifer system reflects topography, the highest heads in the shallow system are, therefore, in areas where the land surface is the highest. During short periods of high stream stages, some surface water may recharge the surficial aquifer, but generally streams in the area act as drains from the system.

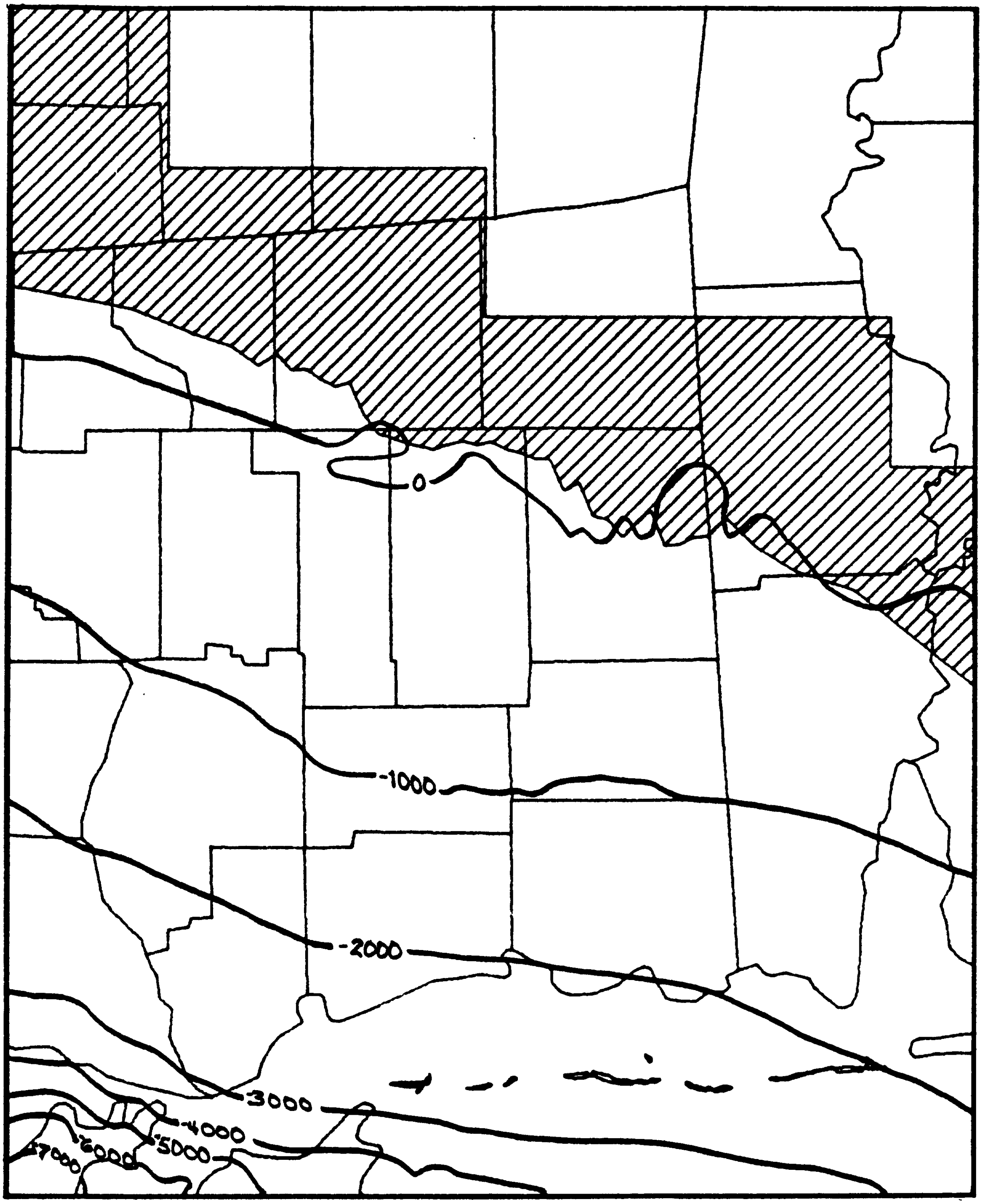
Recharge to the Miocene aquifer system from the underlying Cockfield aquifer by upward leakage through the Jackson and Vicksburg Groups is zero or small compared to total recharge. Head differential probably



EXPLANATION

—— 0 —— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells in 1981. Contour interval 50 feet. Datum is sea level

Figure 6.--Potentiometric surface of the surficial aquifer system.



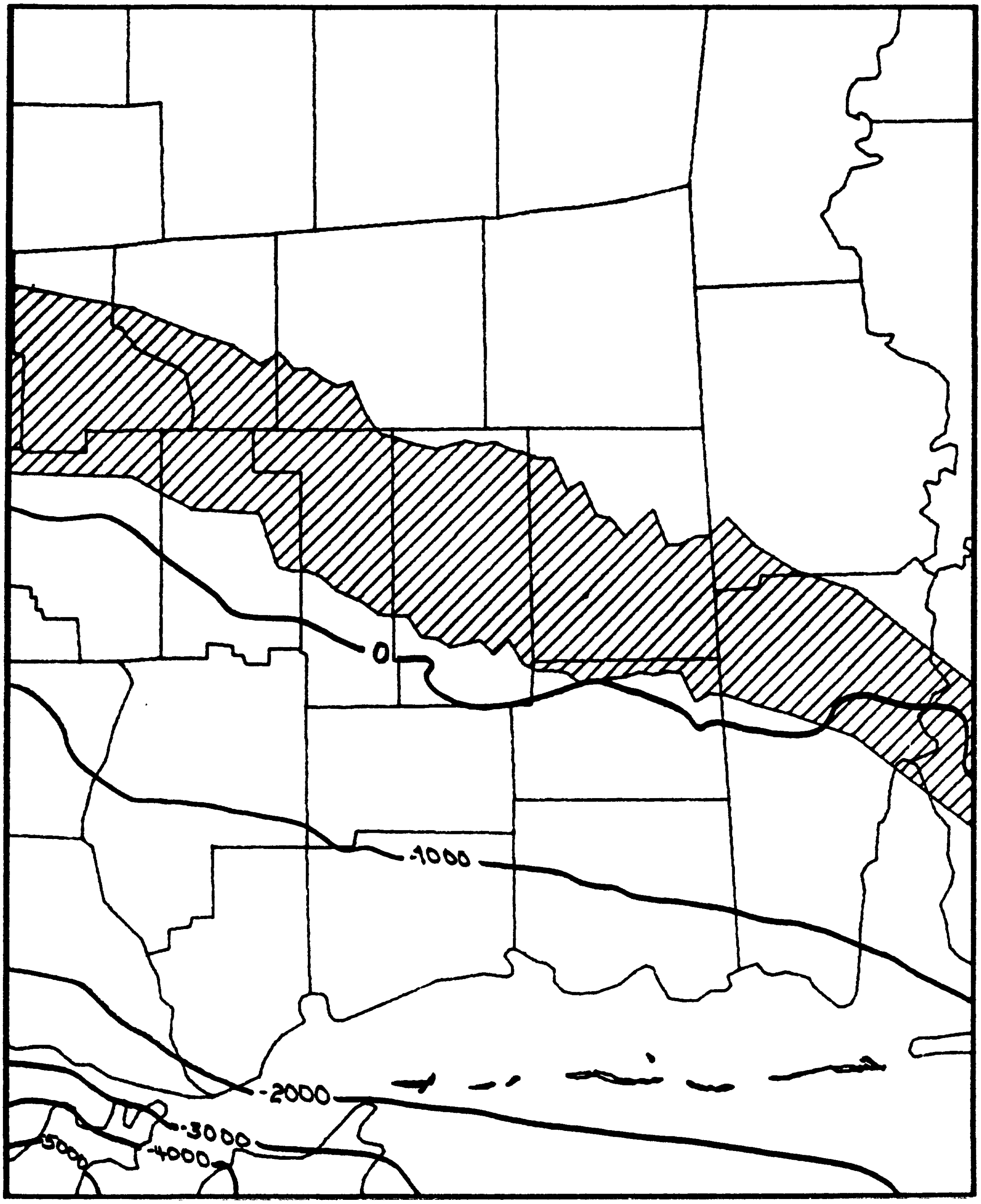
EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

AREA OF SUBCROP OF LAYER 1

—— 1000 —— STRUCTURE CONTOUR--Shows altitude of top of layer 1. Contour interval 1000 feet. Datum is sea level

Figure 7.--Tops of layers of the Miocene aquifer system and subcrops of the layers beneath the surficial aquifer system.



0 10 20 MILES

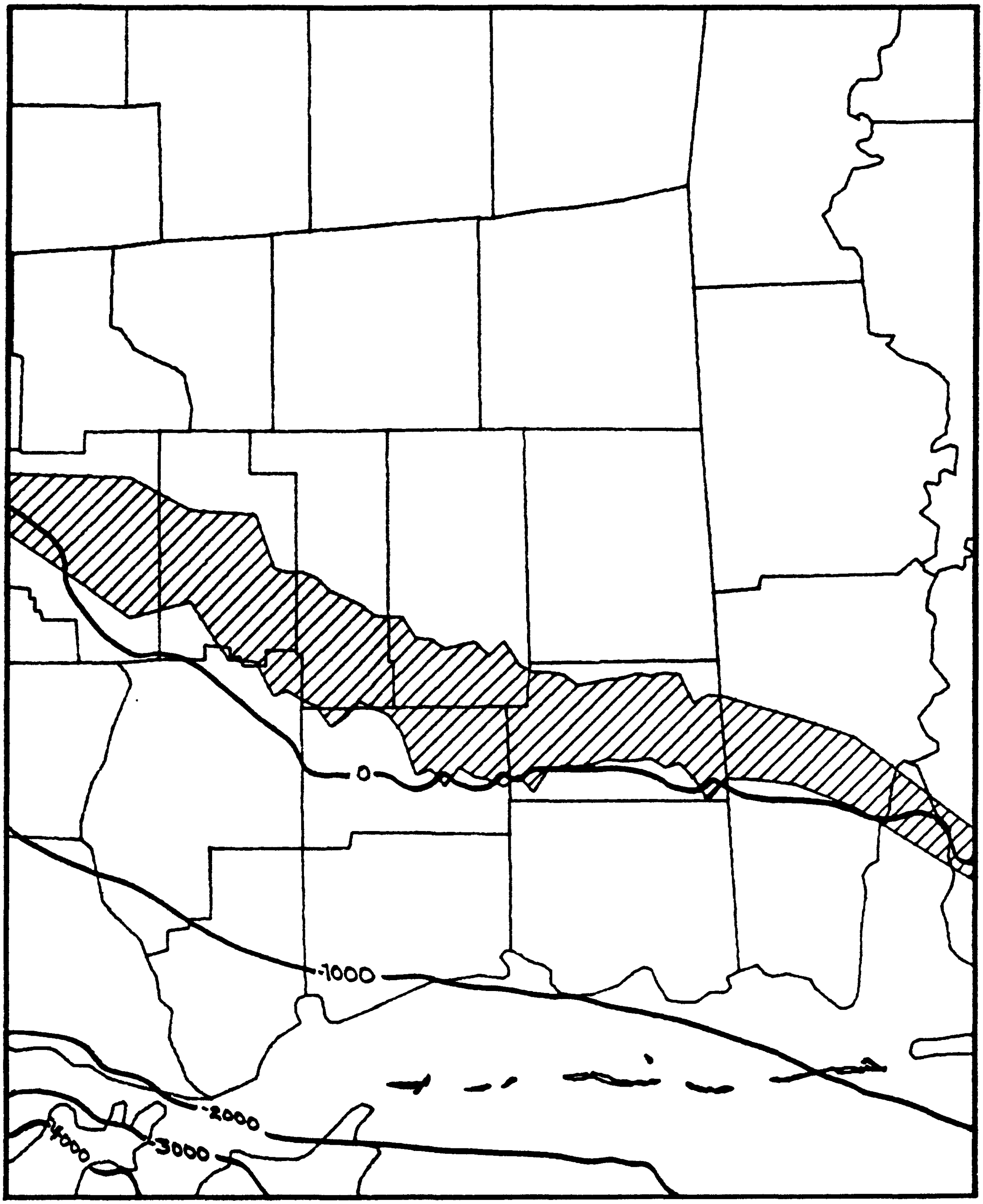
0 10 20 KILOMETERS

EXPLANATION

AREA OF SUBCROP OF LAYER 2

—— 1000 —— STRUCTURE CONTOUR--Shows altitude of top of layer 2. Contour interval 1000 feet. Datum is sea level

Figure 7.--Tops of layers of the Miocene aquifer system and subcrops of the layers beneath the surficial aquifer system.--Continued



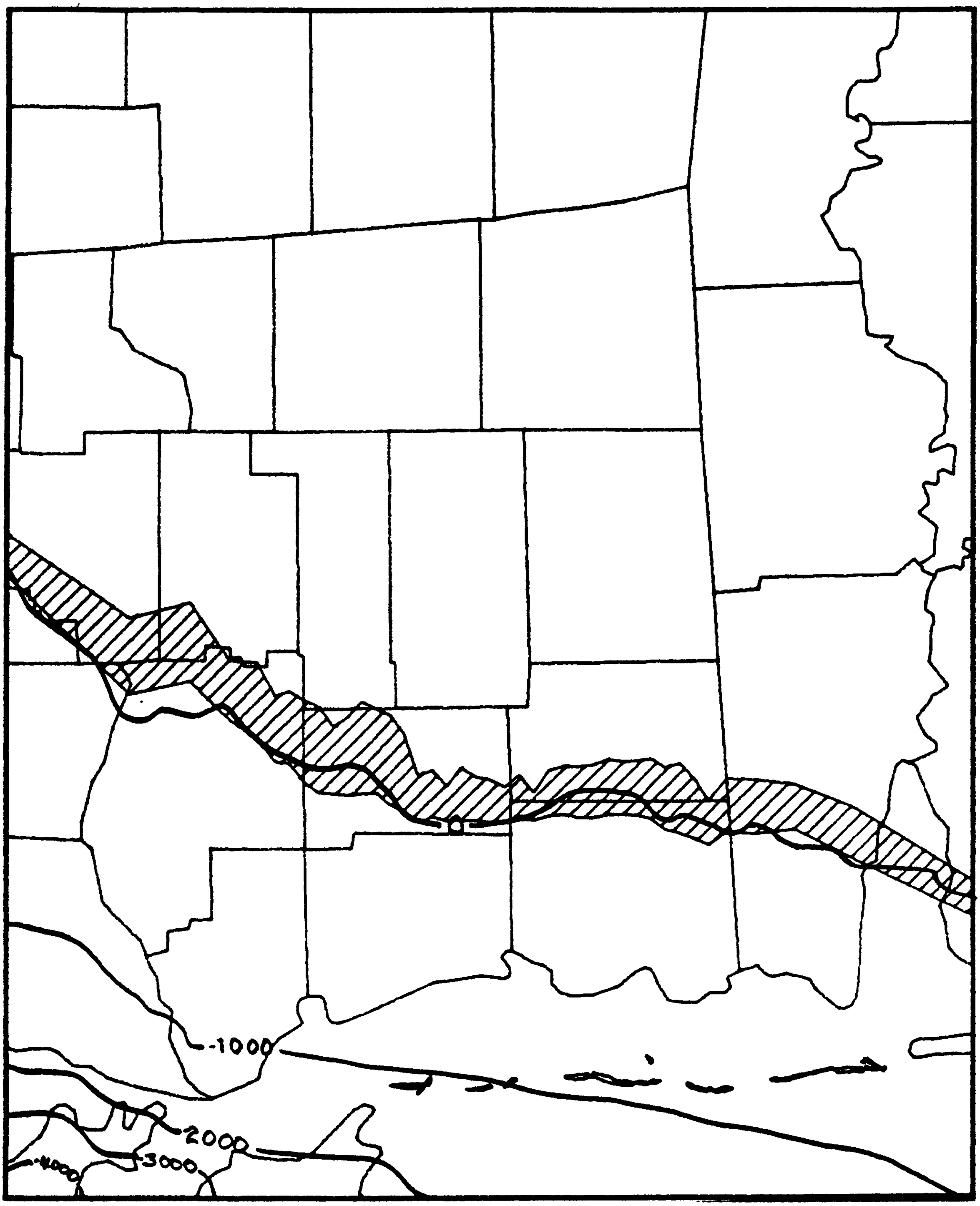
EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

AREA OF SUBCROP OF LAYER 3

—— 1000 —— STRUCTURE CONTOUR--Shows altitude of top of layer 3. Contour interval 1000 feet. Datum is sea level

Figure 7.--Tops of layers of the Miocene aquifer system and subcrops of the layers beneath the surficial aquifer system.--Continued



EXPLANATION

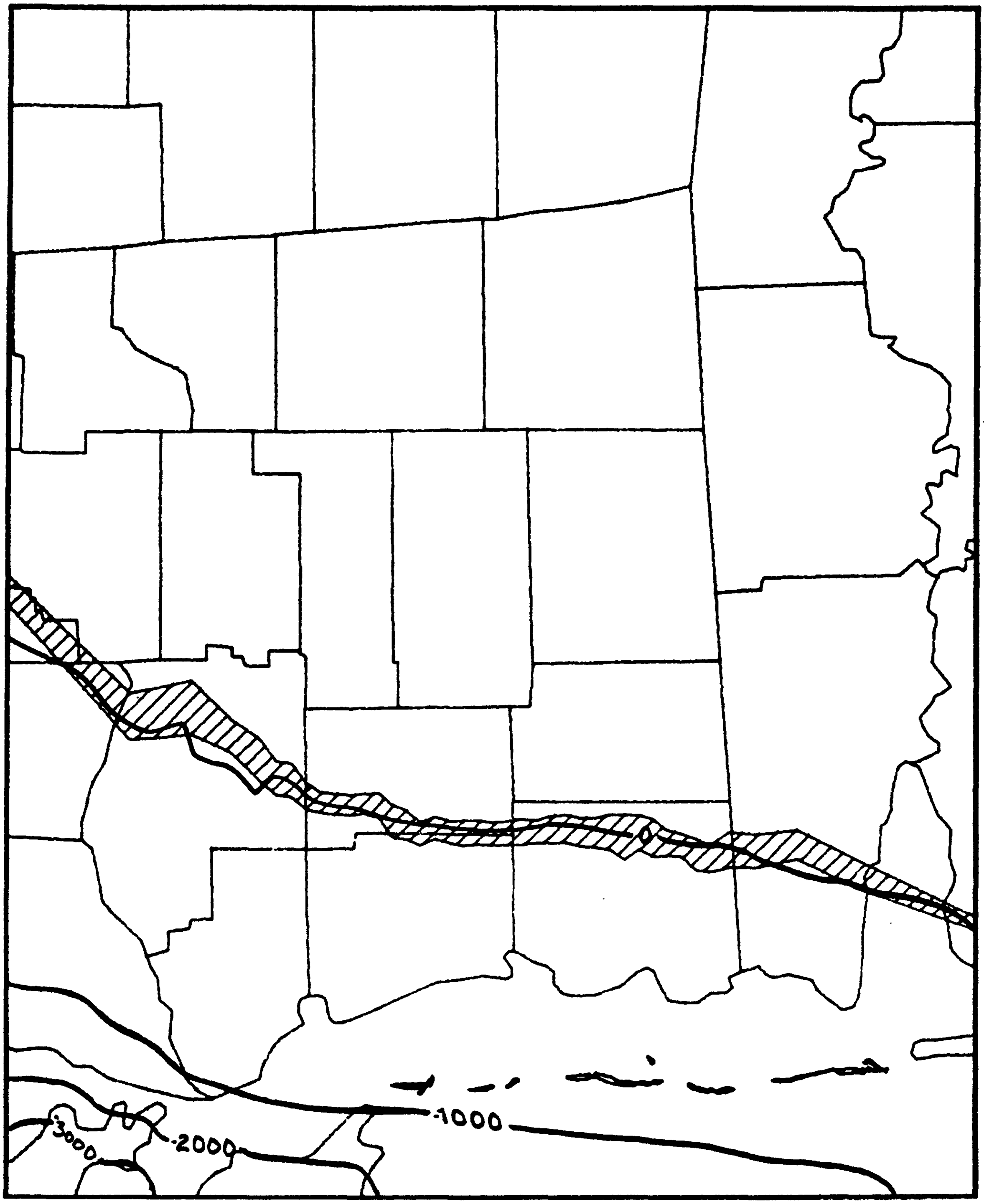
AREA OF SUBCROP OF LAYER 4

—— 1000 —— STRUCTURE CONTOUR--Shows altitude of top of layer 4. Contour interval 1000 feet. Datum is sea level

0 10 20 MILES

0 10 20 KILOMETERS

Figure 7.--Tops of layers of the Miocene aquifer system and subcrops of the layers beneath the surficial aquifer system.--Continued



0 10 20 MILES

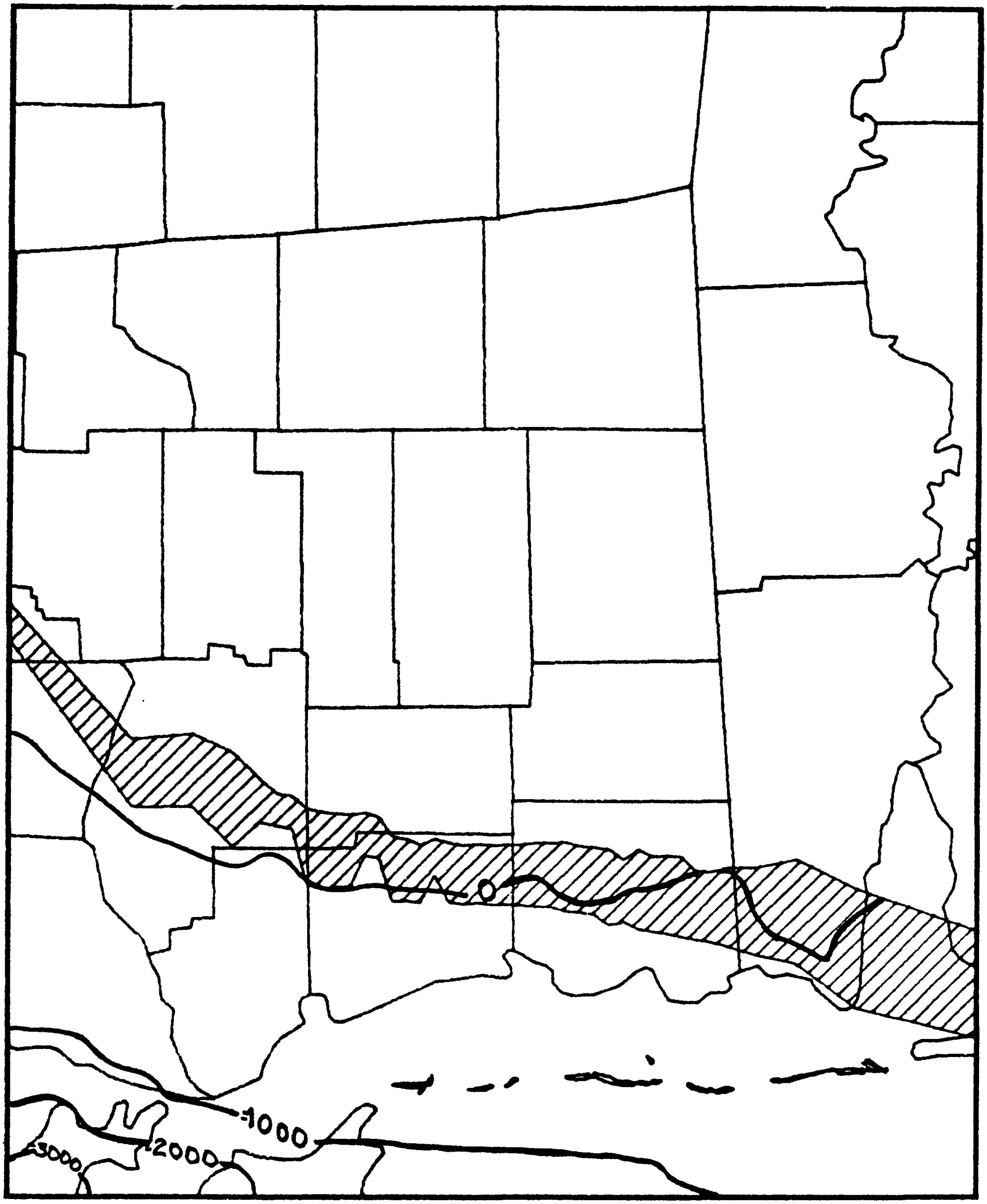
0 10 20 KILOMETERS

EXPLANATION

AREA OF SUBCROP OF LAYER 5

——1000—— STRUCTURE CONTOUR--Shows altitude of top of layer 5. Contour interval 1000 feet. Datum is sea level

Figure 7.--Tops of layers of the Miocene aquifer system and subcrops of the layers beneath the surficial aquifer system.--Continued



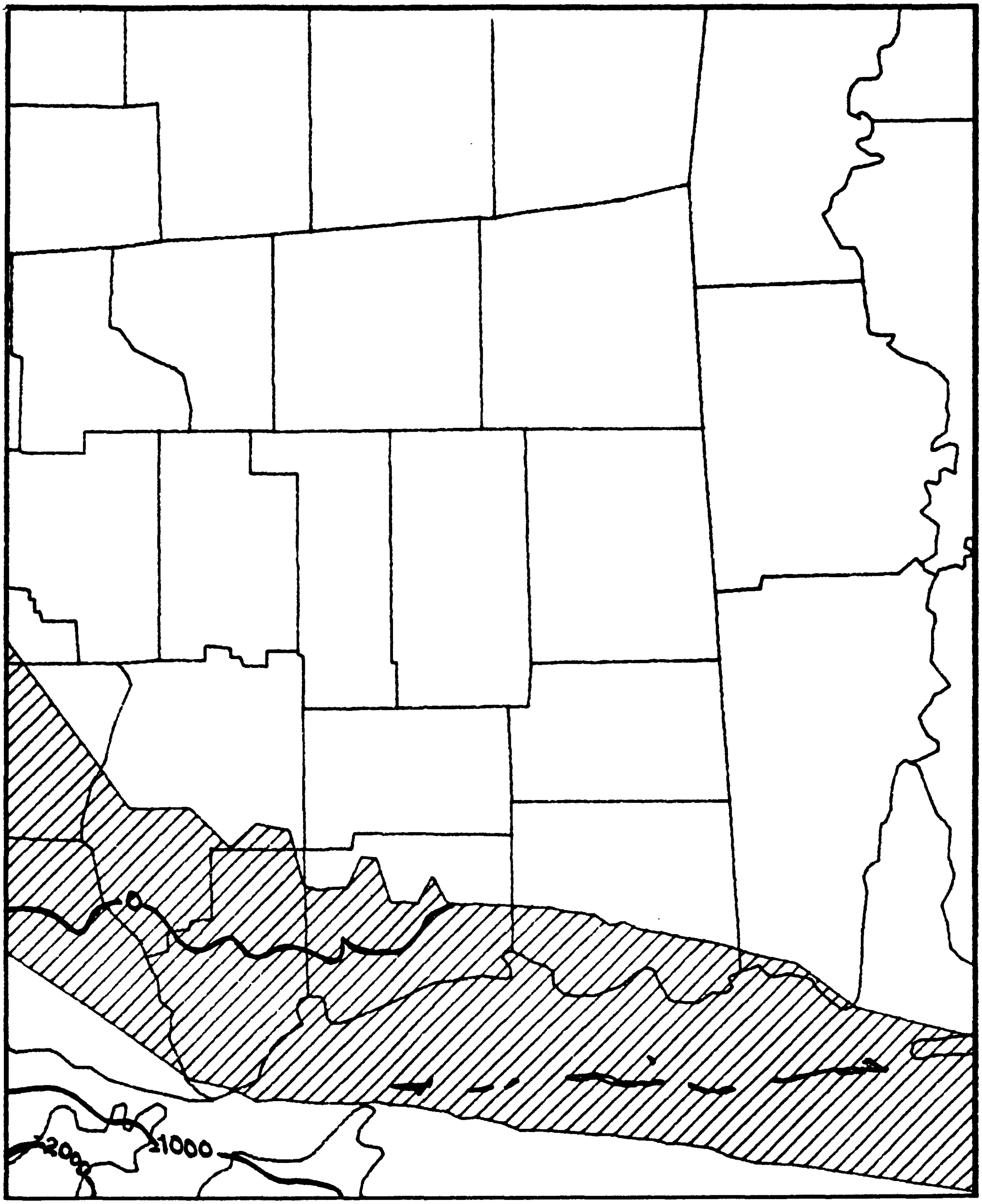
EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

AREA OF SUBCROP OF LAYER 6

—— 1000 —— STRUCTURE CONTOUR--Shows altitude of top of layer 6. Contour interval 1000 feet. Datum is sea level

Figure 7.--Tops of layers of the Miocene aquifer system and subcrops of the layers beneath the surficial aquifer system.--Continued



0 10 20 MILES

0 10 20 KILOMETERS

EXPLANATION

AREA OF SUBCROP OF LAYER 7

1000 — STRUCTURE CONTOUR--Shows altitude of top of layer 7. Contour interval 1000 feet. Datum is sea level

Figure 7.--Tops of layers of the Miocene aquifer system and subcrops of the layers beneath the surficial aquifer system.--Continued

averages less than 50 feet; thickness of the confining units probably averages more than 300 feet; and vertical hydraulic conductivity of the confining units is low (J.K. Arthur, U.S. Geological Survey, oral commun., 1987).

Predevelopment flow

The first deep wells were drilled in southern Mississippi in about 1880. Prior to that time, the aquifers were in a state of dynamic equilibrium where seasonal water-level responses to variations in precipitation occurred but year-to-year water levels remained nearly the same. Water levels in shallow sand beds may have fluctuated by as much as 20 feet annually, either near large streams or in the higher hills. The large water-level fluctuations in some of the shallow aquifers were dampened as these pressure heads were transmitted through confining units to either deeper aquifers or downdip within a sand bed or sandy zone.

A conceptualization of predevelopment ground-water flow is shown in figure 8. Recharge to the Miocene aquifer system occurred in areas where the altitude of the potentiometric surface of the surficial aquifer system (fig. 6) was higher than about 150 feet. Discharge occurred along the coast and in major river valleys where the potentiometric surface was below about 100 feet (fig. 6). From north to south toward the gulf, the potentiometric surface of the layers of the Miocene aquifer system sloped to the south and southeast toward the sea (figs. 9-15), but with a lesser gradient than the surficial aquifer system. Therefore, along the coast the vertical hydraulic gradient was upward through the various layers (fig. 8). A slow but steady flow of fresh and moderately saline water (dissolved-solids concentrations less than 10,000 milligrams per liter) through the Miocene aquifer system established a nearly stagnant freshwater-saltwater interface (fig. 8) beyond which flow was considered to be negligible.

Post-development flow

Early development of ground water along the Mississippi Gulf Coast is summarized as follows by Colson and Boswell (1985):

> The first flowing artesian well is reported to have been drilled in 1884 and until recent years the population along the coast had been supplied with water by flowing wells that had artesian heads as high as 60 to 80 feet above sea level. The drilling firms operating in the coastal area reported to G.F. Brown (1944, p.66) that a total of 83 wells had been drilled by 1901 and by 1903, there were 199 wells, the deepest of which was 1,550 feet. By 1979, U.S. Geological Survey files contained records for about 4,200 wells located within about 6 miles of the coastline.

Withdrawal of water by wells in the various layers of the Miocene aquifer system caused many changes. The effect of these withdrawals on the potentiometric surfaces of the layers is shown in a series of maps

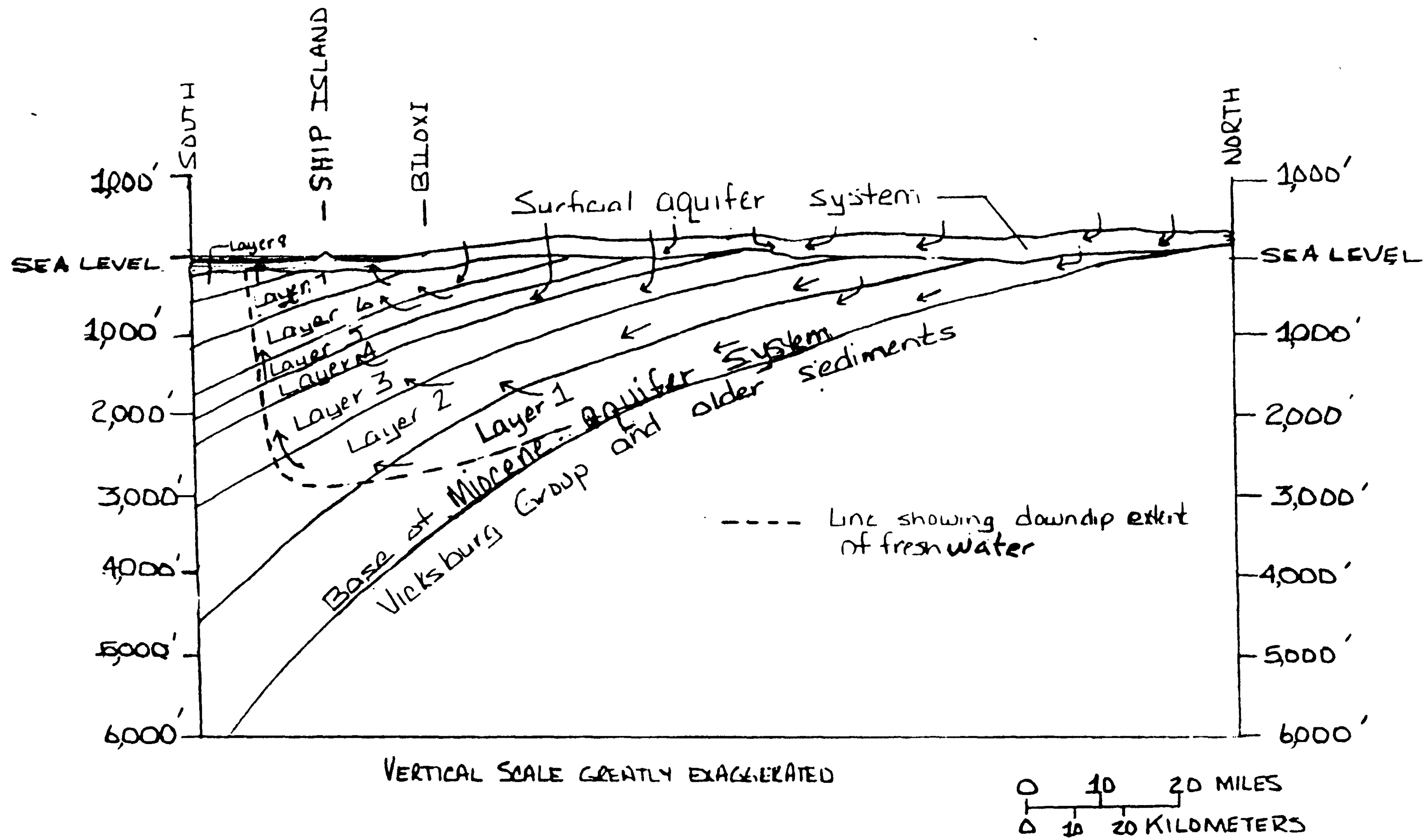


Figure 8.--Diagrammatic section north-south through Biloxi showing ground-water flow among the eight hydrologic layers prior to development.

The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

(hatched area)	AREA OF SUBCROP OF LAYER 1
—50—	POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 1 in various periods. Contour interval 25 feet. Datum is sea level. All contours are approximate
•	WATER-LEVEL MEASUREMENT SITE

Figure 9.--Potentiometric surface of layer 1 in selected years.

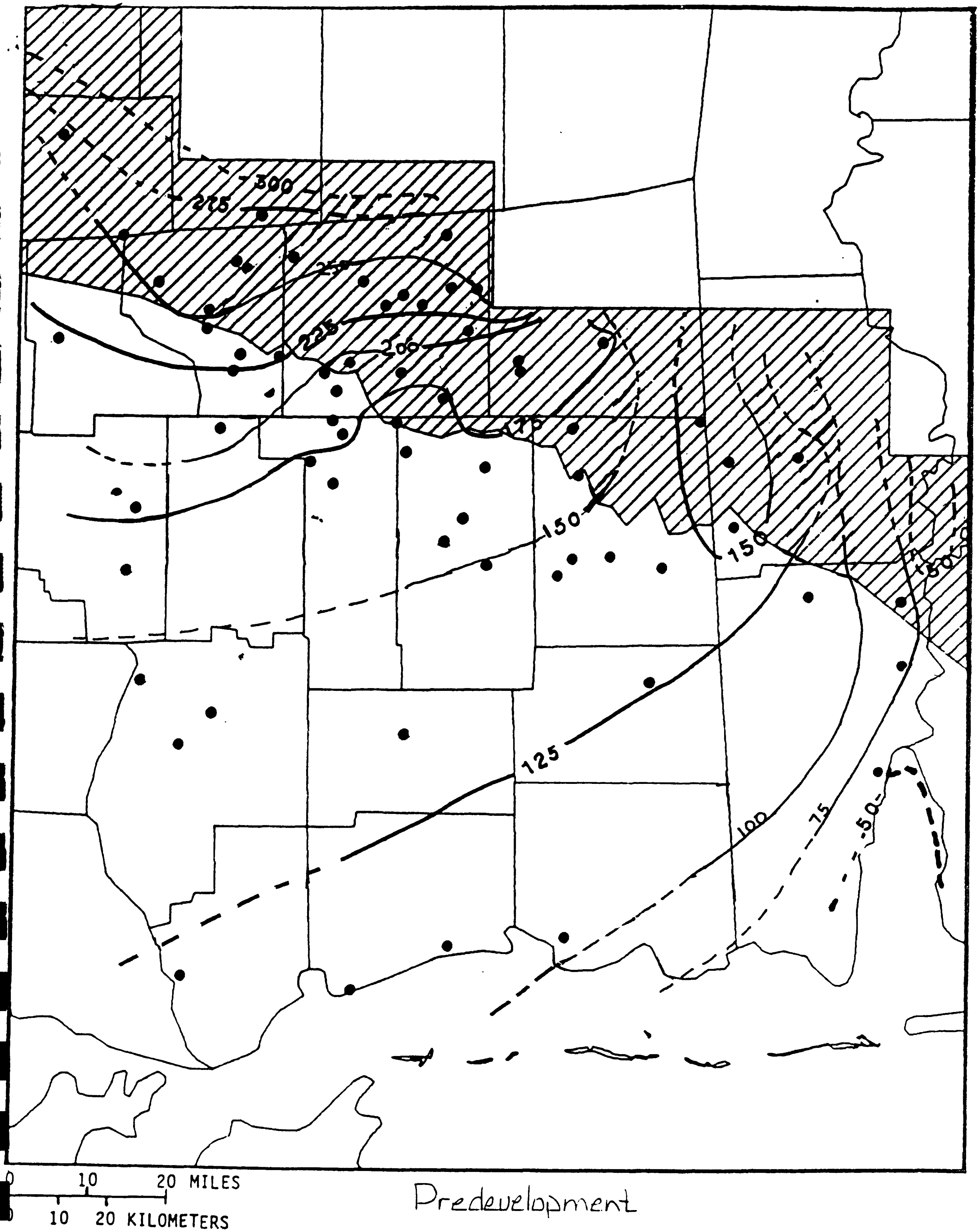
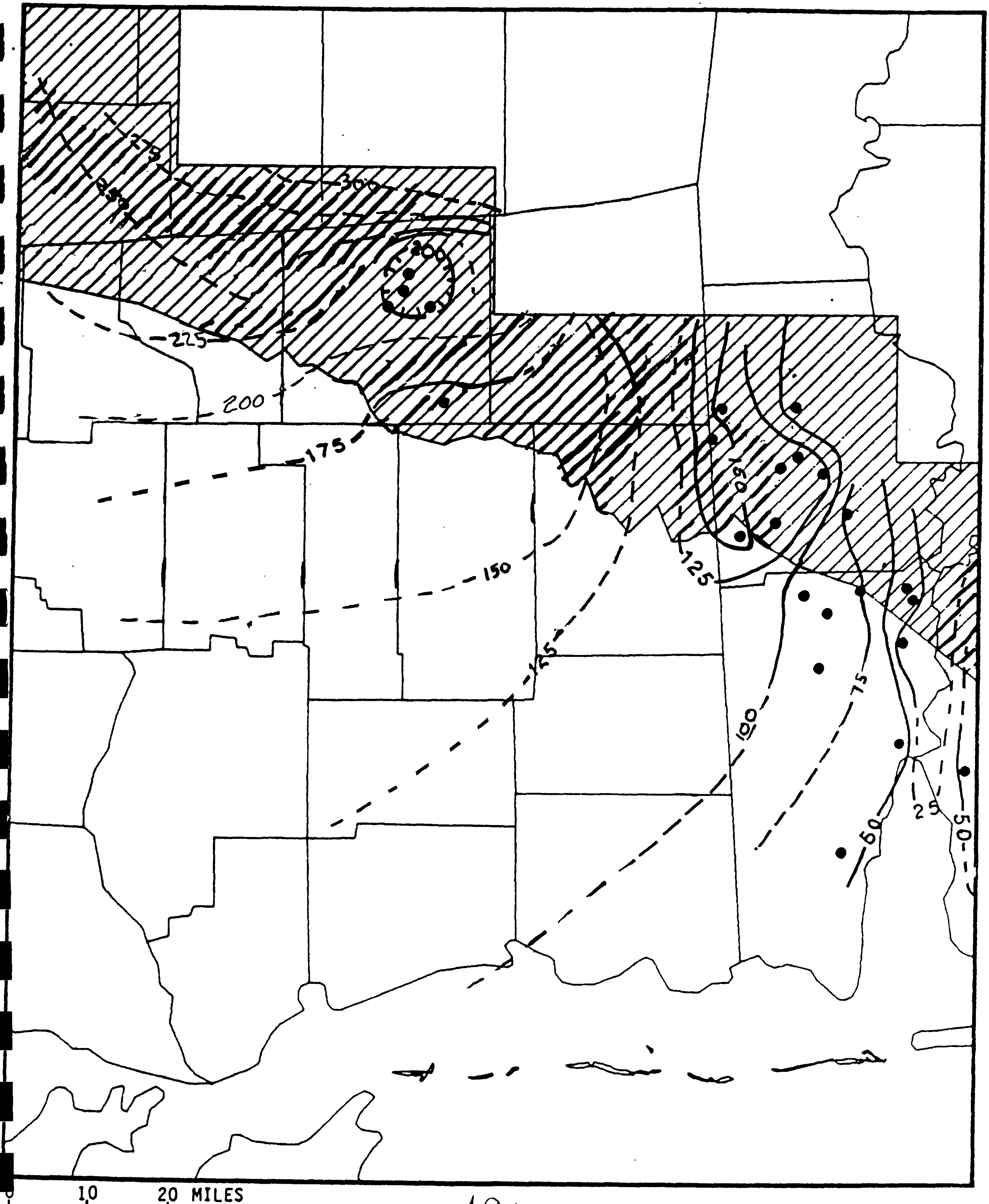


Figure 9. -- Continued



1940

Figure 9.-- Continued 24

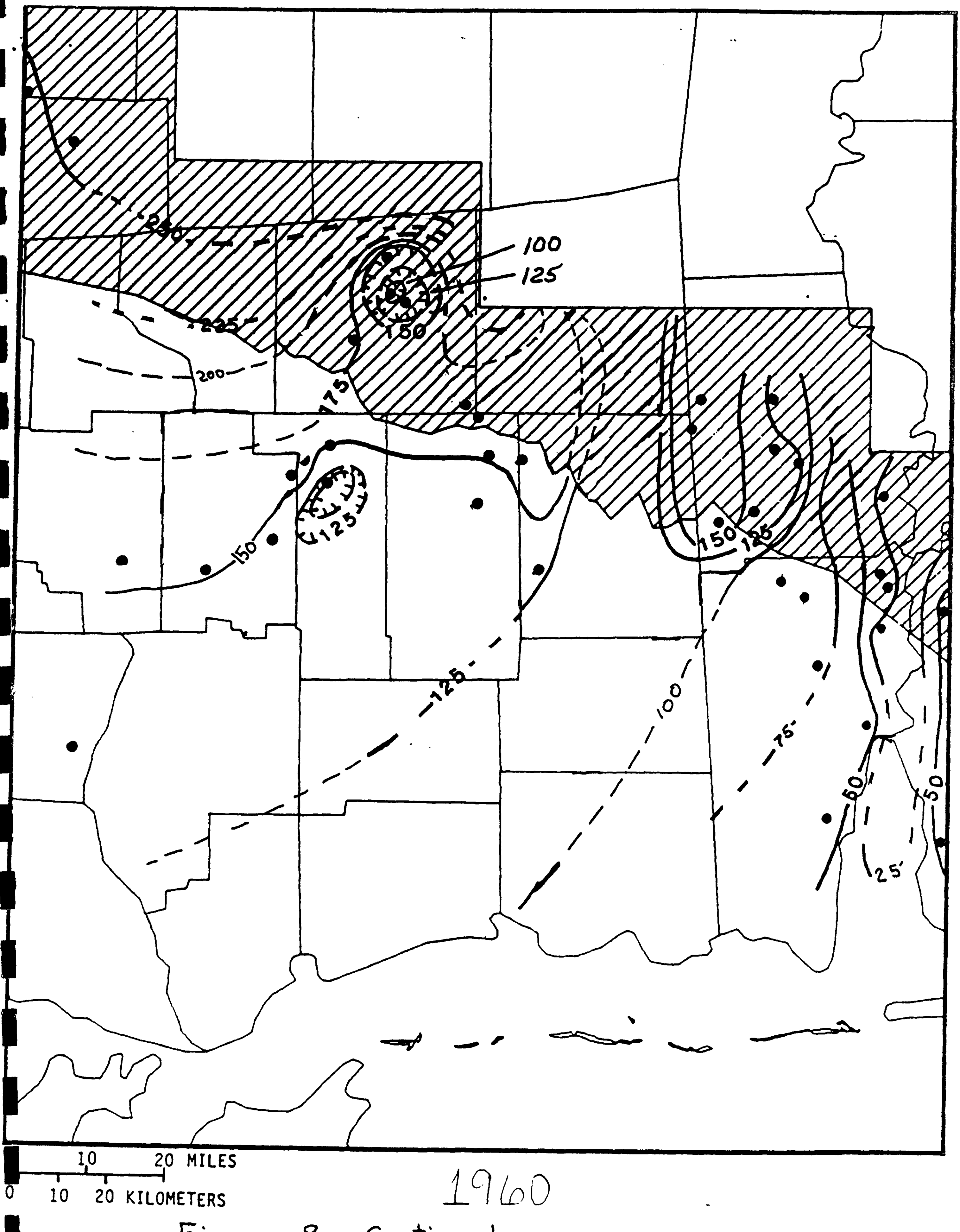


Figure 9. -- Continued

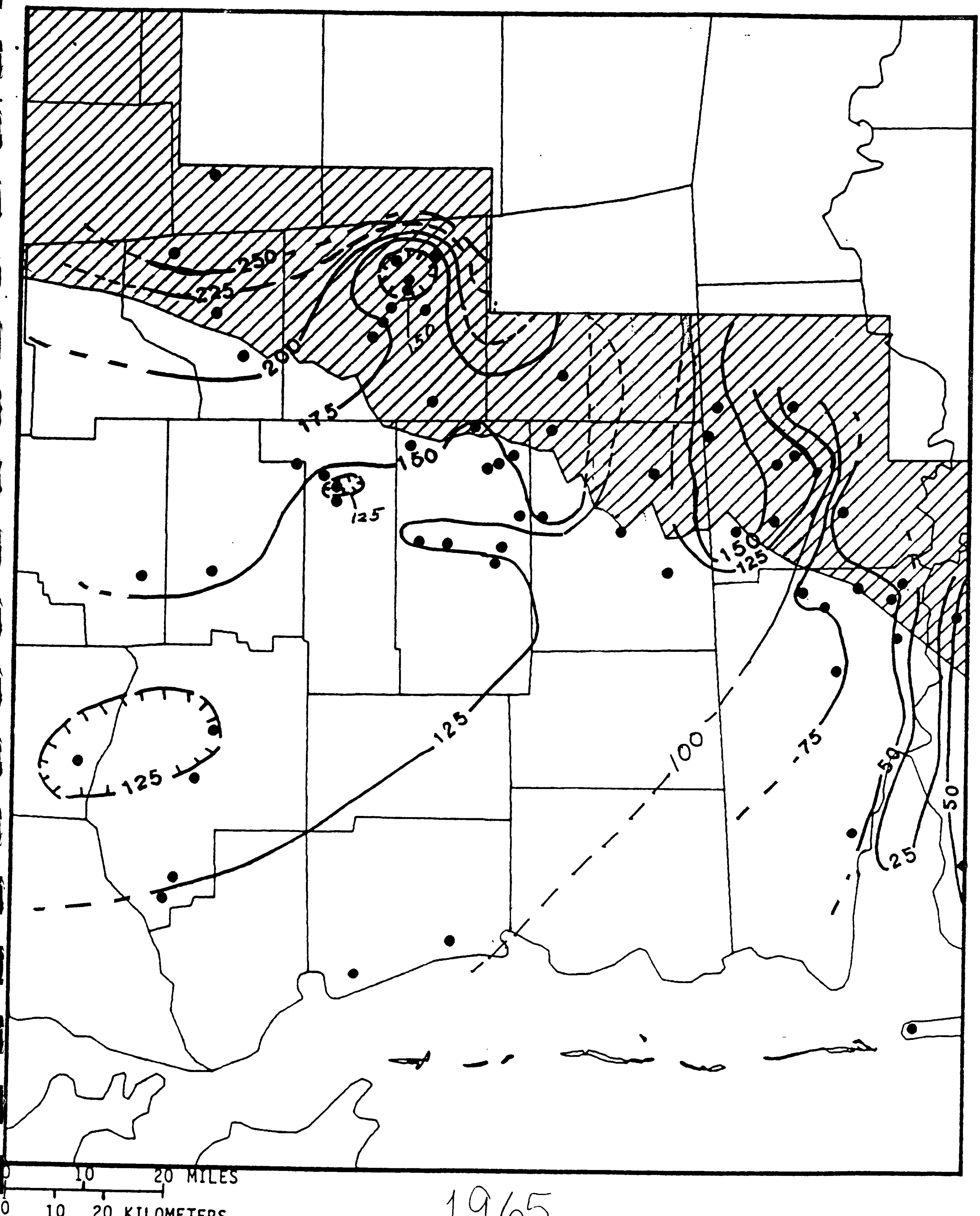


Figure 9. -- Continued

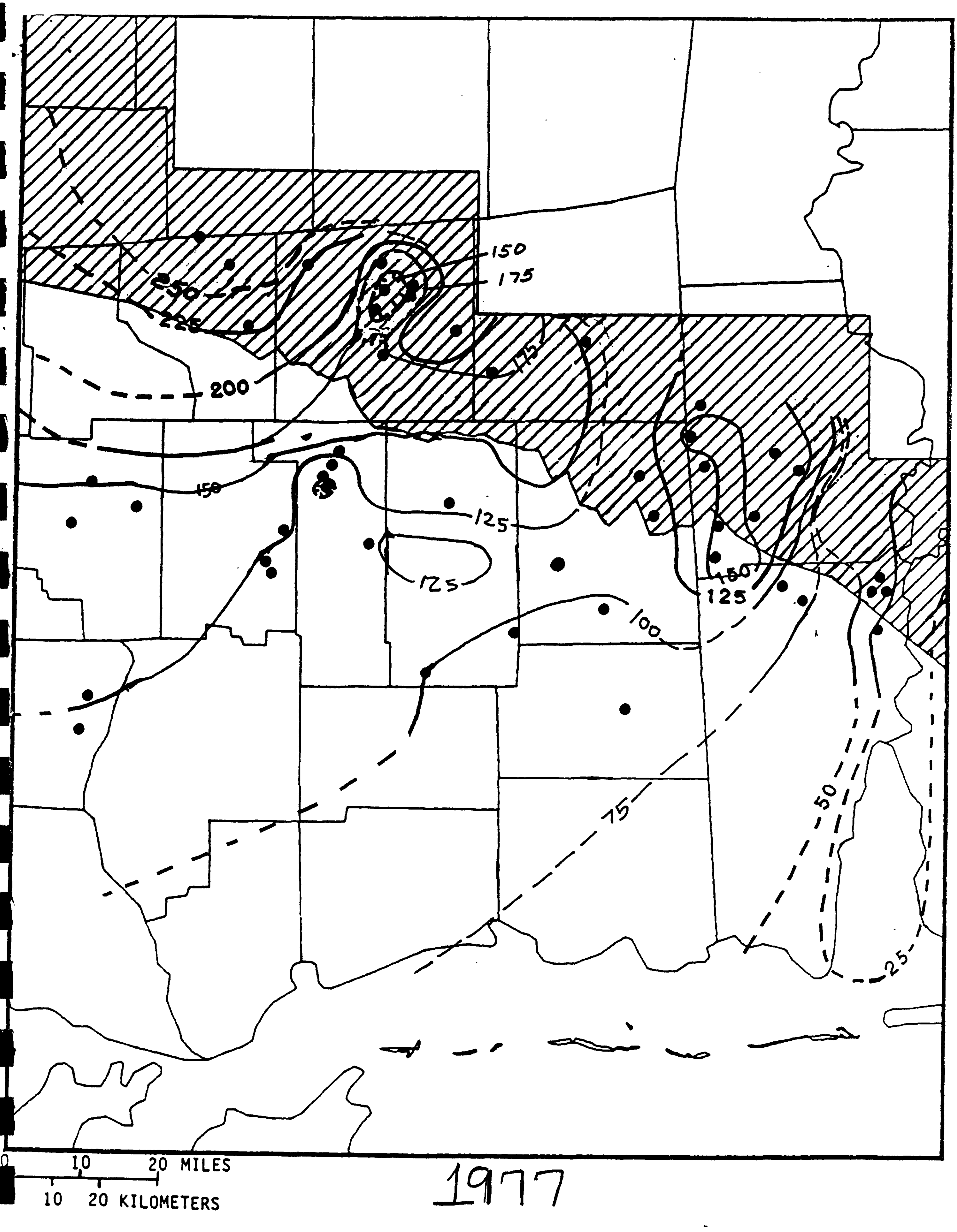


Figure 9. -- Continued

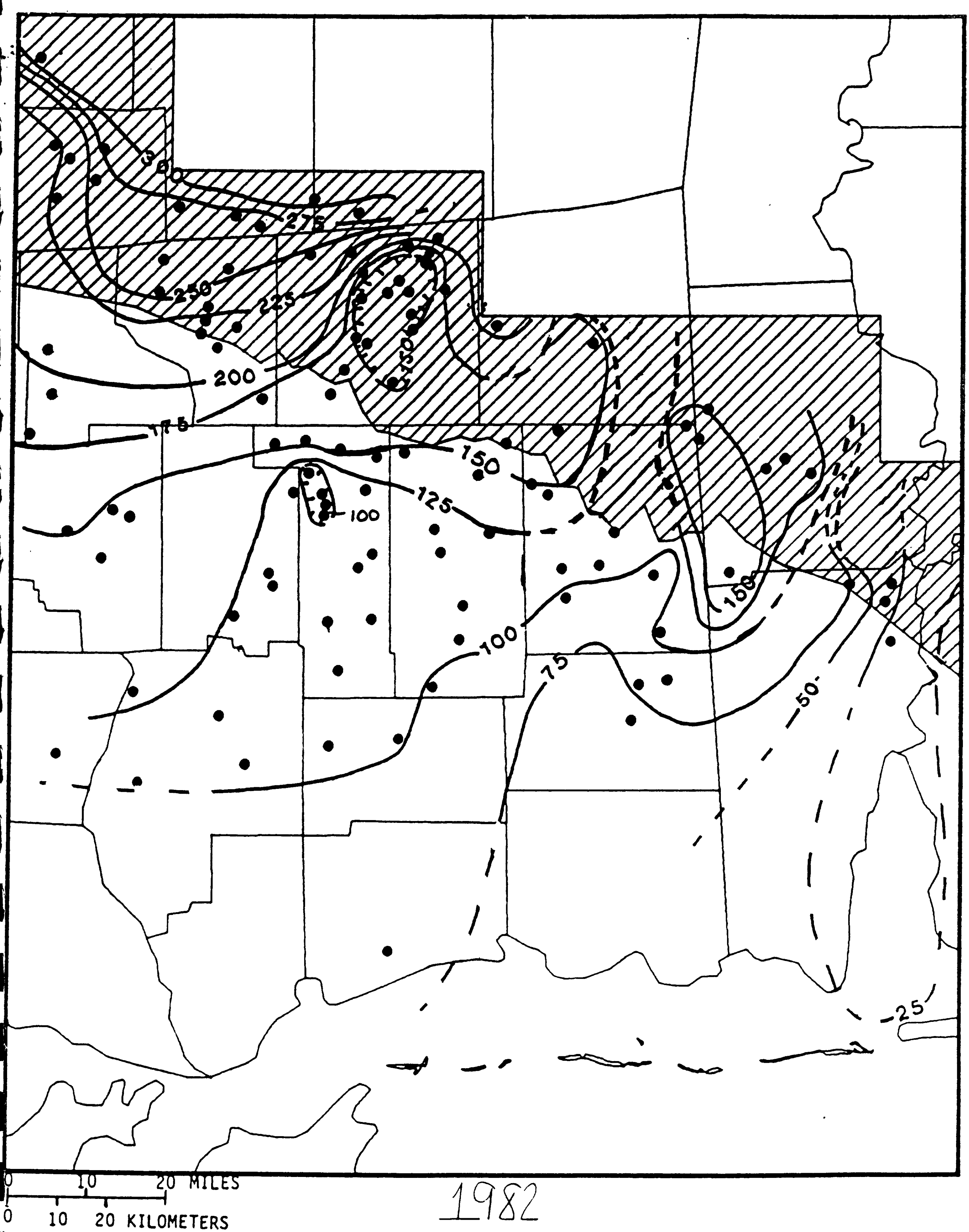


Figure 9. -- Continued

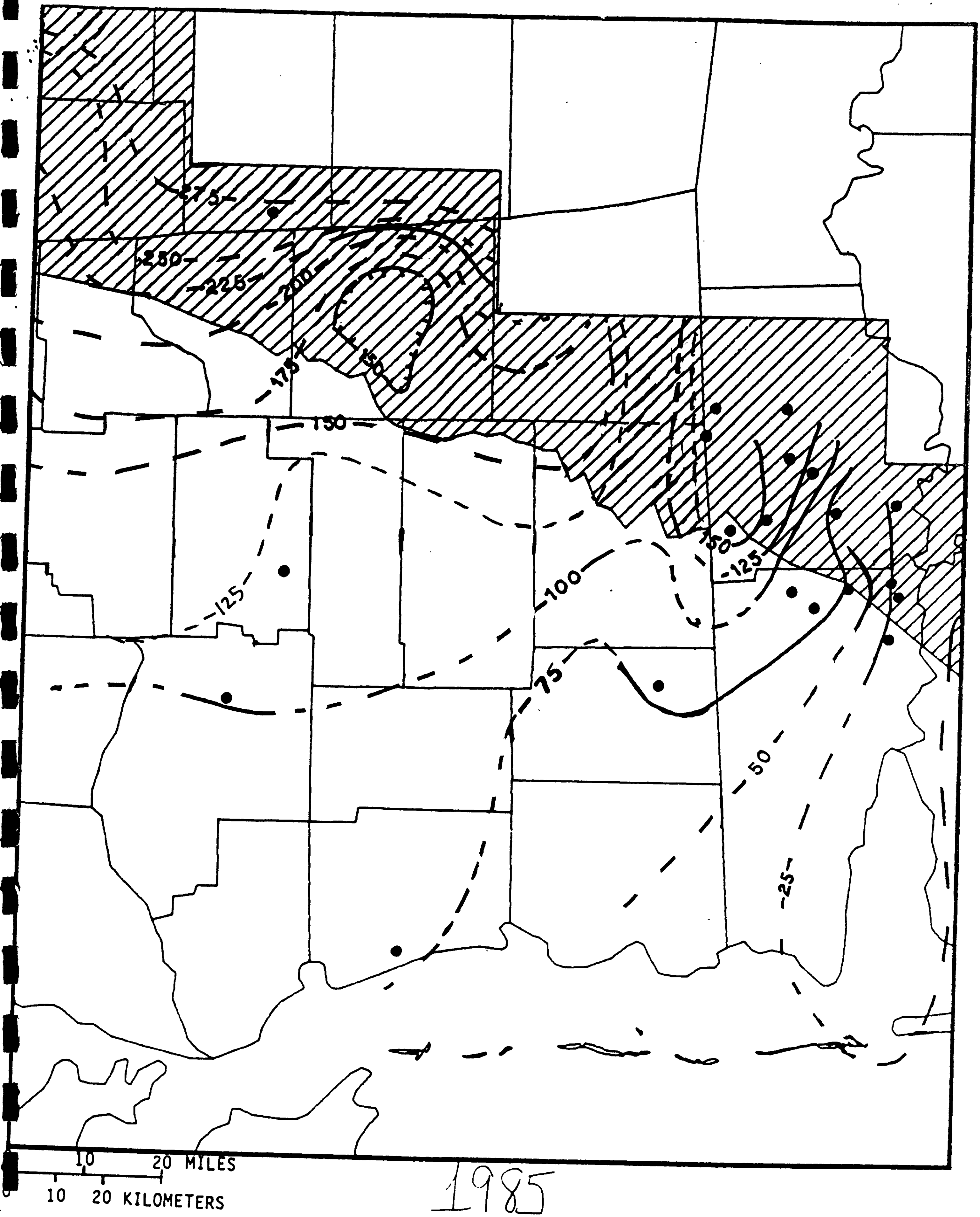


Figure 9.--Continued

The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

	AREA OF SUBCROP OF LAYER 2
—50—	POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 2 in various periods. Contour interval 25 feet. Datum is sea level. All contours are approximate
•	WATER-LEVEL MEASUREMENT SITE

Figure 10.--Potentiometric surface of layer 2 in selected years.

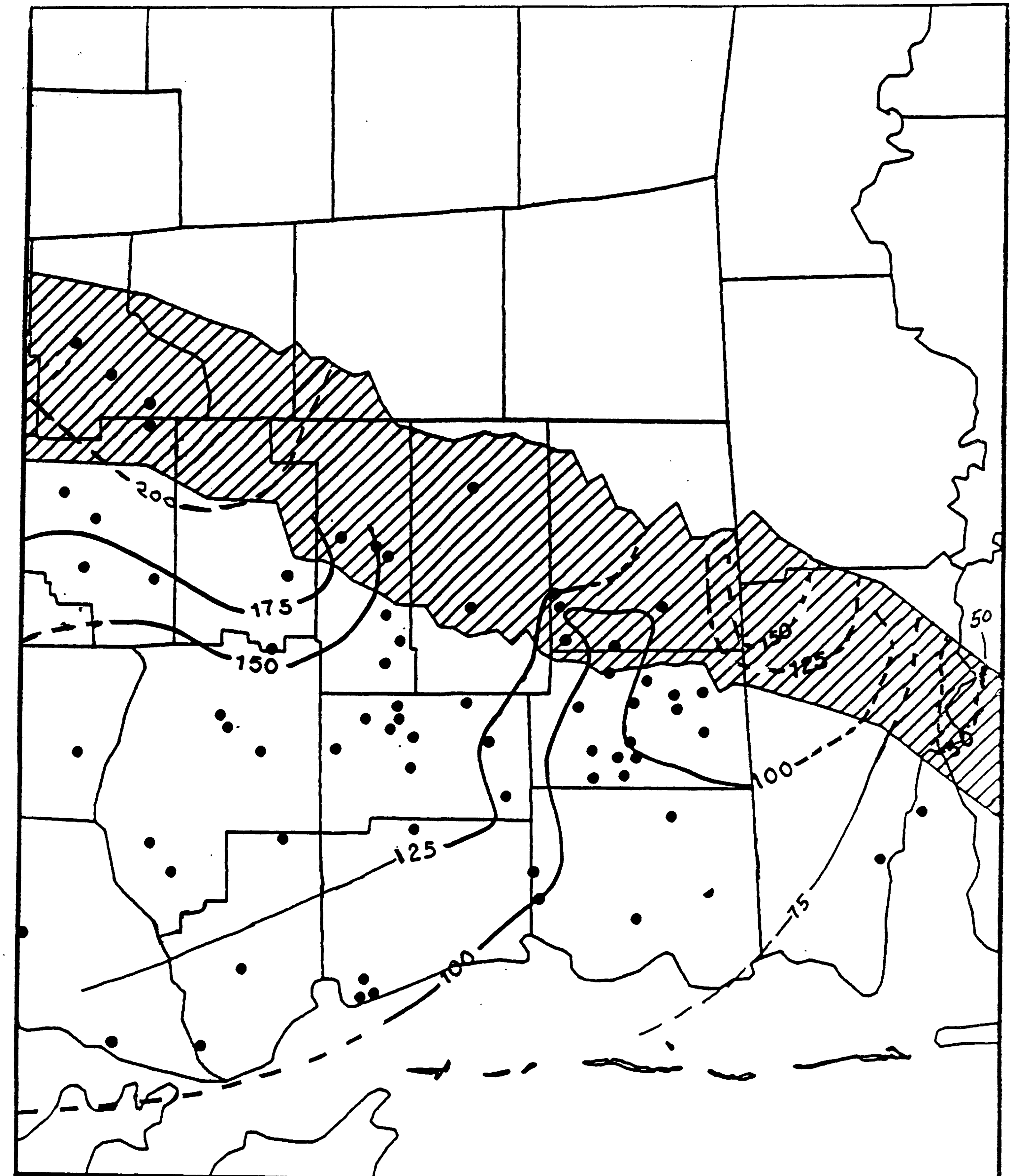
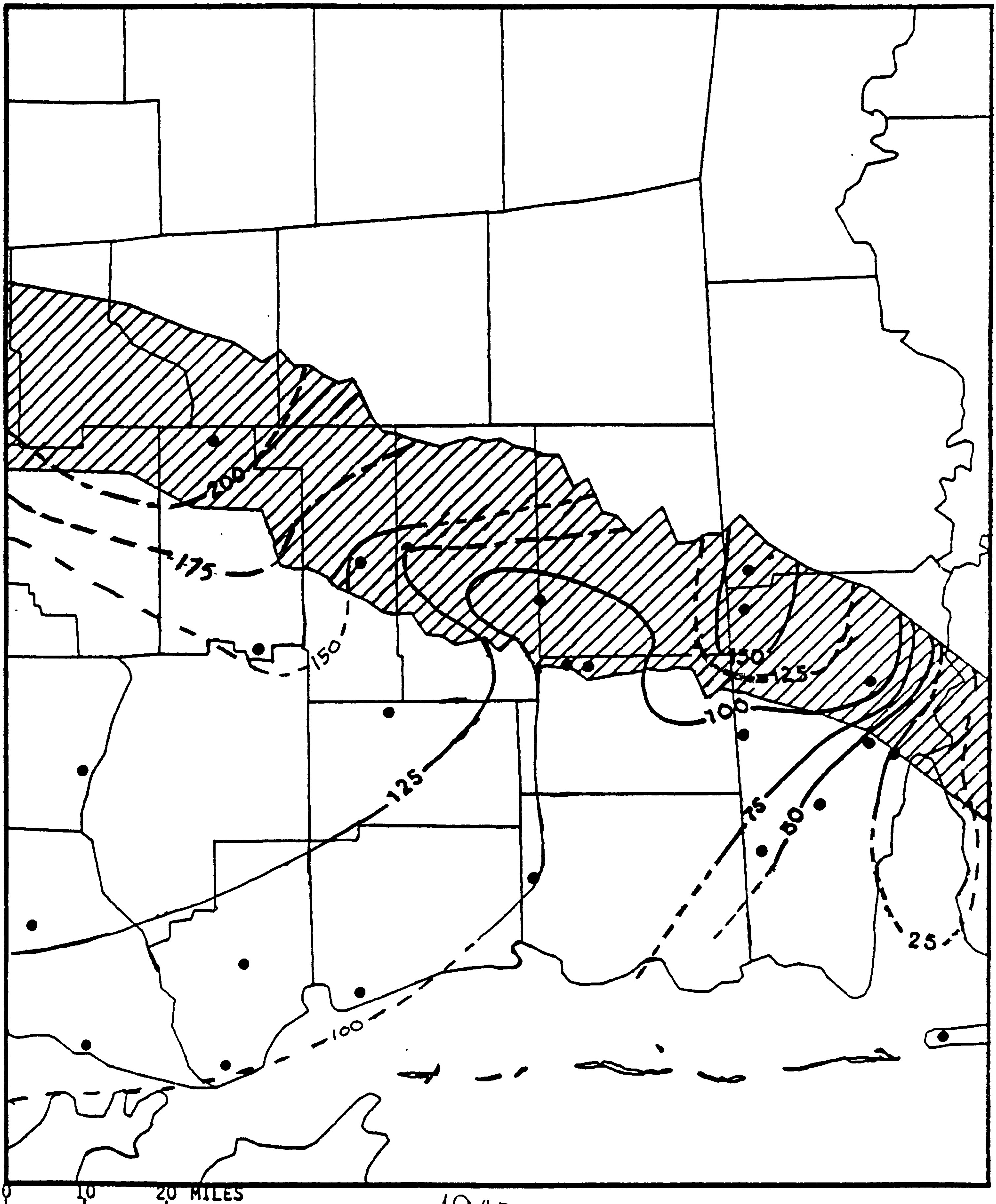
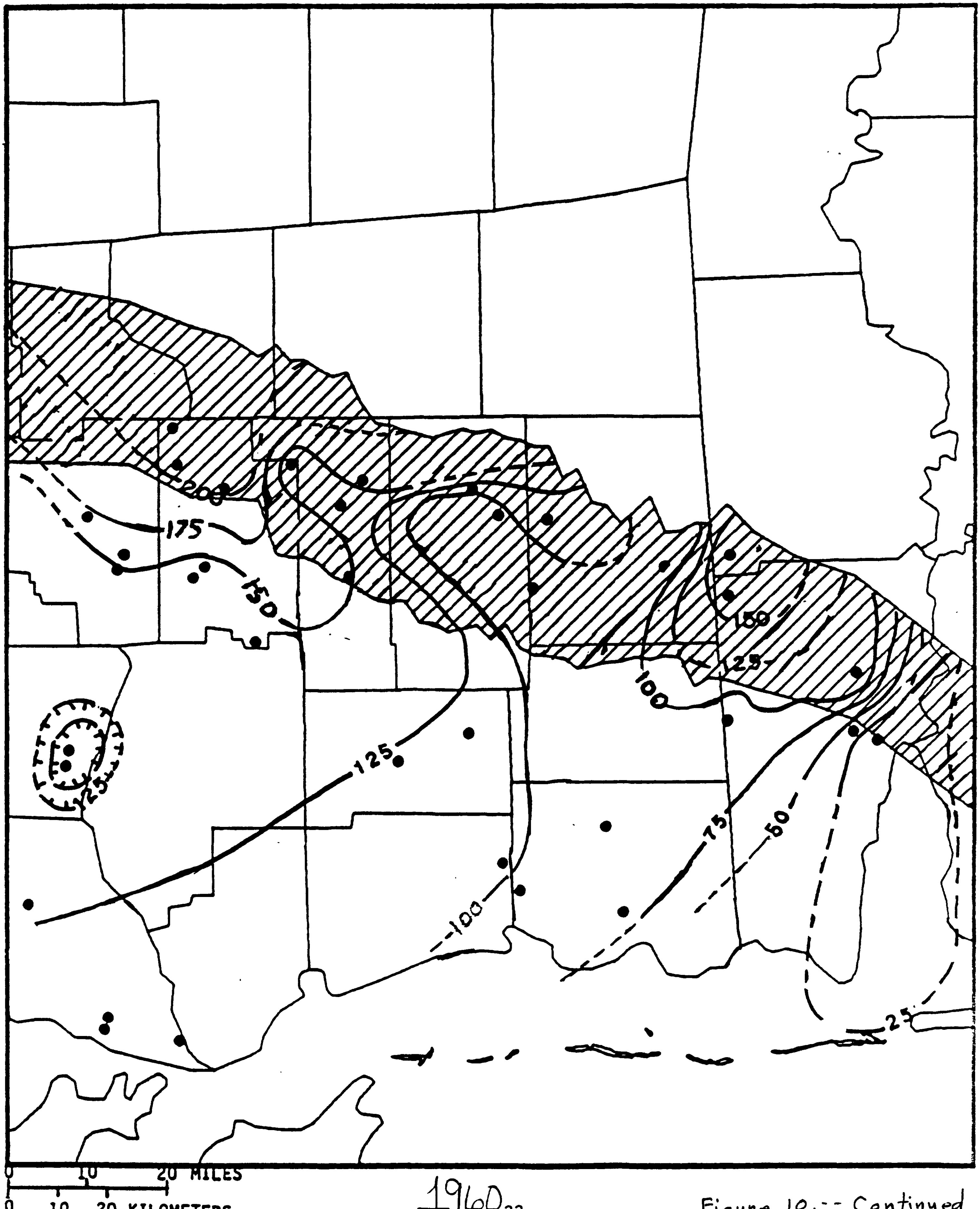


Figure 10.-- Continued



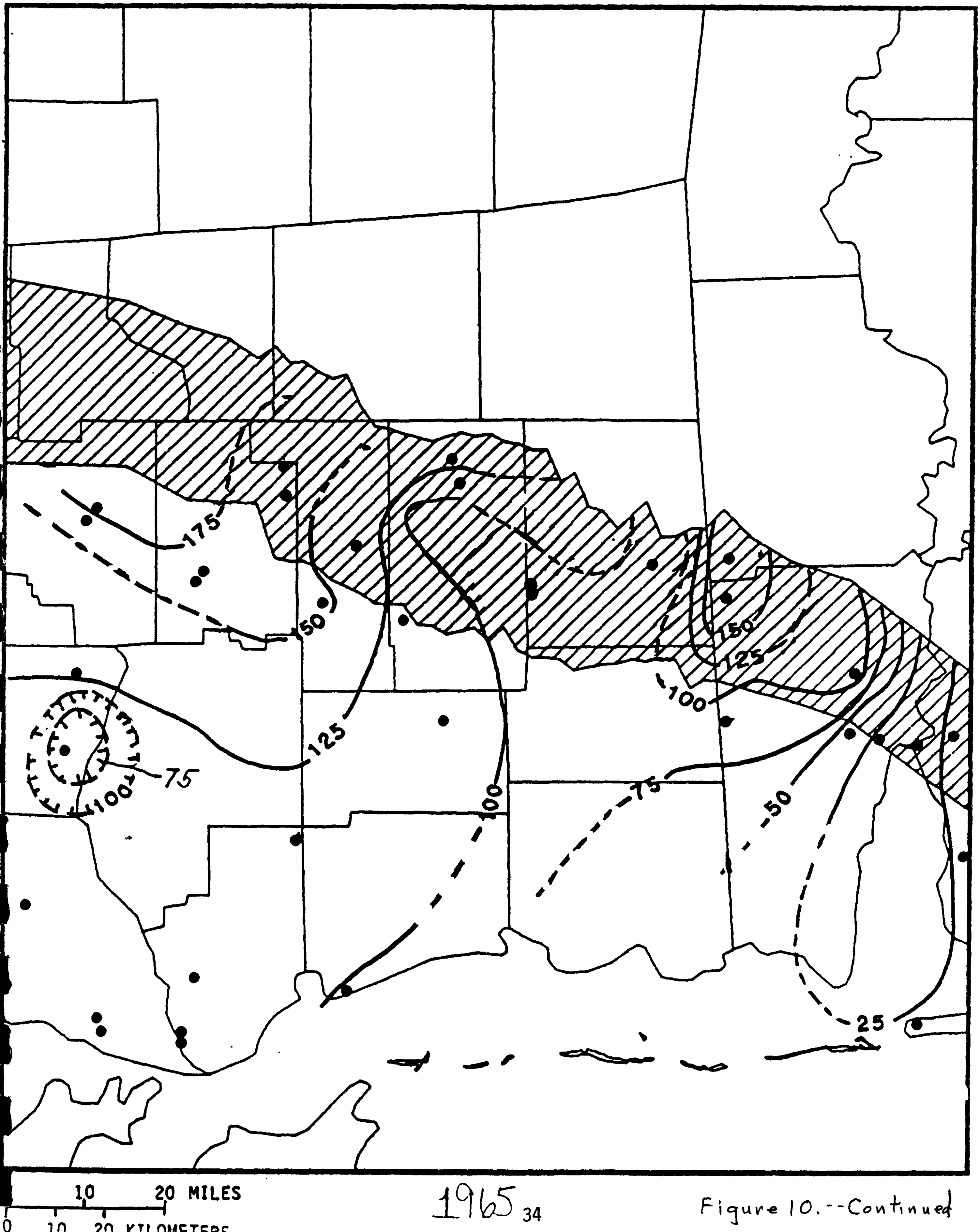
1940

Figure 10.--Continued



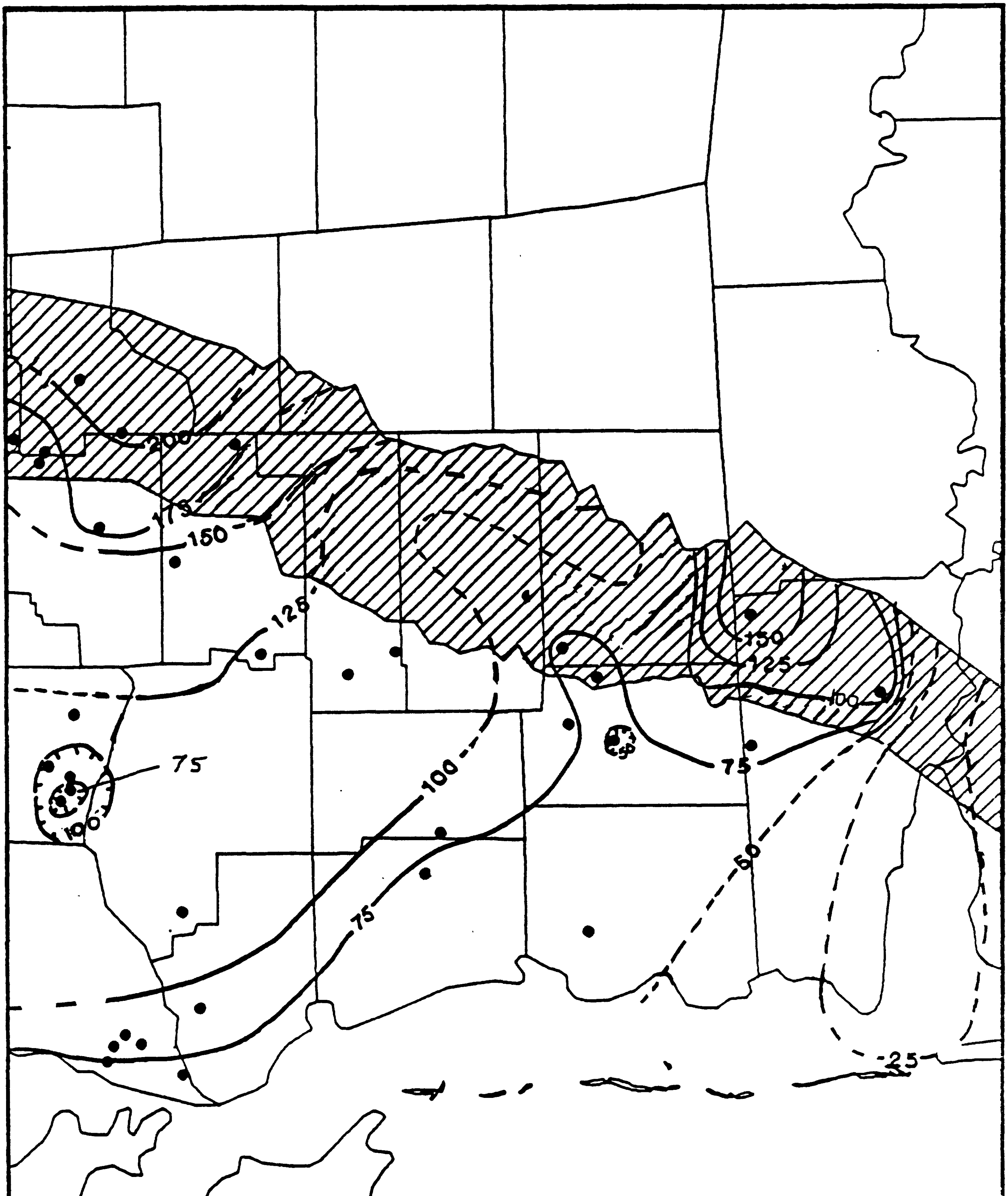
1960

Figure 10.--Continued



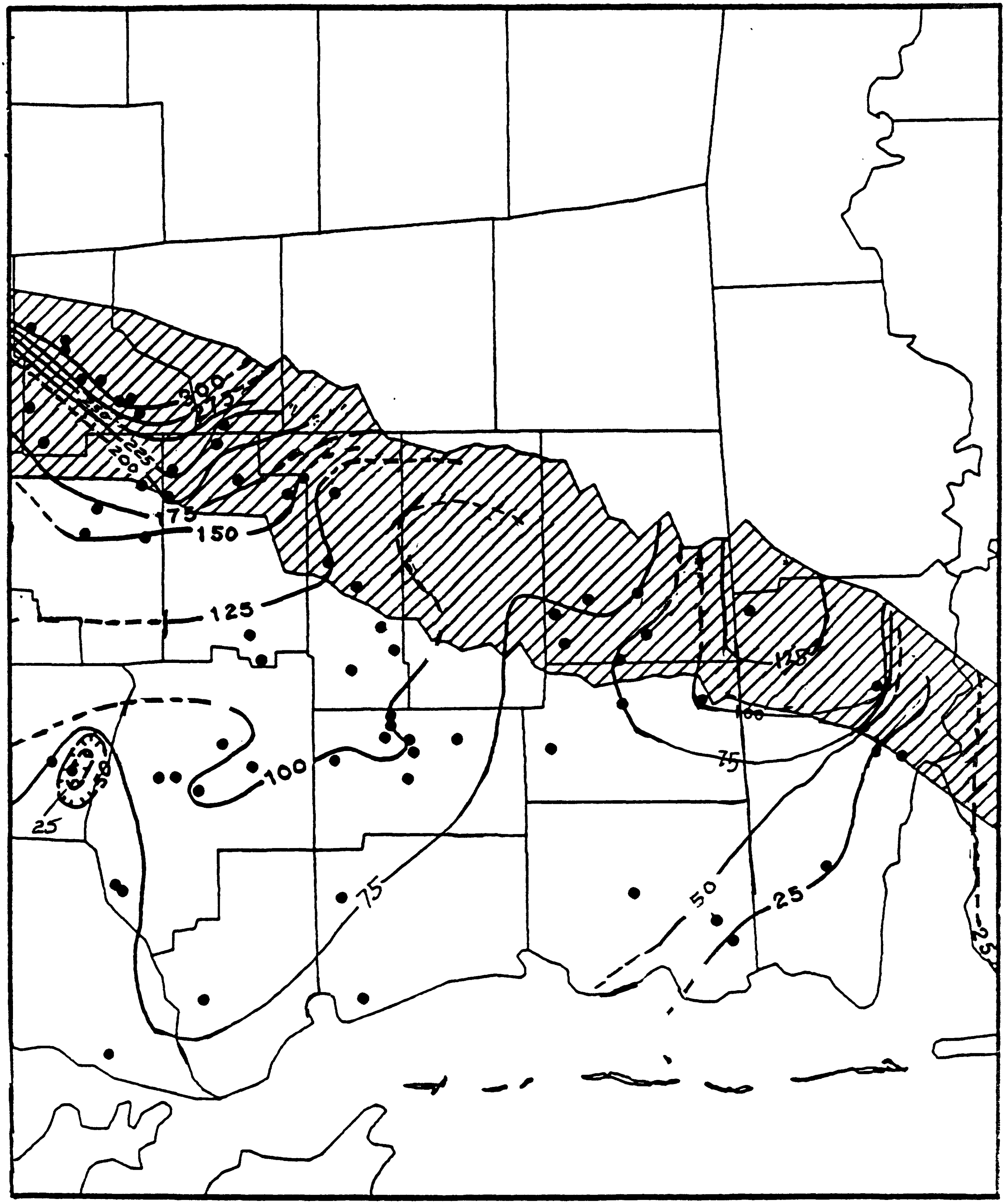
1965

Figure 10.--Continued



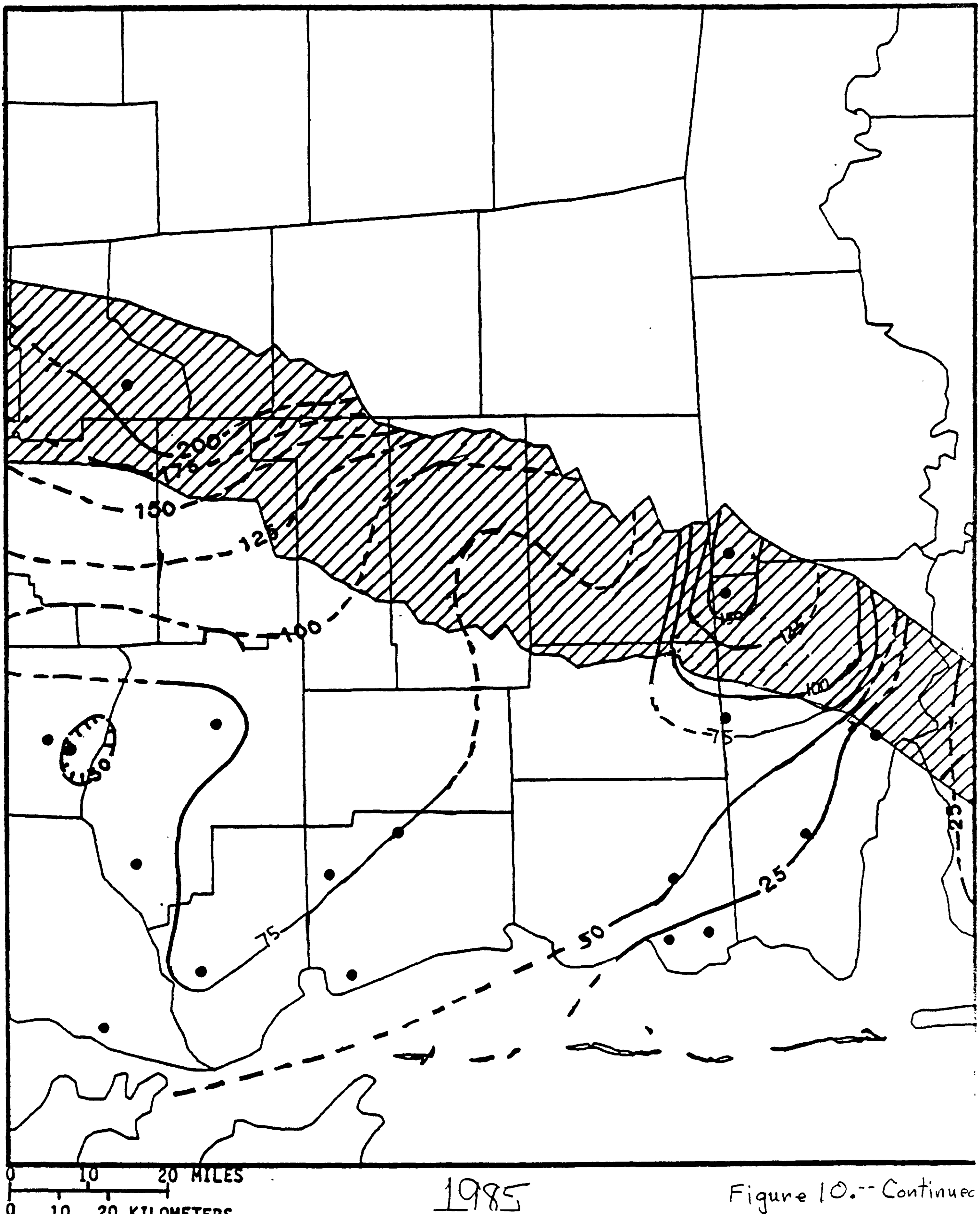
1977

Figure 10.--Continued



1982

Figure 10.--Continued



1985

Figure 10.--Continued

The title and explanation below apply to the following seven pages which make up this multipage illustration.

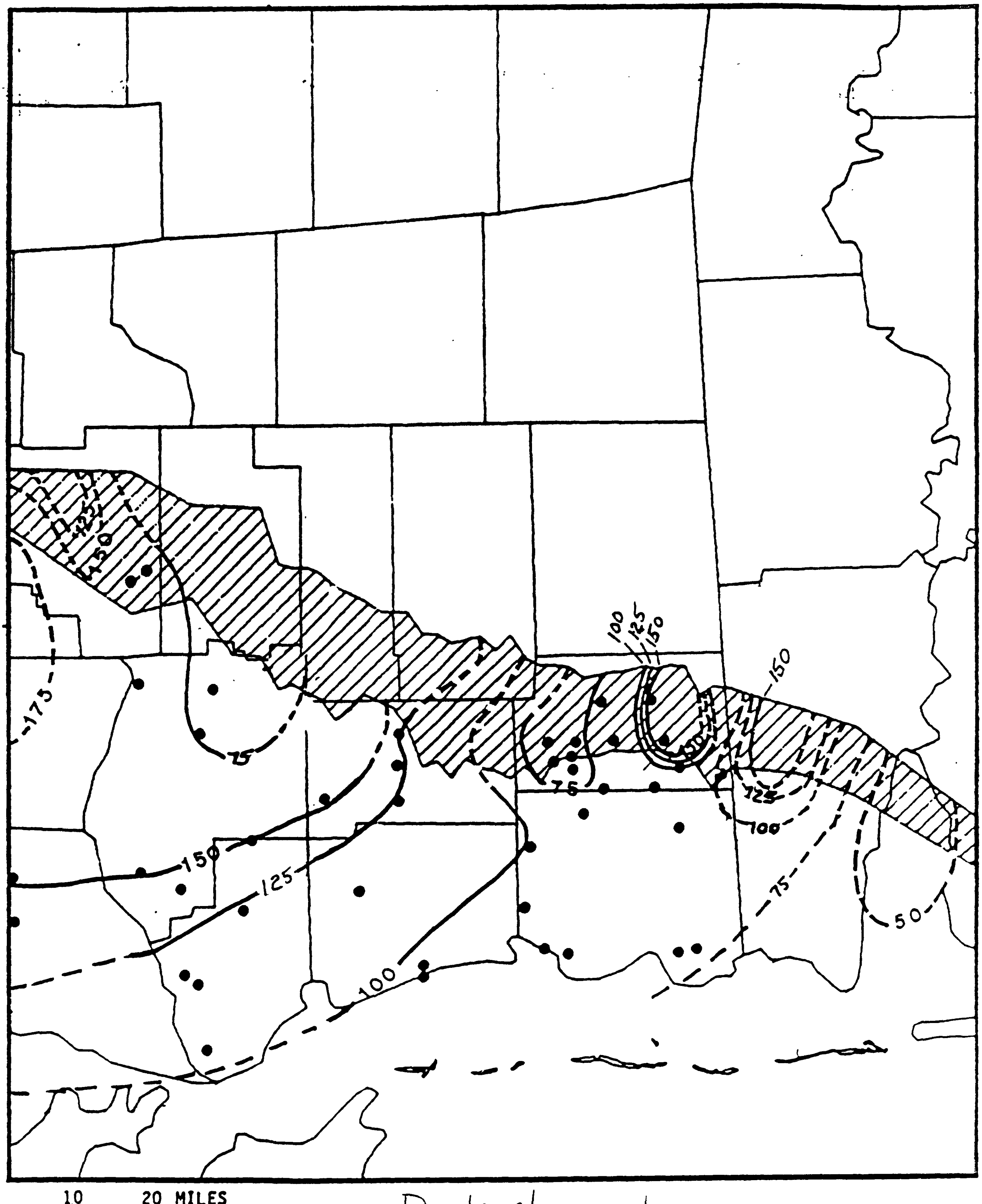
EXPLANATION

AREA OF SUBCROP OF LAYER 3

—50— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 3 in various periods. Contour interval 25 feet. Datum is sea level. All contours are approximate

• WATER-LEVEL MEASUREMENT SITE

Figure 11.--Potentiometric surface of layer 3 in selected years.



Predevelopment

Figure 11.--Continu

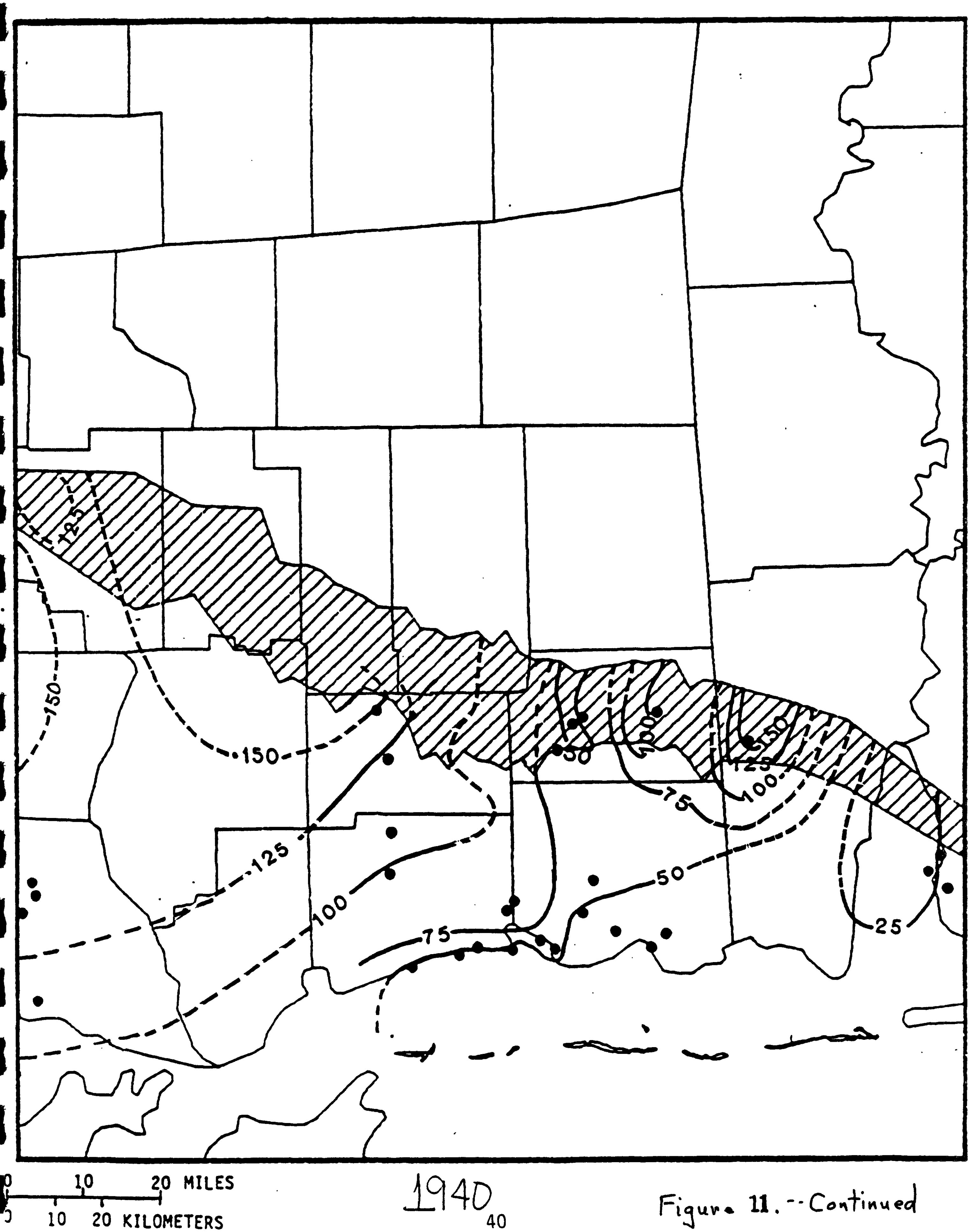
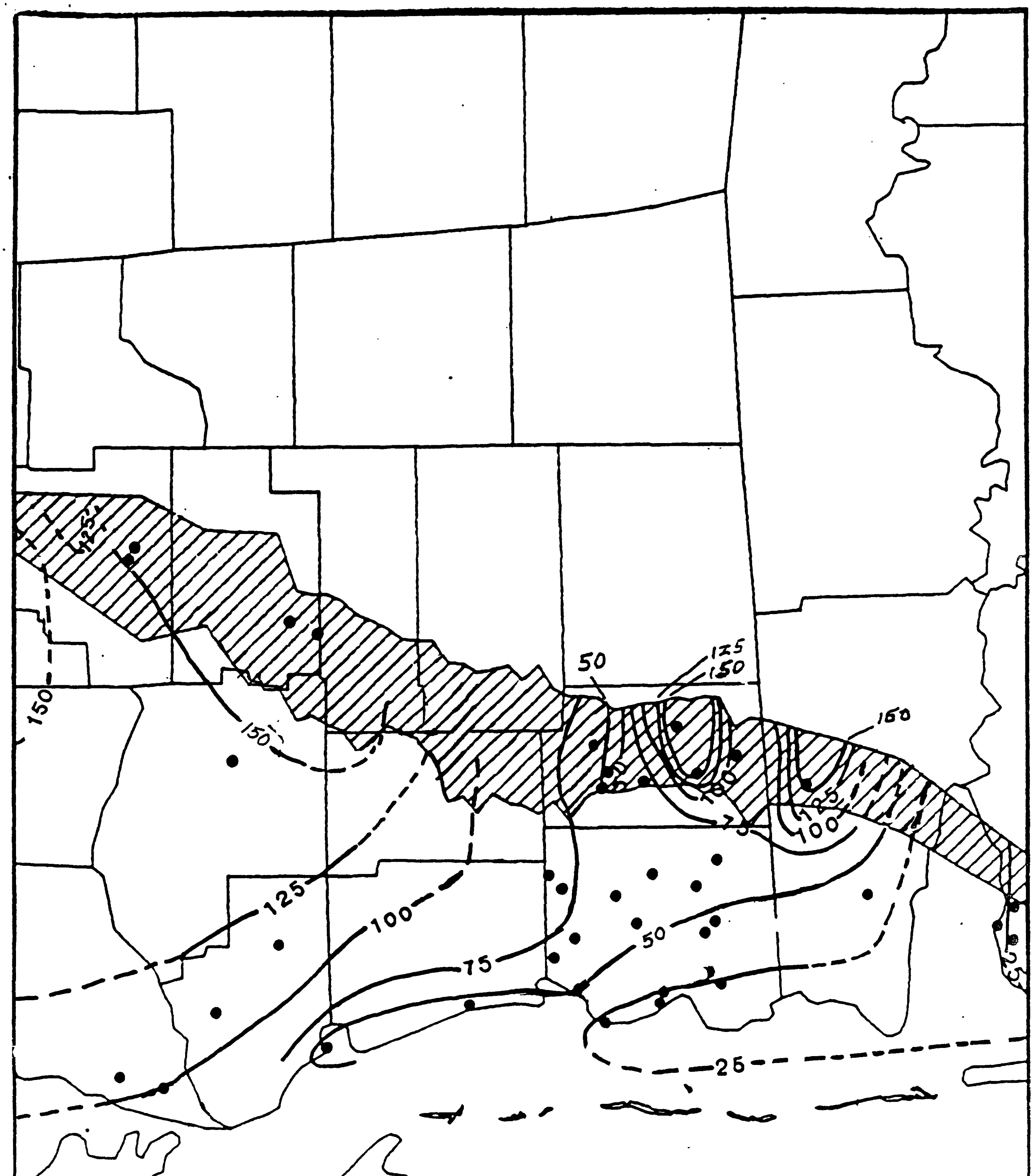
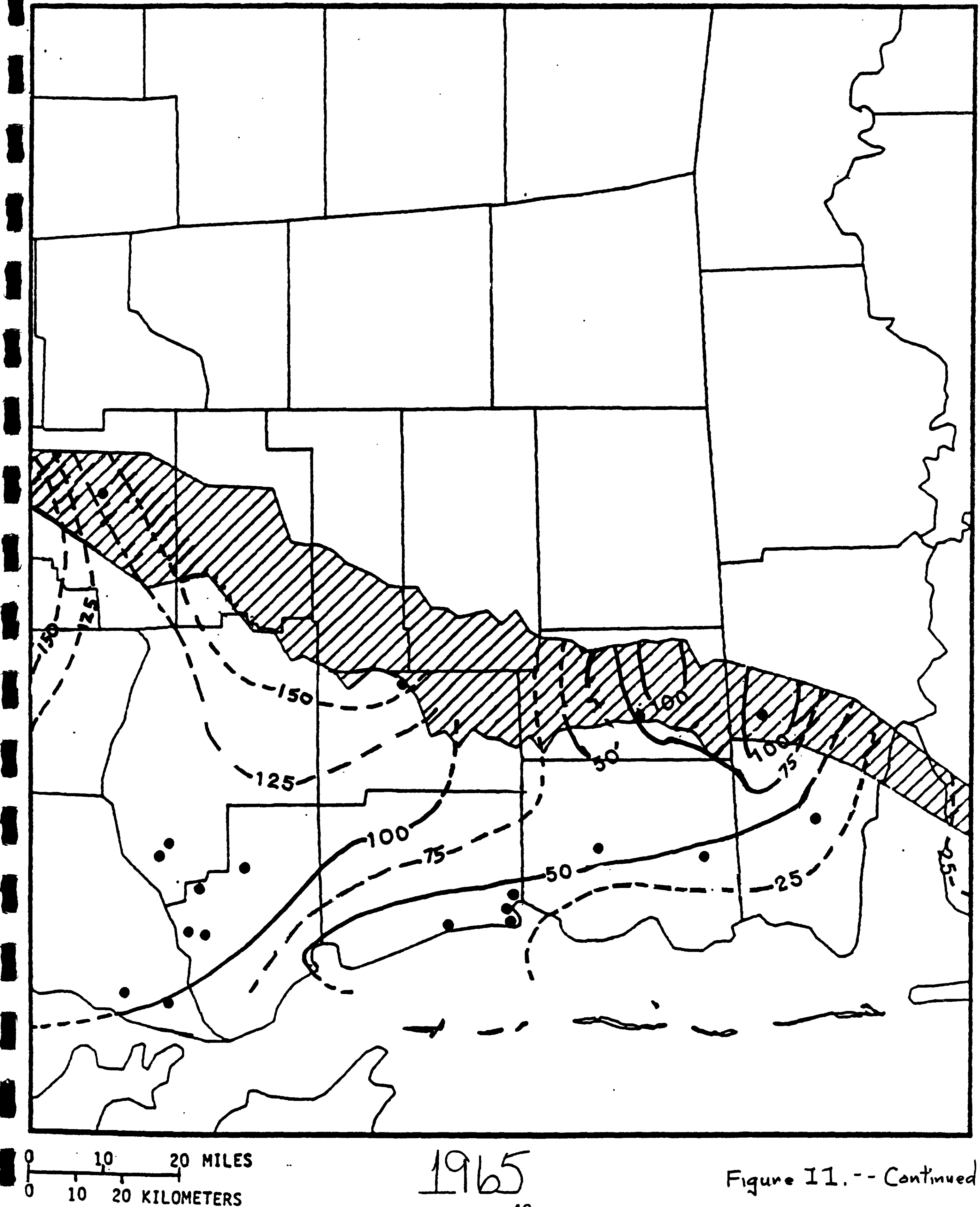


Figure 11.--Continued



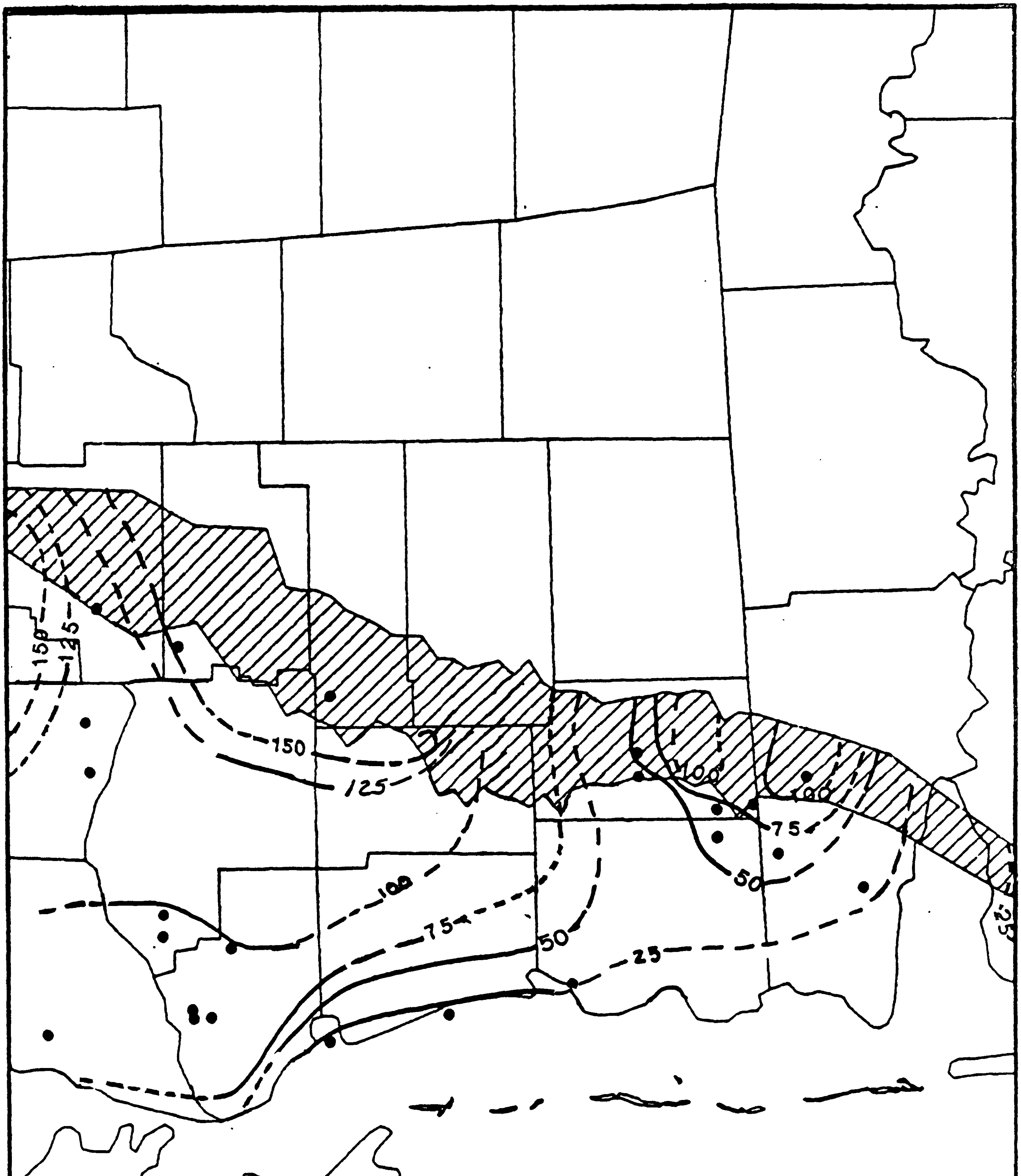
1960

Figure 11.--Continued



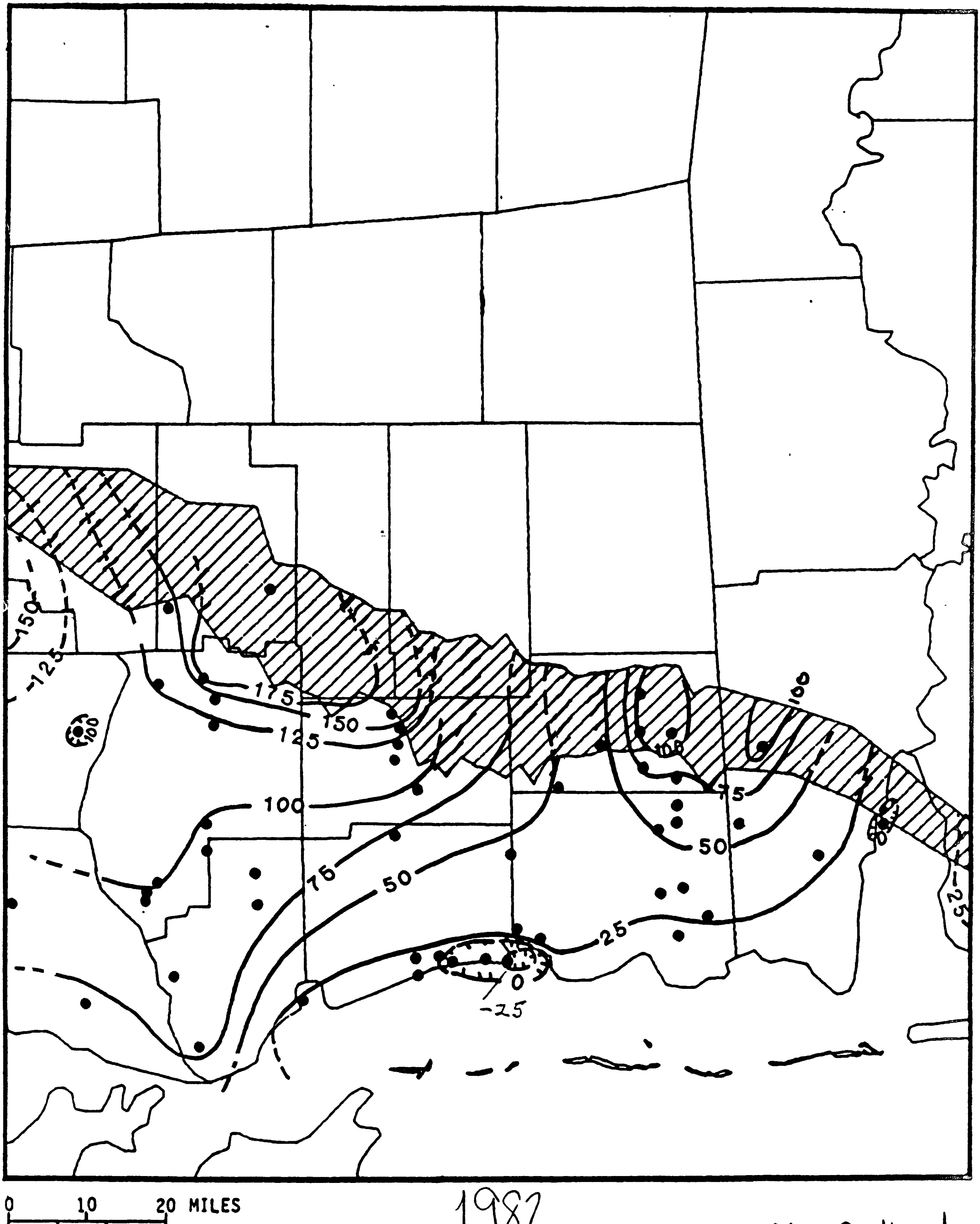
1965

Figure 11.--Continued



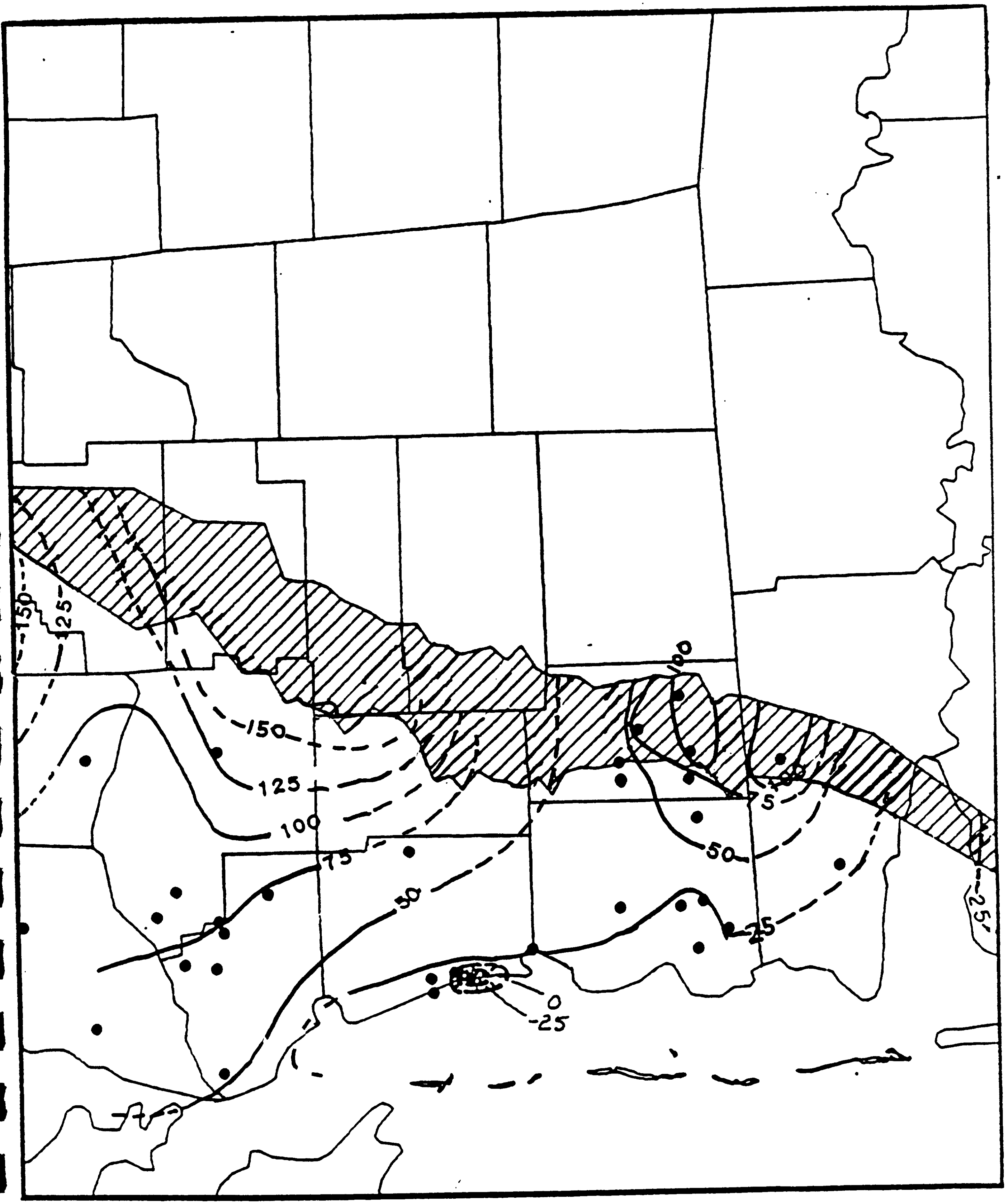
1977

Figure 11.--Continued



1982

Figure 11.--Continued



1985

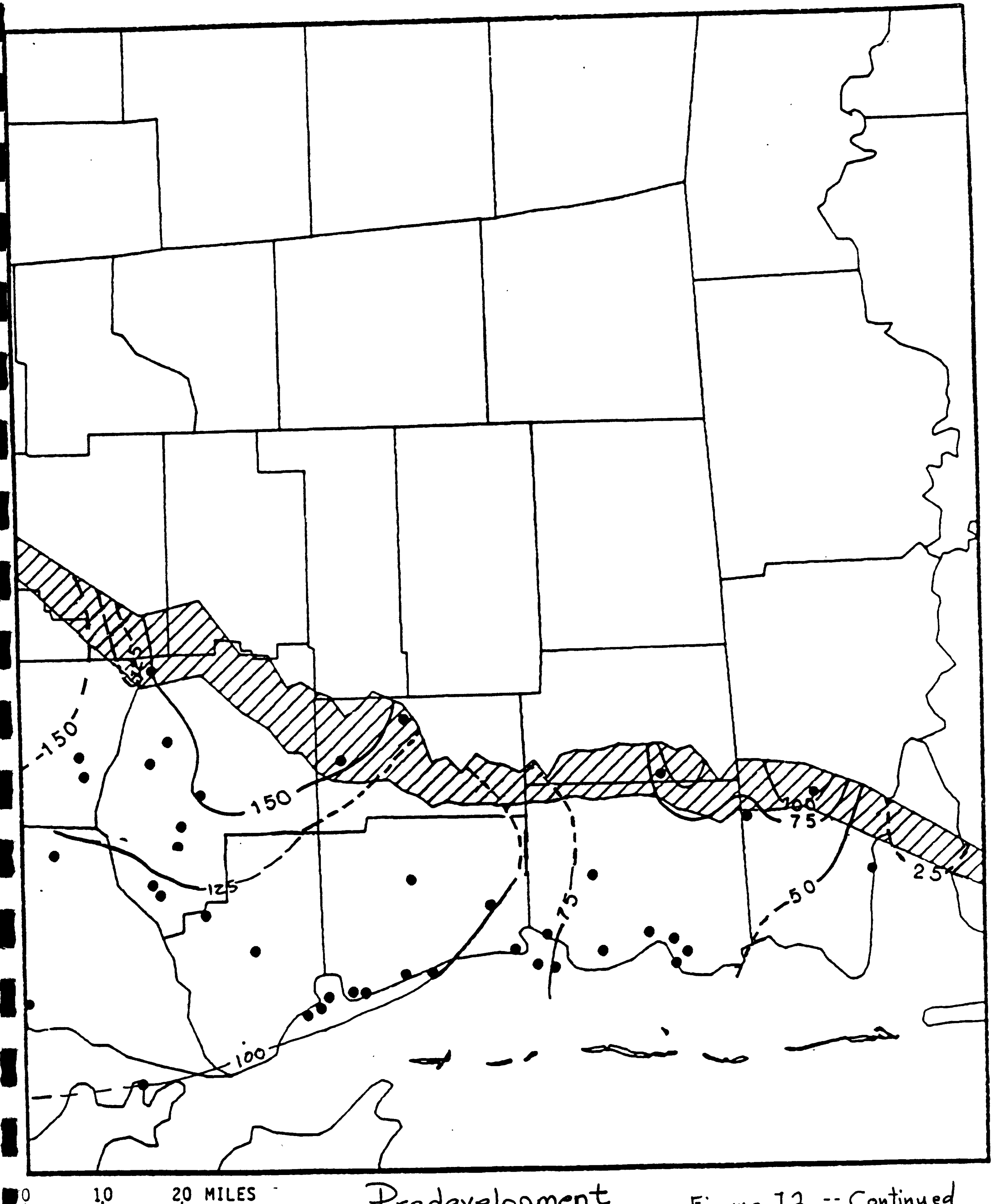
Figure 11.--Continued

The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

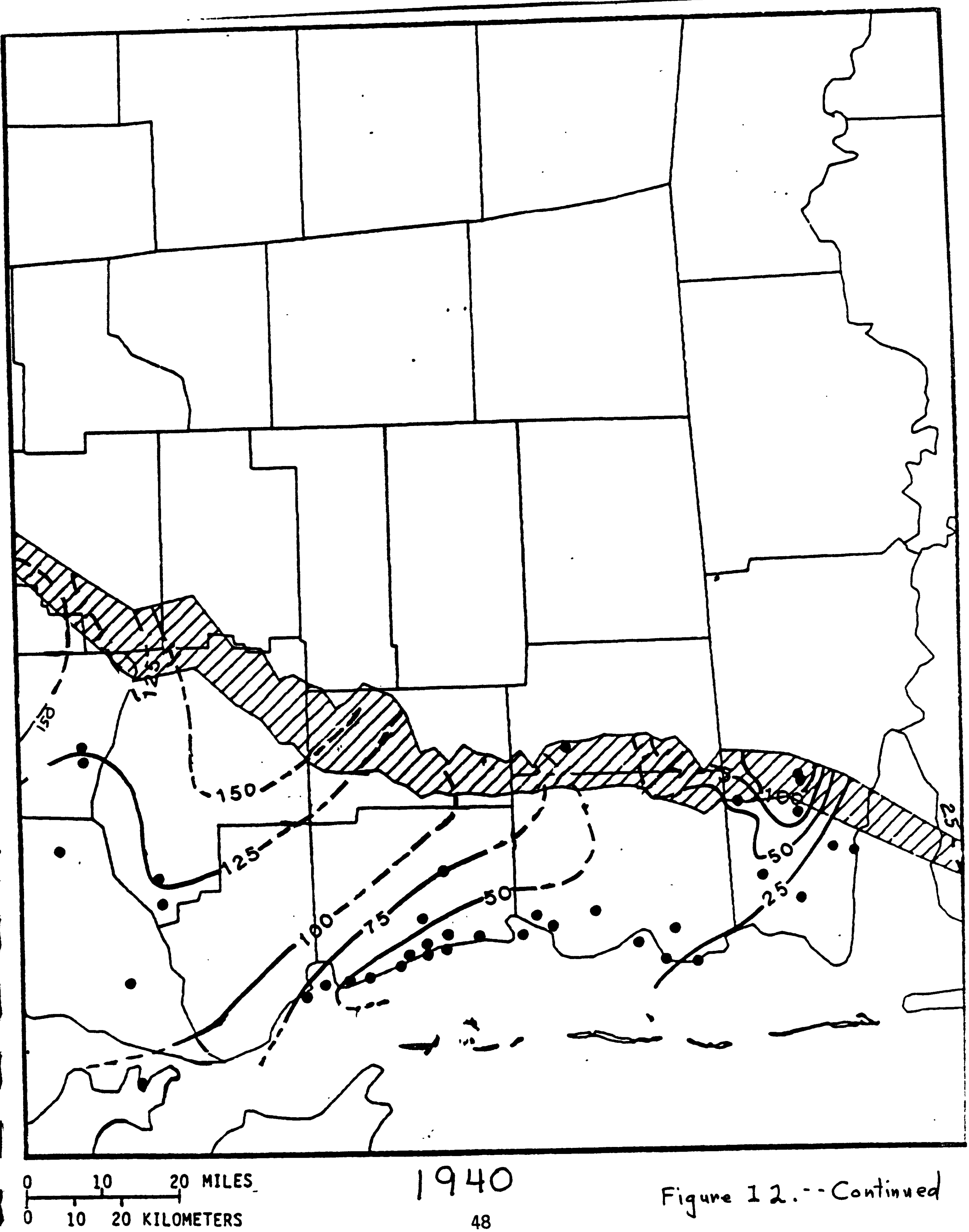
(hatched box)	AREA OF SUBCROP OF LAYER 4
— 50 —	POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 4 in various periods. Contour interval 25 feet. Datum is sea level. All contours are approximate
•	WATER-LEVEL MEASUREMENT SITE

Figure 12.--Potentiometric surface of layer 4 in selected years.



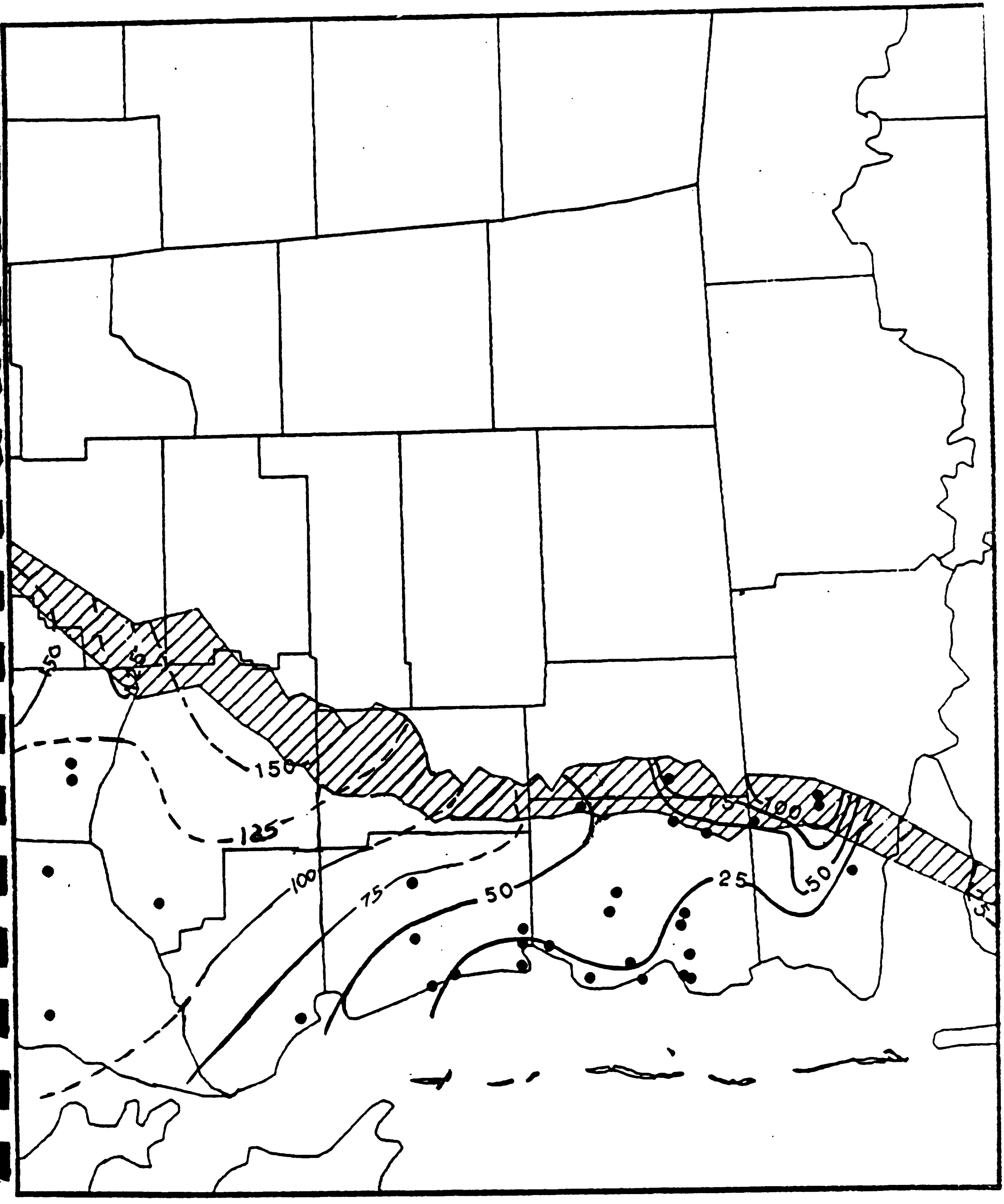
Predevelopment

Figure 12.-- Continued



1940

Figure 12.--Continued



1960

Figure 12.--Continued

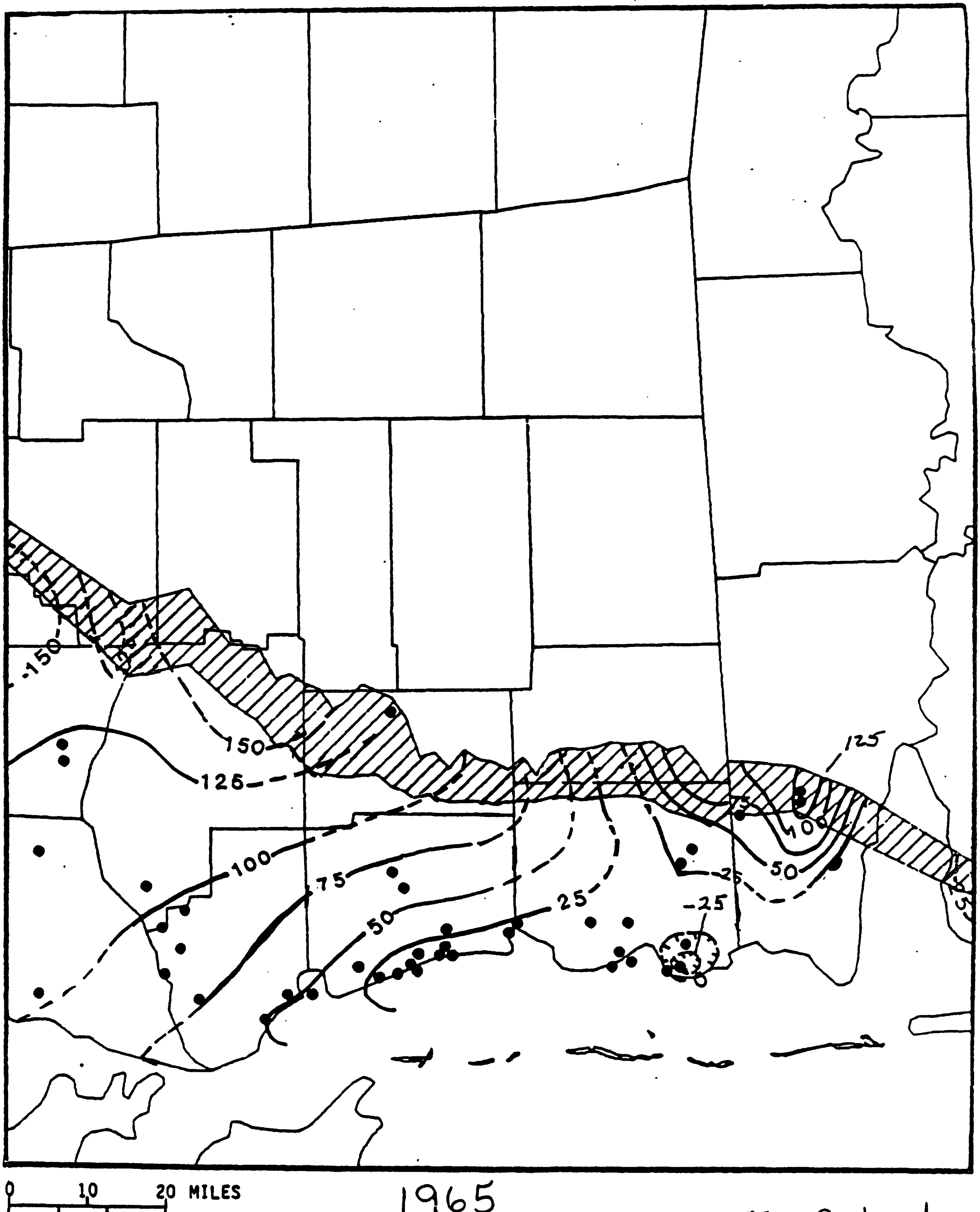
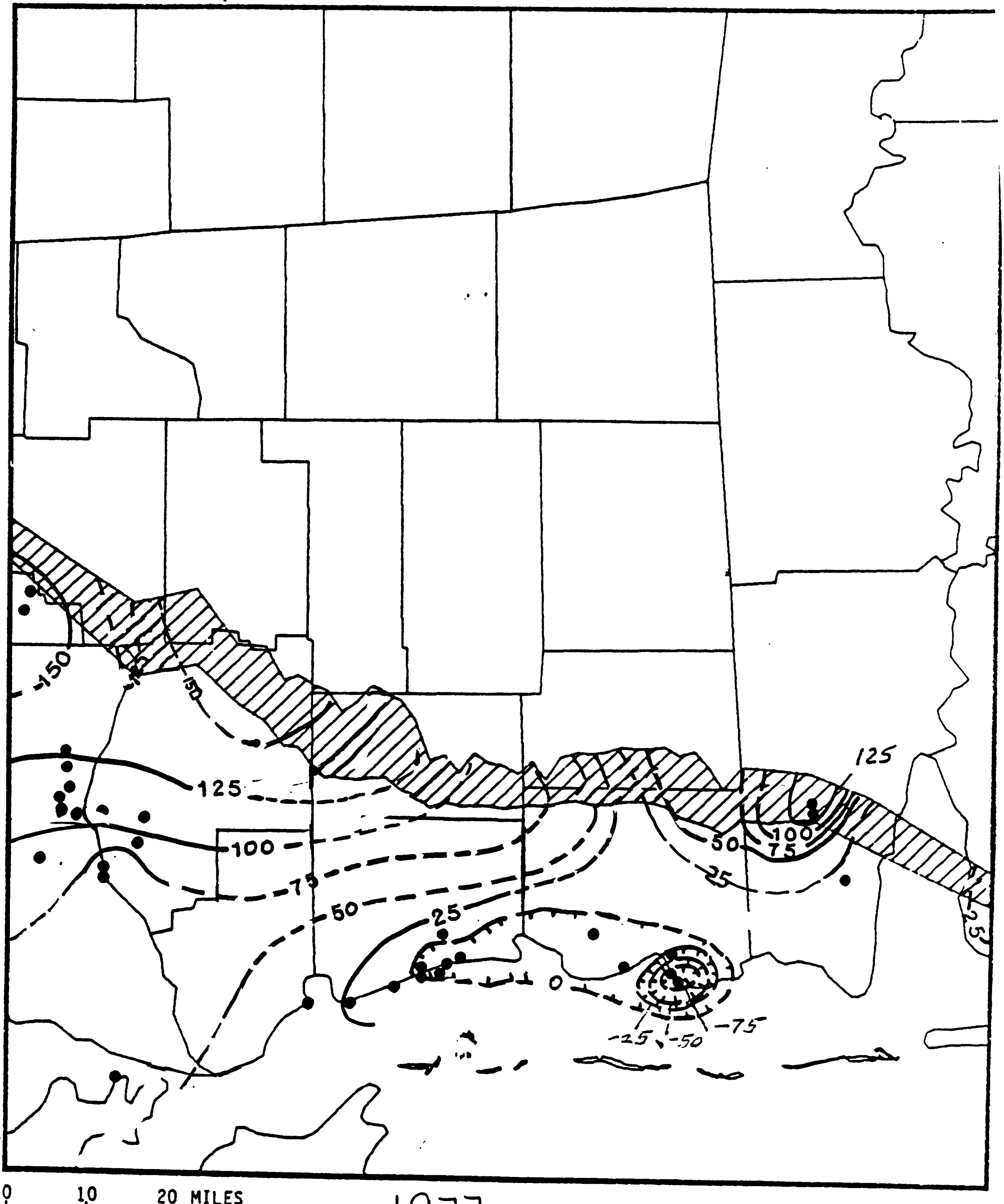
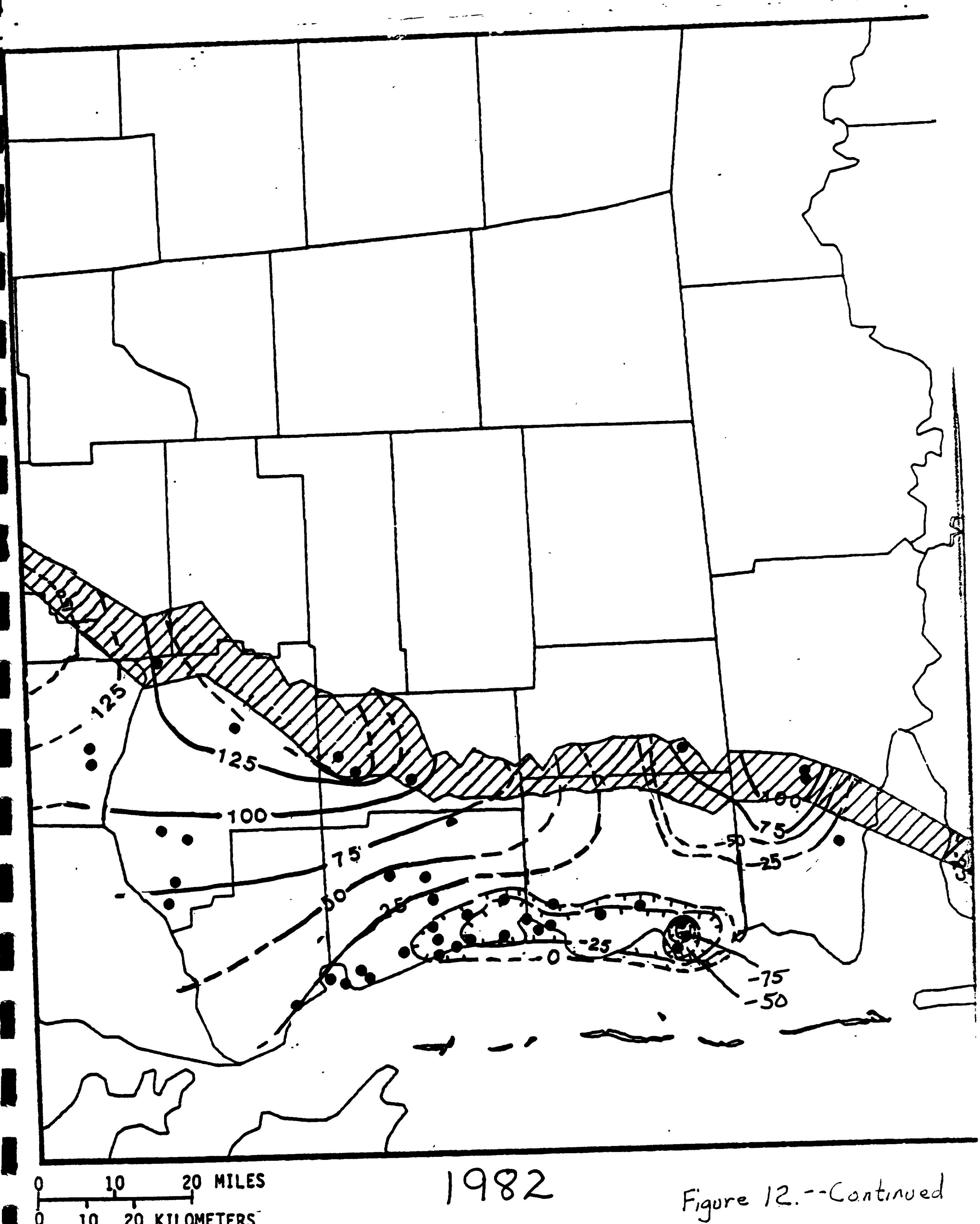


Figure 12.--Continued



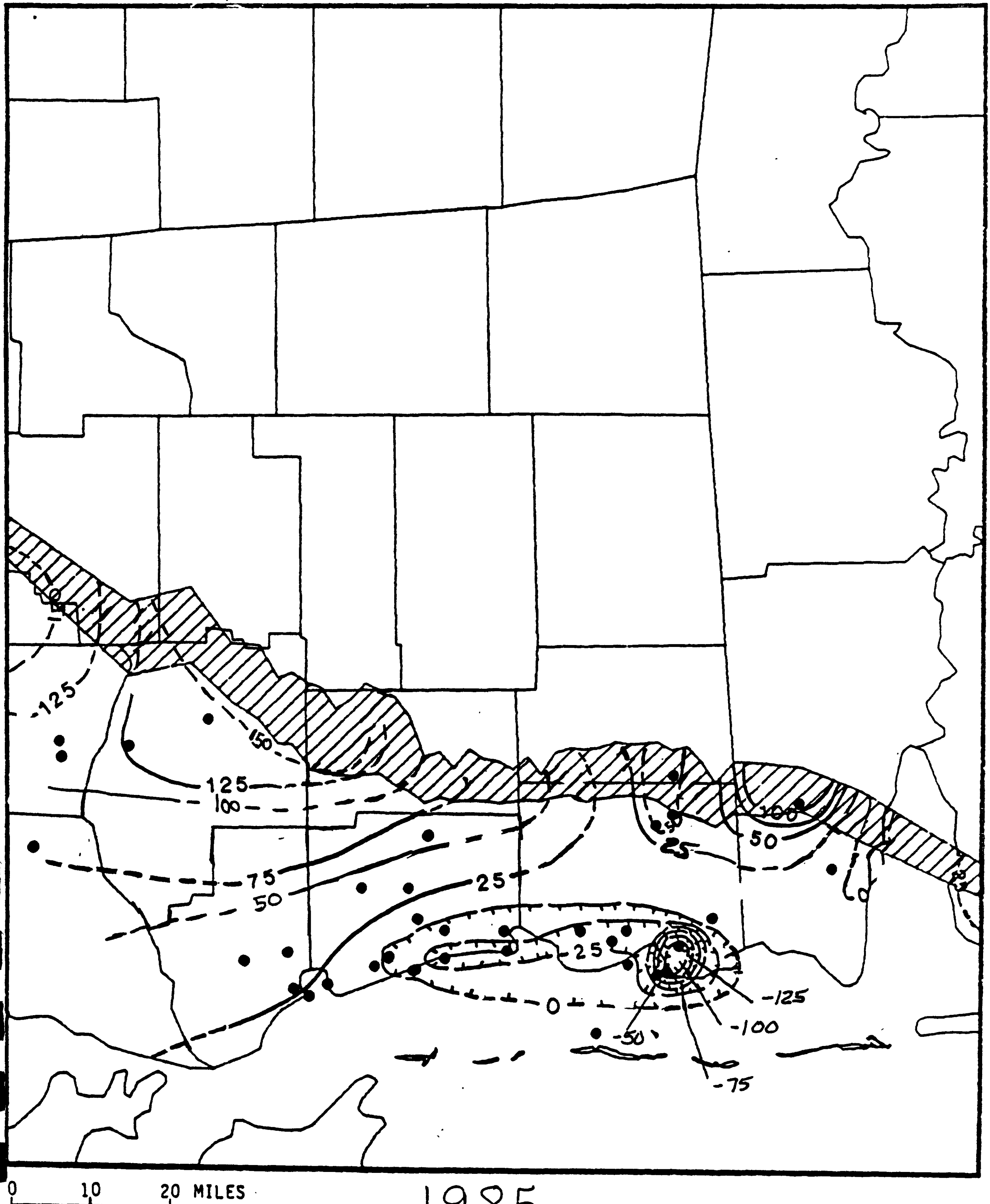
1977

Figure 12.--Continued



1982

Figure 12.--Continued



1985

Figure 12.--Continued

The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

	AREA OF SUBCROP OF LAYER 5
— 50 —	POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 5 in various periods. Contour interval 25 feet. Datum is sea level. All contours are approximate
•	WATER-LEVEL MEASUREMENT SITE

Figure 13.--Potentiometric surface of layer 5 in selected years.

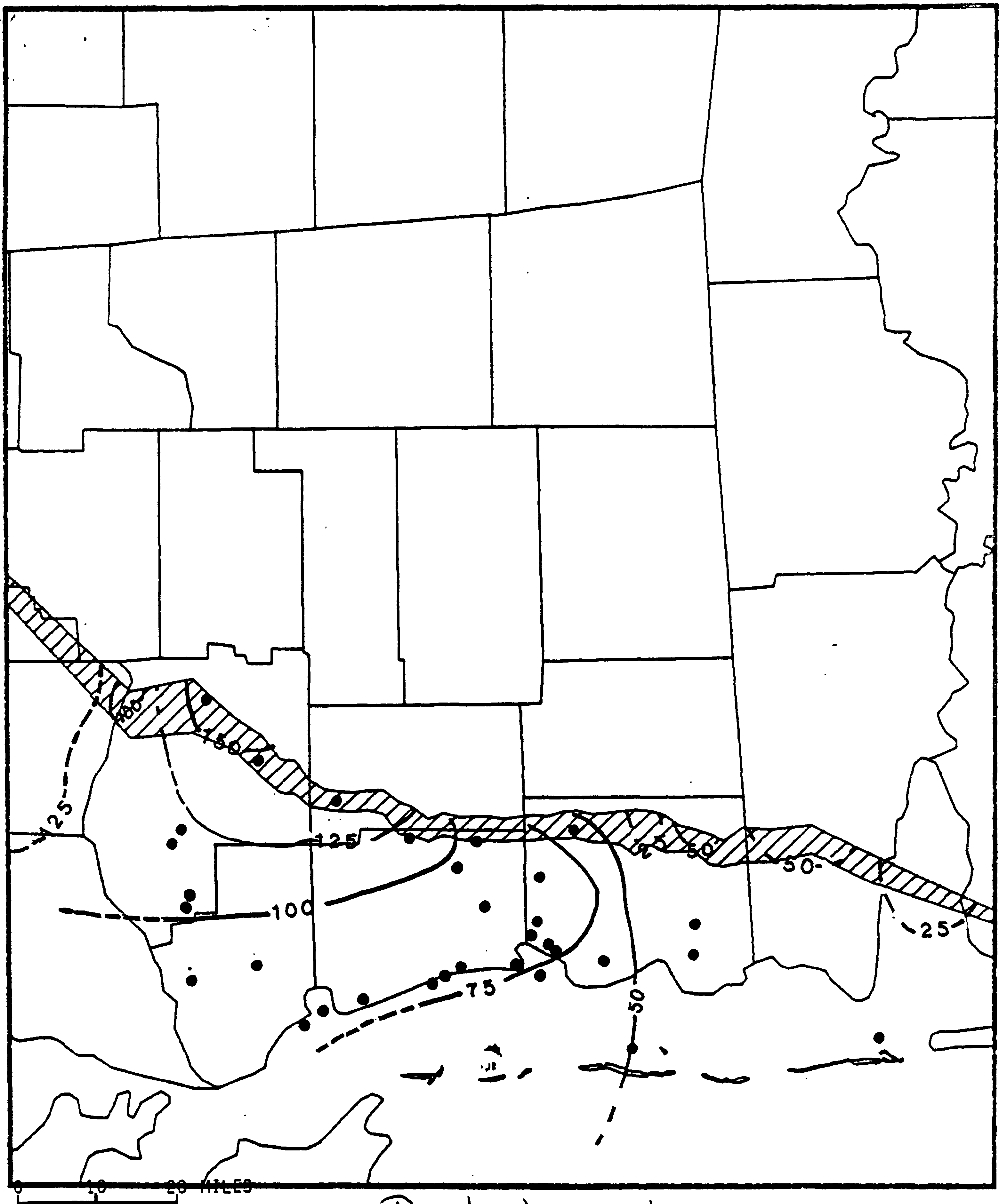
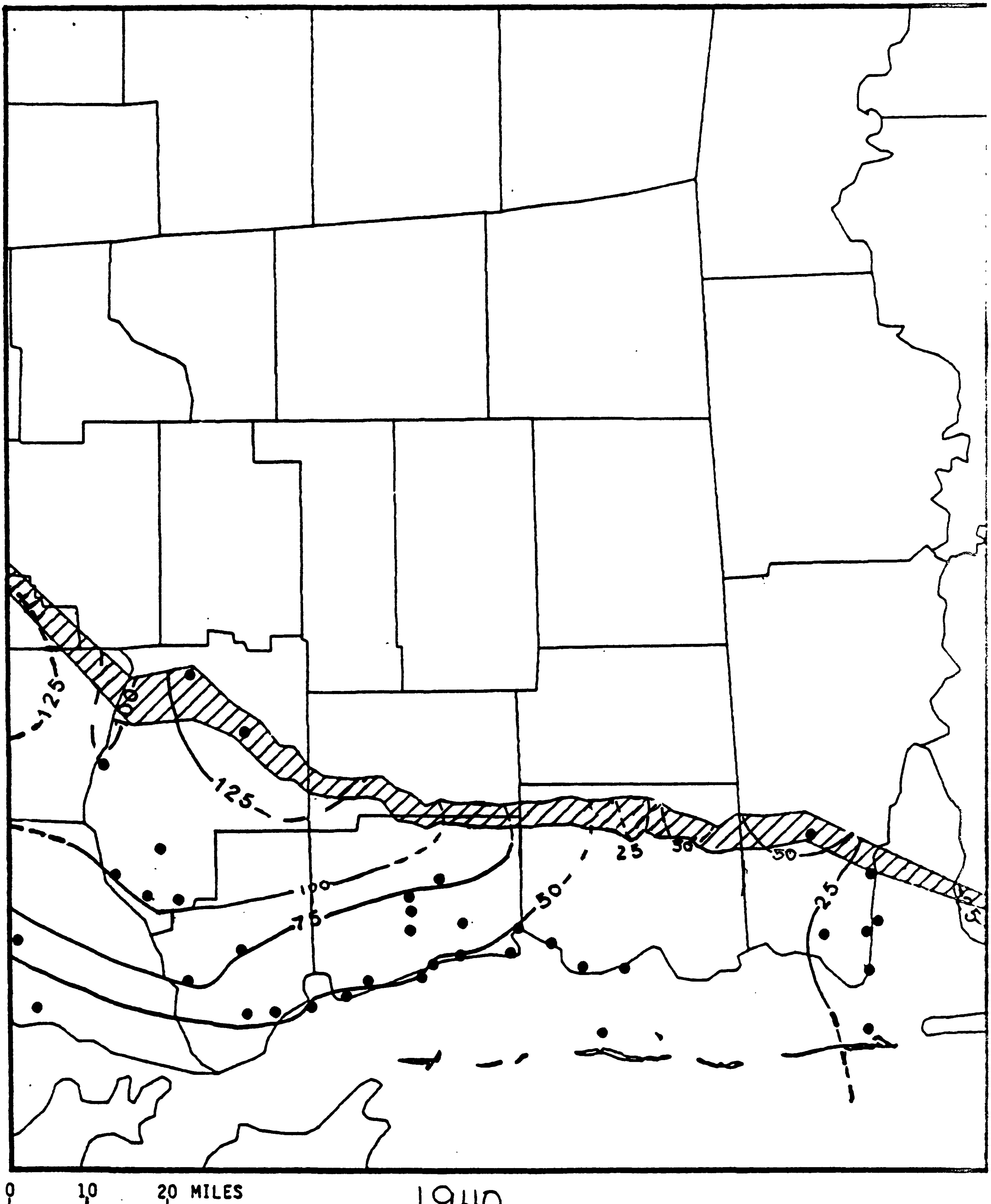
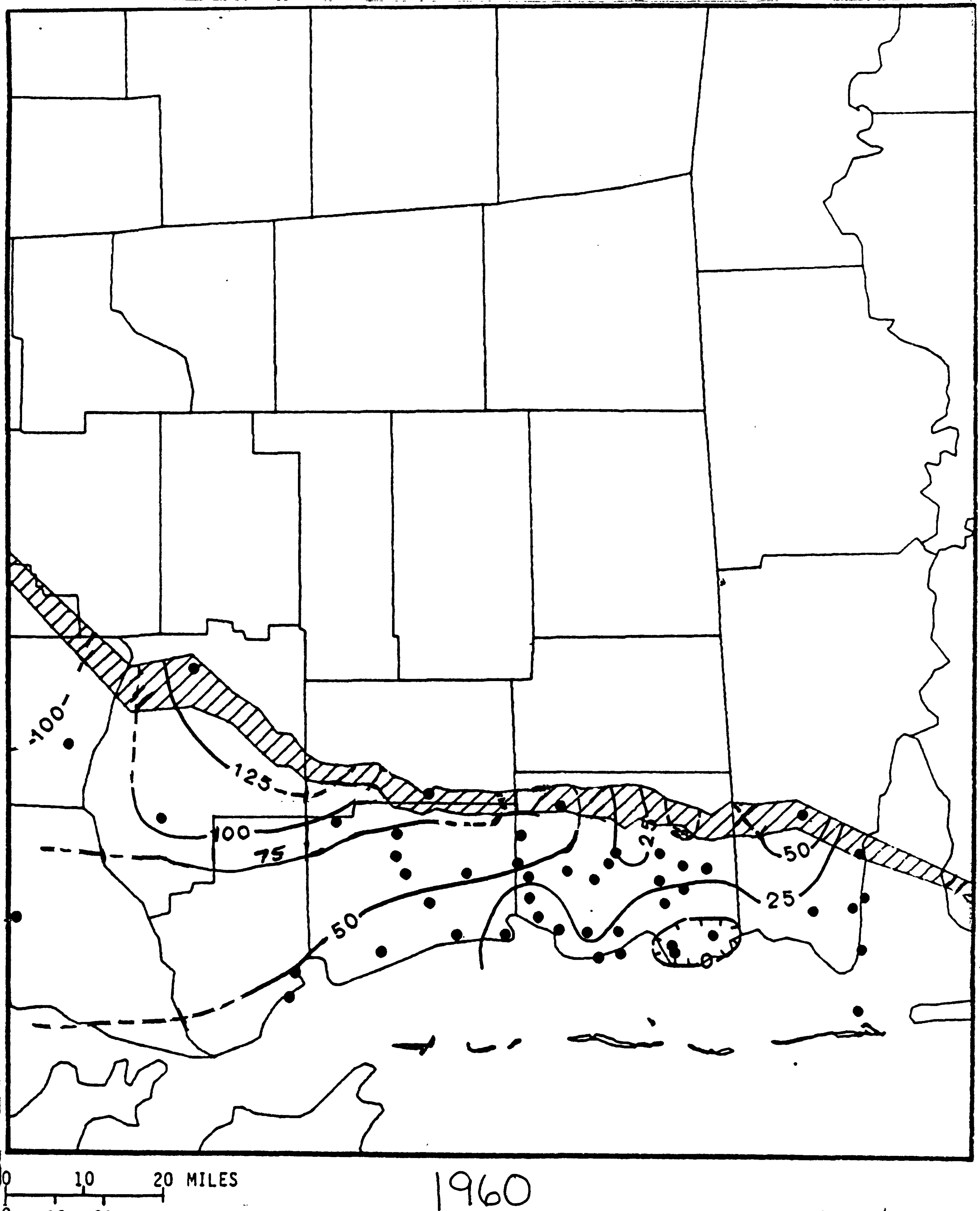


Figure 13. -- Continued



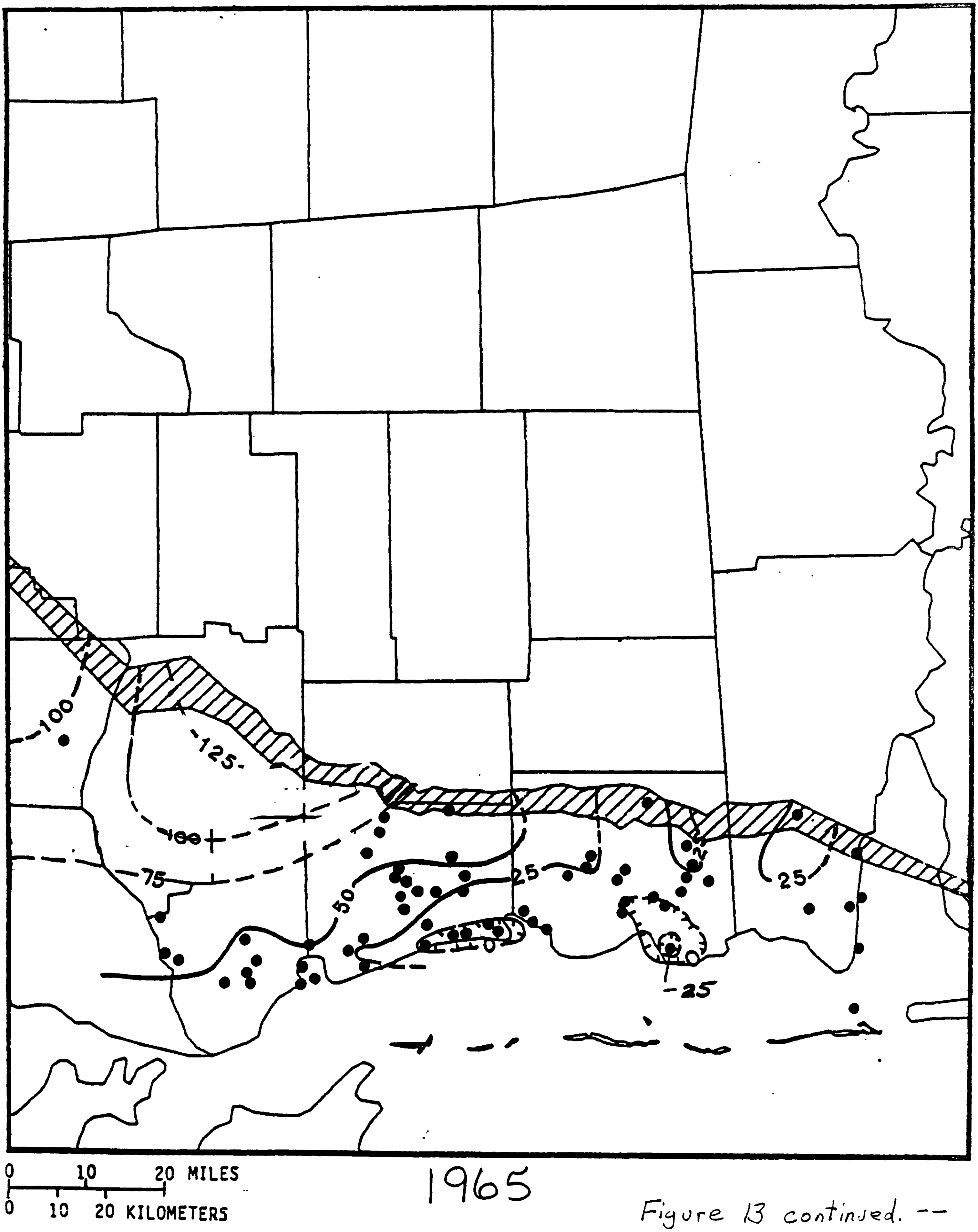
1940

Figure 13.--Continued



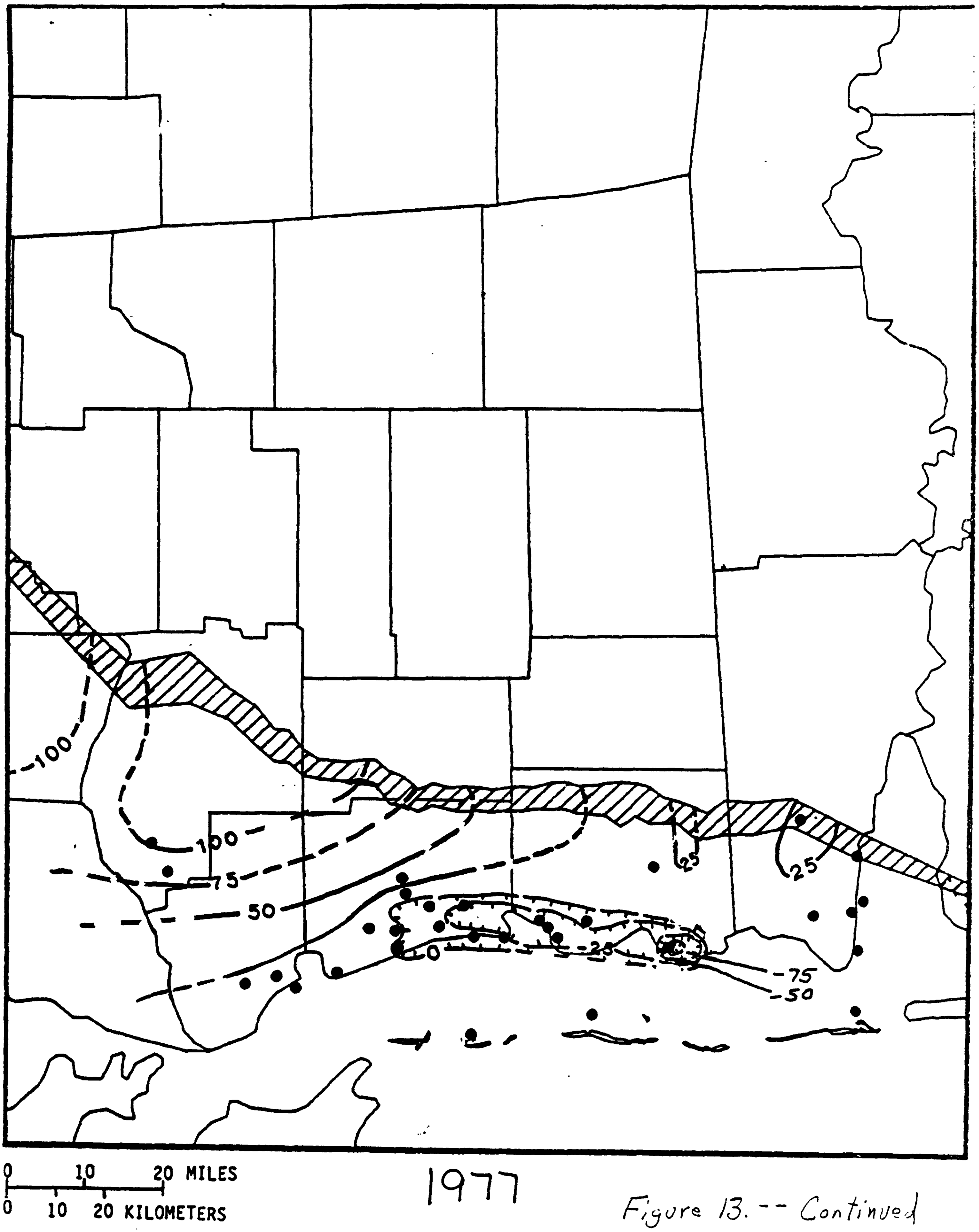
1960

Figure 13.-- Continued



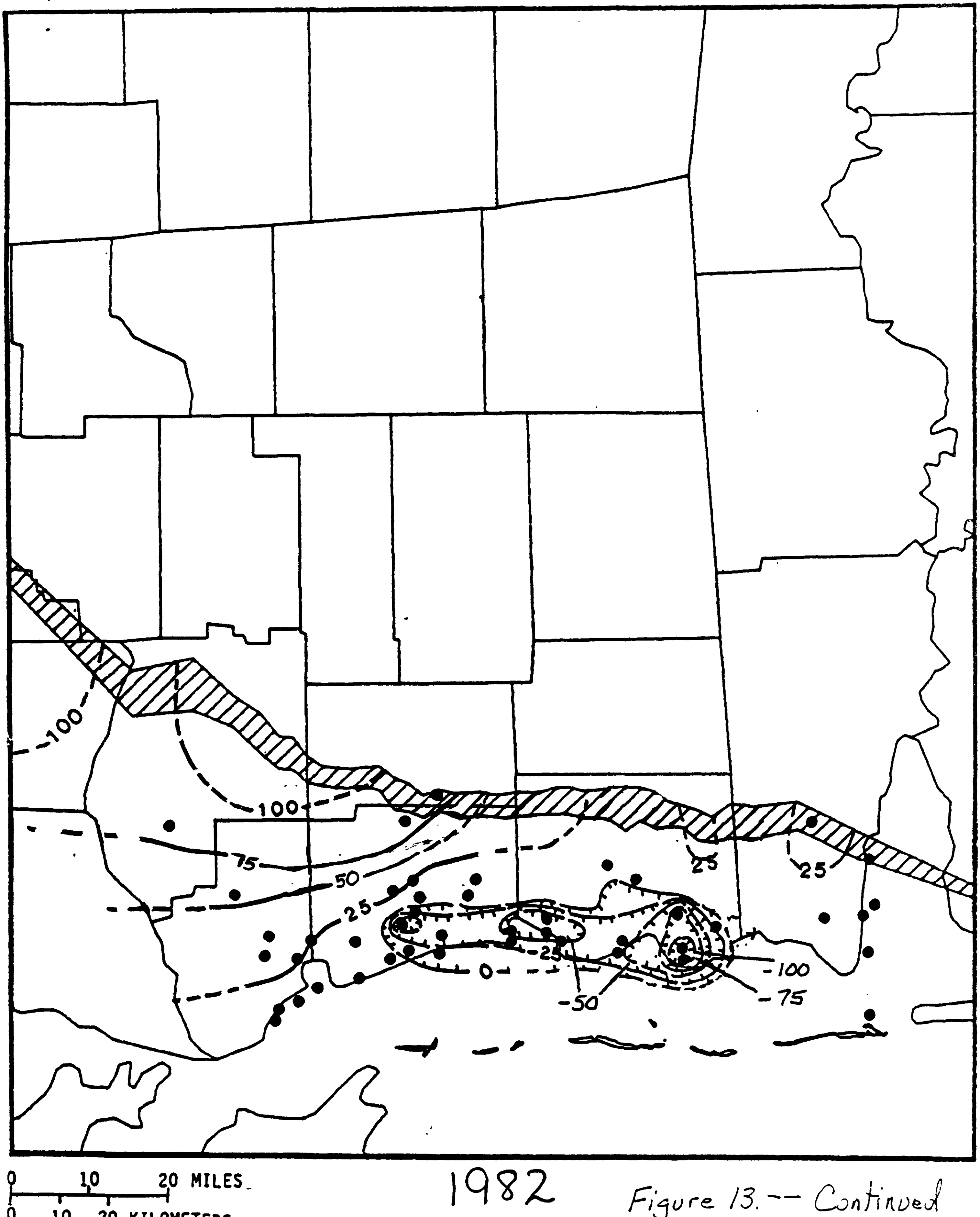
1965

Figure 13 continued. --



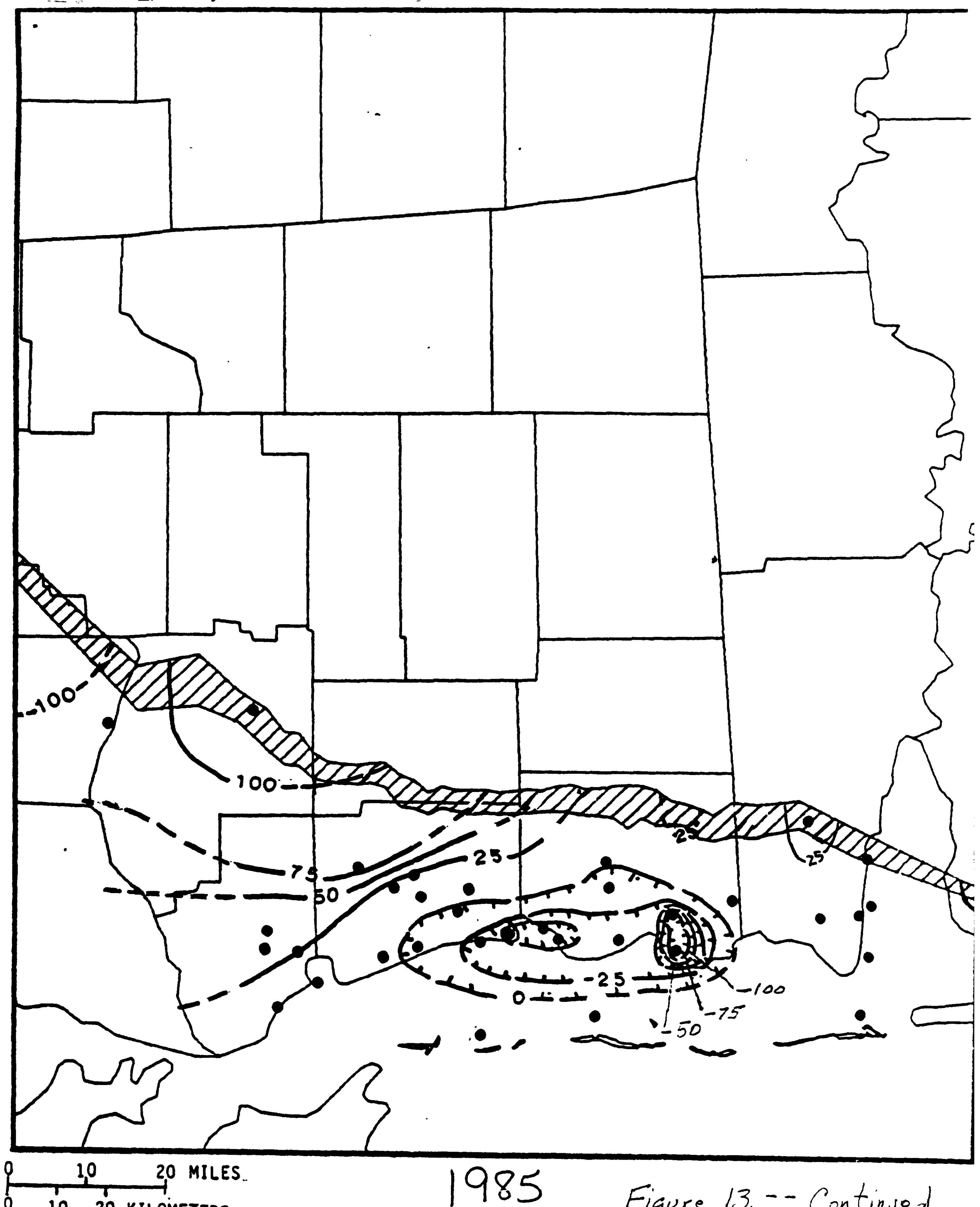
1977

Figure 13.-- Continued



1982

Figure 13.-- Continued



1985

Figure 13. -- Continued

The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

(hatched pattern)	AREA OF SUBCROP OF LAYER 6
— 50 —	POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 6 in various periods. Contour interval 25 feet. Datum is sea level. All contours are approximate
•	WATER-LEVEL MEASUREMENT SITE

Figure 14.--Potentiometric surface of layer 6 in selected years.

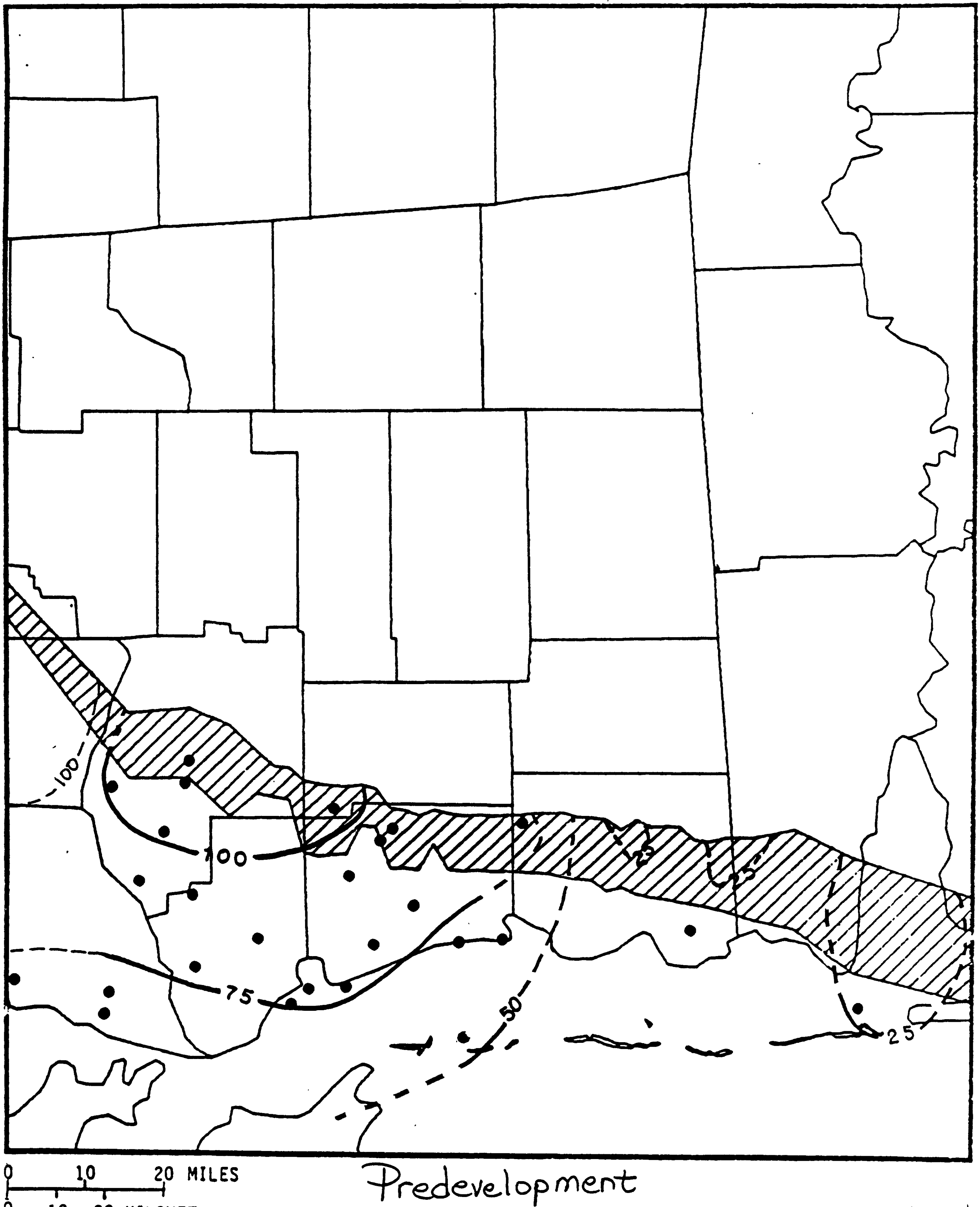
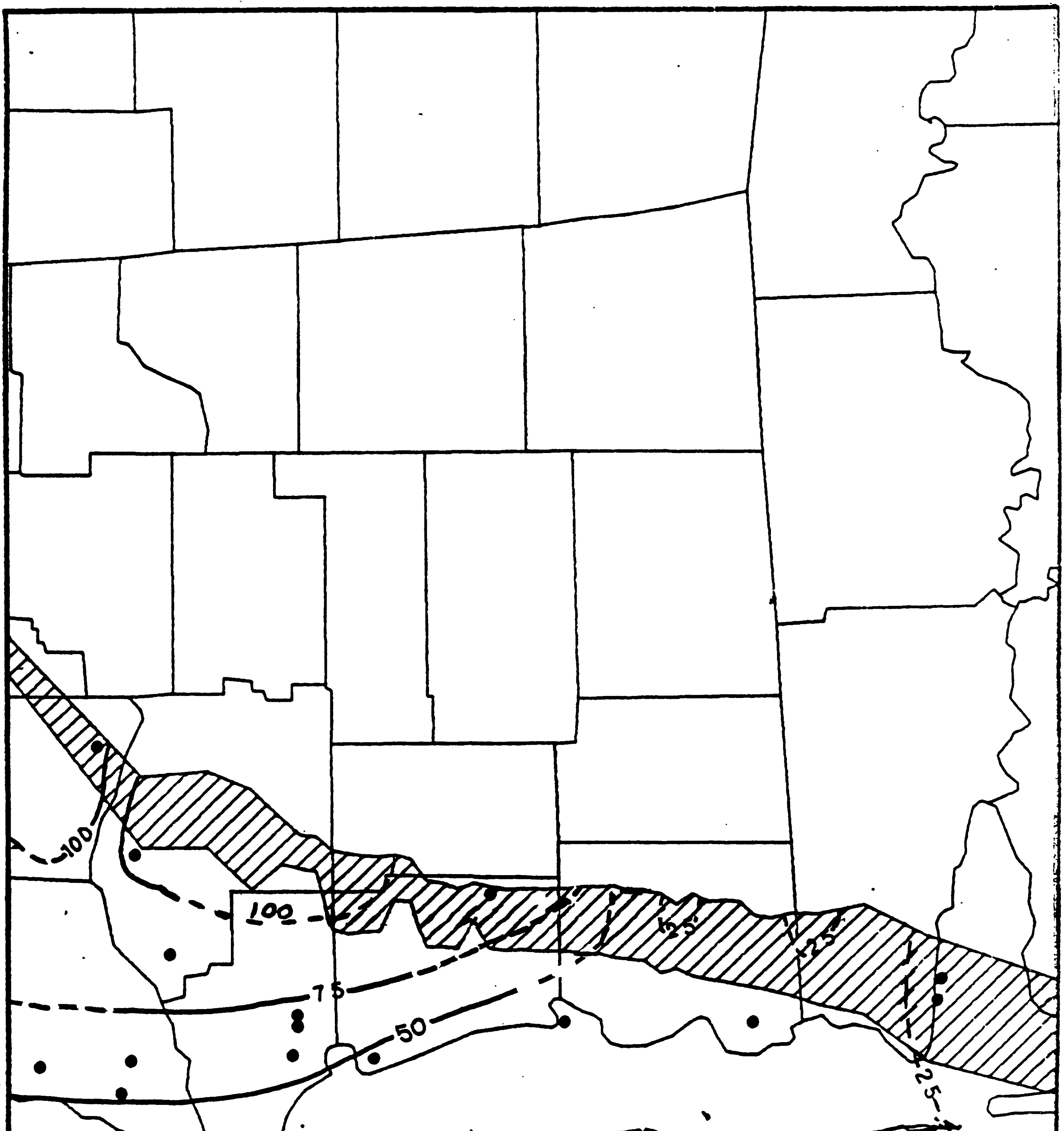


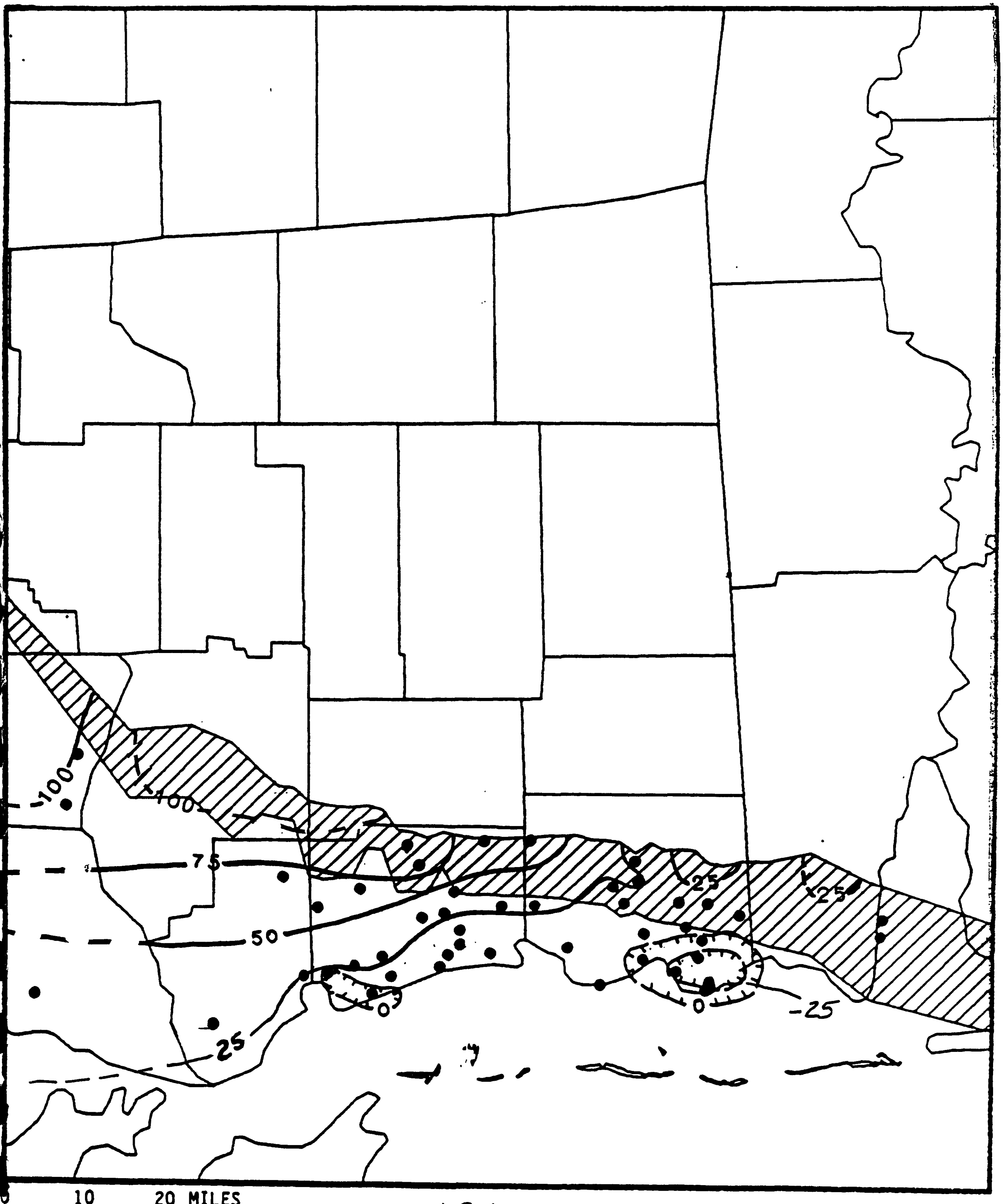
Figure 14.--Continued



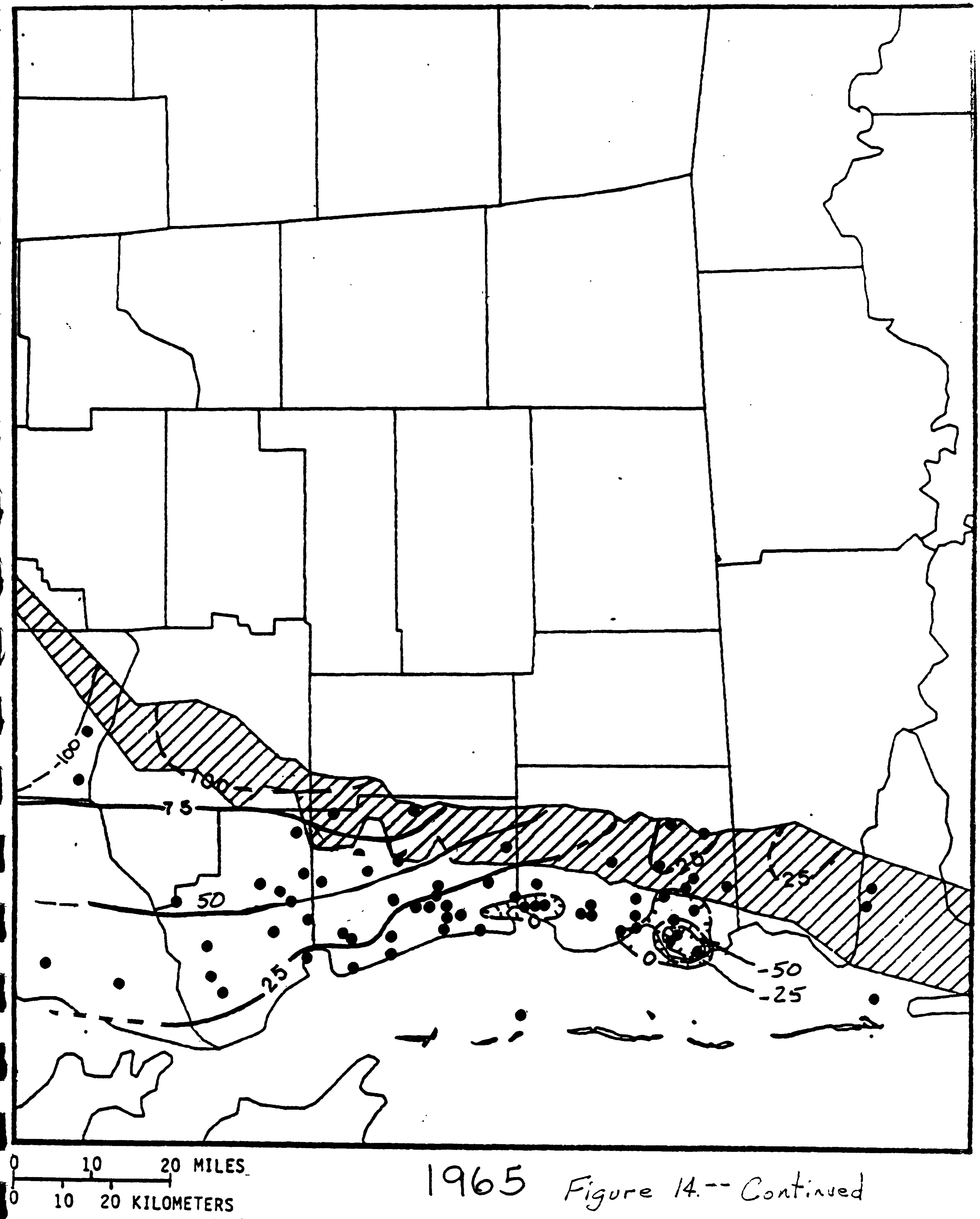
0 10 20 MILES
0 10 20 KILOMETERS

1940

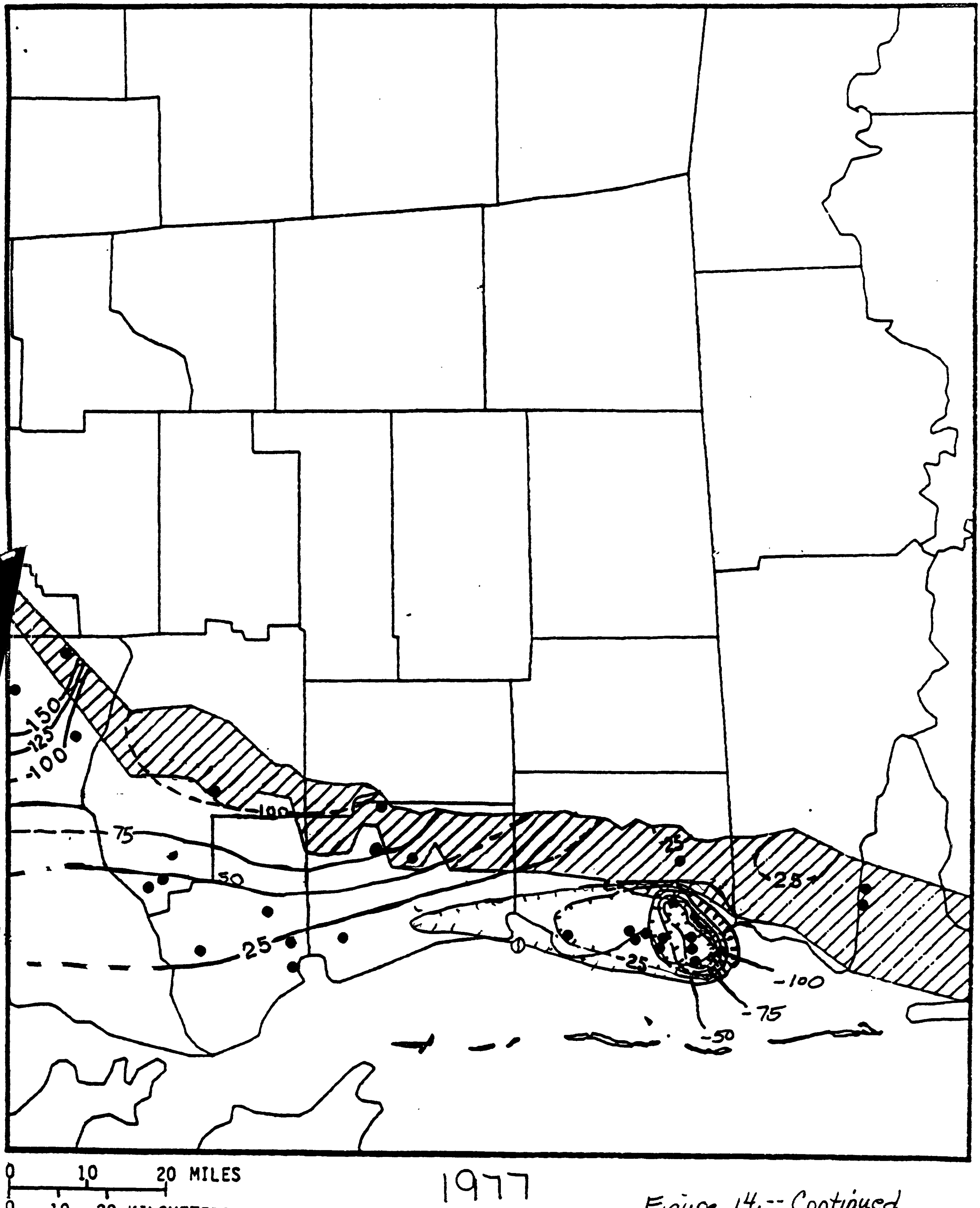
Figure 14.-- Continued



1960 Figure 14.--Continued



1965 Figure 14.-- Continued



1977

Figure 14.--Continued

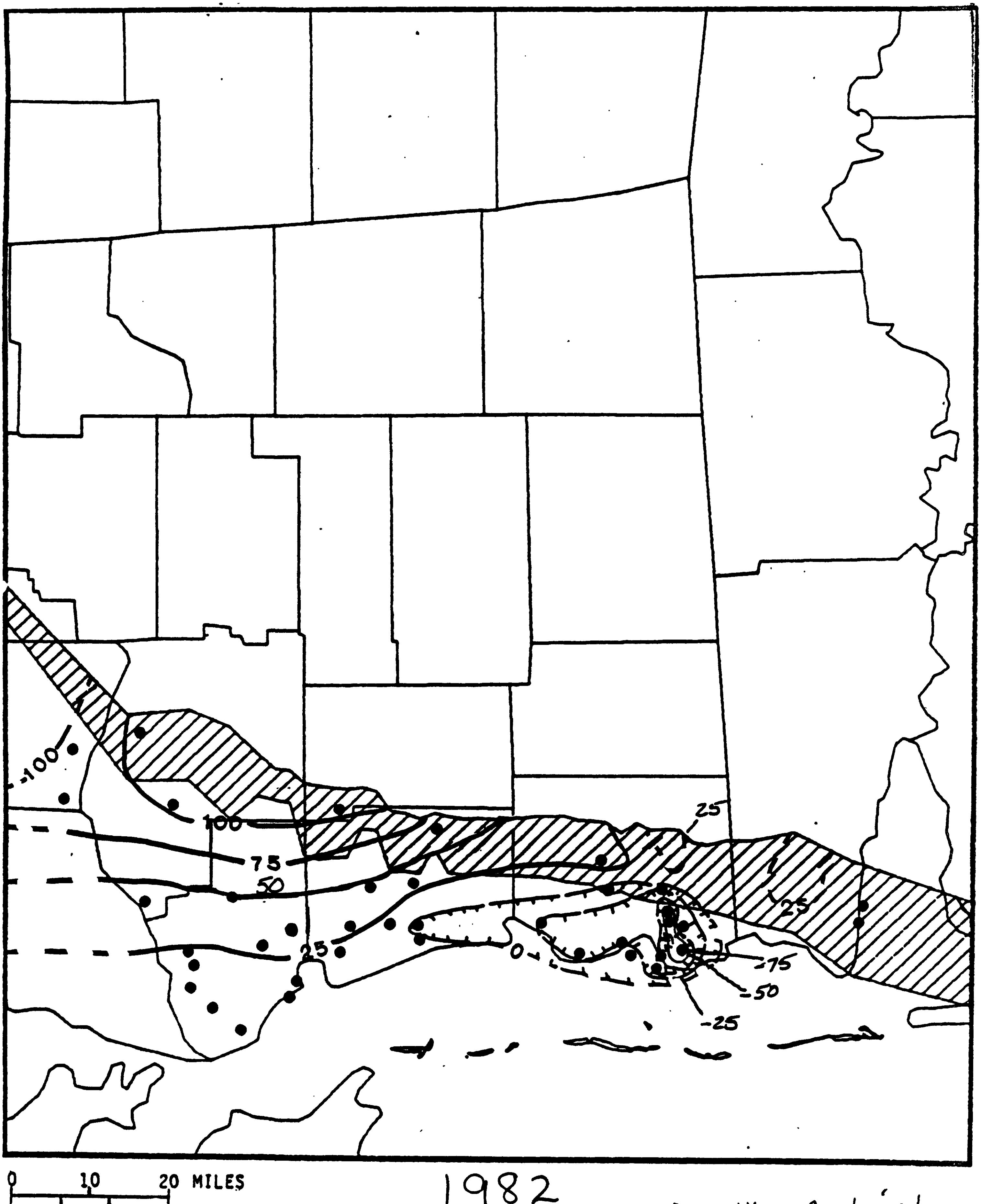
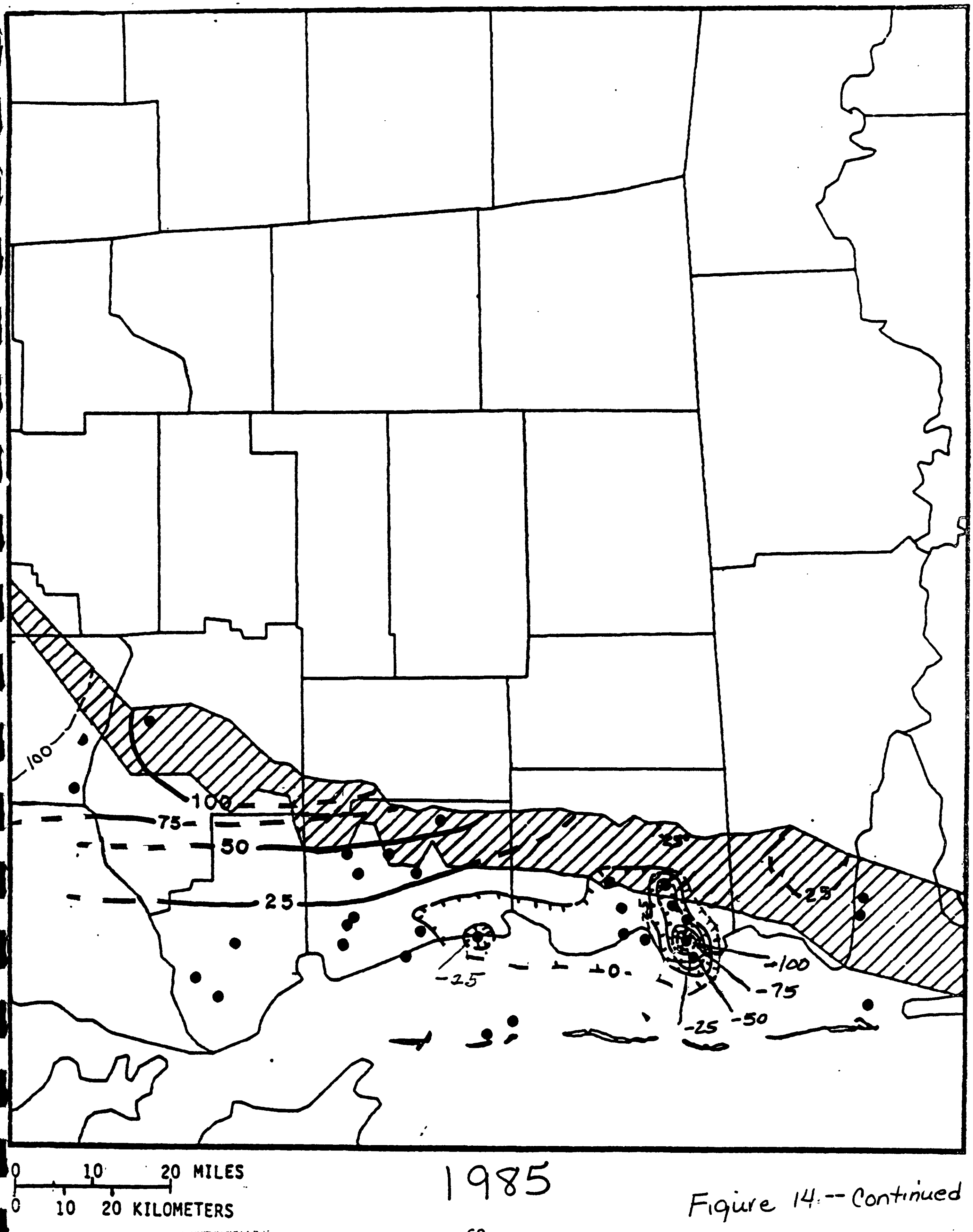


Figure 14.--Continued



1985

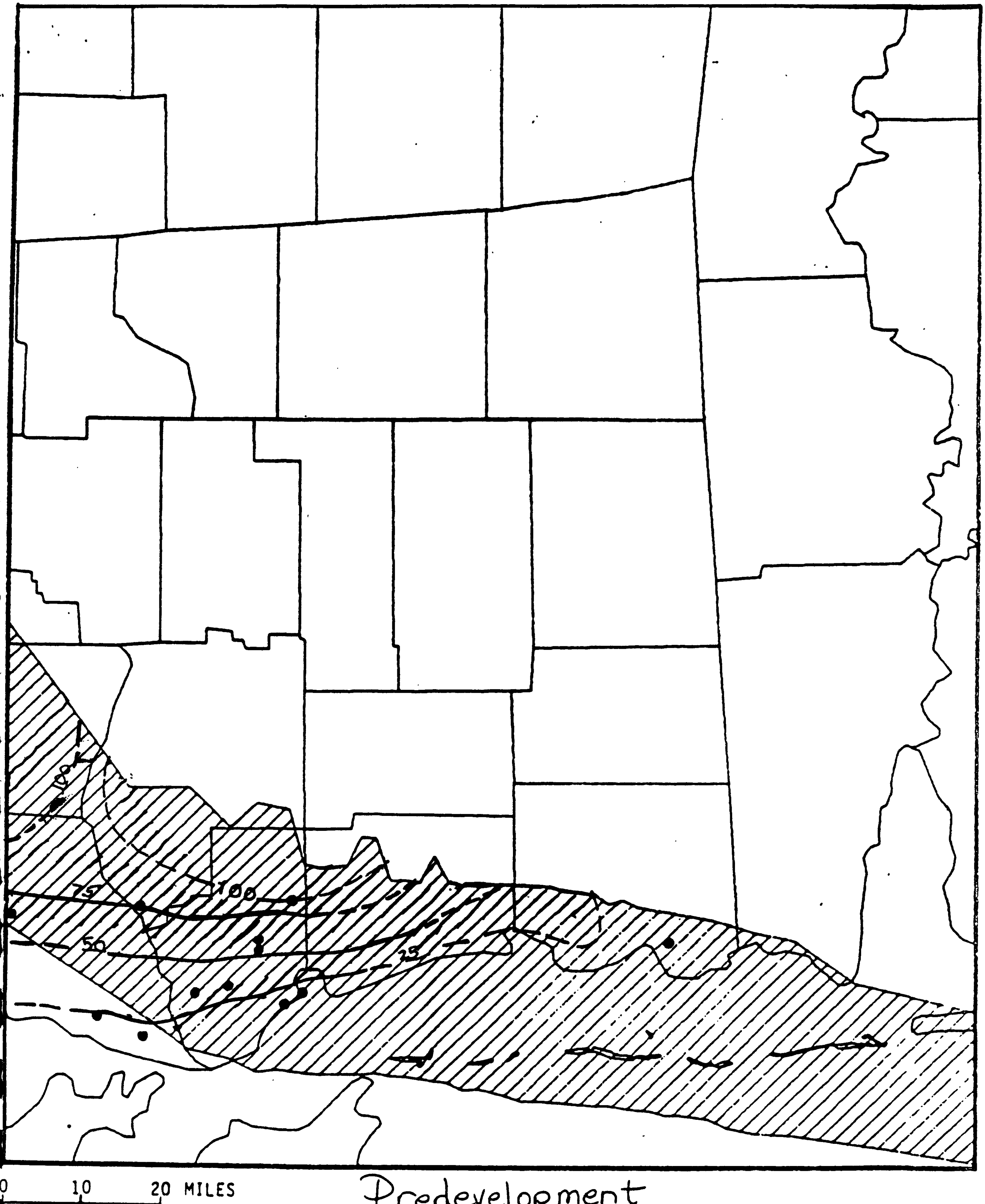
Figure 14.--Continued

The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

(hatched box)	AREA OF SUBCROP OF LAYER 7
— 50 —	POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 7 in various periods. Contour interval 25 feet. Datum is sea level. All contours are approximate
•	WATER-LEVEL MEASUREMENT SITE

Figure 15.--Potentiometric surface of layer 7 in selected years.



Predevelopment

Figure 15. -- Continued

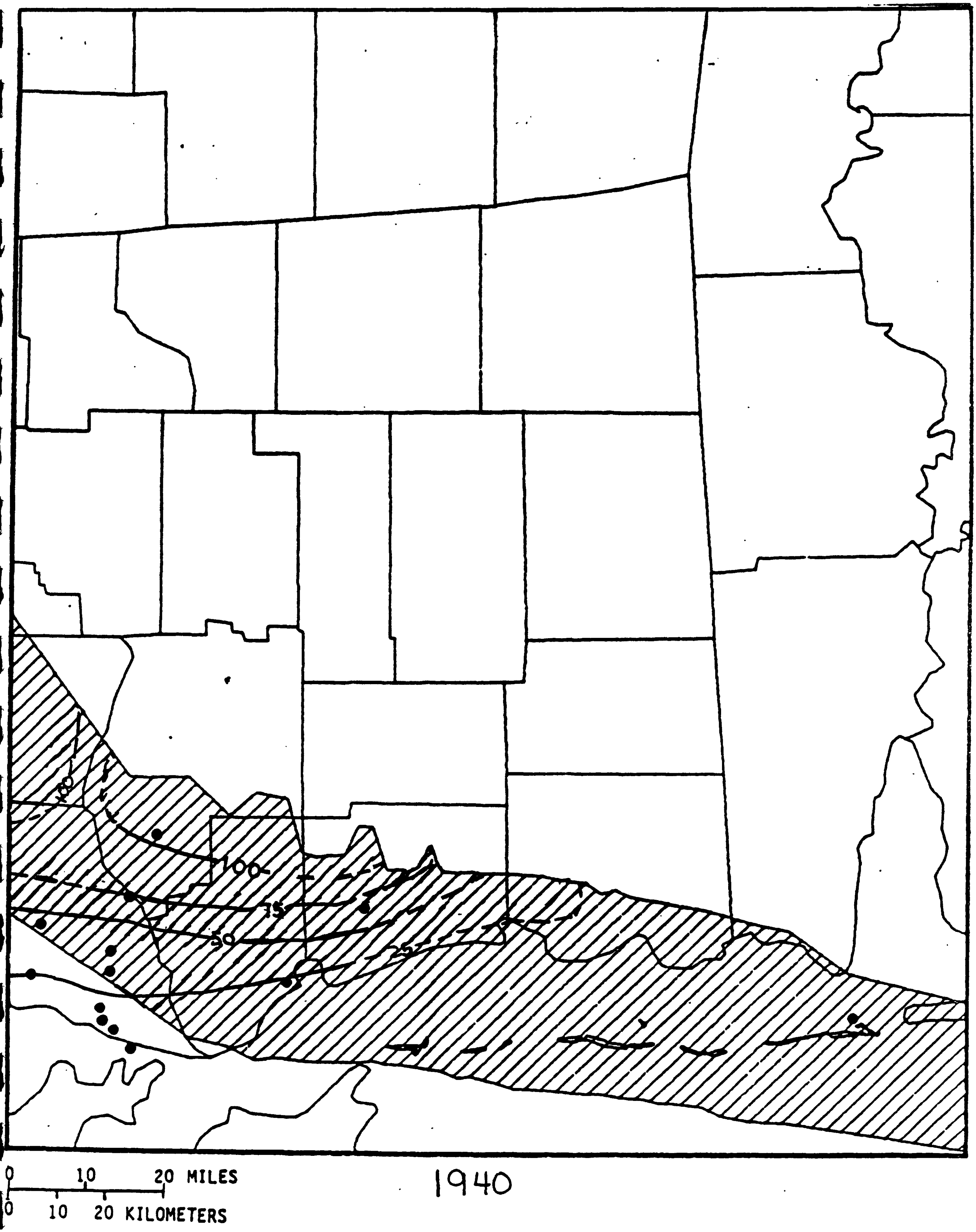
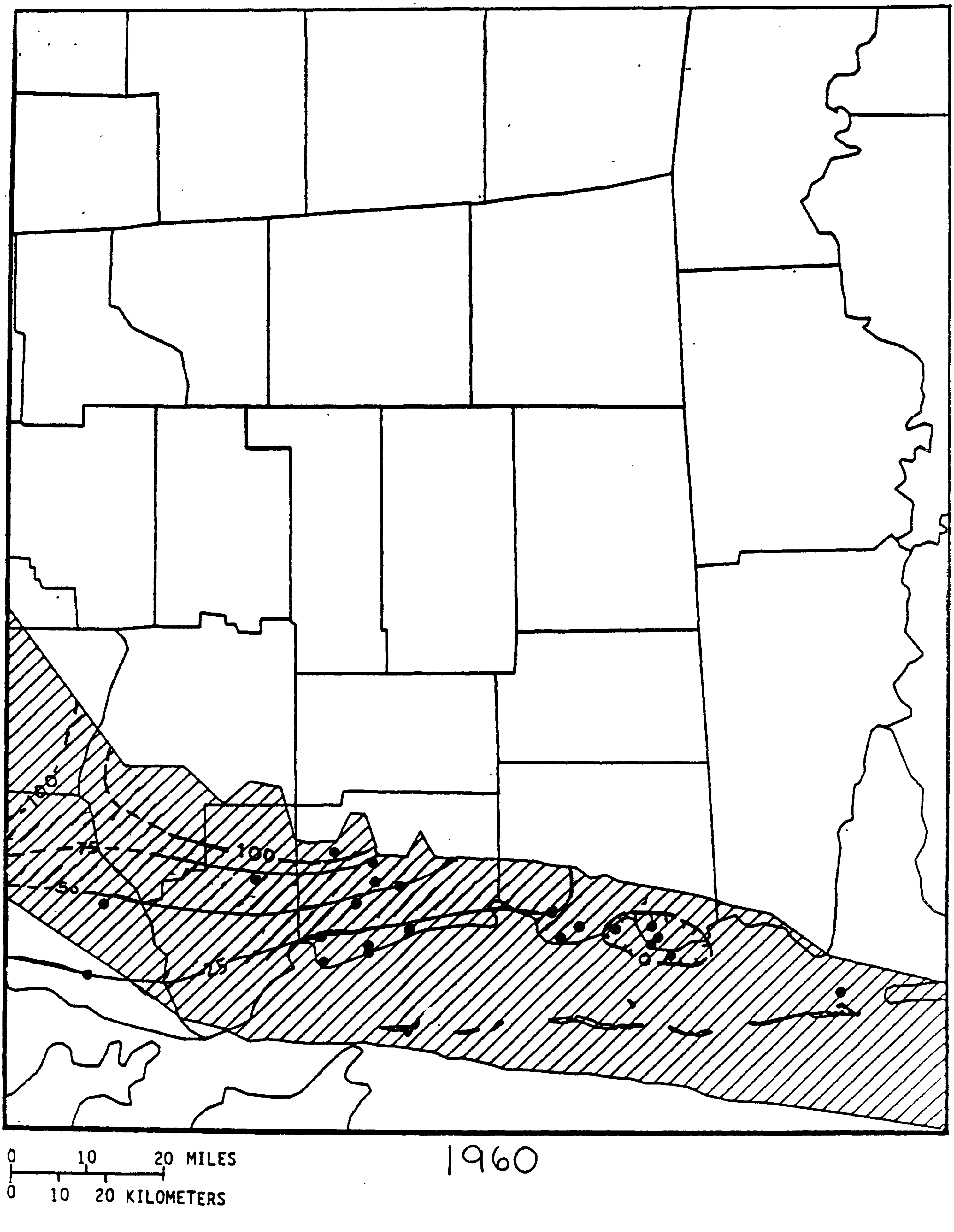
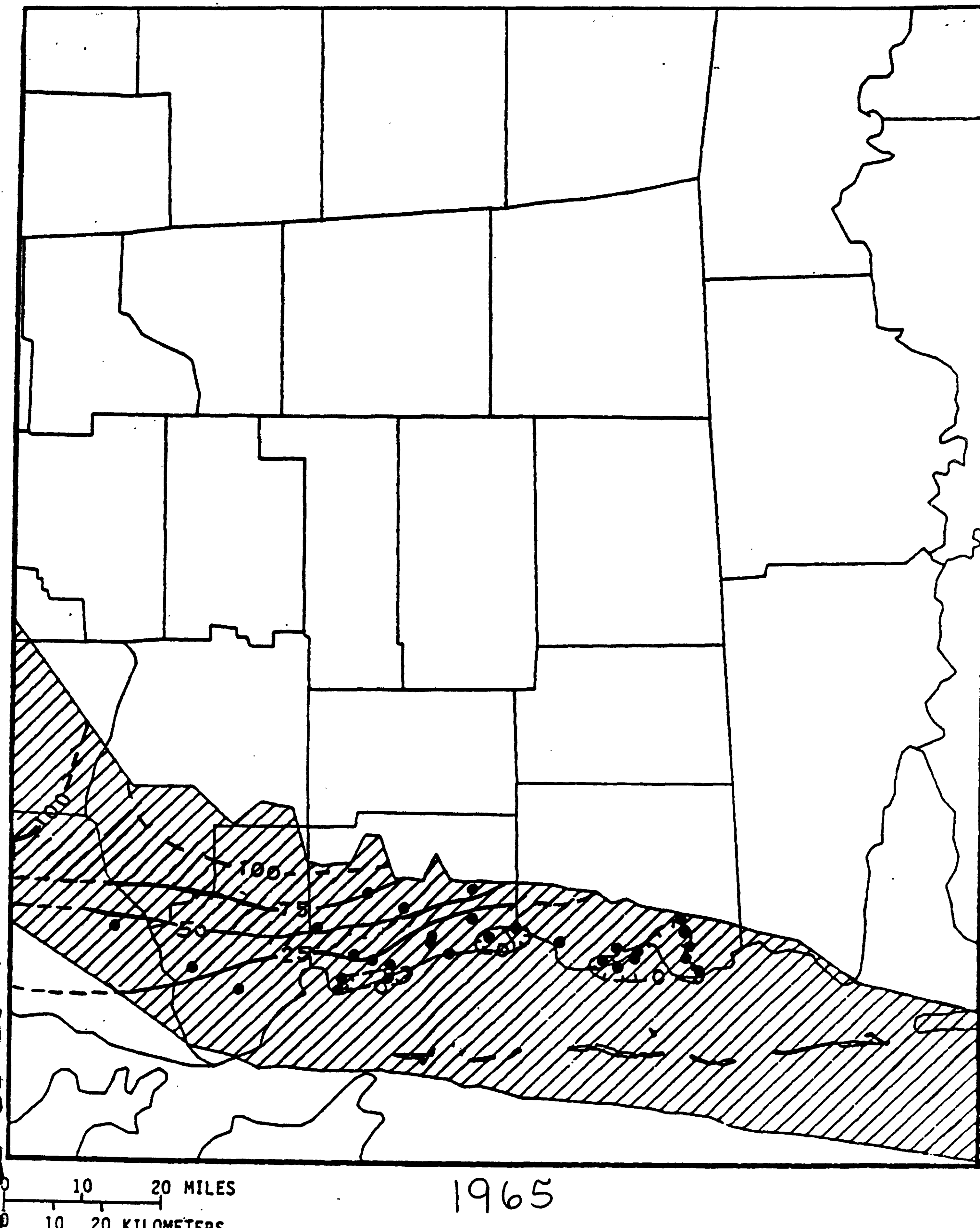


Figure 15. -- Continued



1960

Figure 15.--Continued



1965

Figure 15.-- Continued

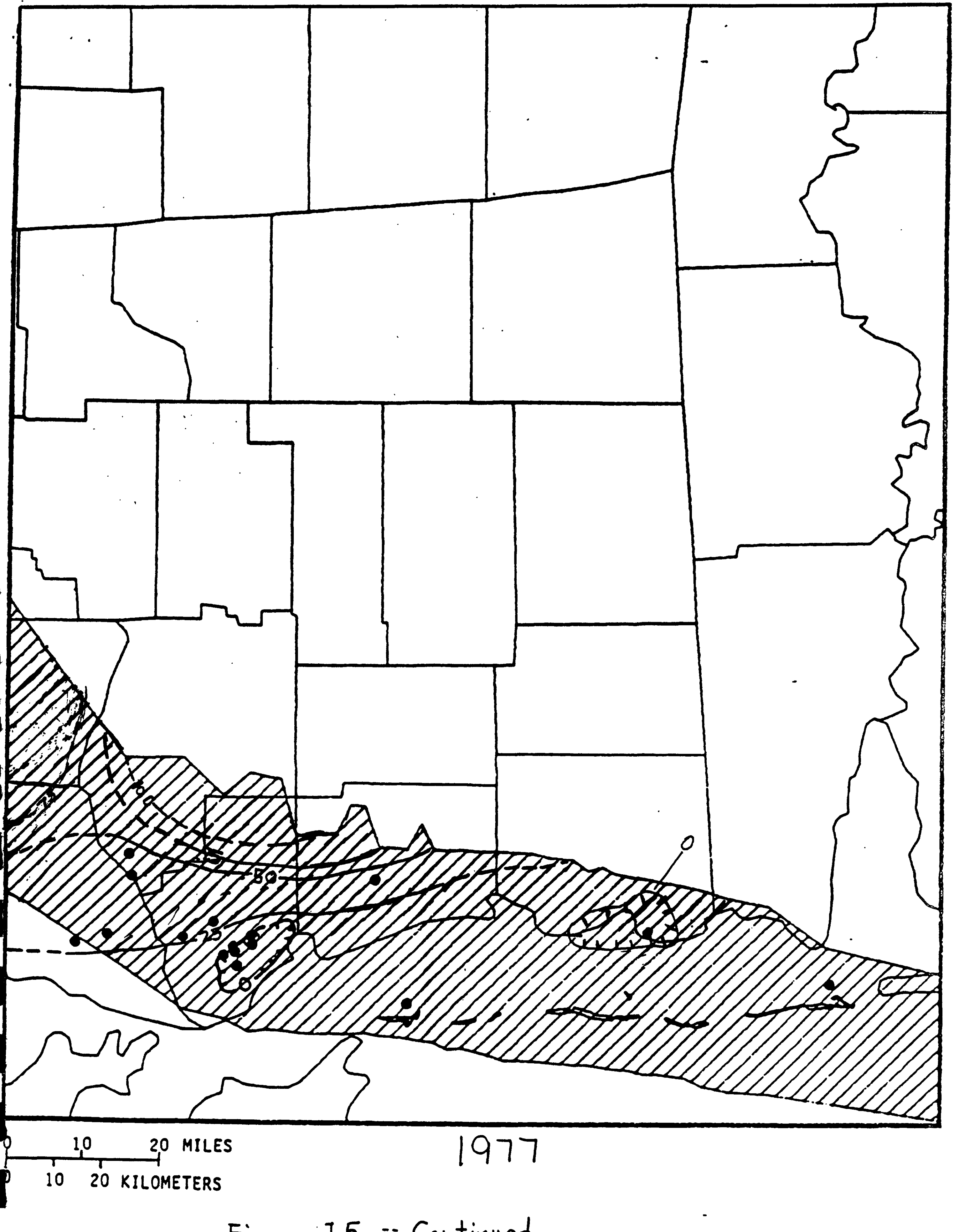


Figure 15. -- Continued

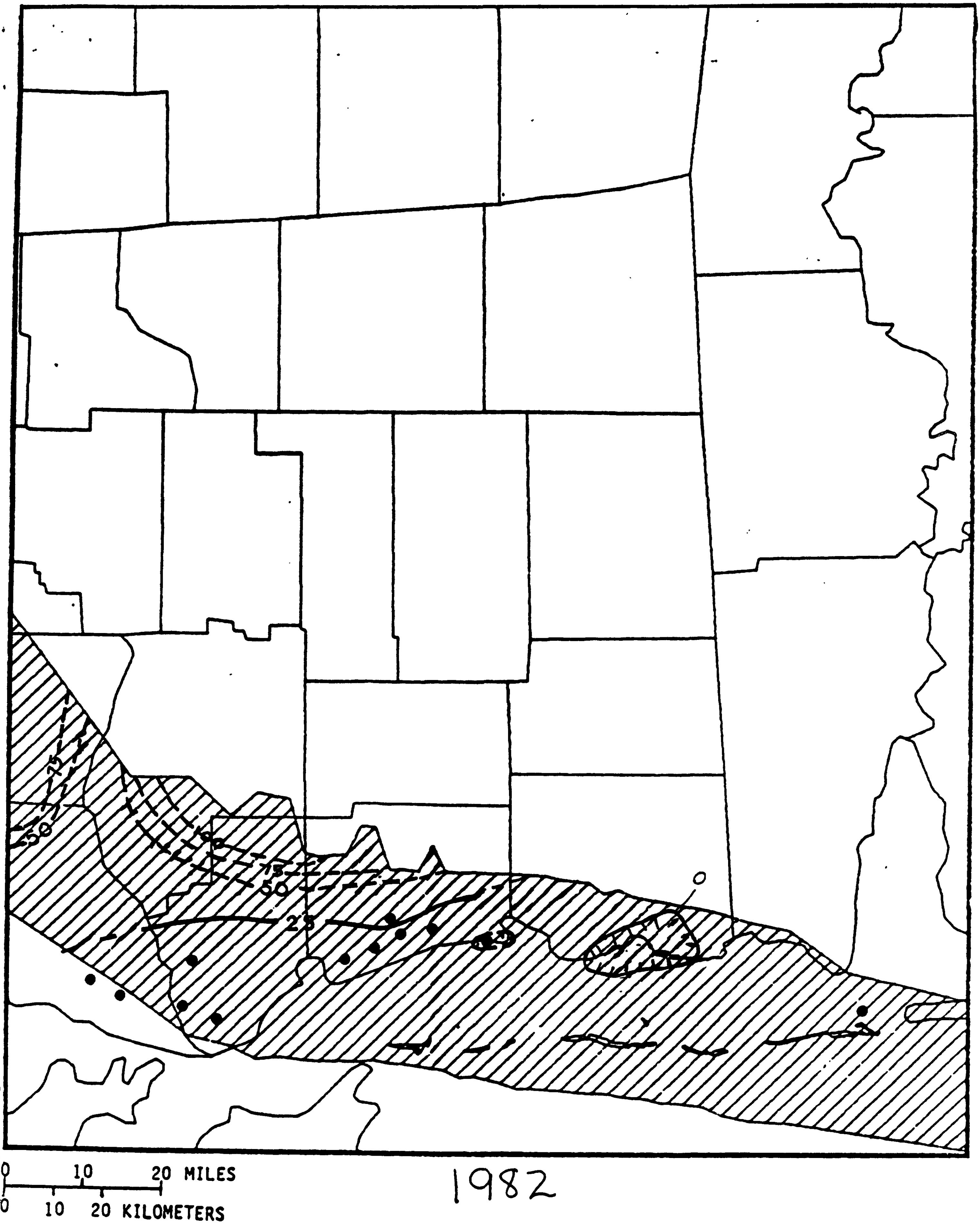
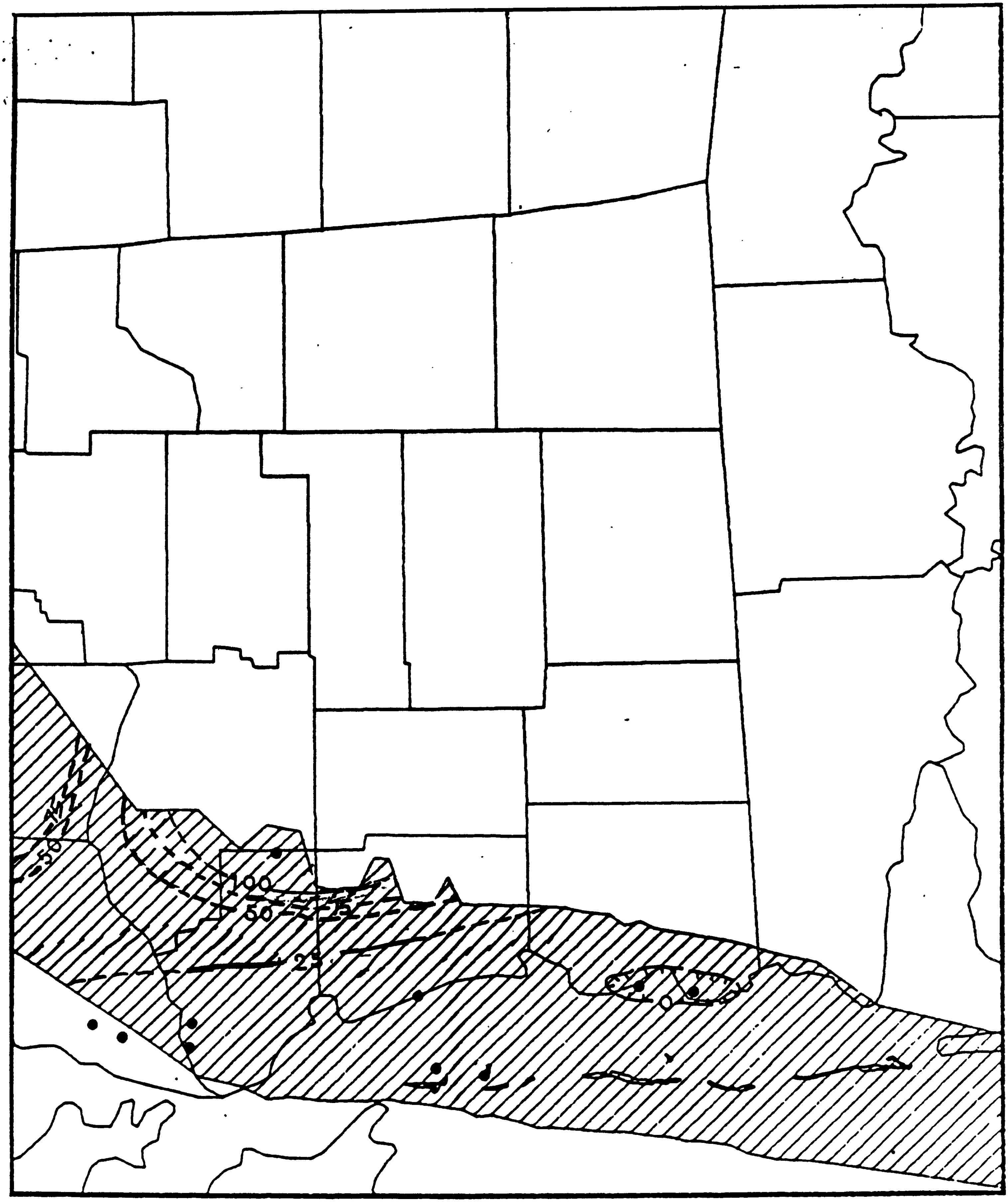


Figure 15,--Continued



0 10 20 MILES
0 10 20 KILOMETERS

1985

Figure 15.--Continued

for predevelopment (1900), 1940, 1960, 1965, 1977, 1982, and 1985 (figs. 9-15). Most water-use and water-level data were collected during these periods.

Water levels have declined as much as 100 feet in large areas of several of the layers along the coast. In layer 1, which is not developed along the coast, large water-level declines have occurred inland at Laurel and Hattiesburg, (figs. 9-15).

Large ground-water withdrawals from a given layer of the Miocene aquifer system have affected not only that layer, but to a lesser extent, the adjoining layers. The effect of these withdrawals, especially along the coast, has been to cause cones of depression around each pumped well or group of wells in an aquifer layer. With time, many of these cones of depression have deepened, expanded, and overlapped to the extent that a trough of depressed water levels occurs in several layers (3, 4, 5, and 6) along the coast (fig. 11-14). In some layers, by 1985, water was moving toward some pumping centers from all horizontal and vertical directions. The resulting depressed potentiometric surfaces in some layers have caused moderately saline water to move in the direction of pumping centers. Pumping caused declines in water levels in 1985 in small areas of the surficial aquifer such that aquifer-to-stream head gradients were reversed.

Hydraulic Characteristics

Transmissivity, hydraulic conductivity, specific storage, and storage coefficient are parameters that indicate the capacity of an aquifer to transmit and store water. Transmissivity is a measure of the ability of an aquifer to transmit water through a unit width of the aquifer in response to a hydraulic gradient. Hydraulic conductivity (transmissivity divided by saturated aquifer thickness) is a measure of the ability of the aquifer to transmit water through a unit area of the aquifer. The storage coefficient is the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head. Storage coefficients for confined aquifers range from about 0.00005 to 0.005.

The maximum, average, and minimum values of hydraulic conductivity from 125 aquifer tests in the Miocene aquifer system (Newcome, 1971) were 350, 118, and 3 ft/d. Newcome (1971) reports an average hydraulic conductivity value of about 100 ft/d for all tests in the Miocene in Mississippi. Storage coefficients from 32 aquifer tests of the Miocene aquifer system (Newcome, 1971) range from 0.0001 to 0.001.

Ground-Water Quality

Ground water of suitable quality for most uses occurs in at least part of the Miocene aquifer system throughout southern Mississippi. Geohydrologic data (Brown, 1944) indicate that the system was once filled with seawater. With time, however, rainfall on the outcrop areas and the downdip movement of freshwater has partially flushed the saltwater from the aquifers.

Dissolved-solids concentrations (an indication of water quality) in the study area are variable. At shallow depths in the outcrop area, away from bays and estuaries, dissolved-solids concentrations generally are less than 100 mg/L (milligrams per liter). These shallow waters generally are a hard, calcium bicarbonate type with a slightly acidic pH and have high concentrations of dissolved iron. As the water moves along the flow path, geochemical reactions alter the quality of the water. These reactions result in increases in dissolved-solids concentrations and pH, and decreases in hardness and in dissolved-iron concentrations. Ground water in the Miocene aquifer system typically is a soft to moderately hard, sodium bicarbonate type water with a pH of about 8.0 and a dissolved-solids concentration of about 500 mg/L. Dissolved-iron concentrations generally are less than 300 micrograms per liter. Farther downgradient, the freshwater begins to mix with saltwater in the aquifer, and changes to a sodium chloride type. Ground water in this area typically is a soft, sodium chloride water with a pH value greater than 8.0 and a low dissolved-iron concentration. Dissolved-solids concentrations generally are greater than 1,000 mg/L.

Concentrations of dissolved solids and major constituents are related to the depth of the well (fig. 16) and the distance from the outcrop area (fig. 17). Dissolved-solids concentrations increase and water changes from a calcium bicarbonate to a sodium chloride type as the water moves along the flow path.

Concentrations of dissolved solids are related to concentrations of several major constituents and to pH as shown in plots of data from approximately 500 wells in the Miocene aquifer system (fig. 18). Sodium and, to a lesser extent, chloride, correlate well with dissolved solids; sulfate concentrations generally are less than 15 mg/L and decrease as dissolved-solids concentrations increase above 200 mg/L. Values of pH increase rapidly from about 6.0 to about 8.5 as dissolved-solids concentrations increase from 100 to 300 mg/L, then remain fairly constant.

Dissolved-solids concentrations continue to increase with depth until the water is no longer fresh (dissolved-solids concentrations less than 1,000 mg/L). The altitude of the base of freshwater in the Miocene aquifer system is variable (fig. 19). In the northernmost one-third of the study area, freshwater occurs to the base of the Miocene sediments. Further south, the altitude of the base of freshwater slopes from approximately 400 feet below sea level to more than 3,000 feet below sea level. Under the Gulf of Mexico, the base of freshwater rises abruptly (figs. 8 and 19). The base of moderately saline water (fig. 20) commonly is a few hundred feet deeper than the base of freshwater. Intersection of the surfaces shown in figures 18 and 19 with the surfaces of the hydrologic layers (fig. 7) describe the lines shown in figures 21 and 22. These figures describe the downdip extent of fresh and moderately saline water in the various layers. The freshwater-saltwater interface is several miles offshore in layers 3 through 7 in most of Hancock and Harrison Counties (fig. 21). However, the interfaces appear to be relatively close to water-supply wells in some of these layers in the Pascagoula and Biloxi areas.

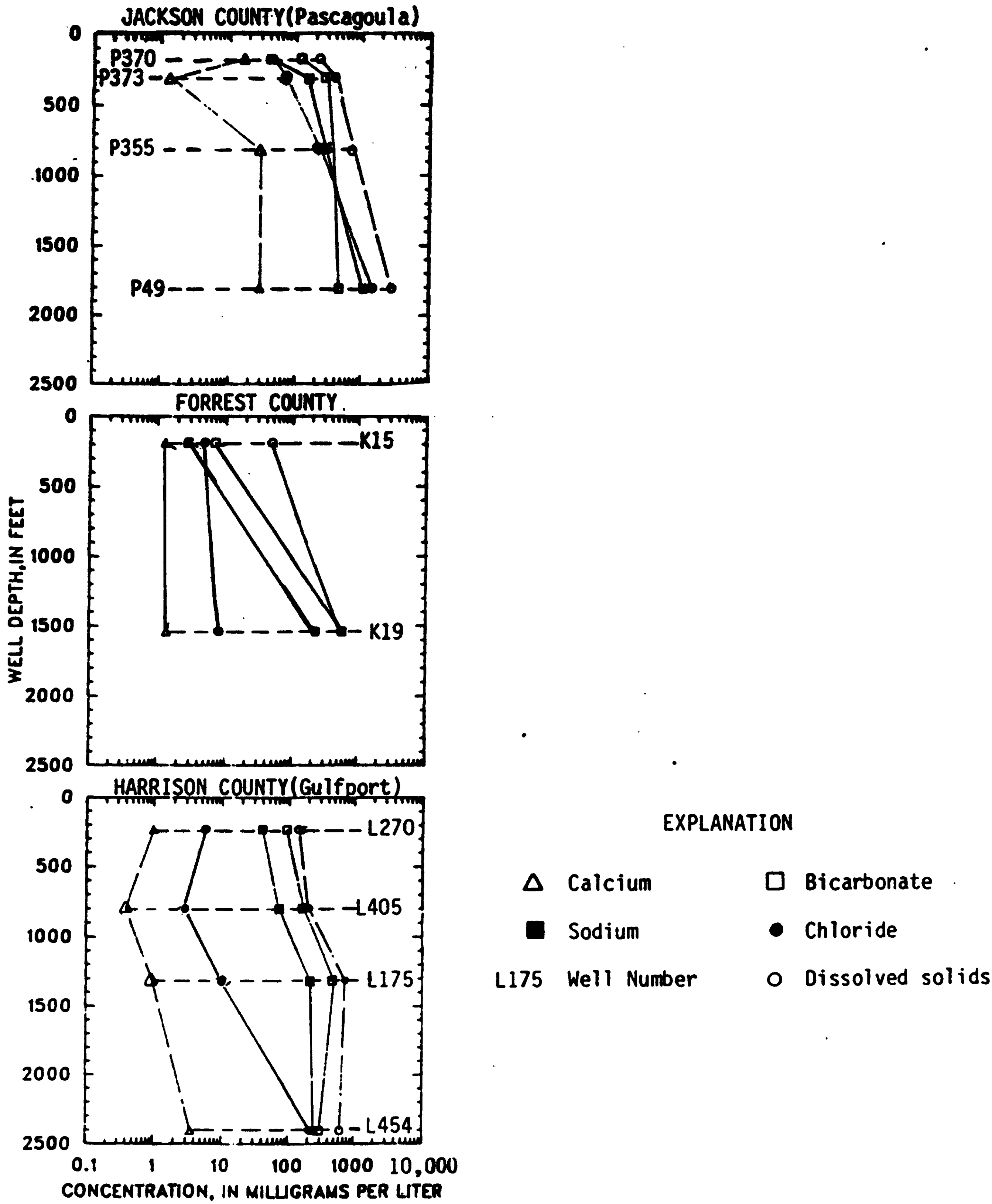


Figure 16.--Concentrations of calcium, sodium, bicarbonate, chloride, and dissolved solids in relation to depth of selected wells in the study area.

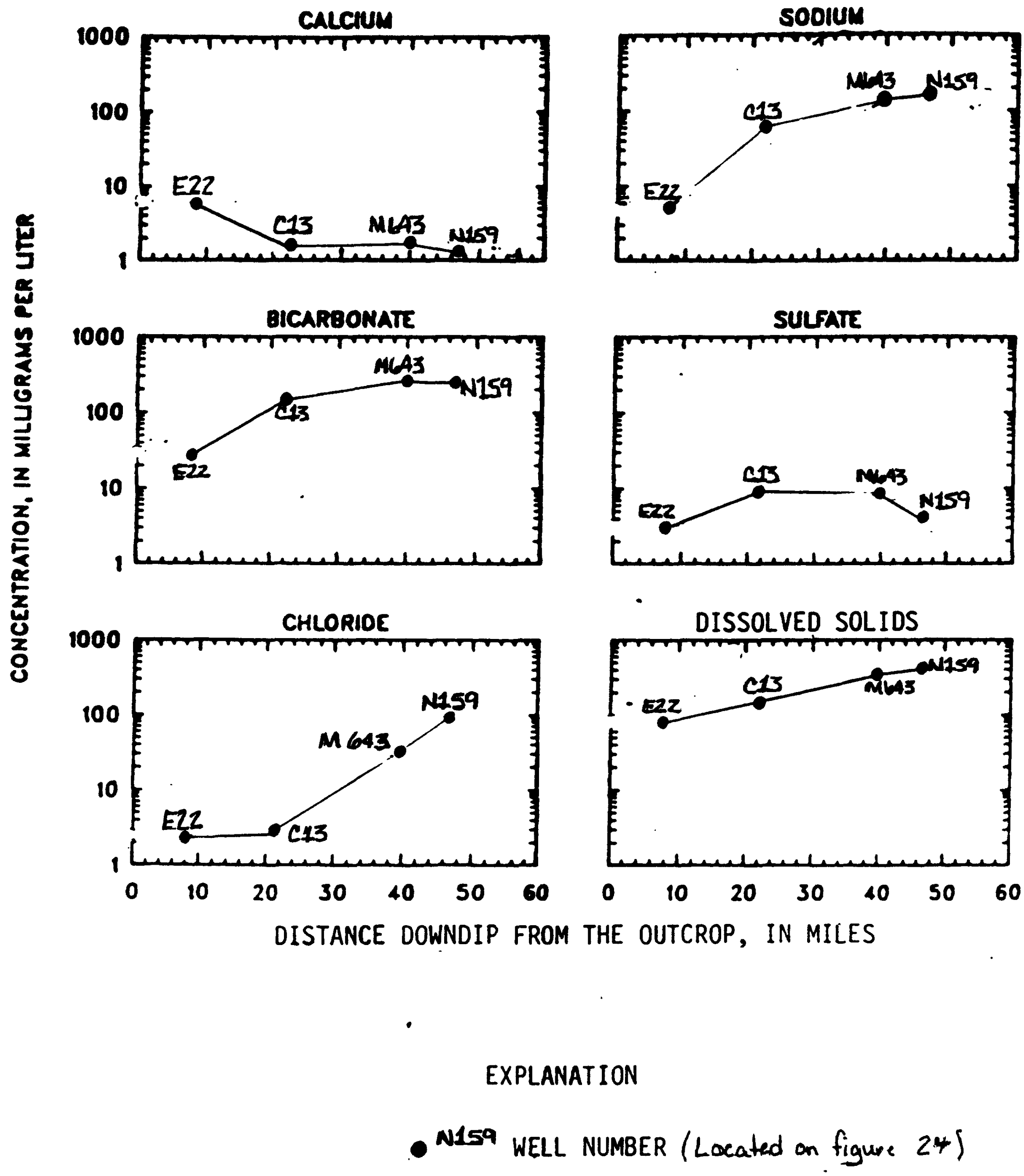


Figure 17.--Concentrations of calcium, sodium, bicarbonate, chloride, and dissolved solids in relation to distance downdip along flow line from the outcrop in layer 4.

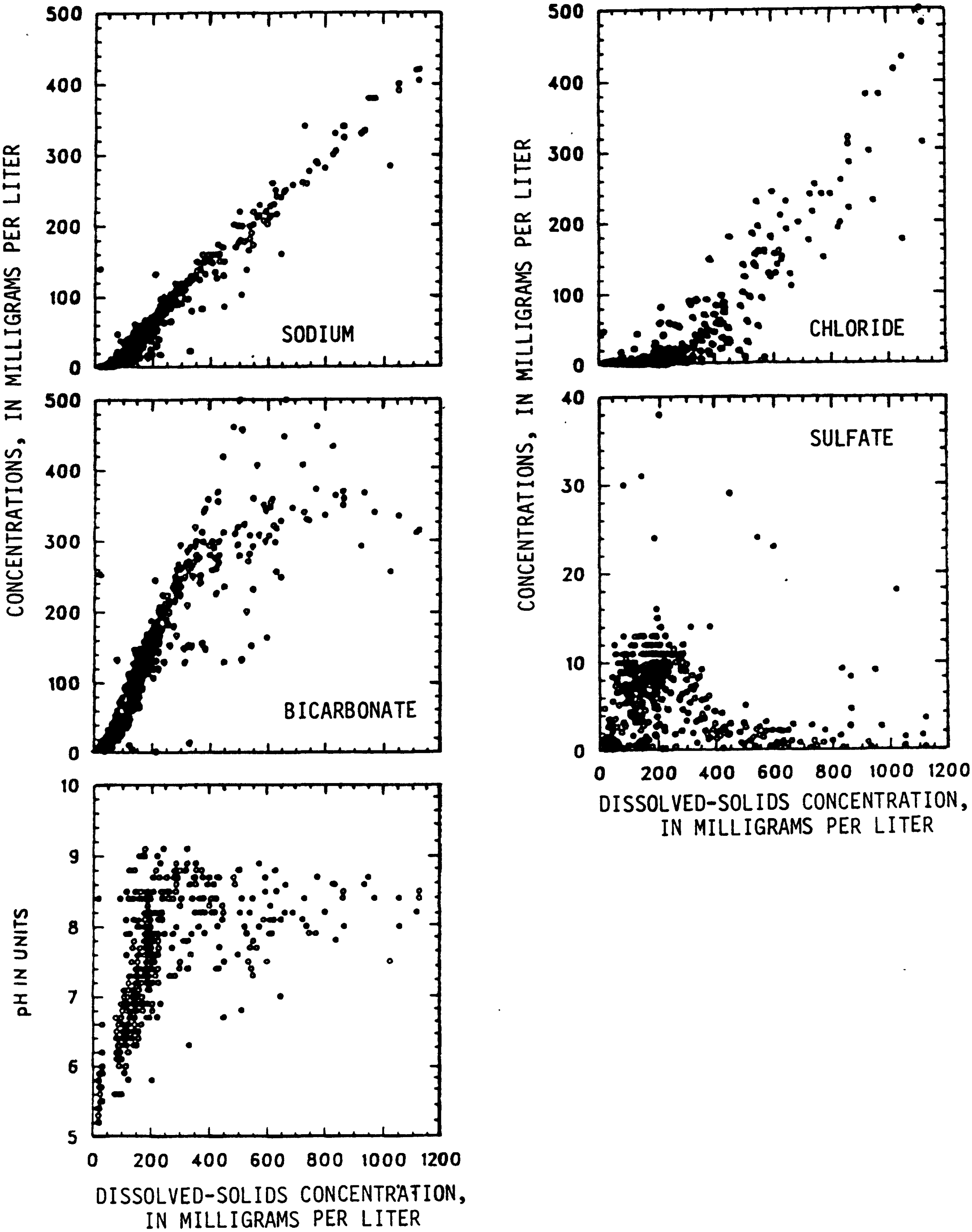
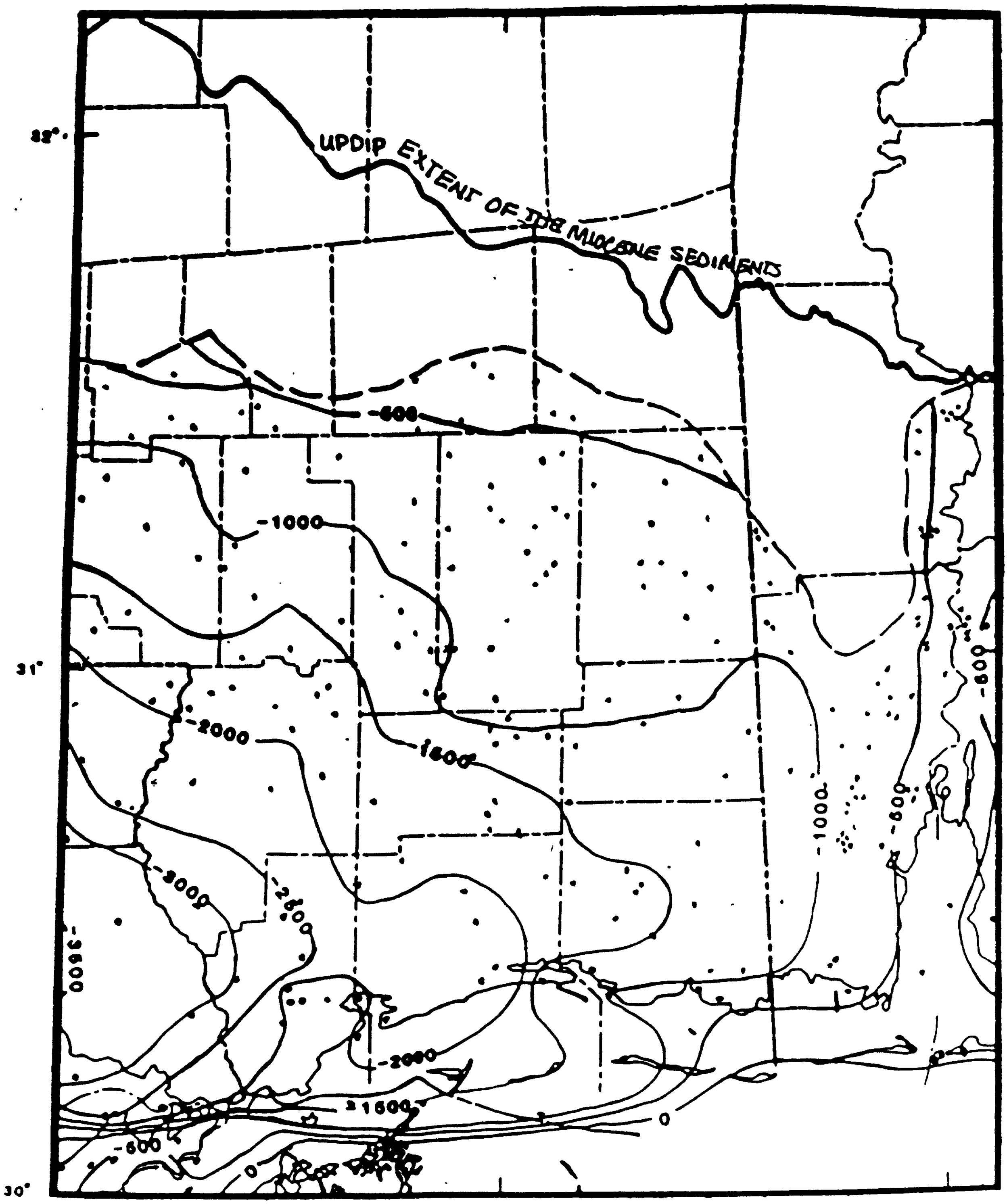


Figure 18,--Relations of selected major constituent concentrations and pH to dissolved-solids concentrations in the Miocene aquifer system.



Modified from Newcome (1975), Gandl (1982), Winslow and others (1968), Rollo (1968), Reed and McCain (1971, 1972), and Newton and others (1972).

EXPLANATION

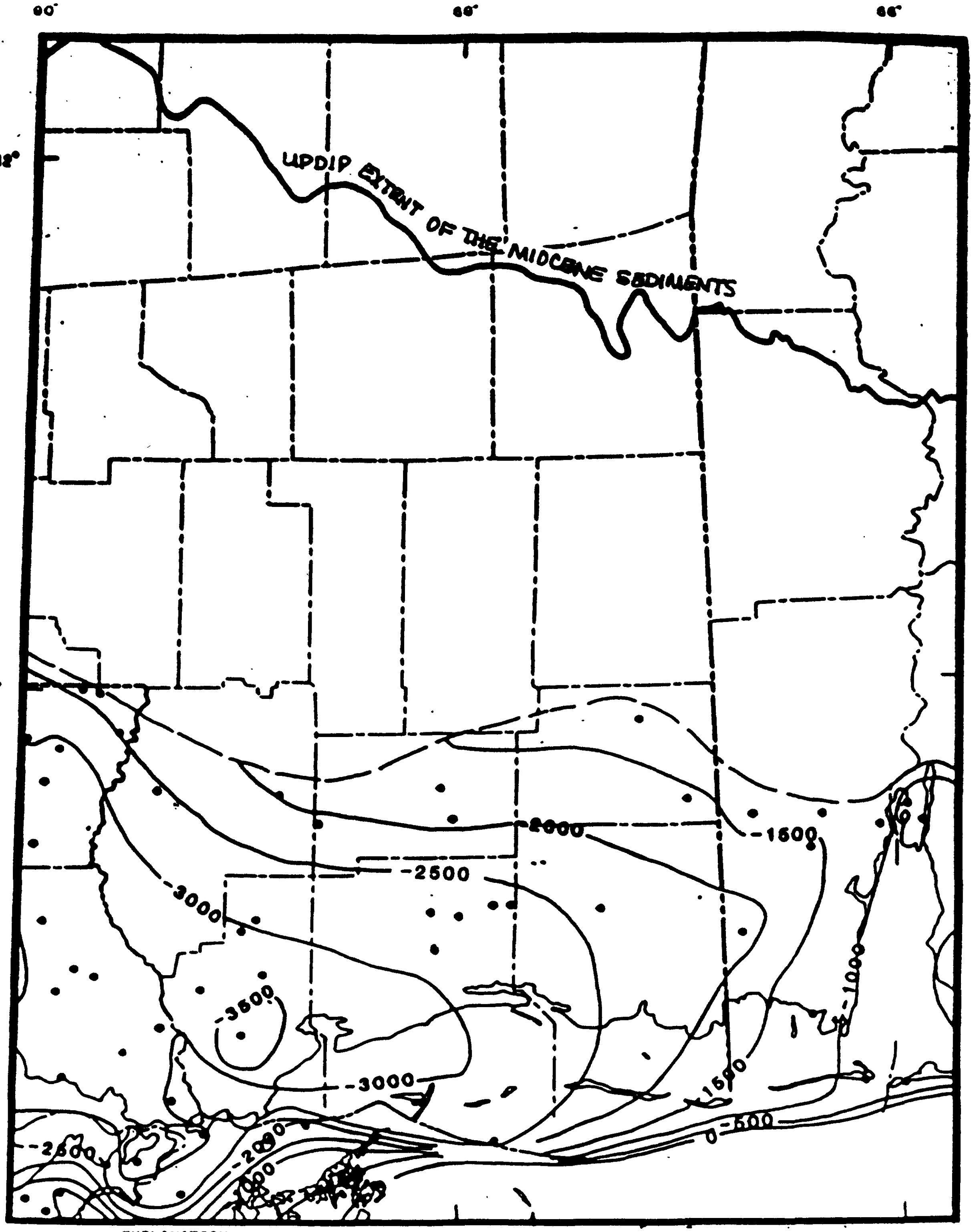
—— -1400 —— CONTOUR LINE--Shows altitude of base of freshwater, less than 1,000 milligrams per liter dissolved solids. Contour interval 500 feet. Datum is sea level. Data are from various dates, but contours are assumed to represent conditions in 1985.

● CONTROL POINT

0 10 20 MILES

0 10 20 KILOMETERS

Figure 19.--Altitude of the base of freshwater in the Miocene aquifer system.



EXPLANATION

——— -1400 ——— CONTOUR LINE--Shows altitude of base of moderately saline water, less than 10,000 milligrams per liter dissolved solids. Contour interval 500 feet. Datum is sea level. Data are from various dates, but contours are assumed to represent conditions in 1985.

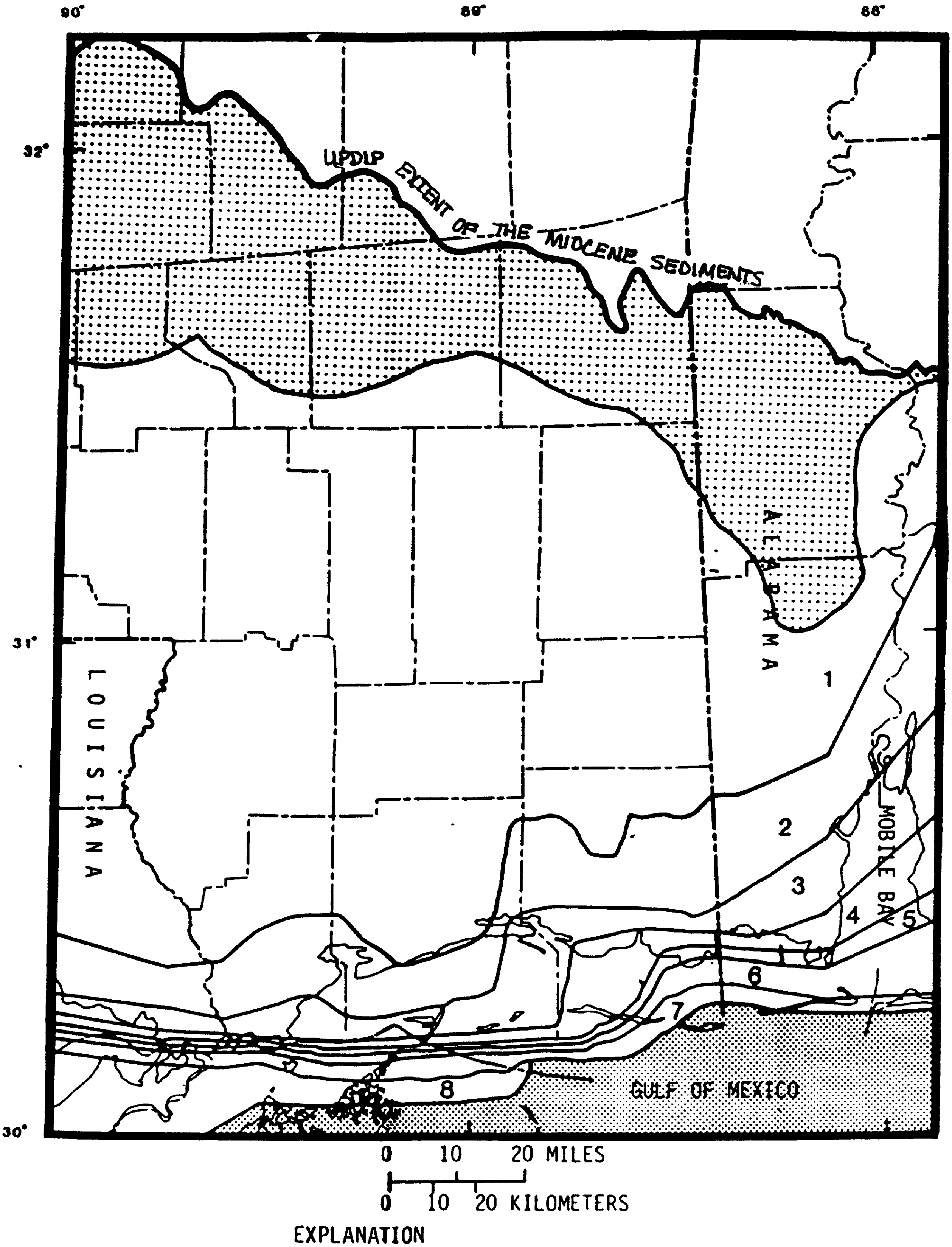
• CONTROL POINT

Modified from Gandl (1982), Winslow and others (1968), and Epsman and others (1983)

0 10 20 MILES

0 10 20 KILOMETERS

Figure 20.--Altitude of the base of moderately saline water in the Miocene aquifer system.



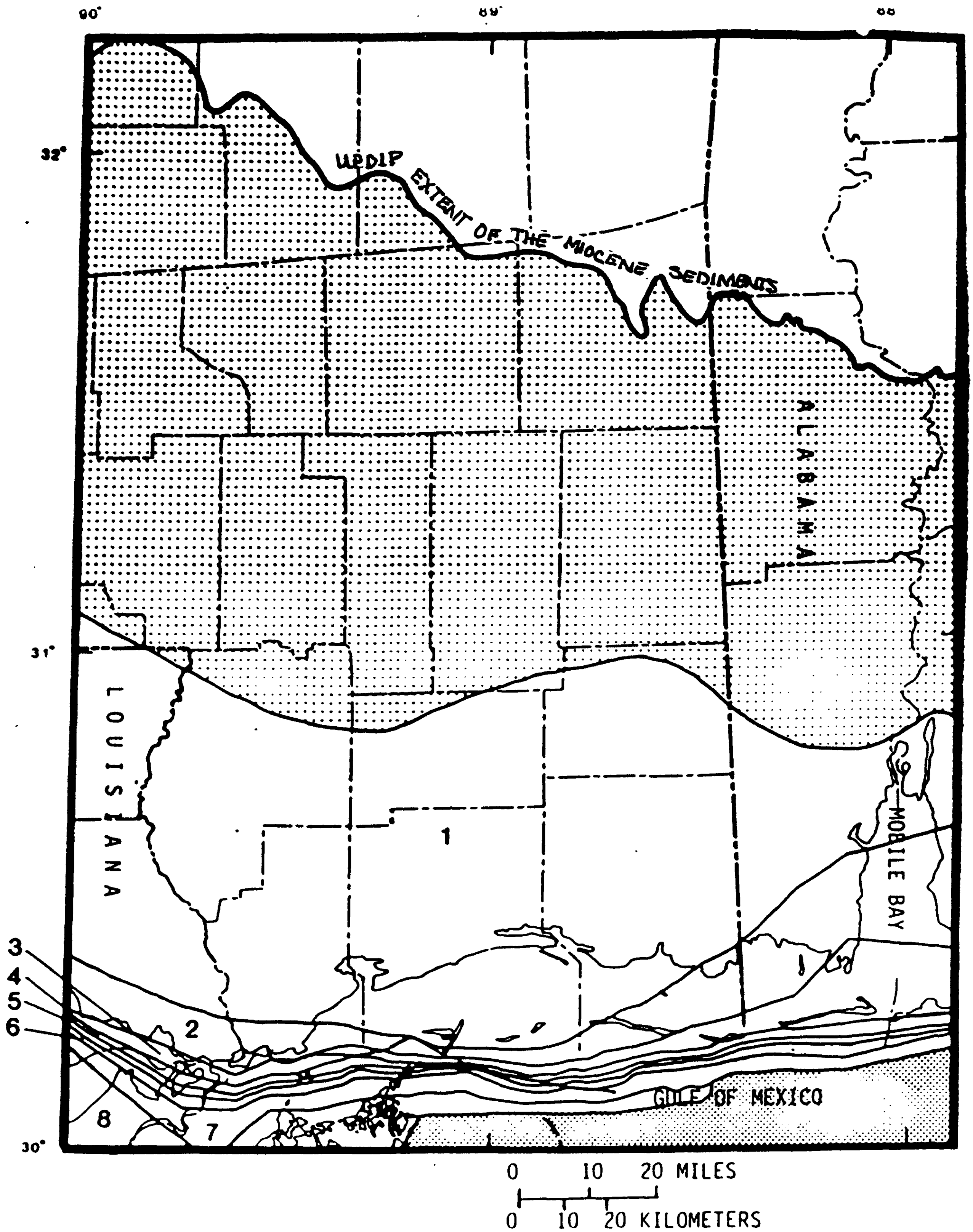
EXPLANATION

Dissolved-solids concentrations in water in all layers is less than 1000 mg/L (fresh).

Dissolved-solids concentrations in water in all layers is greater than 1,000 mg/L.

4 Transition zone in the designated model layer -- base of freshwater moves from base to top of layer.

Figure 21.--Extent of freshwater within each hydrologic layer.



EXPLANATION

Dissolved-solids concentrations in water in all layers is less than 10,000 mg/L (moderately saline).

Dissolved-solids concentrations in water in all layers is greater than 10,000 mg/L.

4 Transition zone in the designated model layer--base of moderately saline water moves from base to top of layer.

Figure 22.--Extent of moderately saline water within each hydrologic layer.

Chloride concentrations in water from wells in hydrologic layers 3, 4, 5, and 6 in Harrison and Jackson Counties, where the threat of saltwater contamination is greatest, are shown in figures 23-26. Chloride concentrations greater than 50 mg/L generally are restricted to the Biloxi-Pascagoula area. Generally, the deeper the layer, the larger the area that contains the higher chloride concentrations. Variations in chloride concentrations with time for selected wells are also shown in figures 23-26. These wells were selected to show increases or decreases with time--most wells have no detectable change in water quality over the period of record available.

In layer 3, the deepest of the production aquifers along the coast, chloride concentrations exceed 100 mg/L in Pascagoula, much of southeast Jackson County, and in a relatively large area encompassing most of Biloxi and Ocean Springs (fig. 23). Chloride concentrations exceed 500 mg/L in a few wells in these areas. Although water-quality data indicate chloride concentrations in water from most wells in this aquifer are not increasing, small increases are apparent in a few wells in the Biloxi and Pascagoula areas. Chloride concentrations tend to be more variable and are more likely to be increasing in water from those wells that have concentrations greater than about 300 mg/L. Water from these wells probably has a dissolved-solids concentration approaching or exceeding 1,000 mg/L and may be of limited use for municipal supply.

In layer 4, the chloride concentrations exceed 100 mg/L in Pascagoula, part of Moss Point, and much of southeastern Jackson County, but in only a few wells in the Biloxi-Ocean Springs area (fig. 24). Chloride concentrations exceed 300 mg/L in several wells in south Pascagoula and exceed 500 mg/L in a few wells. Changes in chloride concentrations with time are shown for several wells in layer 4 in figure 24. The chloride concentrations in wells L144 and N3 in Harrison County are relatively low and have not changed appreciably in the last 20 years. A slight increase in chloride concentrations in water from well P124 near the center of pumping in Pascagoula has occurred over the past 40 years. A decreasing trend in chloride concentrations in well O53 west of Pascagoula suggests that the eastward movement of freshwater toward the large pumping center in the Pascagoula area may be improving the quality of water in the Gautier area.

In layer 5, the concentrations of chloride exceed 100 mg/L in much of Pascagoula, Moss Point and southeast Jackson County but not in Ocean Springs, Biloxi, or Gulfport (fig. 25). Concentrations of chloride in layer 5 exceed 300 mg/L only in a small area in southeast Pascagoula. However, concentrations in three of these wells have increased sharply in the past few years. Chloride concentrations increased from about 370 to 450 mg/L in well Q164 and from about 300 to 380 mg/L in well Q181 between 1983 and 1985 (fig. 25). These increases suggest that the freshwater-saltwater interface has arrived at or is near the southernmost wells at this pumping center in southeast Pascagoula. A reduction in chloride concentrations in well O286 west of Pascagoula between 1979 and 1983 suggests that in layer 5, as in layer 4, the movement of water southeastward toward the pumping center is bringing less mineralized water into the area west of Pascagoula.

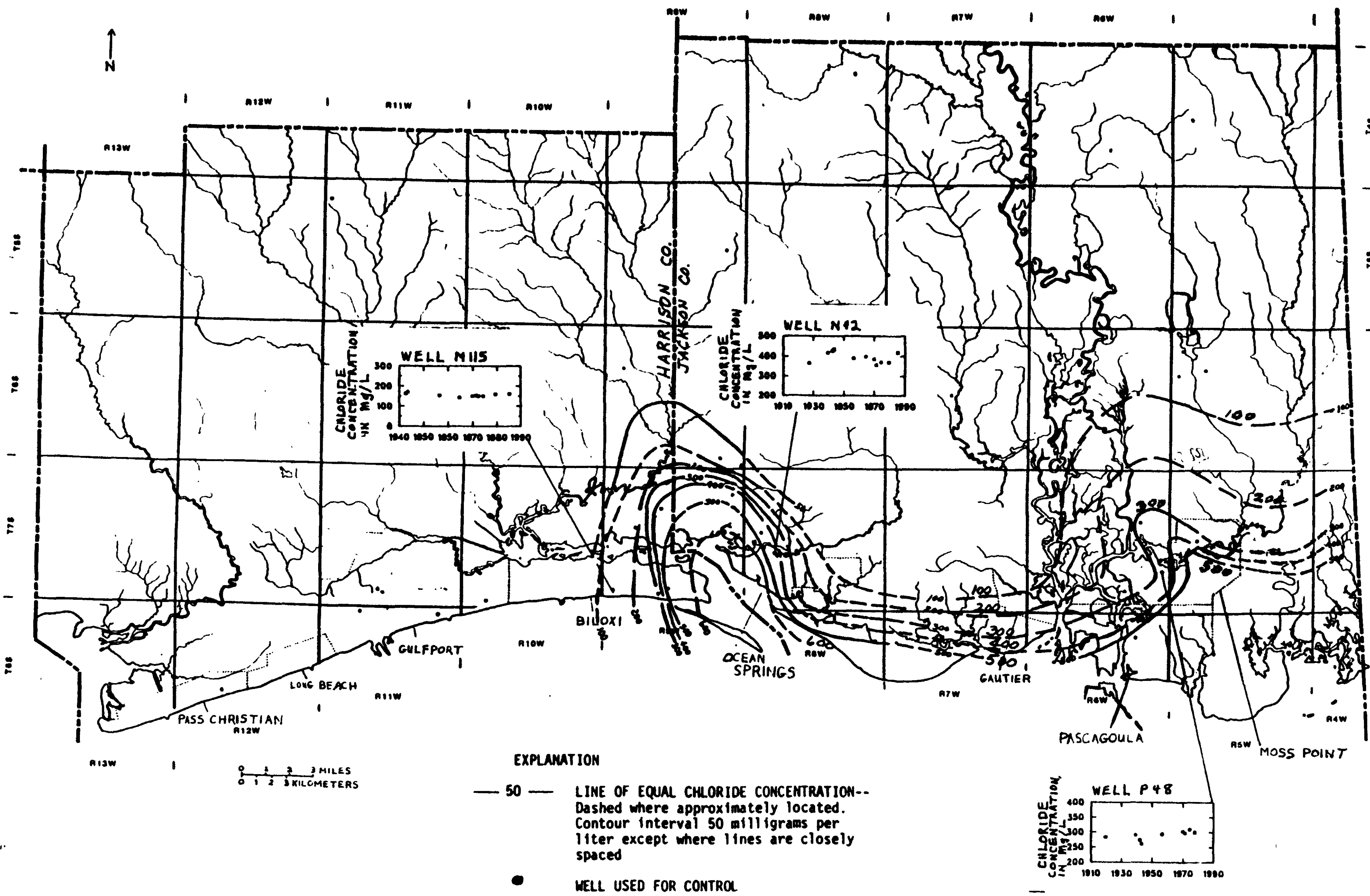
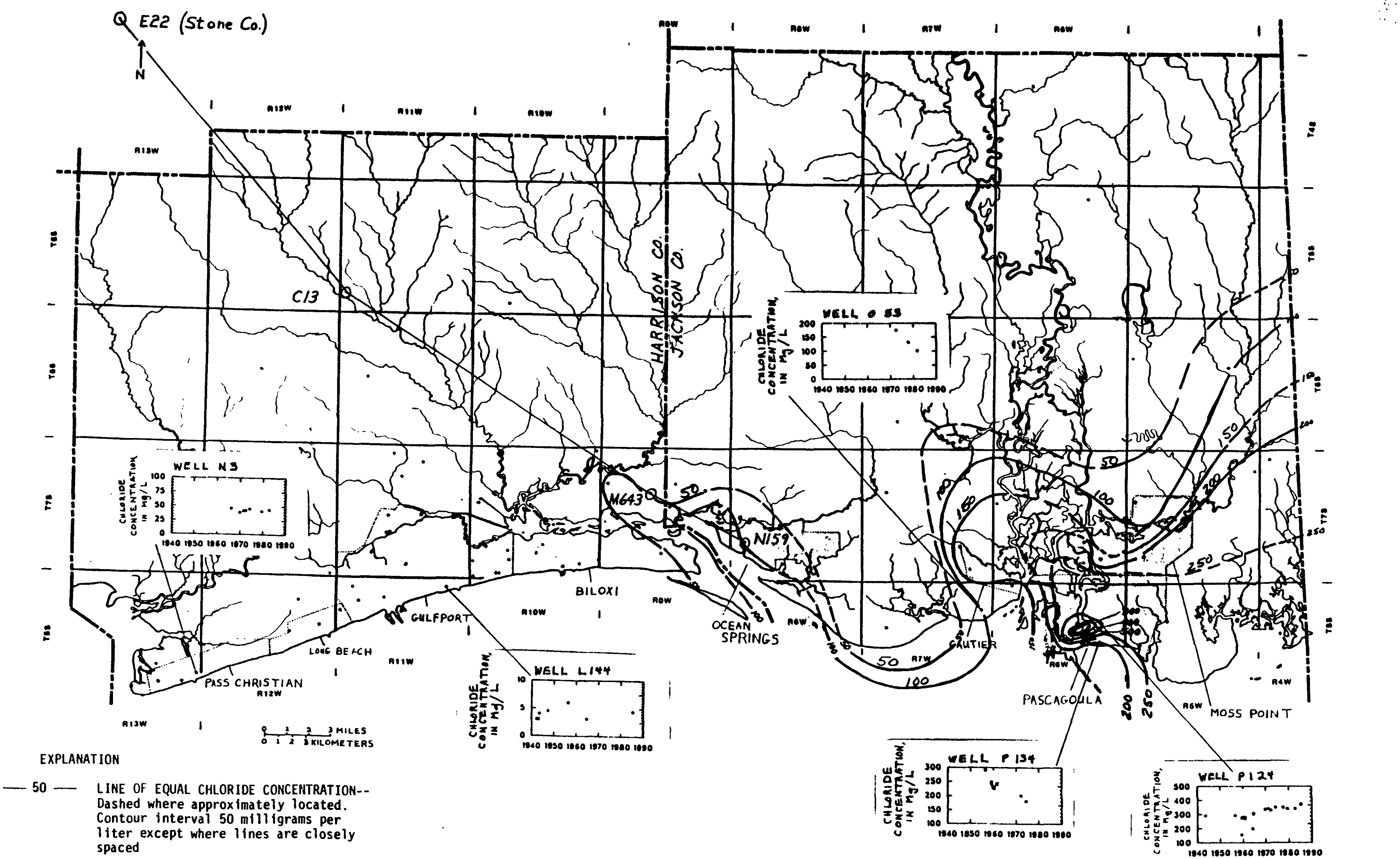


Figure 23.--Chloride concentrations in layer 3 of the Miocene aquifer system in Harrison and Jackson Counties in 1985.



EXPLANATION

— 50 — LINE OF EQUAL CHLORIDE CONCENTRATION--Dashed where approximately located. Contour interval 50 milligrams per liter except where lines are closely spaced

C13 WELL NUMBER AND FLOW LINE SHOWN IN FIGURE 17

• WELL USED FOR CONTROL

Figure 24.--Chloride concentrations in layer 4 of the Miocene aquifer system in Harrison and Jackson Counties in 1985.

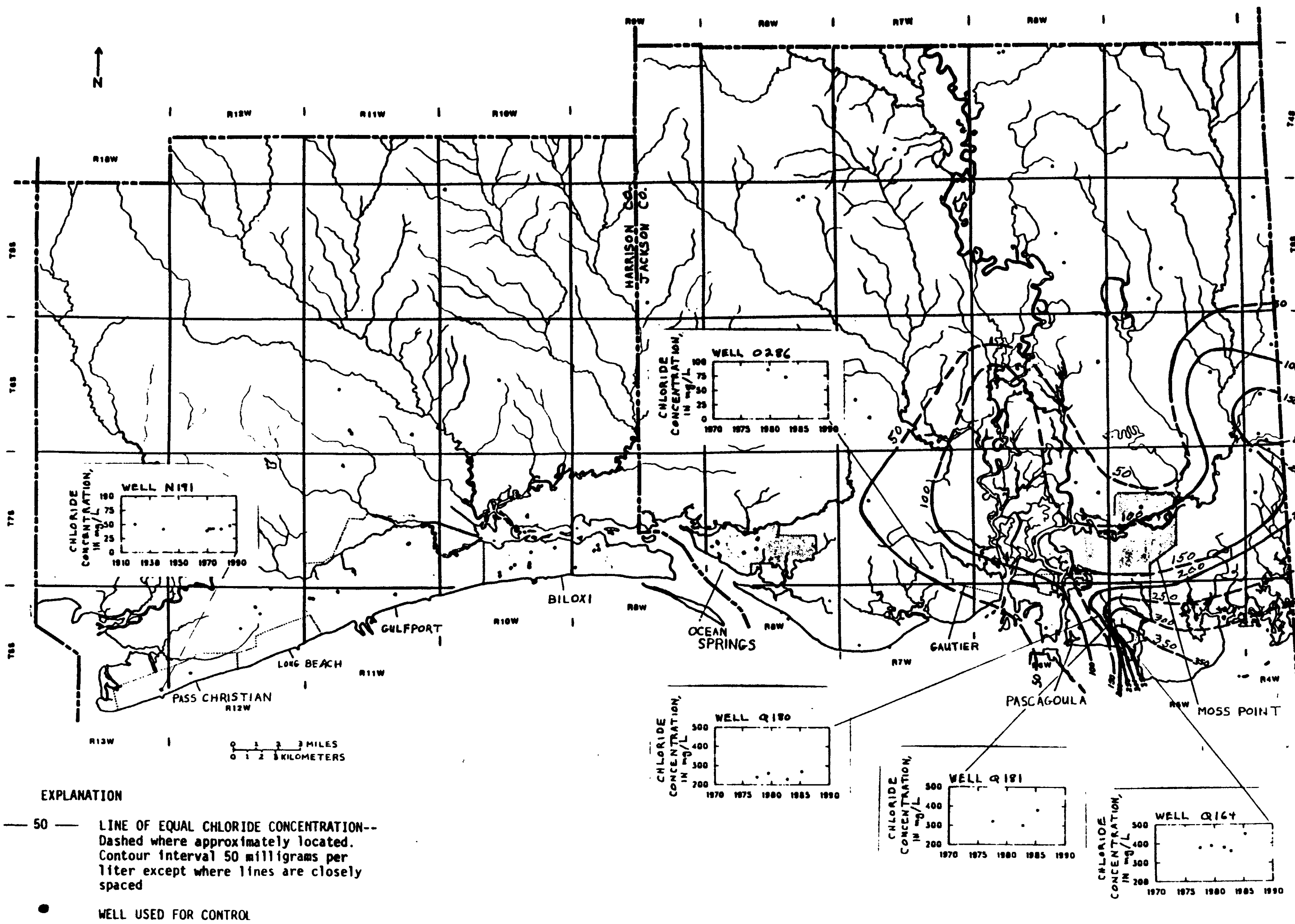


Figure 25.--Chloride concentrations in layer 5 of the Miocene aquifer system in Harrison and Jackson Counties in 1985.

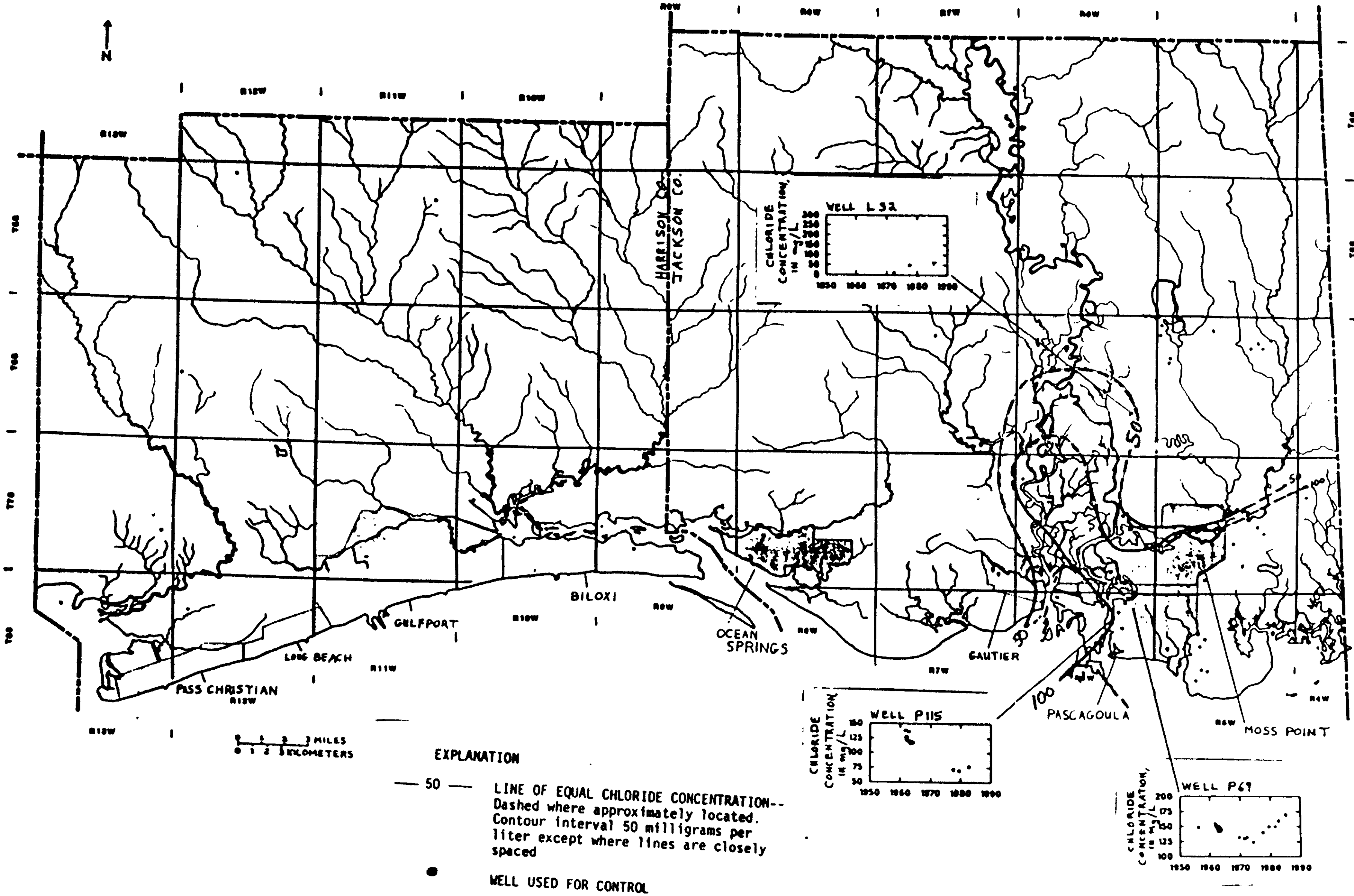


Figure 26.--Chloride concentrations in layer 6 of the Miocene aquifer system in Harrison and Jackson Counties in 1985.

In layer 6, the shallowest of the production aquifers, chloride concentrations exceed 100 mg/L in much of Pascagoula, Moss Point, and the extreme southeastern part of Jackson County (fig. 26). Limited data also suggest that chloride concentrations may exceed 100 mg/L in the area of the layer that underlies the salt marshes of the Pascagoula and Escatawpa Rivers in the vicinity of the town of Escatawpa. However, chloride concentrations in this layer generally are less than 200 mg/L. Chloride concentrations in wells P68 and P69 in Pascagoula have fluctuated over a relatively wide range (about 50 mg/L) in the past 30 years. The reason for the upward trend in well P69 since 1970 is not clear, but may be related to changes in the distribution of pumping. Chloride concentrations in wells P115 and P68 have decreased in recent years. This probably is the result of the eastward movement of less mineralized water toward the pumping centers in Pascagoula and Bayou Casotte. In the Gautier-Pascagoula area, layer 6 is believed to be hydraulically separated from the overlying surficial aquifer system, but farther north the hydraulic connection between these aquifers increases. With water levels in layer 6 now below sea level in much of southeast Jackson County, there is potential for additional saltwater movement in this layer from the estuarine reaches of streams and shallow beds of sands along these streams.

NUMERICAL MODEL OF THE GROUND-WATER SYSTEM

A ground-water flow system can be simulated by a numerical model, which will solve the ground-water flow equation subject to imposed boundary conditions. The validity of the model will depend on 1) the adequacy of the geohydrologic concept of the system, 2) the finite-difference resolution of the grid used in the numerical model, and 3) the quantity and validity of data used in the model construction and calibration. The U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model (McDonald and Harbaugh, 1984) was used to simulate the ground-water flow system of the study area.

Model Construction

Model construction consisted of specification of the spatial distribution of hydraulic properties (transmissivity, vertical leakance, and storage coefficient), boundary conditions, and aquifer stresses, as defined by the conceptualization of the system. Because knowledge of the hydraulic parameters is limited, model simulations were made for periods for which the changes in the potentiometric surface are known, as a means of inferring these parameters. The model was calibrated by varying the hydraulic parameters, within acceptable limits, until the model simulated the known potentiometric surface reasonably well. Model calibration was based on the results of simulations of ground-water flow during two periods, predevelopment ending in 1900 and 1940-85. Predevelopment simulation approximated the steady-state flow conditions existing prior to ground-water withdrawals. Transient simulation incorporated known ground-water withdrawals to approximate flow conditions during the period 1940-85 (fig. 27). The transient simulation was subdivided into five stress periods (time periods during which all stresses are assumed constant). Stress periods chosen were 1940-60, 1961-65, 1966-77, 1978-82, and 1983-85, when head changes were reasonably well known. Rates of ground-water withdrawal during the period 1940-1985 were estimated from records of water use compiled by the U.S. Geological Survey. Distribution and quantity of water withdrawn in 1985 are shown by layer and by community in figure 28. Most of the pumpage along the coast is from layers 4, 5, and 6. Most of the pumpage inland is from layers 1 and 2. Distribution and quantity of water withdrawn during 1982-85 are shown by layer and by model nodes in figure 29.

Model Grid

A ground-water flow system must be discretized (gridded) to allow for a numerical solution of the equations describing the system. Because this flow model is intended to be used as a management tool for the Mississippi Gulf Coast, the grid is finer in that area (fig. 30) --10,000 feet parallel to the coastal potentiometric trough and 5,000 feet perpendicular to the trough. Grid expansion away from the coastal Mississippi area is used to simplify the model in areas not of primary interest. The grid system is roughly oriented with respect to the east-west coastal potentiometric trough. The modeled area is 810,000 feet (about 153 miles) in the north-to-south direction by 670,000 feet (about 127 miles) in the east-to-west direction. The grid is 37 rows by 41 columns. Vertical discretization is controlled by the eight hydrologic layers previously described. The center of each grid cell is referred to as a node.

Model Boundaries

Boundary conditions of a numerical model describe the relation between the system being studied and the area adjacent to the system. Boundaries in the McDonald-Harbaugh model can be of several types: specified head, specified flux, or head-dependent flux. The only specified flux boundaries used for this study are no-flow boundaries (flux = 0). Choice of a boundary type depends on the particular hydrologic situation being considered. The no-flow boundary between Miocene and pre-Miocene sediments was chosen as the lower boundary of the system because a negligible amount of water passes from or through the thick, relatively impermeable beds of the Vicksburg and Jackson Groups.

A head-dependent flux boundary was chosen as the upper boundary of the model because of the complex relation between the surficial aquifer system and the Miocene aquifer system being studied. The hydrologic complexity of the surficial aquifer system is not of importance in this study--only the effect on the deeper flow system is of interest. Magnitude and direction of the flow between the surficial aquifer system and the Miocene aquifer system is determined by the degree of hydraulic connection and the head differential between the two systems. Specified heads of the surficial aquifer system were those shown in the poten-

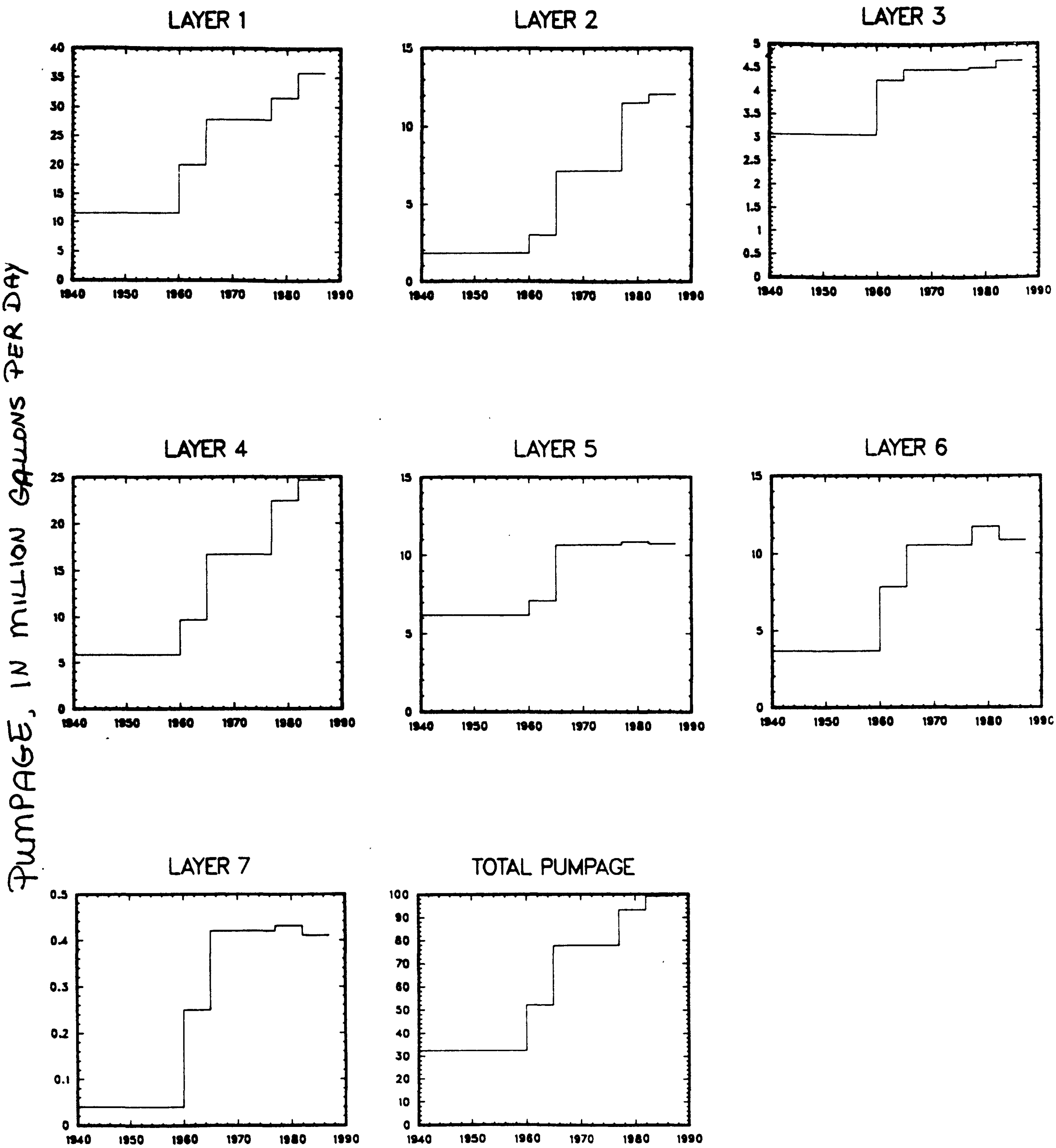
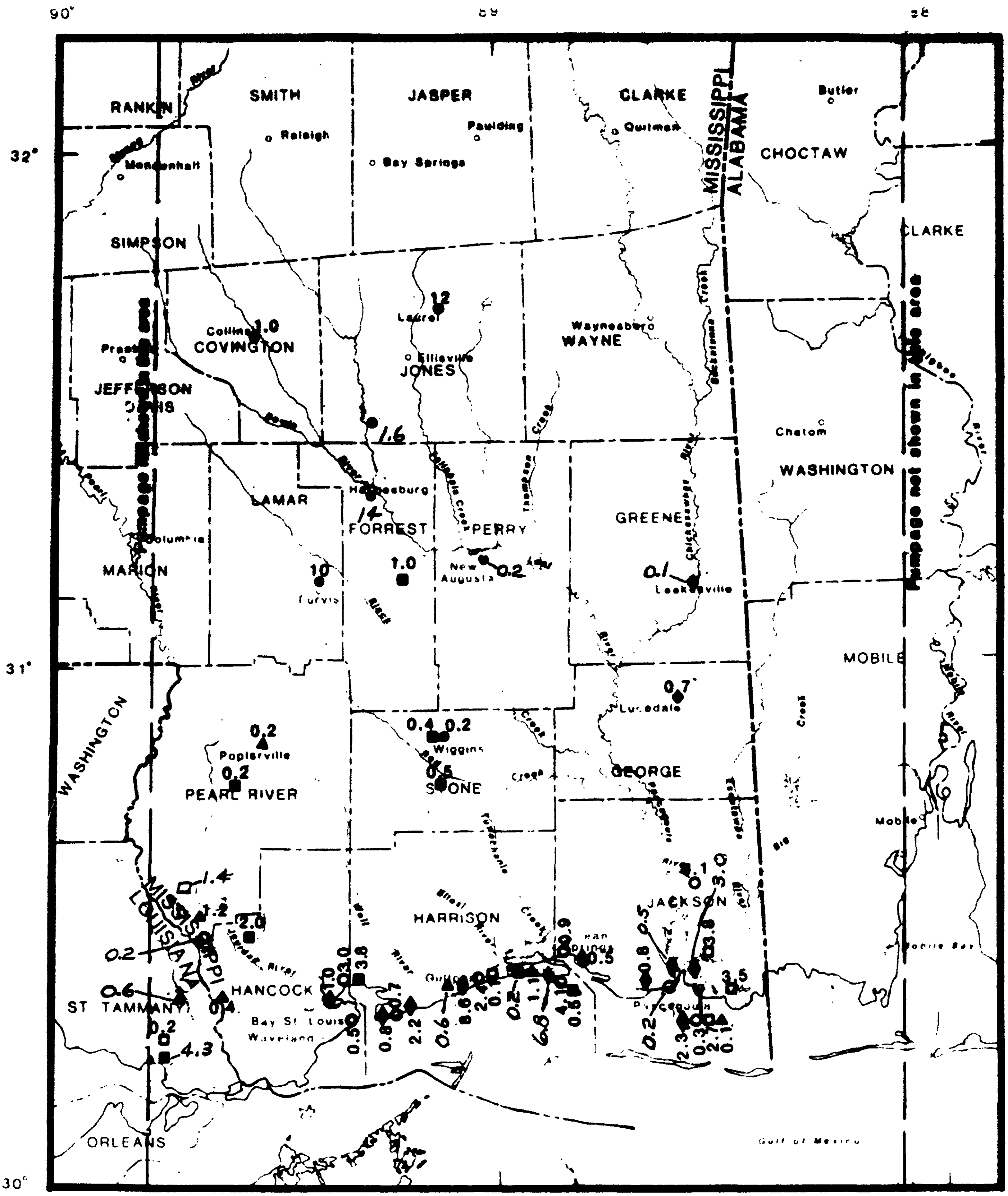


Figure 27.--Pumpage from the various layers of the Miocene aquifer **system** and total pumpage for stress periods from 1940 through 1985.

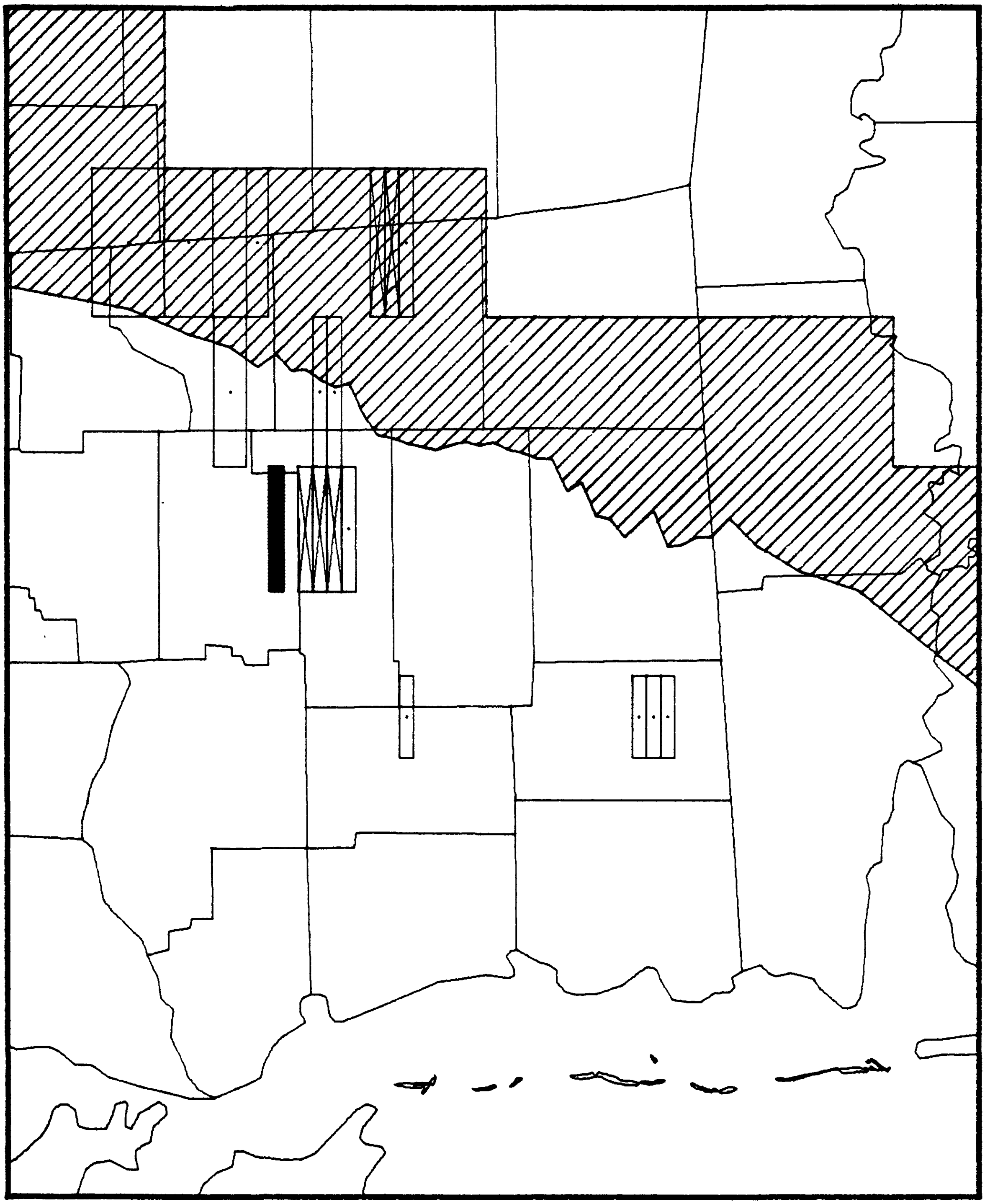


EXPLANATION

SYMBOLS FOR HYDROLOGIC LAYERS (NUMBERS SHOW PUMPAGE IN MILLION GALLONS PER DAY)

●	LAYER 1	○	LAYER 5
■	LAYER 2	□	LAYER 6
▲	LAYER 3	△	LAYER 7
◆	LAYER 4	◇	LAYER 8

Figure 28.--Distribution and quantity of water withdrawn in 1985 by layer and community.



EXPLANATION

AREA OF OUTCROP OF LAYER 1

WITHDRAWAL FLUX GREATER THAN 0 AND LESS THAN 2 INCHES PER YEAR

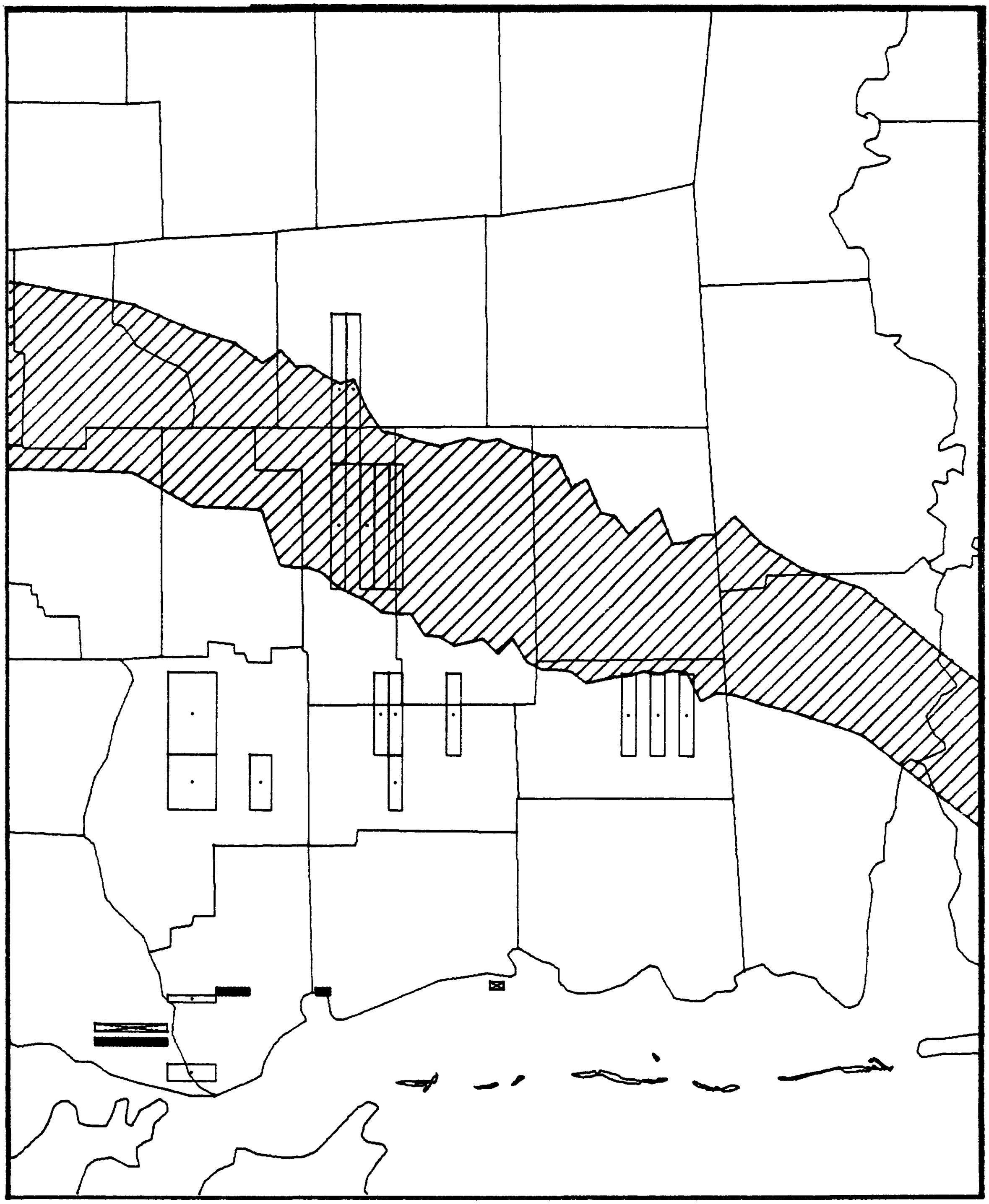
WITHDRAWAL FLUX GREATER THAN 2 AND LESS THAN 5 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 5 INCHES PER YEAR

0 10 20 MILES

0 10 20 KILOMETERS

Figure 29.--Distribution and quantity of water withdrawn during 1982-85 by layers and by model nodes.--Continued



EXPLANATION

AREA OF OUTCROP OF LAYER 2

WITHDRAWAL FLUX GREATER THAN 0 AND LESS THAN 2 INCHES PER YEAR

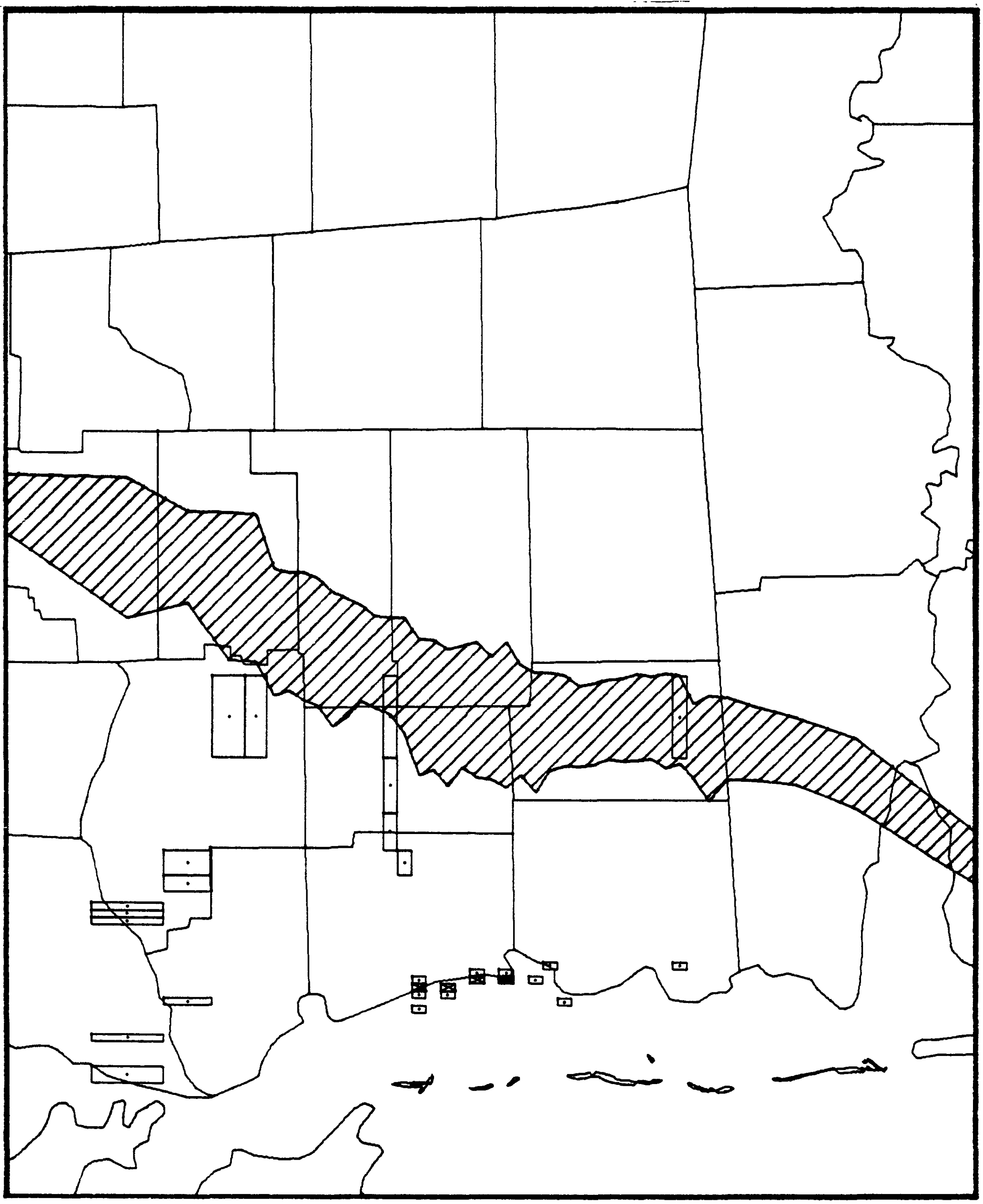
WITHDRAWAL FLUX GREATER THAN 2 AND LESS THAN 5 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 5 INCHES PER YEAR

0 10 20 MILES

0 10 20 KILOMETERS

Figure 29.--Distribution and quantity of water withdrawn during 1982-85 by layers and by model nodes.--Continued



EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

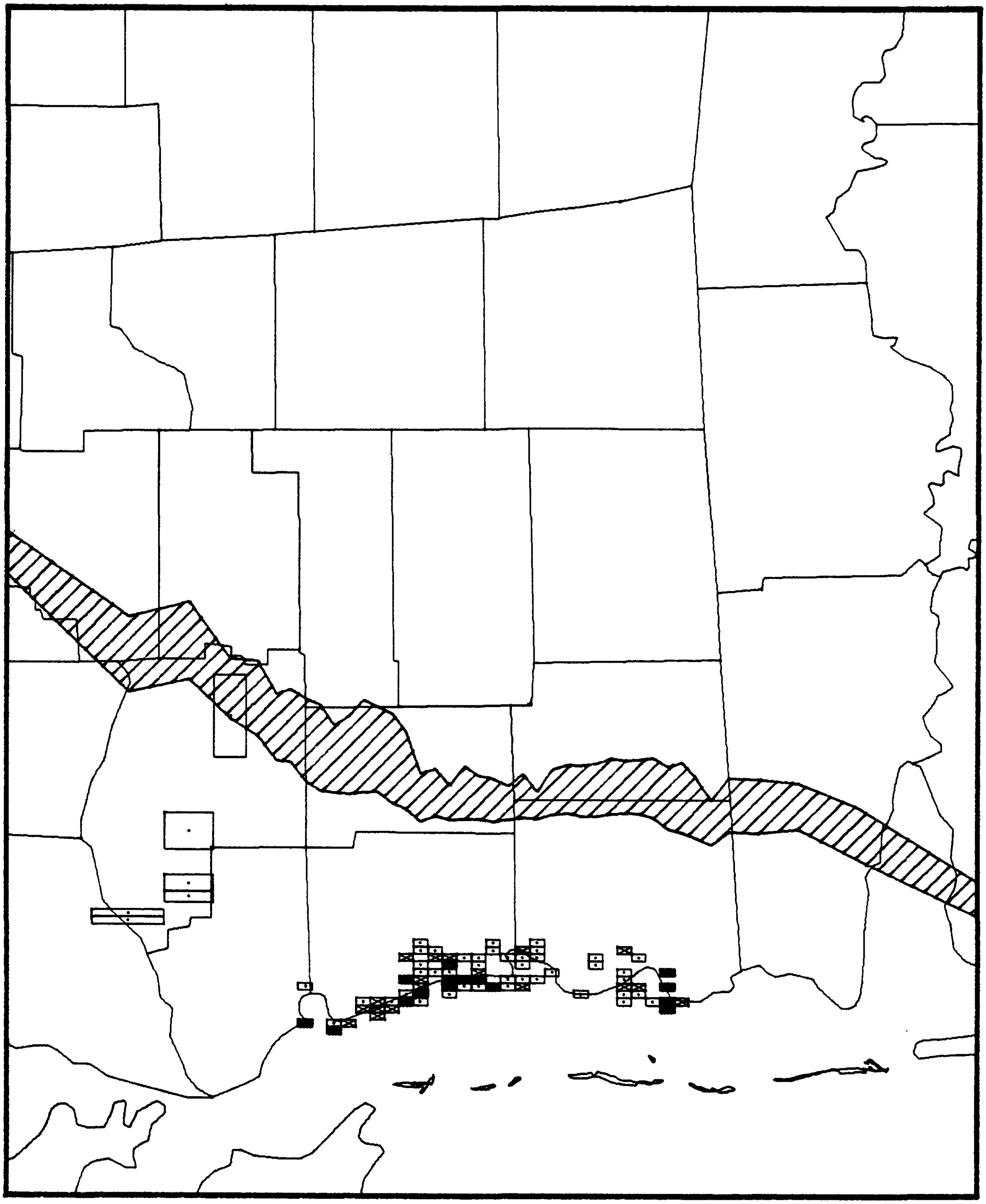
AREA OF OUTCROP OF LAYER 3

WITHDRAWAL FLUX GREATER THAN 0 AND LESS THAN 2 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 2 AND LESS THAN 5 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 5 INCHES PER YEAR

Figure 29.--Distribution and quantity of water withdrawn during 1982-85 by layers and by model nodes.--Continued



EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

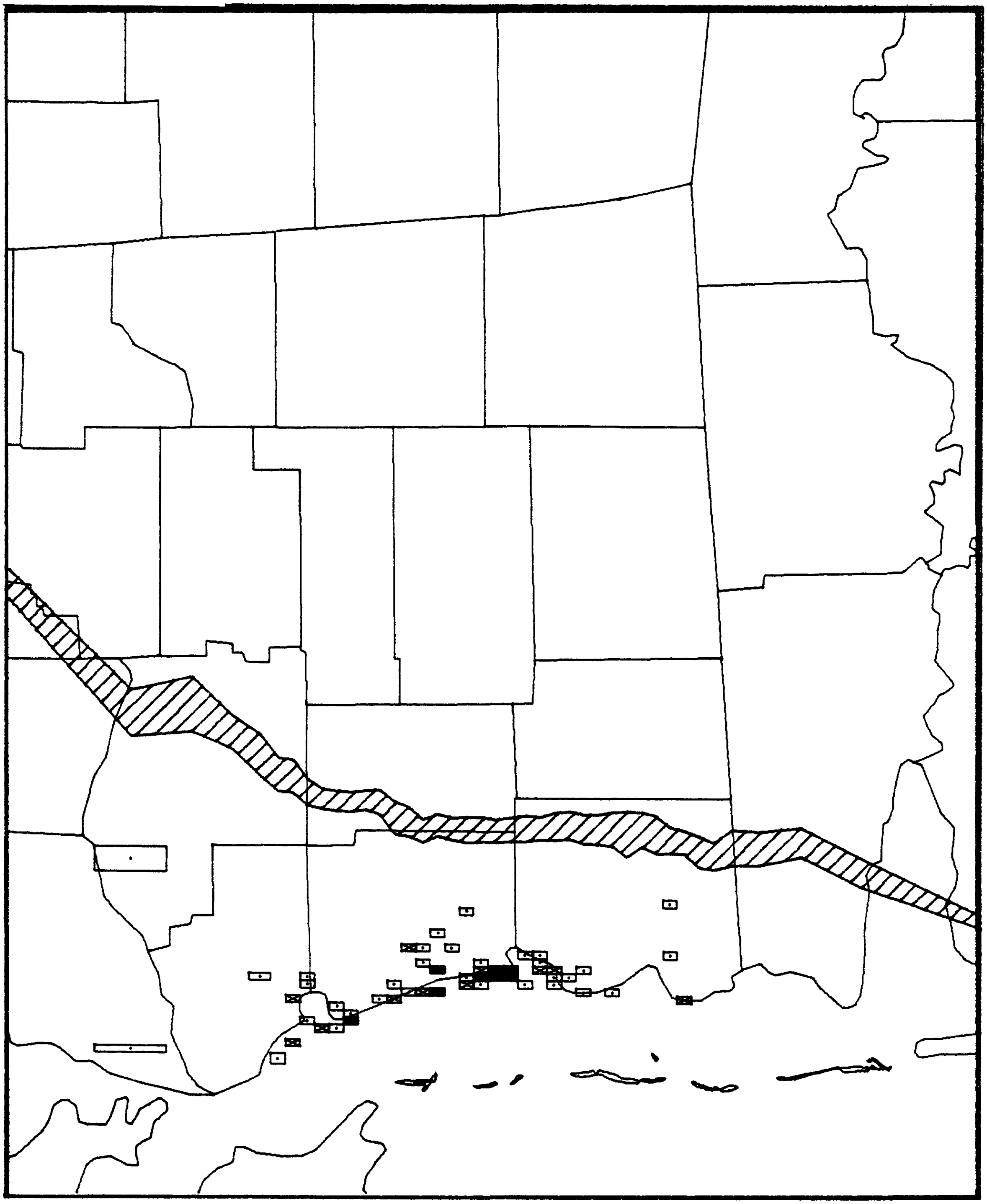
AREA OF OUTCROP OF LAYER 4

WITHDRAWAL FLUX GREATER THAN 0 AND LESS THAN 2 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 2 AND LESS THAN 5 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 5 INCHES PER YEAR

Figure 29.--Distribution and quantity of water withdrawn during 1982-85 by layers and by model nodes.--Continued



EXPLANATION

AREA OF OUTCROP OF LAYER 5

WITHDRAWAL FLUX GREATER THAN 0 AND LESS THAN 2 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 2 AND LESS THAN 5 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 5 INCHES PER YEAR

0 10 20 MILES

0 10 20 KILOMETERS

Figure 29.--Distribution and quantity of water withdrawn during 1982-85 by layers and by model nodes.--Continued

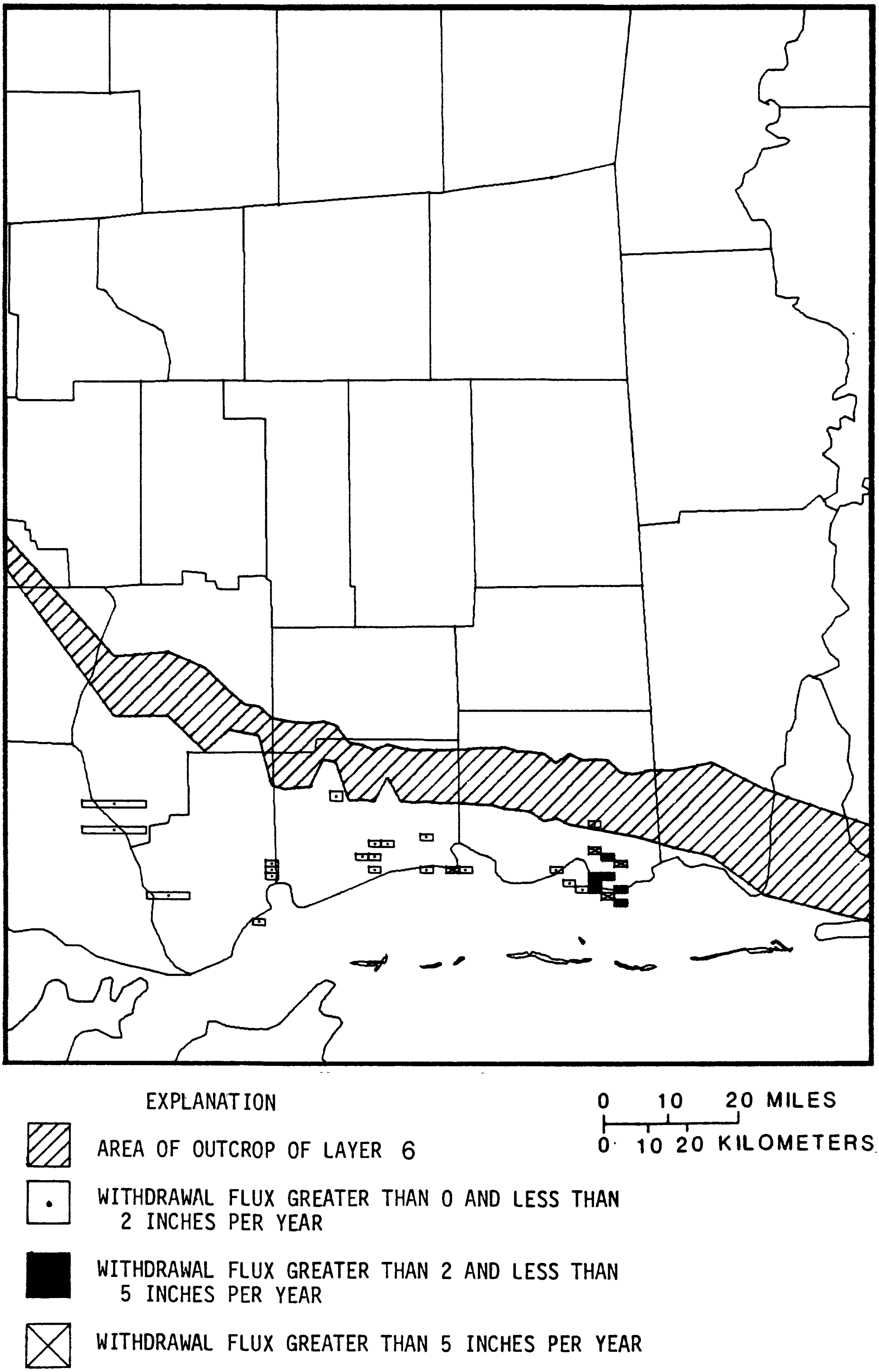
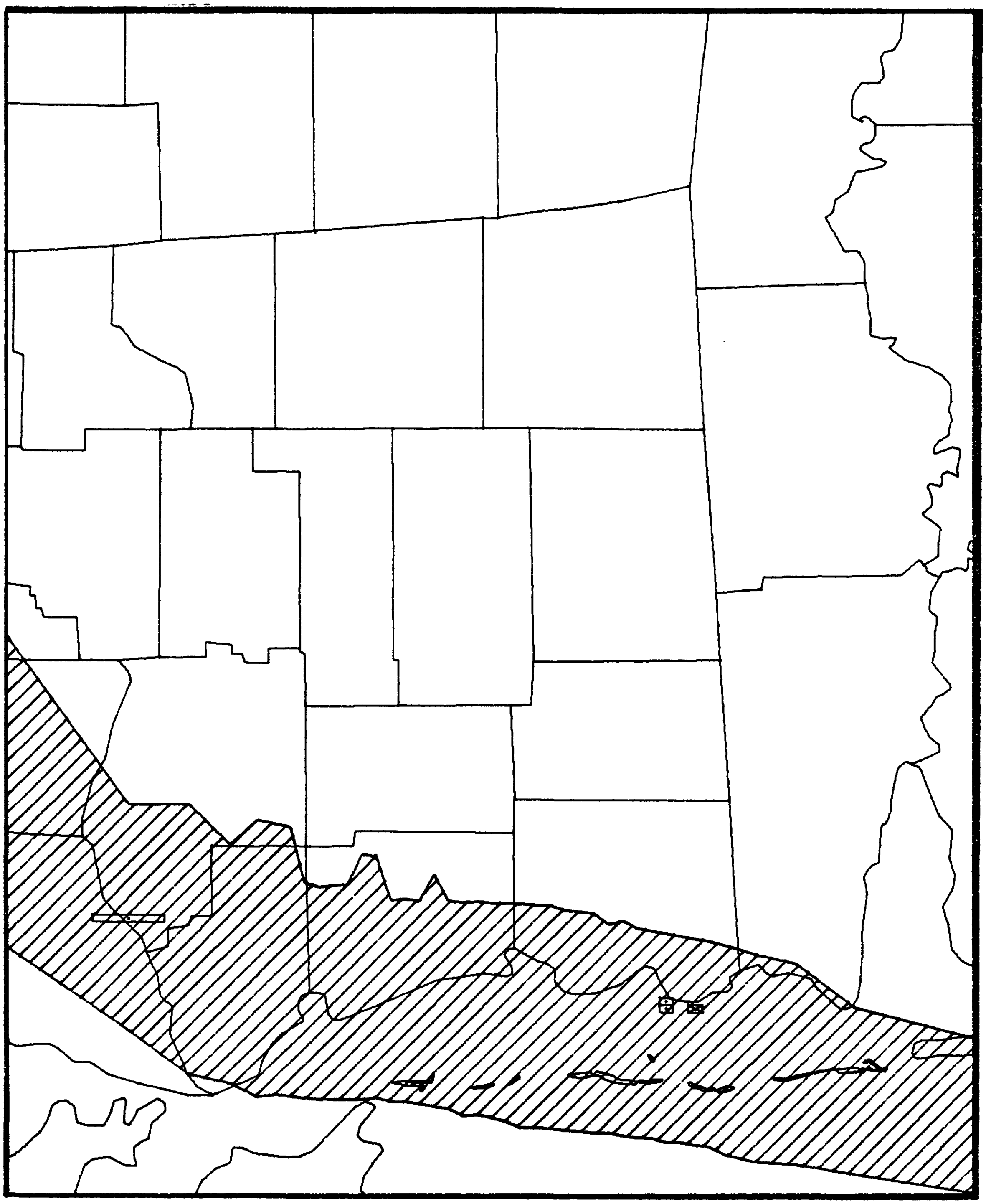


Figure 29.--Distribution and quantity of water withdrawn during 1982-85 by layers and by model nodes.--Continued



EXPLANATION

AREA OF OUTCROP OF LAYER 7

WITHDRAWAL FLUX GREATER THAN 0 AND LESS THAN 2 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 2 AND LESS THAN 5 INCHES PER YEAR

WITHDRAWAL FLUX GREATER THAN 5 INCHES PER YEAR

0 10 20 MILES

0 10 20 KILOMETERS

Figure 29.--Distribution and quantity of water withdrawn during 1982-85 by layers and by model nodes.--Continued

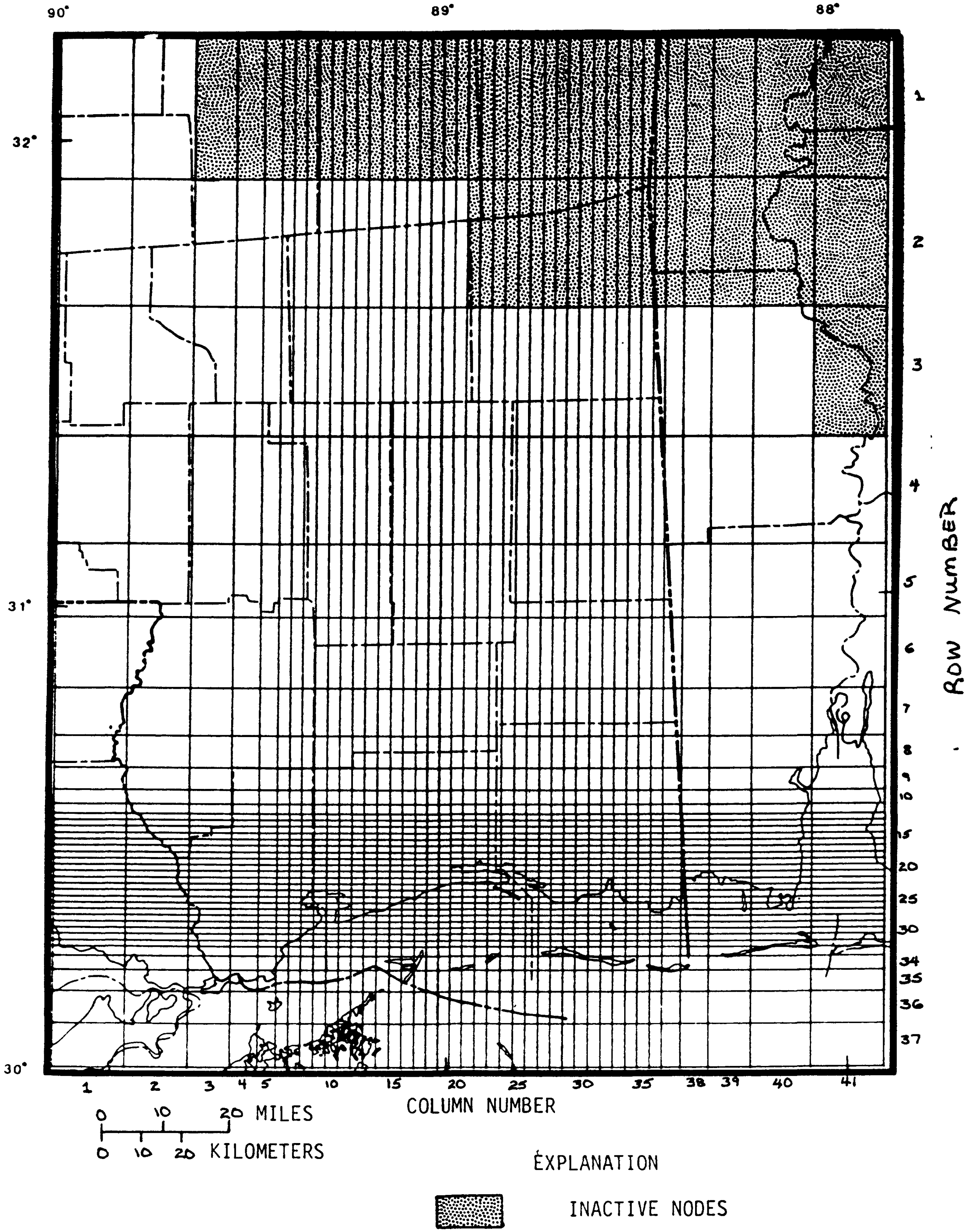


Figure 30.--Grid used in the numerical flow model.

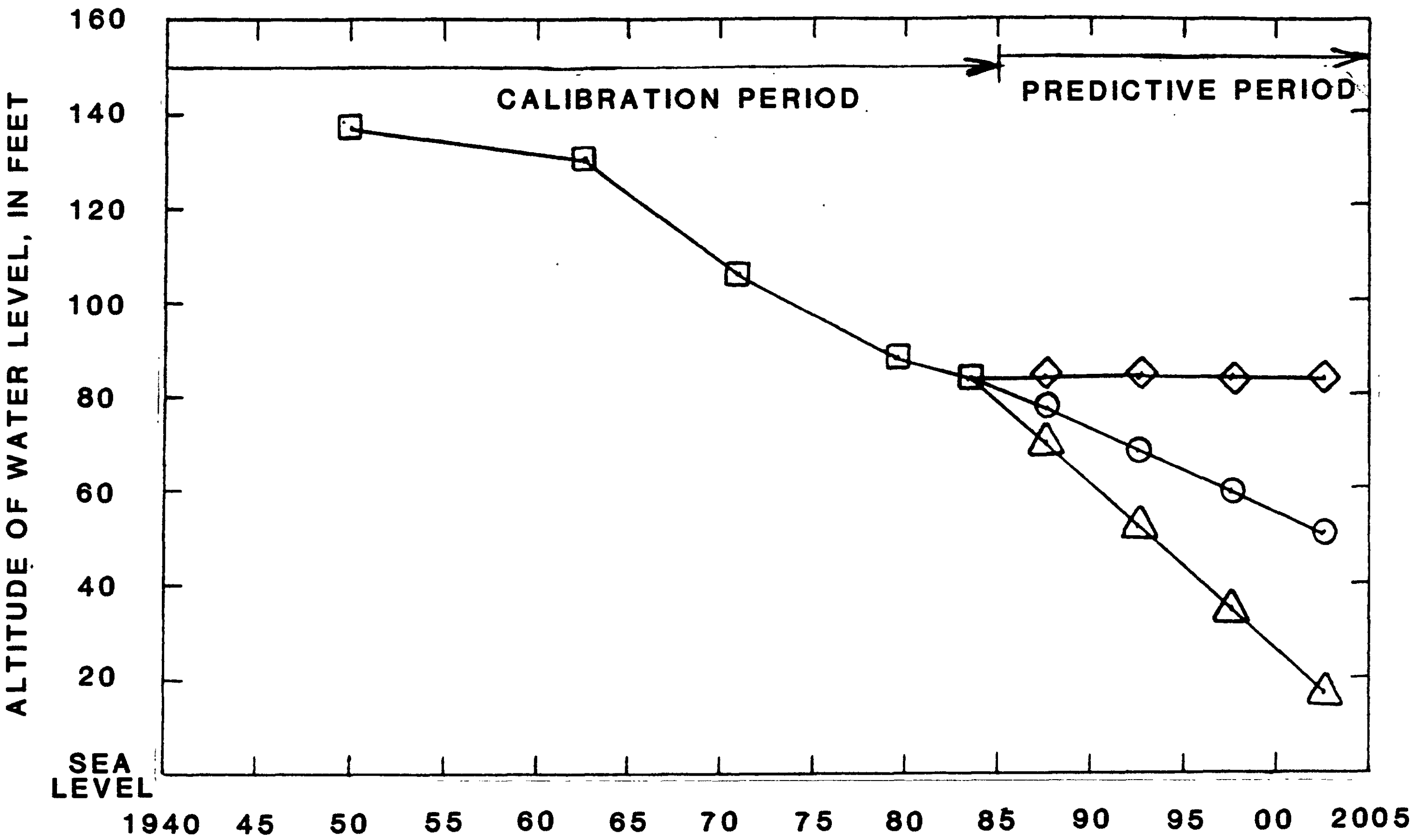
tiometric map (fig. 6). Leakance between the surficial aquifer system and subcropping layers was defined by confining layer thickness within interlayer 8 and an assumed value of vertical hydraulic conductivity (10^{-4} ft/d).

Prior to development, flow in the southwestern part of the study area was generally north-to-south along longitude 90° W. in all hydrologic layers (figs. 9-15). For predevelopment simulations, a no-flow boundary was placed at longitude 90° W. to follow north-to-south flow lines. A specified head western boundary was necessary for the transient simulations (1940-85) because of pumping-induced changes in the distribution of potentiometric head along the boundary (figs. 9-15). Specified heads were updated to observed heads at each stress period throughout the simulation. Figure 31 illustrates the updating of one specified-head node in the western boundary during calibration.

The Mobile River and Mobile Bay were drains for the Miocene aquifer system prior to development. Ground water moved laterally toward the river and bay from both sides and then discharged vertically. Thus, the Mobile River and Mobile Bay were selected as a no-flow eastern boundary to lateral flow for predevelopment flow simulations. Although this boundary prohibits horizontal flow, vertical leakage to the Mobile River and Mobile Bay is allowed by the head-dependent flux boundary to the surficial system. Because of ground-water development, a specified head eastern boundary was used for transient flow simulations. As for the western boundary, nodal head values along the eastern boundary were updated for each stress period. Because most of the pumpage in the Mobile, Ala., area is from shallow wells, water levels in the deeper layers of the Miocene in this area have shown little decline over the years as shown in figures 9-15.

A no-flow boundary was selected to represent the downdip limit of the Miocene aquifer system for predevelopment simulations. Numerous investigations (such as Wait and others, 1986) have assumed that prior to development, equilibrium conditions existed and the downdip unflushed saline water was virtually stagnant. Selection of the arbitrarily determined interface between freshwater and saline water satifies the assumption of the numerical model (McDonald and Harbaugh, 1984) that the density of water is uniform throughout the flow system. Relatively dense saline water (dissolved-solids concentrations greater than 10,000 mg/L) is excluded from the analysis.

The choice of a downdip boundary is not as obvious for transient simulations, because ground-water withdrawals from the freshwater system can induce movement of the saline water. A rigorous analysis of the saltwater movement would require solution of a more general form of the ground-water flow equation in which water density is not assumed uniform. Also, the changing spatial distribution of water density would require solutions of equations describing transport of the dissolved constituents with time. Such an endeavor is beyond the scope of this study and would be severely limited by data inadequacies. Very few data are available to describe pressure, density, temperature, and viscosity distributions within saline water areas, and the effects of dispersion on transport of dissolved constitutents.



EXPLANATION

Water levels for a specified head node (layer 3, row 7, column 1) in the western boundary of the model.

- ⊡ CALIBRATION MODEL
- ⊙ PREDICTIVE MODEL--(Resulting potentiometric map shown in figure 46, layer 3)
- ◇ FIRST SENSITIVITY ANALYSIS--no head change after 1983. (Resulting potentiometric map shown in figure 47)
- △ SECOND SENSITIVITY ANALYSIS--head changes from the 1983 values to the predictive model values were doubled. (Resulting potentiometric map shown in figure 48)

Figure 31.--Hydrograph of alternative water-level projections used as input to the model to determine sensitivity of the model to changes in the specified heads along the western boundary.

A decision was made to place a no-flow boundary at 30° N. latitude for two reasons: 1) the boundary is sufficiently distant from areas of ground-water withdrawal that induced leakage across this boundary can be considered negligible, and 2) to allow flow across the freshwater-saltwater interface. The disadvantage of this procedure is that water density within the enclosed flow system is variable. The amount of error introduced by the violation of the uniform-density assumption can only be completely evaluated with more data collection in the downdip areas and rigorous solution of the more general flow equations.

Model Parameters

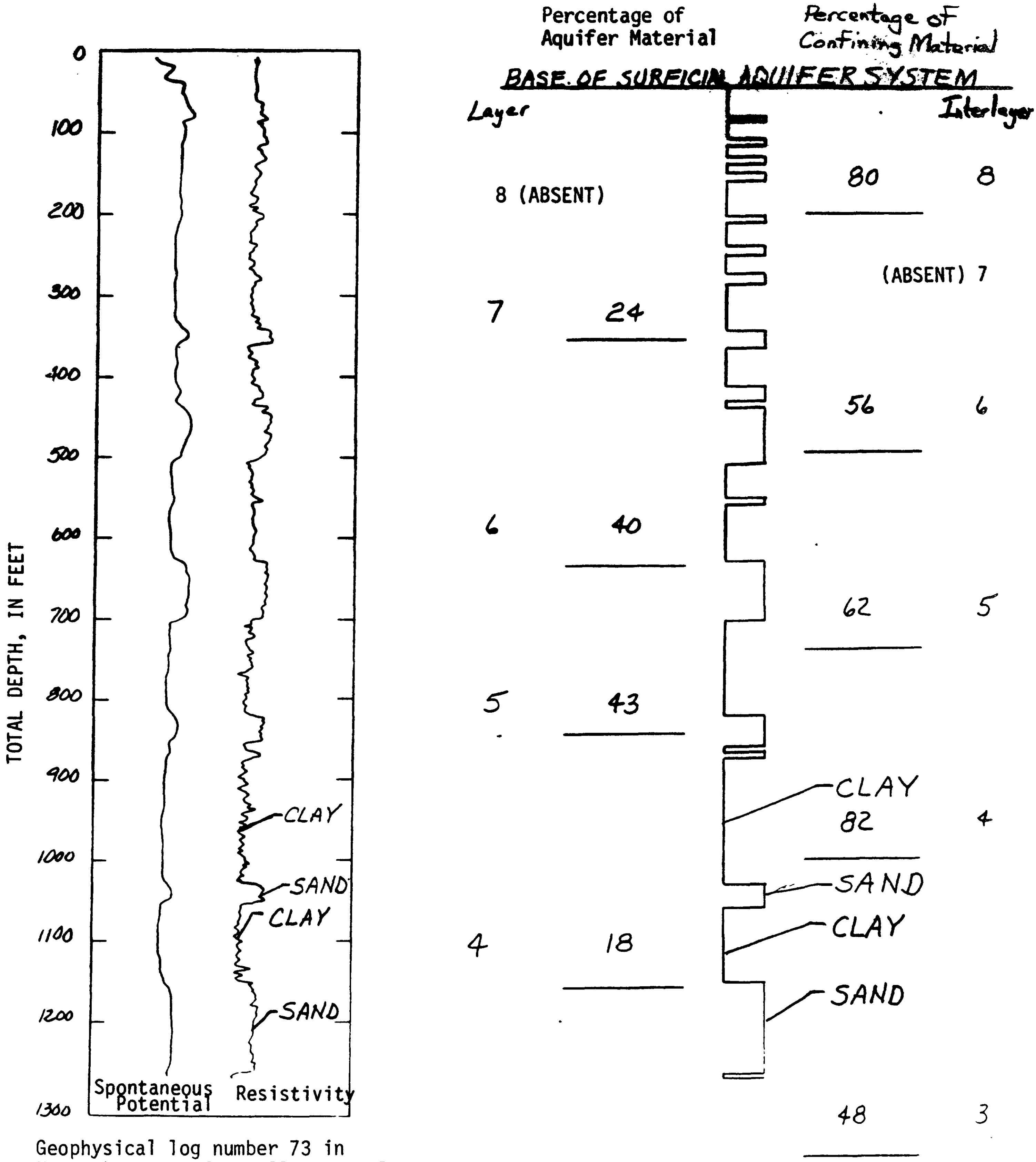
The model parameters describing the hydraulic characteristics of a given geohydrologic setting determine the ground-water flow for that set of imposed stresses and boundary conditions. Transmissivity, vertical leakance, and storage coefficient were specified for each node of the model.

Sediments in the study area function as either confining material (clay and silt, which are relatively restrictive to ground-water flow) or aquifer material (sand and gravel, which are relatively unrestrictive.) Because lithologic units within the sediments comprising the Miocene aquifer system in southern Mississippi tend to be lenticular, horizontal ground-water flow is controlled by the distribution of sand and gravel, whereas vertical flow is controlled by the distribution of clay and silt. To quantify horizontal and vertical flow, these lithologic distributions were obtained by interpreting geophysical well logs.

More than 1,200 electrical logs were analyzed. Lithology indicated on each log was defined as either aquifer or confining-unit material (fig. 32).

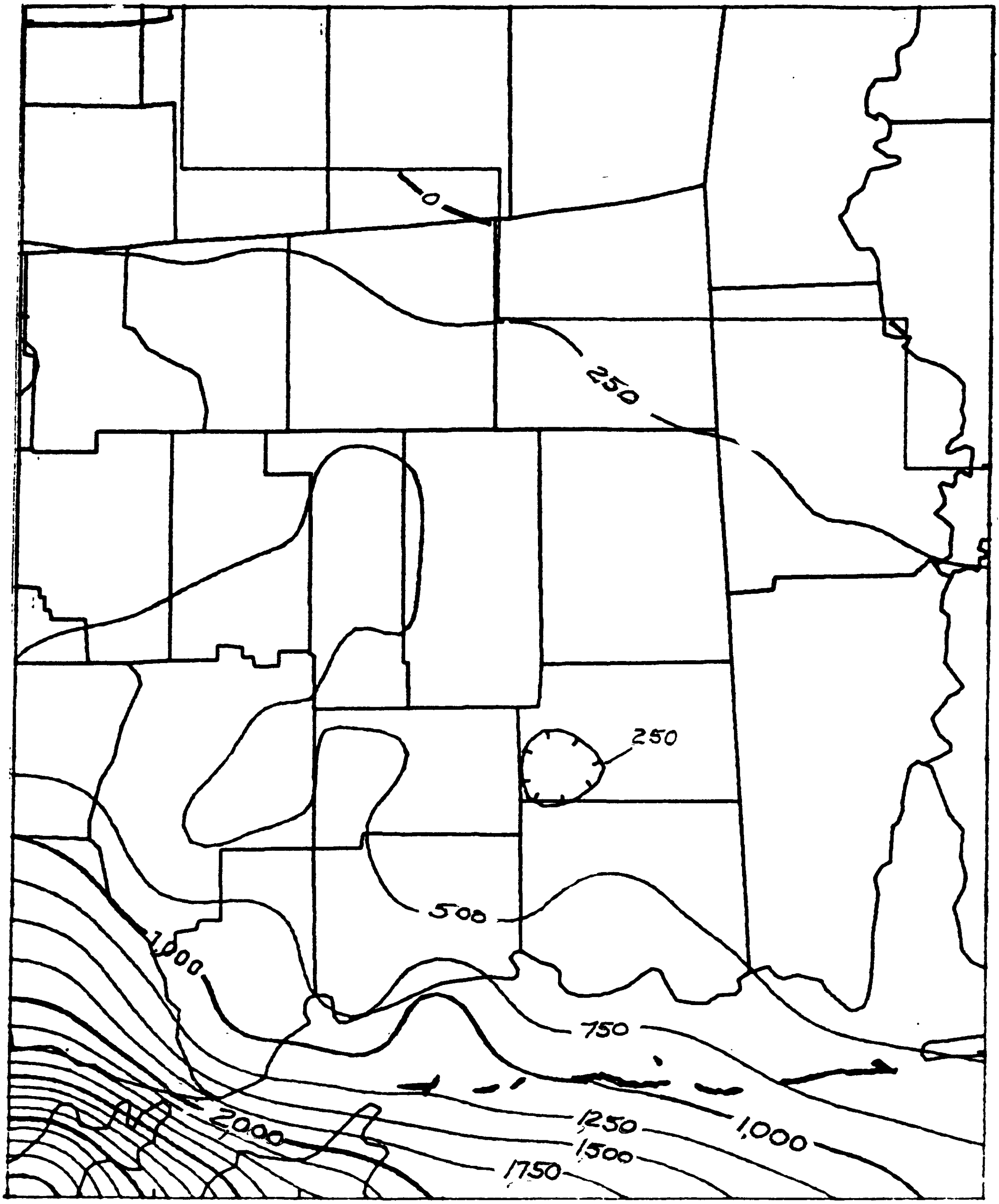
The percentage of aquifer materials within layers was determined by superimposing the hydrologic layers on each log. Similarly, the percentage of confining material within interlayers was determined. Interlayers are defined as the interval between layer midpoints and are numbered from bottom to top. For example, the interval between layers 1 and 2 is interlayer 1. Interlayer 8 is always the interval between the midpoint of a subcropping layer and the base of the surficial aquifer system. The lithologic percentages determined in this manner were gridded by means of a distance-weighted average to node centers. In areas of sparse data, particularly offshore, the extrapolated values are less reliable.

The extrapolated lithologic percentages were multiplied by the corresponding layer or interlayer thickness to calculate lithologic thickness (figs. 33 and 34). These thickness distributions provided the basis for estimating the distributions of hydraulic parameters used in the numerical model in a manner similar to that used by Premchitt and Das Gupta (1981).



Geophysical log number 73 in
Hancock County for well no. K221
Location: NE¼NE¼NE¼ sec. 10, T. 8 S., R. 14 W.

Figure 32.--Transition from geophysical log to lithologic percentages within and between hydrologic layers.



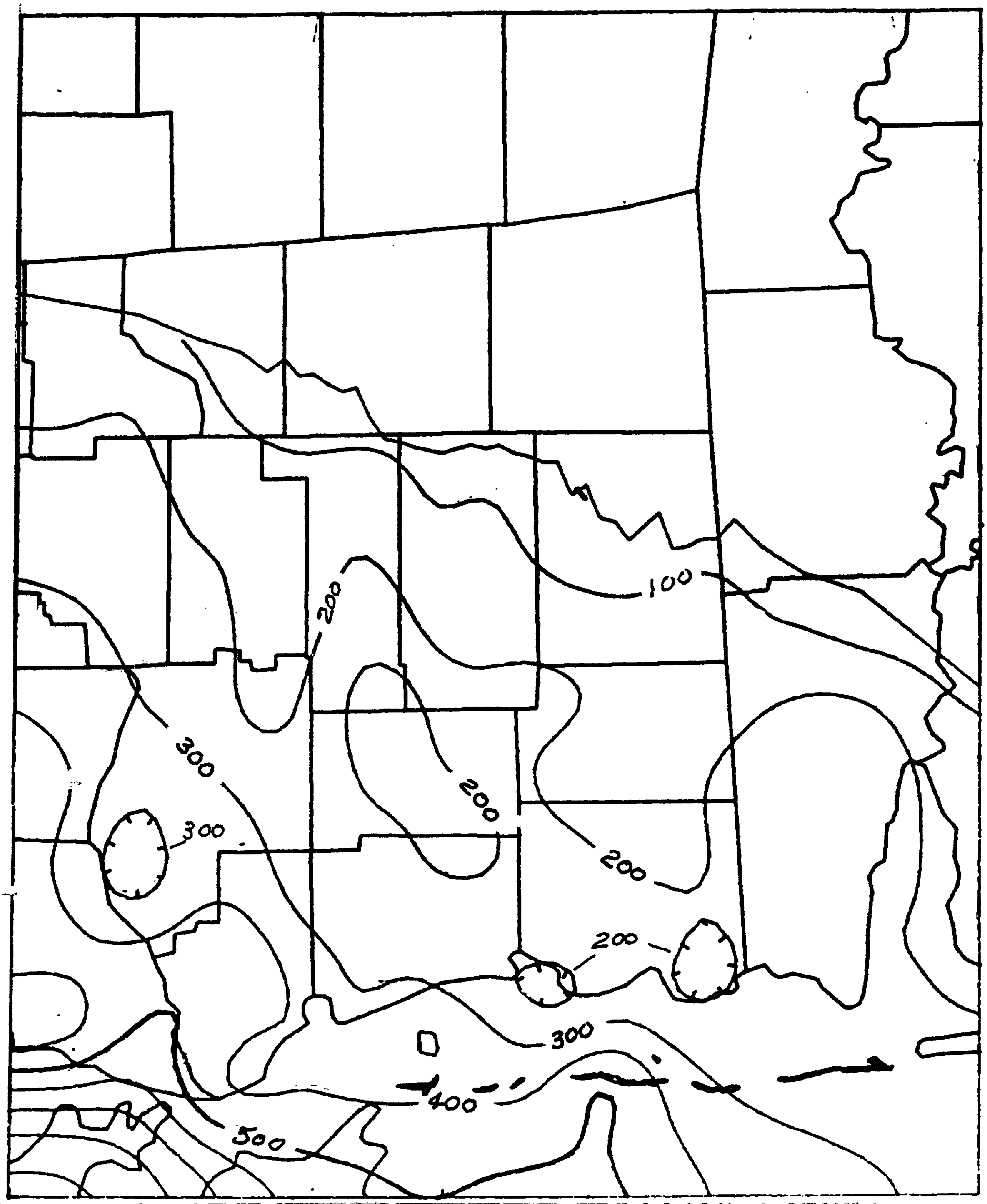
EXPLANATION

—2000— **LINE OF EQUAL VALUE--Shows** thickness of sand in layer 1. Contour interval 250 feet

0 10 20 MILES

0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.

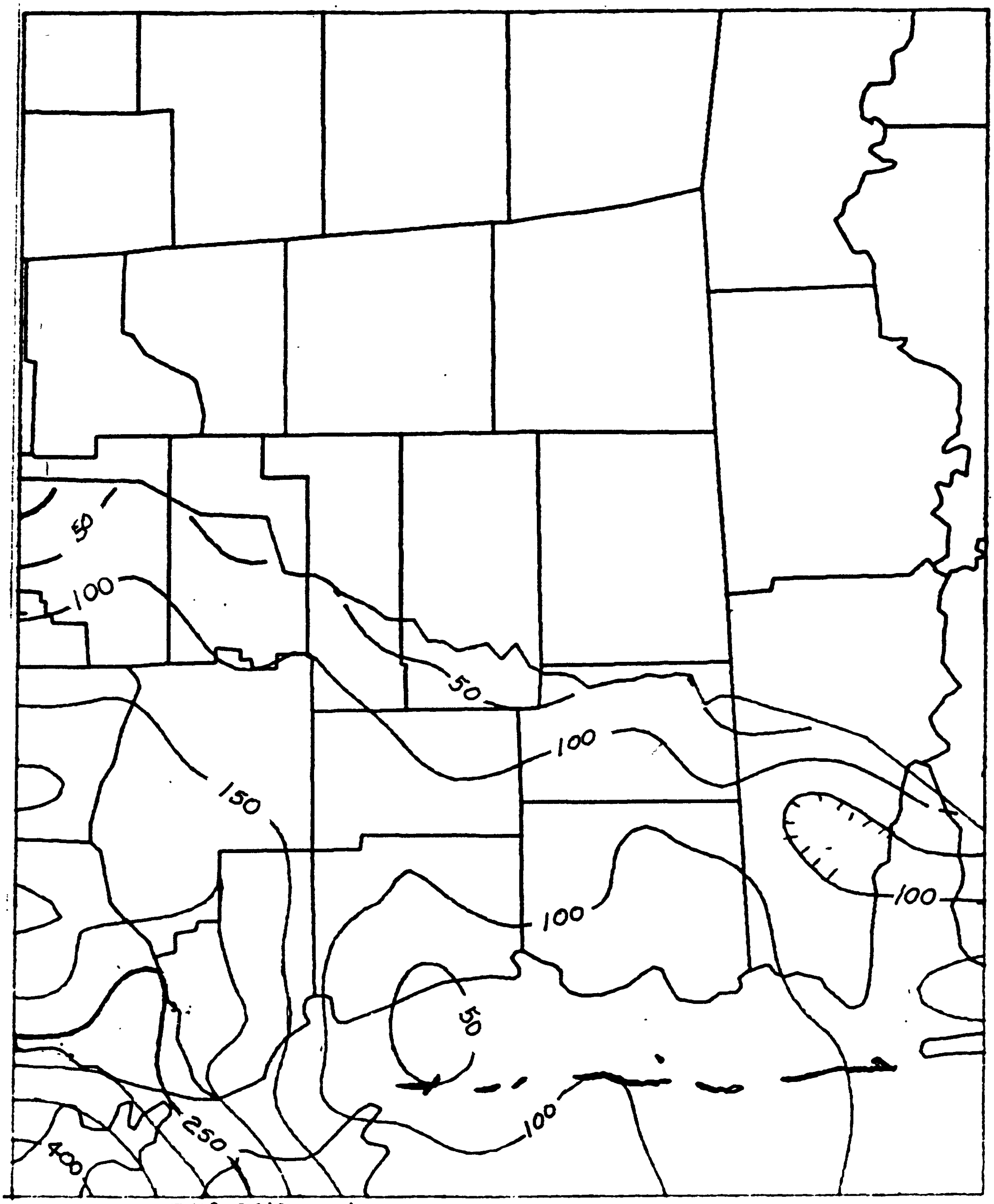


EXPLANATION

—— 400 —— LINE OF EQUAL VALUE--Shows thickness of sand in layer 2. Contour interval 100 feet

0 10 20 MILES
0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.--Continued

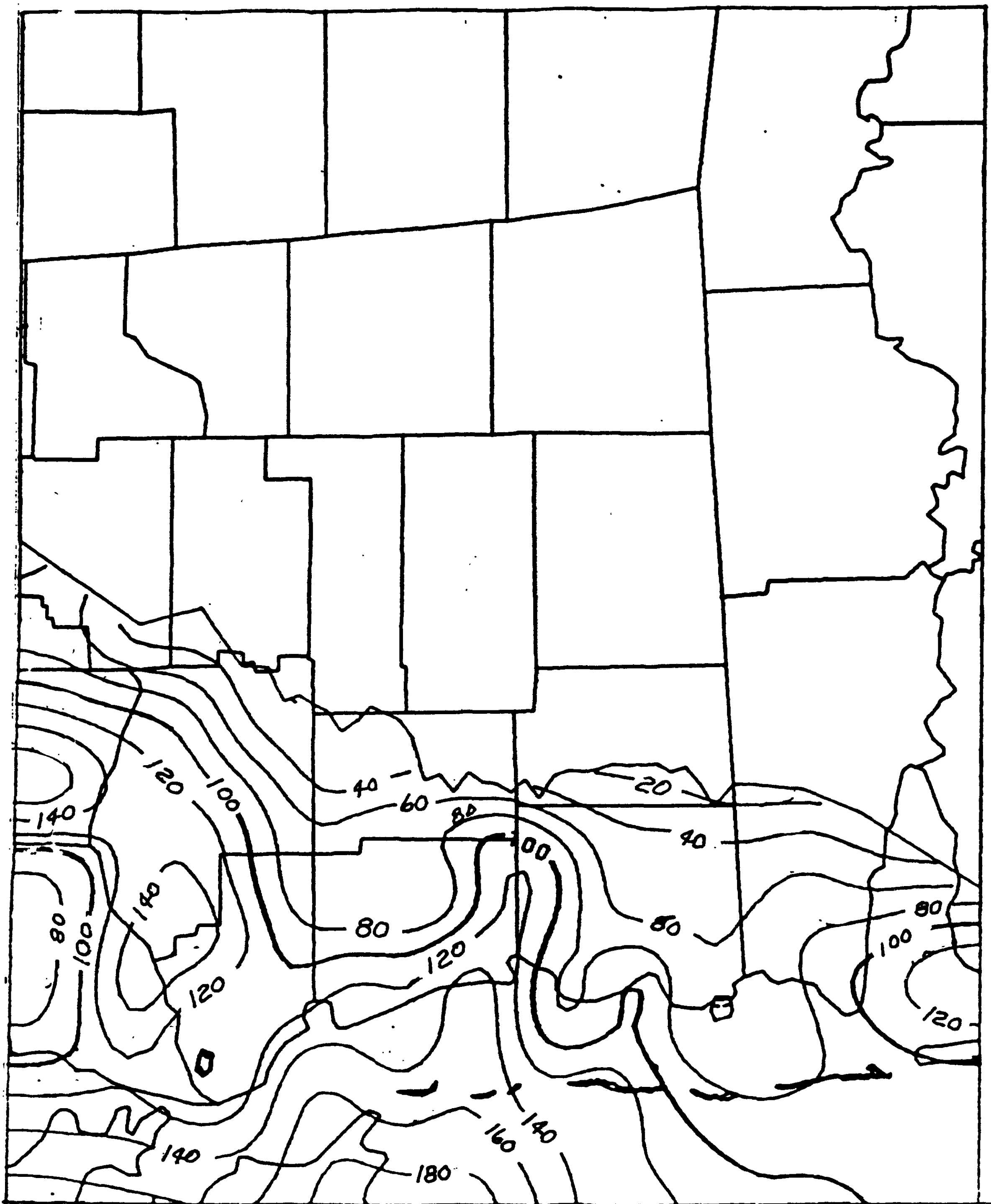


EXPLANATION

—— 400 —— LINE OF EQUAL VALUE--Shows thickness of sand in layer 3. Contour interval 50 feet

0 10 20 MILES
0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.--Continued

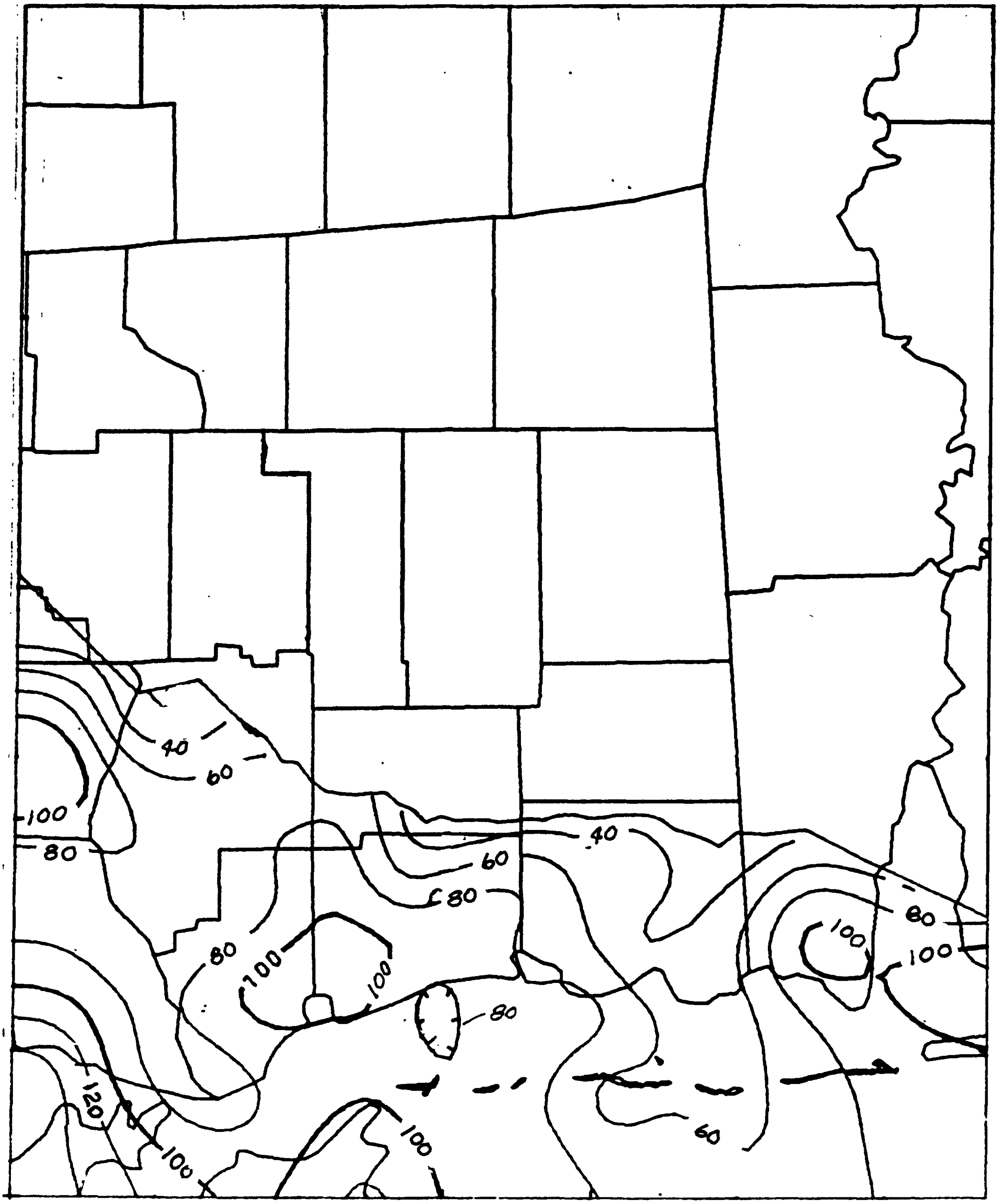


EXPLANATION

—140— LINE OF EQUAL VALUE--Shows thickness of sand in layer 4. Contour interval 20 feet

0 10 20 MILES
0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.--Continued

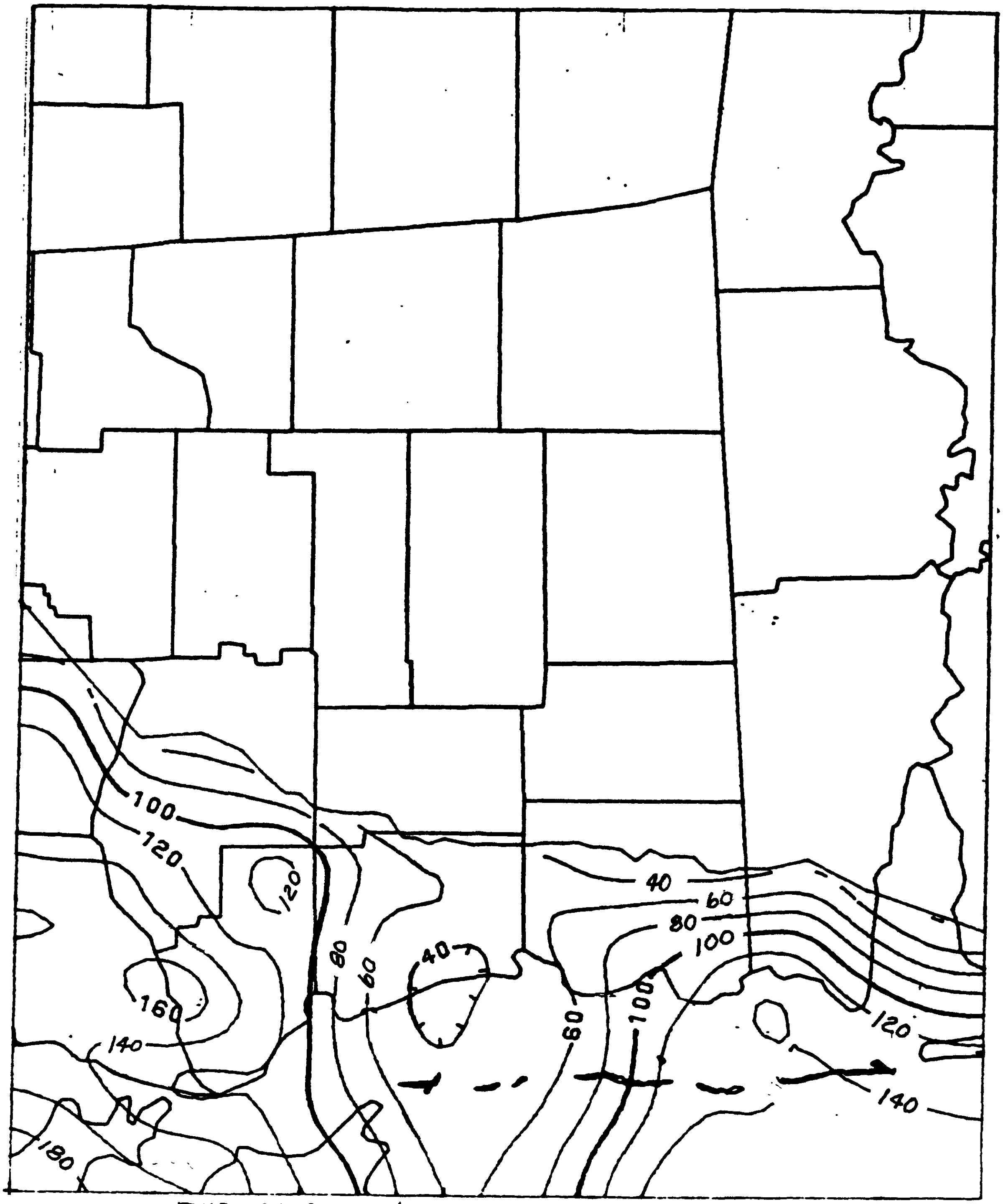


EXPLANATION

—— 100 —— **LINE OF EQUAL VALUE--Shows** thickness of sand in layer 5. Contour interval 20 feet

0 10 20 MILES
0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.--Continued

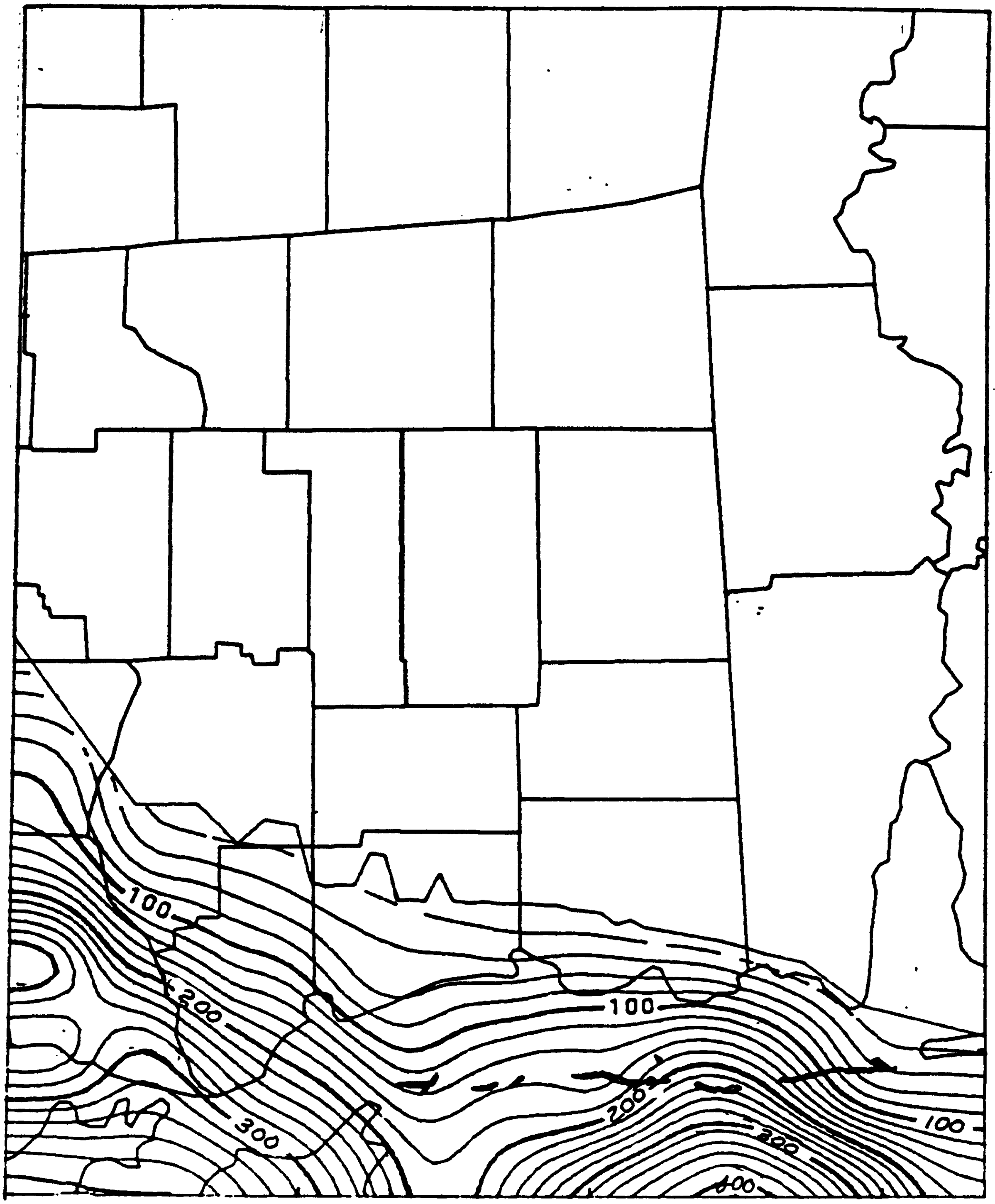


EXPLANATION

— 180 — LINE OF EQUAL VALUE--Shows thickness of sand in layer 6. Contour interval 20 feet.

0 10 20 MILES
0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.--Continued

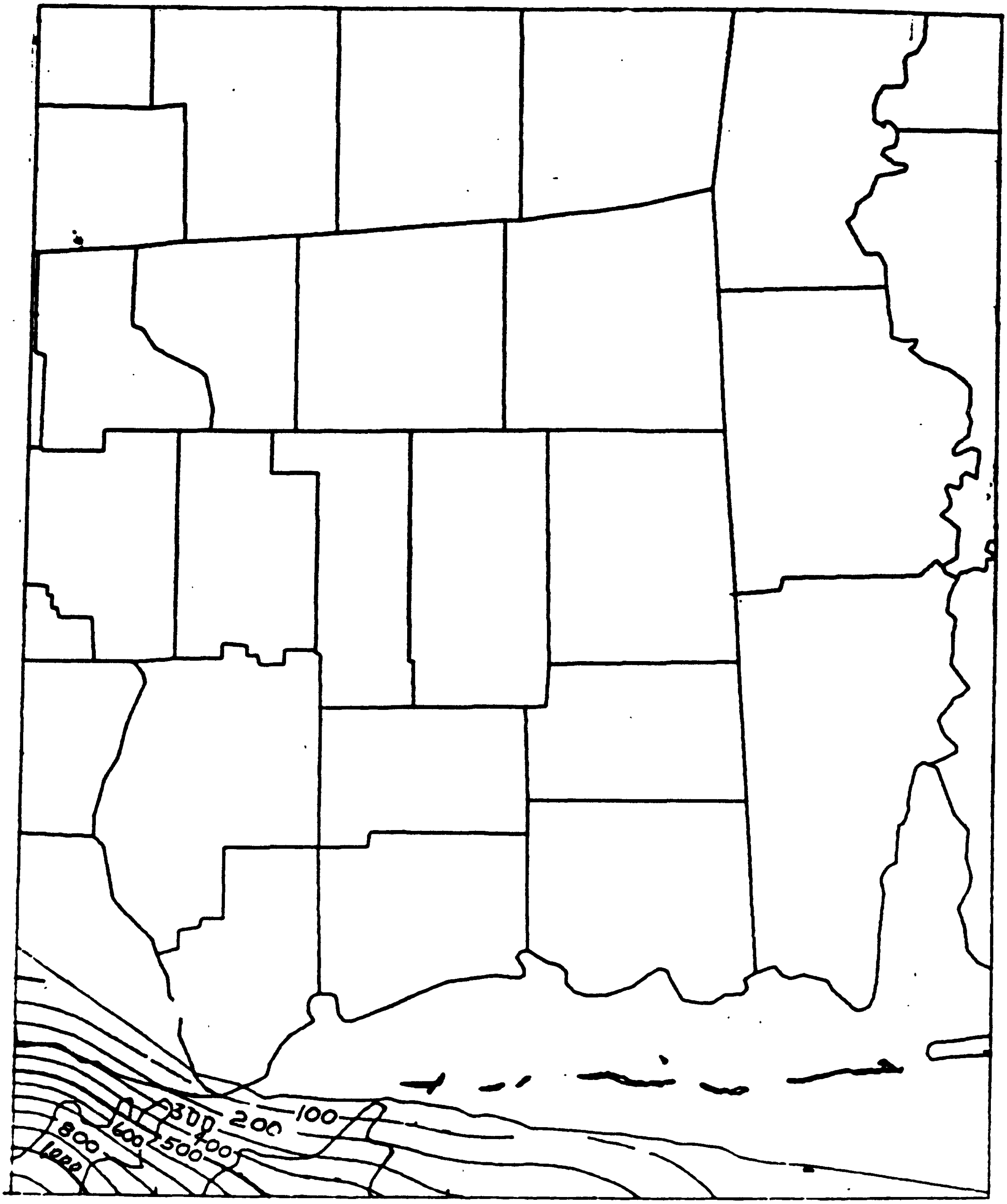


EXPLANATION

——300—— LINE OF EQUAL VALUE--Shows thickness of sand in layer 7. Contour interval 20 feet

0 10 20 MILES
0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.--Continued



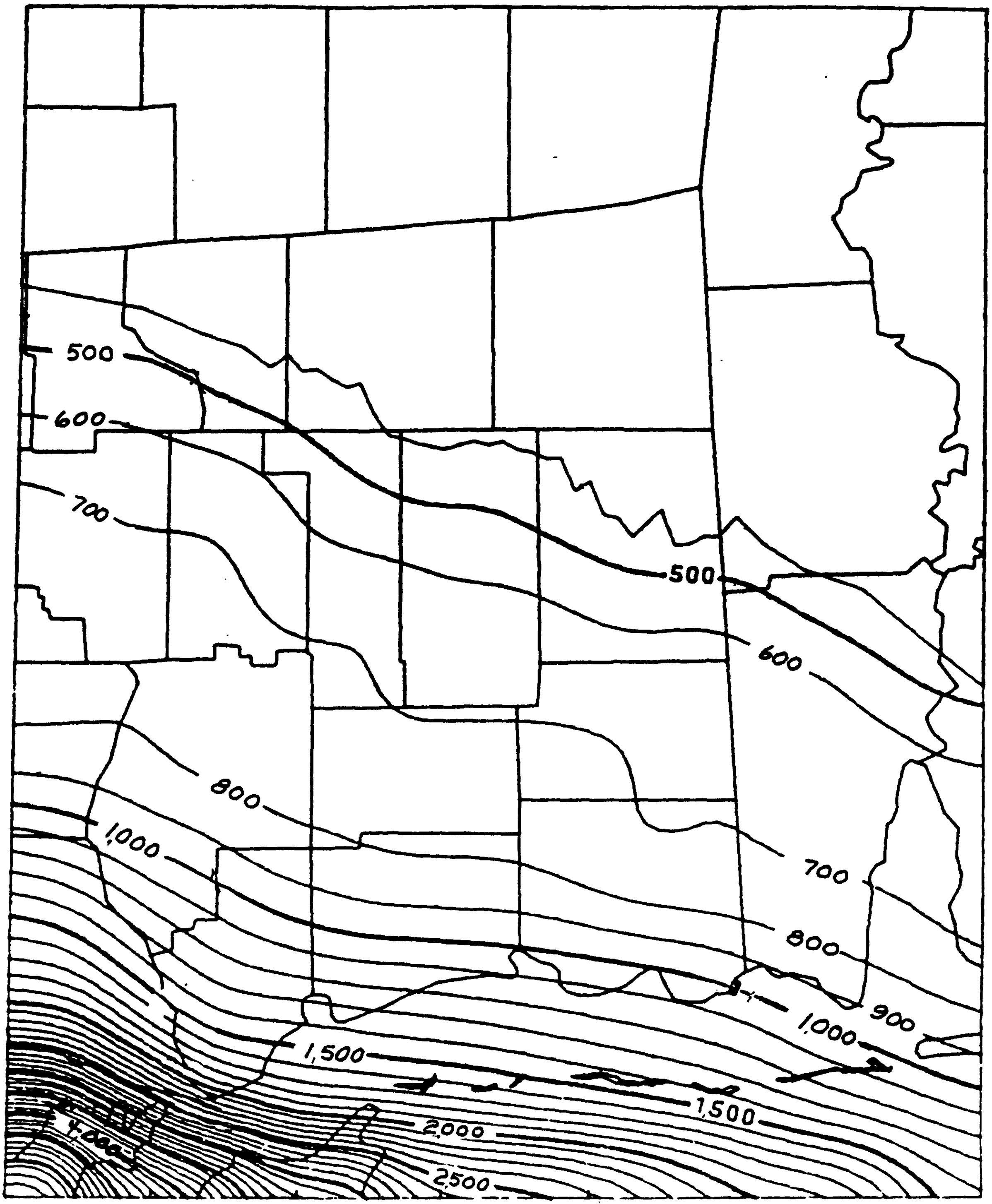
EXPLANATION

—800— LINE OF EQUAL VALUE--Shows thickness of sand in layer 8. Contour interval 100 feet

0 10 20 MILES

0 10 20 KILOMETERS

Figure 33.--Thickness of sand within layers.--Continued

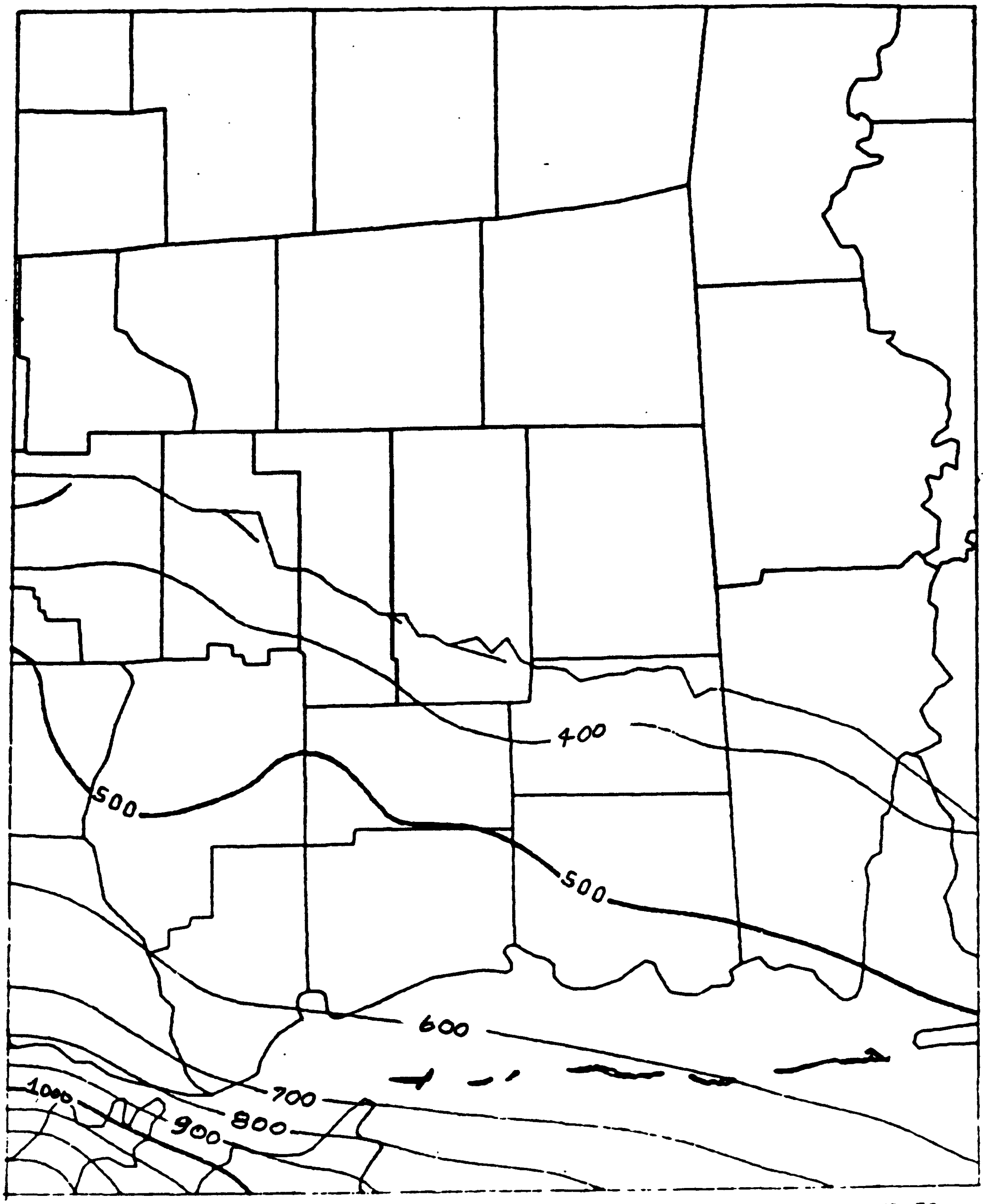


EXPLANATION

— 1000 — LINE OF EQUAL VALUE--Shows thickness of clay in interlayer 1. Contour interval 100 feet

0 10 20 MILES
0 10 20 KILOMETERS

Figure 34.--Thickness of clay within interlayers.

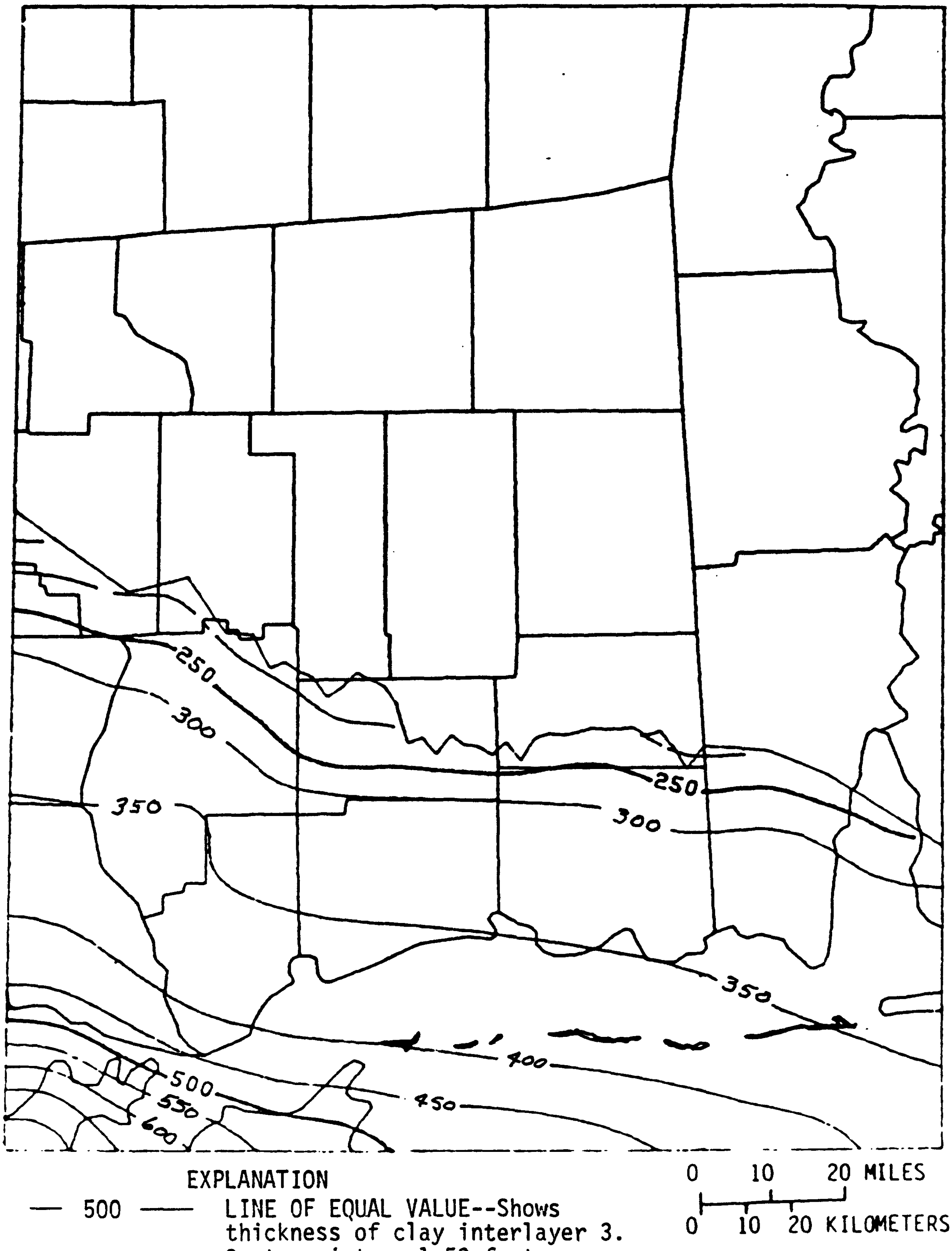


EXPLANATION

—— 1000 —— LINE OF EQUAL VALUE--Shows thickness of clay in interlayer 2. Contour interval 100 feet

0 10 20 MILES
0 10 20 KILOMETERS

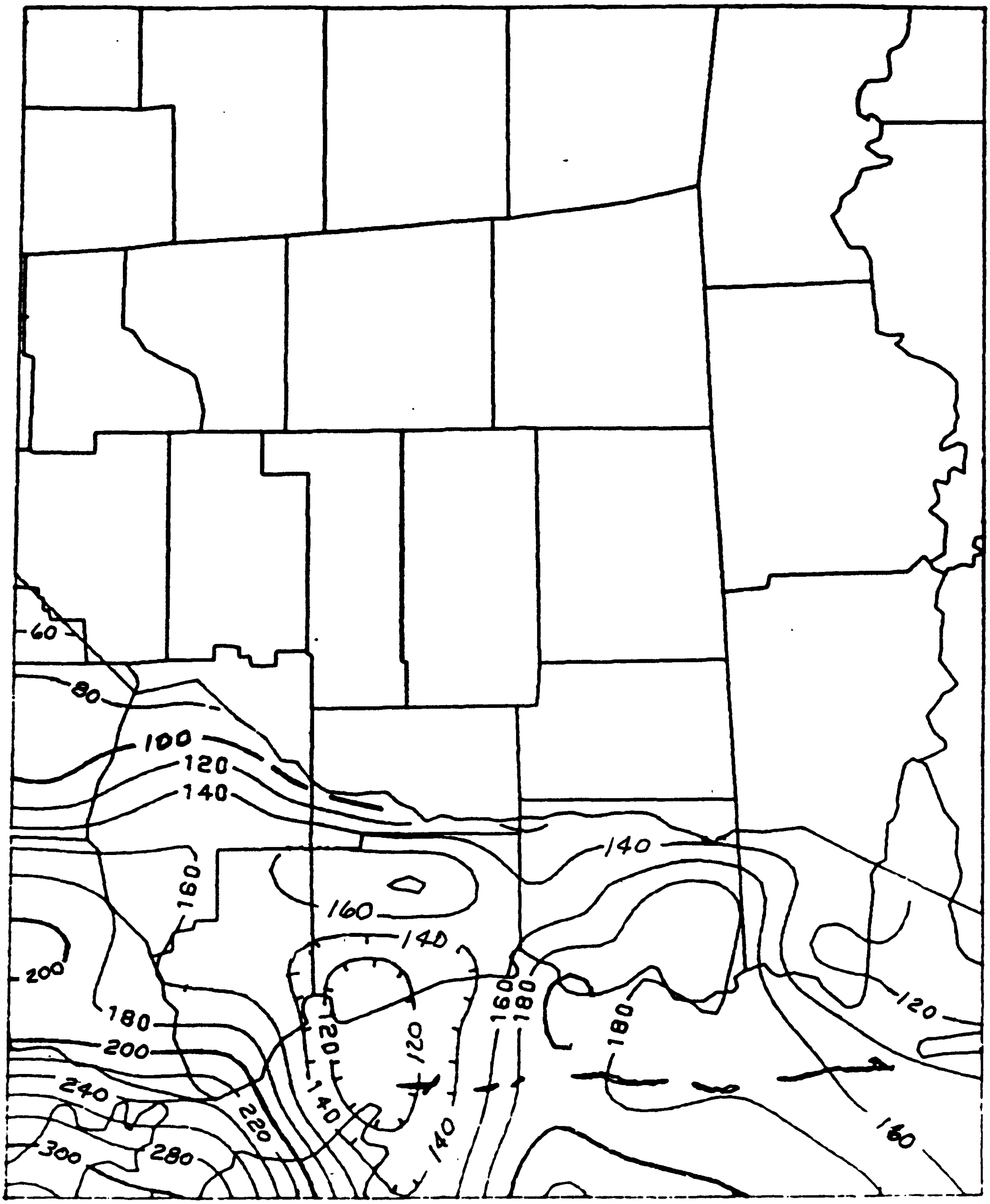
Figure 34.--Thickness of clay within interlayers.--Continued



EXPLANATION

— 500 —— LINE OF EQUAL VALUE--Shows thickness of clay interlayer 3. Contour interval 50 feet

Figure 34.--Thickness of clay within interlayers.--Continued



EXPLANATION

— 100 —— LINE OF EQUAL VALUE--Shows thickness of clay in interlayer 4. Contour interval 20 feet

0 10 20 MILES

0 10 20 KILOMETERS

Figure 34.--Thickness of clay within interlayers.--Continued

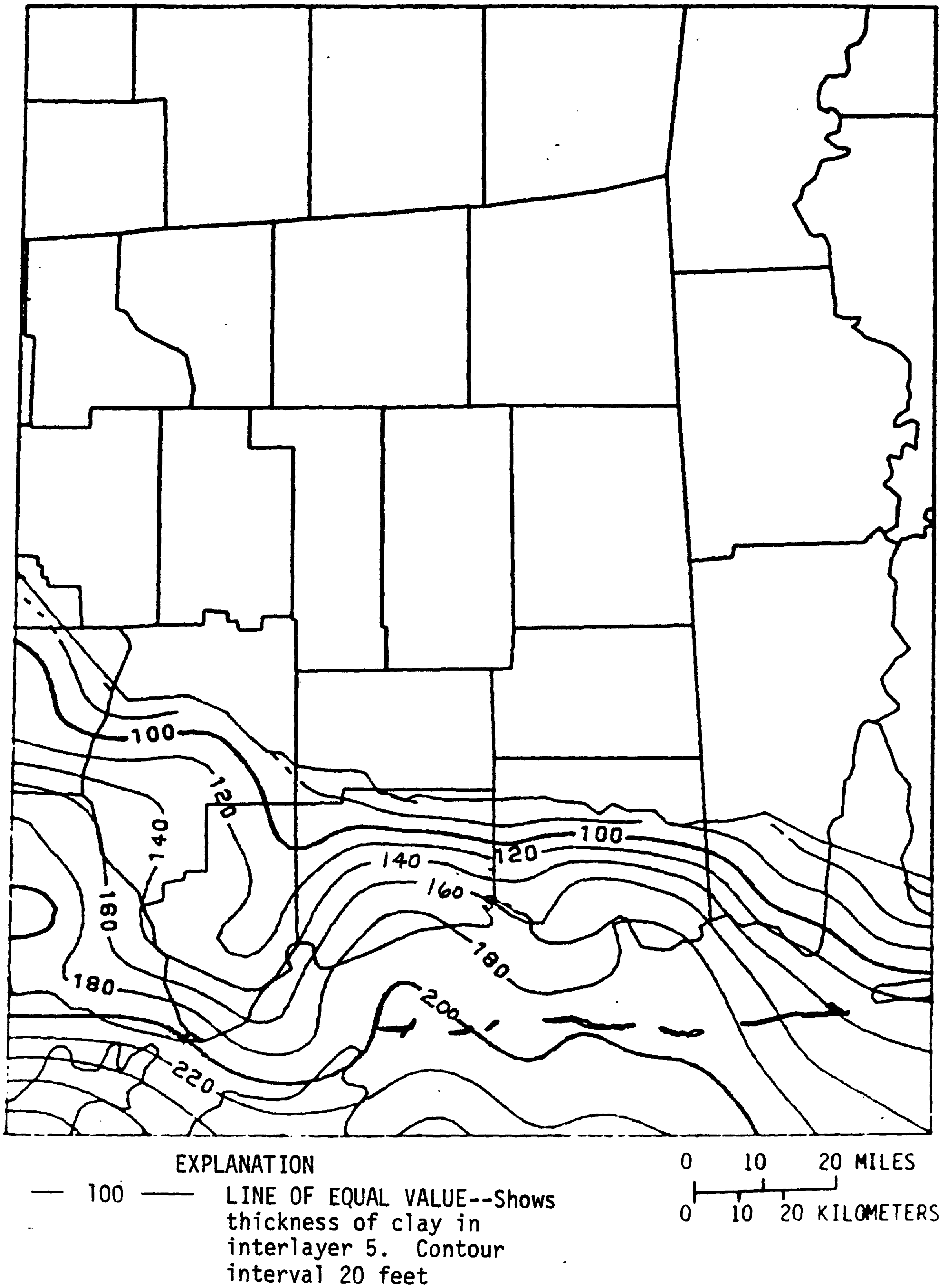
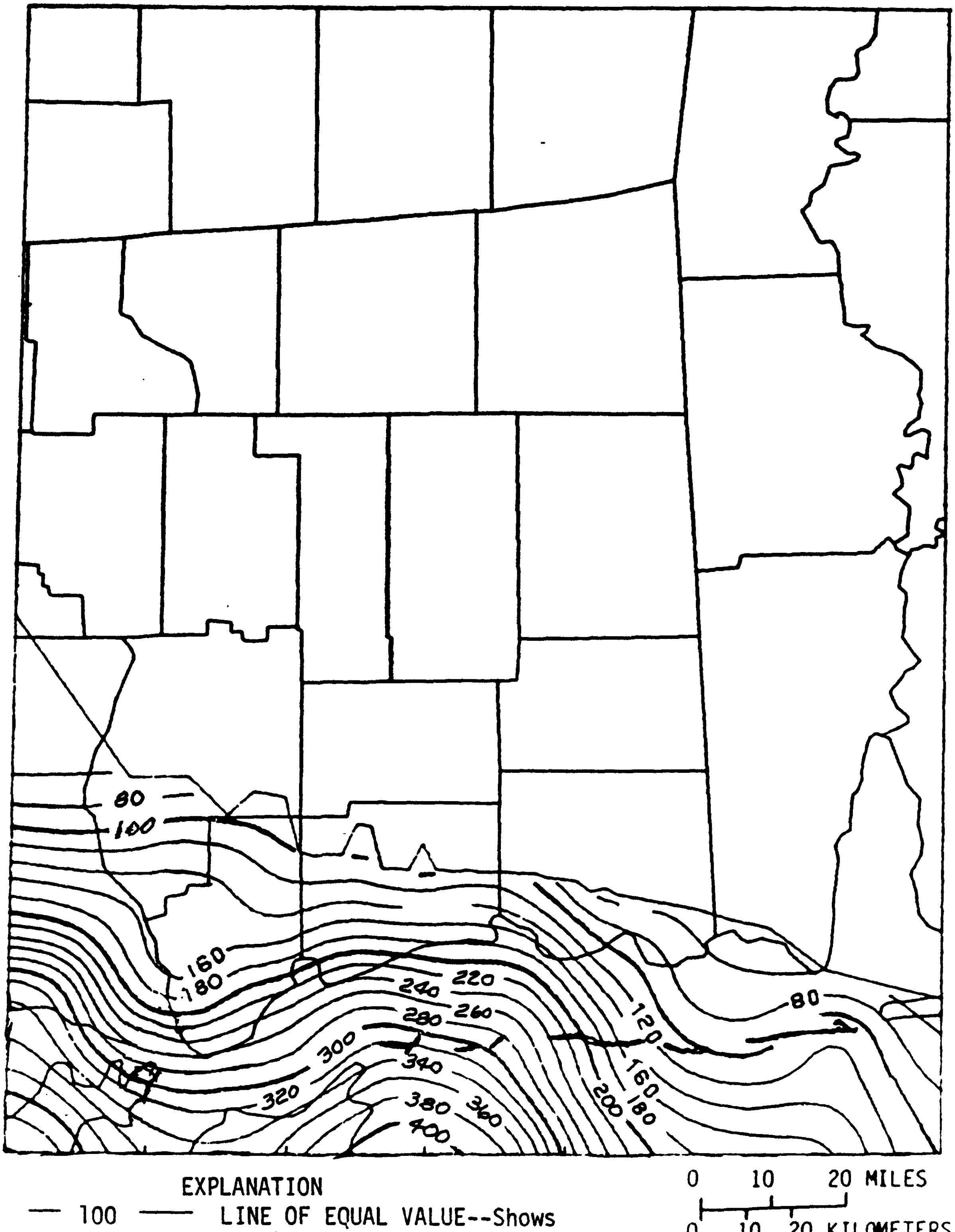


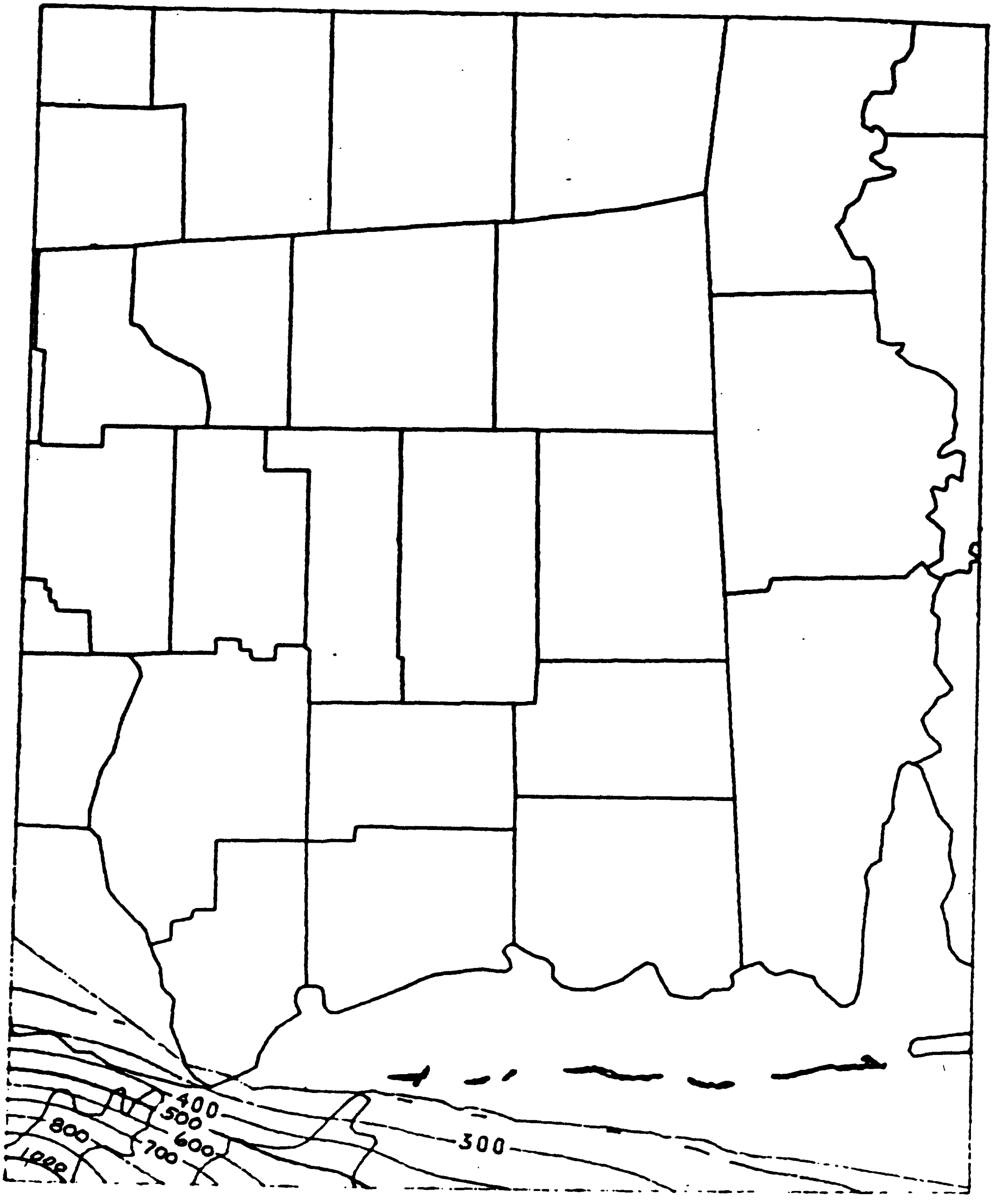
Figure 34.--Thickness of clay within interlayers.--Continued



EXPLANATION

— 100 —— LINE OF EQUAL VALUE--Shows thickness of clay in interlayer 6. Contour interval 20 feet

Figure 34.--Thickness of clay within interlayers.--Continued

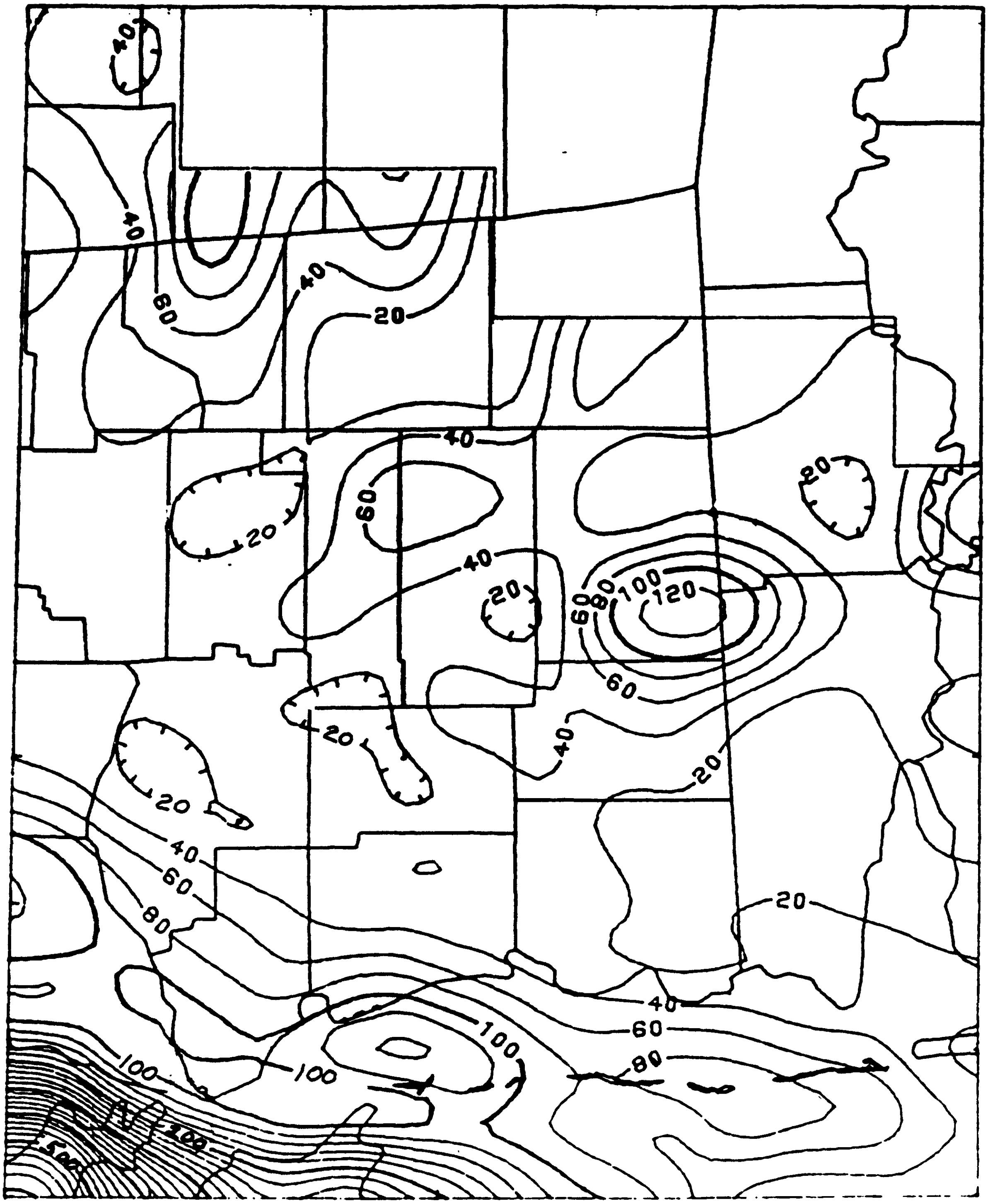


EXPLANATION

— 400 — LINE OF EQUAL VALUE--Shows thickness of clay in interlayer 7. Contour interval 100 feet

0 10 20 MILES
0 10 20 KILOMETERS

Figure 34.--Thickness of clay within interlayers.--Continued



EXPLANATION

— 100 —— LINE OF EQUAL VALUE--Shows thickness of clay in interlayer 8. Contour interval 20 feet

0 10 20 MILES

0 10 20 KILOMETERS

Figure 34.--Thickness of clay within interlayers.--Continued

The distribution of transmissivity within each layer was calculated to describe the ability of the ground-water system to transmit water laterally under given lateral-head gradients. The distribution of transmissivity within each layer is equal to the estimated aquifer-material thickness multiplied by horizontal hydraulic conductivity.

The distribution of vertical leakance between layers (and between the subcropping part of layers and the surficial aquifer system) was calculated to describe the ability of the ground-water system to transmit water vertically under given vertical-head gradients. The distribution of vertical leakance within each interlayer is equal to the vertical hydraulic conductivity divided by the estimated thickness of confining material.

The distribution of storage coefficient within layers was calculated to describe the ability of the ground-water system to yield water from storage or to take water into storage in response to a change in potentiometric head. The flow system under study is confined (unconfined or water-table conditions exist only within the surficial aquifer system). Therefore, the storage changes to be considered are related to the expansion and contraction of the sediments and the water within the sediments.

Specific storage values of fine-grained materials are much higher than those of coarse-grained materials (Premchitt and Das Gupta, 1981) because of the greater compressibility of silt and clay (Helm, 1984). However, the release of water from storage in a confining unit is delayed after the imposition of a stress in an adjacent aquifer, because of the low hydraulic conductivity values common for confining units. Thus, a short-term aquifer test might yield a low storage coefficient, when in fact, the long-term yield would be much greater because water would be released slowly from storage in confining units.

A test was made in the Miocene sediments of the Mobile, Ala., area (Parr and others, 1983), in which piezometers were placed in both the pumped aquifer and the adjacent confining units. Values of hydraulic diffusivity of the adjacent confining units, determined by the ratio method of Neuman and Witherspoon (1972) were 7.3 and 13.1 ft2/d. The analytical solution, which is based on layered geology, of Bredehoeft and Pinder (1970) can be used to estimate the time required for the effects of delayed yield to become negligible after a stress is imposed on an adjacent aquifer. This time is calculated from:

$$t = \frac{b^2}{2\left(\frac{K}{S_s}\right)}$$

where

t = time,

b = thickness of confining unit,

K = hydraulic conductivity of confining unit,

S_s = specific storage of confining unit, and

$\frac{K}{S_s}$ = hydraulic diffusivity of confining unit.

Because confining beds in the study area are more lenticular, more surface area will be available for drainage than is assumed using the solution of Bredehoeft and Pinder, thereby overestimating the time required for delayed yield to become insignificant. Using 7.3 ft2/d as a conservative estimate of hydraulic diffusivity for a 100-foot thick confining unit, delayed-yield effects will become insignificant after more than 2 years. This is a short time period compared to the stress periods used in this study; consequently, the effects of delayed yield from storage in confining units are assumed to be negligible. Although, the release of water from confining unit storage is considered to be instantaneous, the amount of water released may be significant. The present model should not be used to analyze very short pumping periods, or in areas where confining units are extremely thick.

Distribution of the storage coefficient within each layer is equal to the estimated confining-unit thickness within the layers multiplied by a value of specific storage.

Model Calibration

Model calibration provided a means of inferring the value of three model parameters -- horizontal hydraulic conductivity of aquifer materials, vertical hydraulic conductivity of confining materials, and specific storage of confining materials. Other parameters, such as specified heads and pumpage, were not adjusted during model calibration. Calibration was based on water-level measurements during two periods, predevelopment and 1940-85.

Before the development of ground-water supplies, the flow system was at equilibrium with no changes in storage. The predevelopment model was calibrated first, because of its independence from the effects of storage, simplifying estimates of other parameters. Predevelopment potentiometric surfaces (figs. 9-15) were estimated based on the earliest recorded measurements. Measurements made in areas where the grid is greatly expanded were considered but were not used in model calibration, because these measurements may not be representative of the nodal average.

Because aquifer tests available in the area did not show a consistent regional pattern of hydraulic conductivity, an initial calibration strategy involved varying both a uniform value of horizontal hydraulic conductivity for all layers of aquifer material (fig. 33) and a uniform value of vertical hydraulic conductivity over reasonable ranges for all layers of confining material (fig. 34). This approach was basically unsuccessful in reproducing observed estimates of predevelopment water levels. The head error was layer-biased, that is, simulated heads generally were higher than observed heads in layers 1-3 and were lower than observed in layers 4-8. This bias indicated that any change in model parameters should be made by layer. The observed-simulated head discrepancy could be remedied by two methods. Increasing the vertical hydraulic conductivity of older interlayers would allow more upward vertical leakage from older layers, thus, lowering heads in the older layers and increasing heads in the younger layers. Alternatively, lowering horizontal aquifer hydraulic conductivity for older layers would reduce heads in all layers, but the reduction would be greatest in older layers. Most conceptualizations of clay diagenesis and compaction effects would suggest lower values of hydraulic conductivity of the older, deeper confining units compared to younger, shallower confining units. Therefore, the former approach was rejected and a uniform value of vertical hydraulic conductivity was maintained throughout model calibration. Horizontal hydraulic conductivity, however, was allowed to vary by layer.

Values of hydraulic conductivity determined by calibration of the predevelopment model were held constant for initial transient calibration. Initial heads for the transient simulation were produced by predevelopment simulations. A uniform value of confining-material specific storage was assumed because of inadequate data describing spatial distribution of the long-term storage characteristics of the ground-water system.

Discrepancies between the 961 observed water-level measurements made throughout the simulated period (1940-85) and computed heads were minimized through trial-and-error manipulation of specific storage. Transient calibration indicated changes in some parameter values determined by predevelopment calibration. The modified values were preferred over the original values because of the greater parameter sensitivity of the transient model. All of the parameter modifications were slight with the exception of an order of magnitude reduction in the value of horizontal hydraulic conductivity for layer 5 east of the Pascagoula River. The relatively low values of horizontal hydraulic conductivity in the eastern part of layer 5 is supported by specific-capacity data. The calibration-derived parameter values considered to best represent the hydraulic properties of the system are summarized in table 2.

The calibration-derived values of horizontal hydraulic conductivity are lower for all layers than Newcome's (1971) average of about 100 ft/d. This discrepancy is to be expected because 1) aquifer tests generally are performed on production sands, which are selected because of high yields, and 2) some lenticular aquifers do not contribute significantly to the regional flow system because of the lack of good

Table 2.--Calibration-derived hydraulic parameter values

Hydraulic parameter and value	Layer or interlayer
Horizontal hydraulic conductivity of aquifer, in ft/d	
40	Layer 8 (shallowest)
40	Layer 7
30	Layer 6
3 (east of Pascagoula River)	Layer 5
30 (west of Pascagoula River)	Layer 5
30	Layer 4
10	Layer 3
5	Layer 2
5	Layer 1 (deepest)
Vertical hydraulic conductivity of confining beds in ft/d	all interlayers
1×10^{-4}	
Specific storage of confining material, in ft^{-1}	all layers
1×10^{-5}	

hydraulic connection with the regional system. Calibration results indicate that hydraulic conductivity decreases with depth. Supporting evidence includes calibration-derived values of horizontal hydraulic conductivity for the ground-water model constructed by the Gulf Coastal Plain Regional Aquifer-System Analysis (GC RASA), which includes southern Mississippi as part of its much larger study area. The Miocene aquifer system in this report was divided into three layers in the GC RASA study. Values of horizontal hydraulic conductivity (C.D. Whiteman, Jr., U.S. Geological Survey, oral commun., 1987) in the GC RASA model are 19 ft/d in the basal layer, and 40 and 45 ft/d in the middle and upper layers, respectively. The uniform value of 1×10^{-4} ft/d for vertical hydraulic conductivity of confining material is reasonably close to the range of values used in the GC RASA flow model of this area (6.0×10^{-4} to 1.9×10^{-3}).

The calibration-derived value of specific storage of 1.0×10^{-6} ft^{-1} is reasonably close to the value (1.6×10^{-5} ft^{-1}) determined by means of compaction tests on clay samples from the Baton Rouge, La., area (Whiteman, 1980) and to the value (1.5×10^{-5} ft^{-1}) used in a flow model of the "2,000-foot" sand at Baton Rouge (Torak and Whiteman, 1982).

The simulated predevelopment heads compare favorably to the observed predevelopment heads in 117 wells having a root-mean square error of 21.4 feet. Both simulated and observed potentiometric surfaces are shown for predevelopment in figure 35. In the coastal area, differences in elevation between the two surfaces generally is less than 20 feet. A correlation coefficient of 0.91 was determined by a least squares regression analysis of observed and computed predevelopment heads (fig. 36). Likewise, the comparison between 961 observed and computed heads within the 1940-85 transient simulations generally is favorable, with a root-mean-square error of 29.88 feet and a correlation coefficient of 0.89 (fig. 37). Hydrographs showing the comparison of observed and computed water levels for 25 selected wells are located in figures 38 and 39. In most instances, adequate simulation of hydrographs was achieved. Vertical head variations within a node both vertically and areally and the highly generalized model parameter values contribute to producing the occasional poor hydrograph simulation.

Flow Budget

The nature of the simulated predevelopment flow system is shown by potentiometric maps (fig. 35) and a schematic of flow (fig. 40). The schematic shows that much of the flow is between the surficial aquifer system and the parts of the layers that immediately underly the surficial aquifer. The potentiometric surface in each layer is highest in areas where the water level in the immediately overlying surficial aquifer system is highest. Relatively high heads within the western part of the subcrop of each layer result in generally north to south and northwest to southeast flows within each layer (fig. 35). The Mobile, Pearl, and Pascagoula Rivers act as drains for the system, but the Mobile is the most effective. Within the southern parts of each layer, upward vertical leakage is prevalent. The magnitude of fluxes, both between layers and from or to the surficial aquifer system, is

The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

—— 100 —— SIMULATED POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface. Contour interval 20 feet. Datum is sea level

— — — 100 — — OBSERVED POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface. Contour interval 25 feet. Datum is sea level

Figure 35.--Potentiometric surfaces of layers as simulated by the steady-state model for predevelopment and as observed for predevelopment.

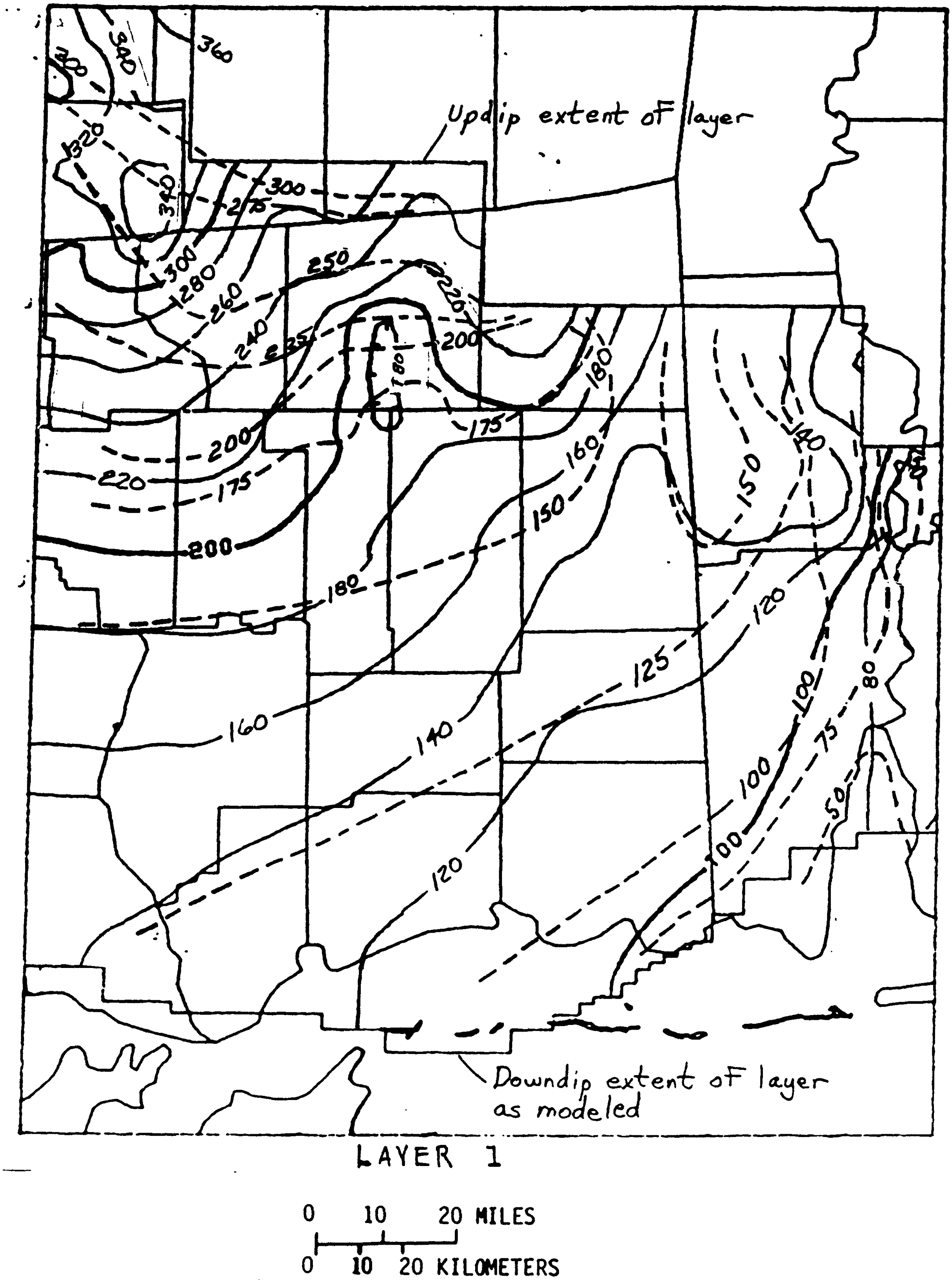
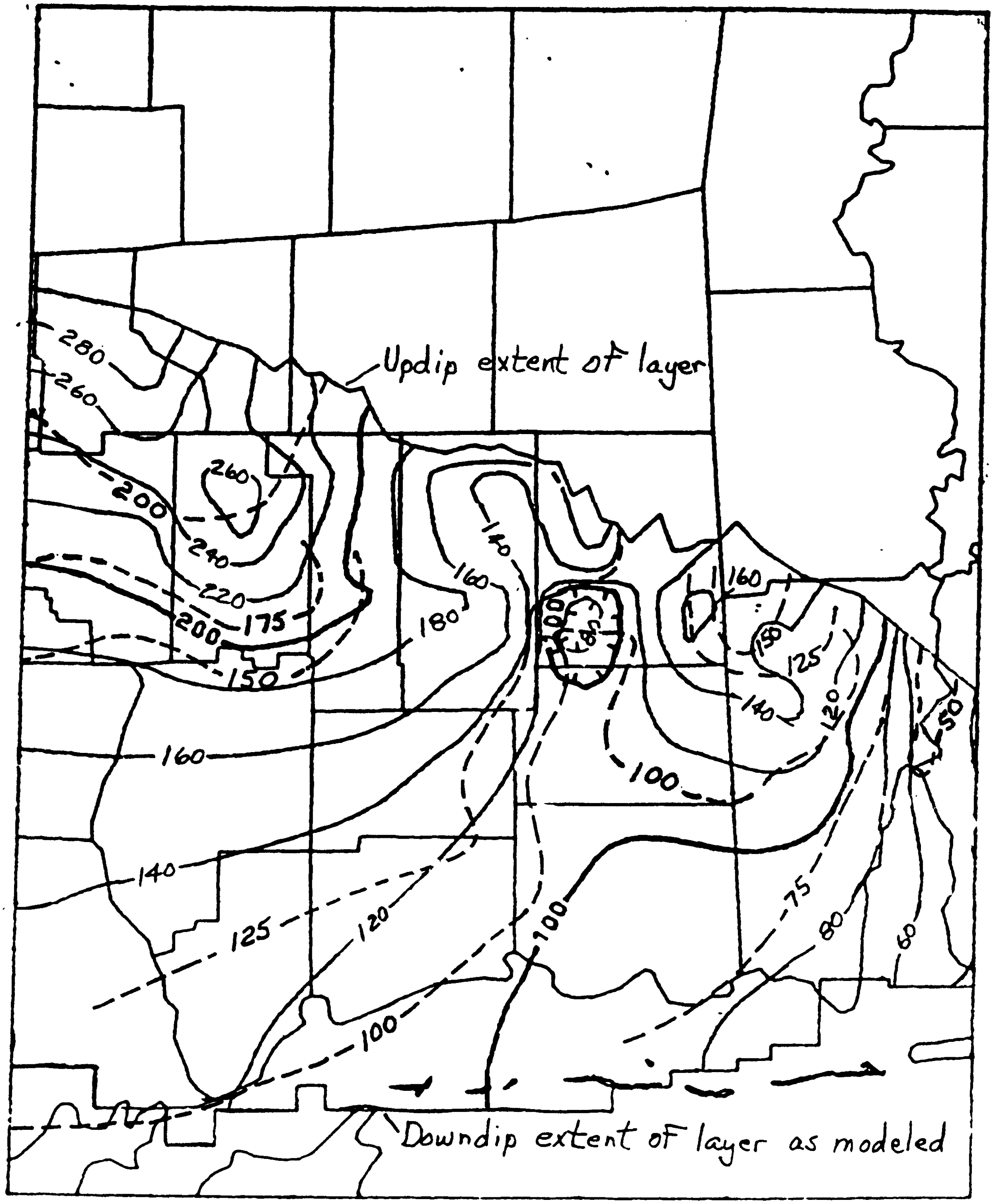


Figure 35. -- Continued



LAYER 2

0 10 20 MILES
0 10 20 KILOMETERS

Figure 35. -- Continued

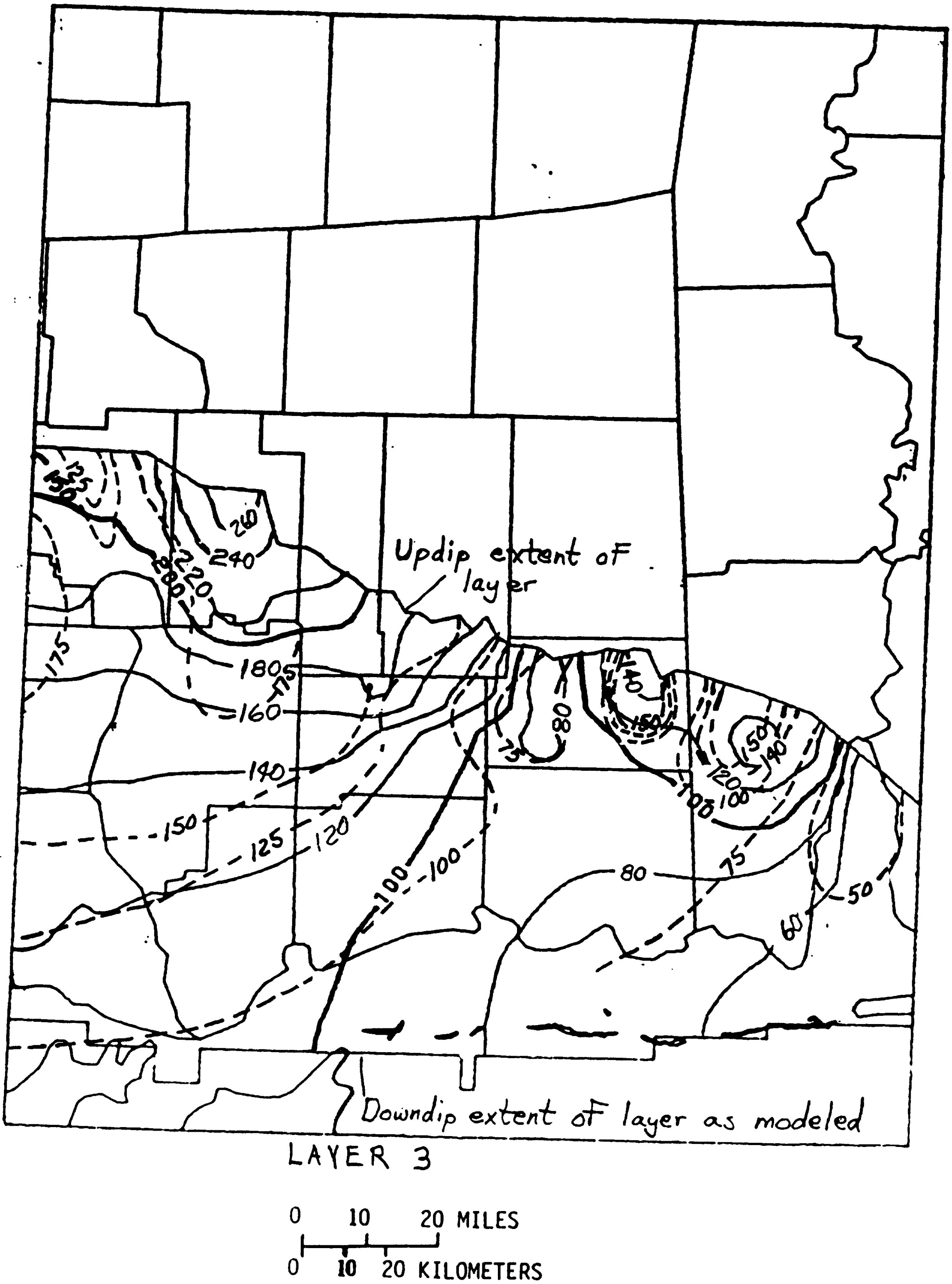


Figure 35.-- Continued

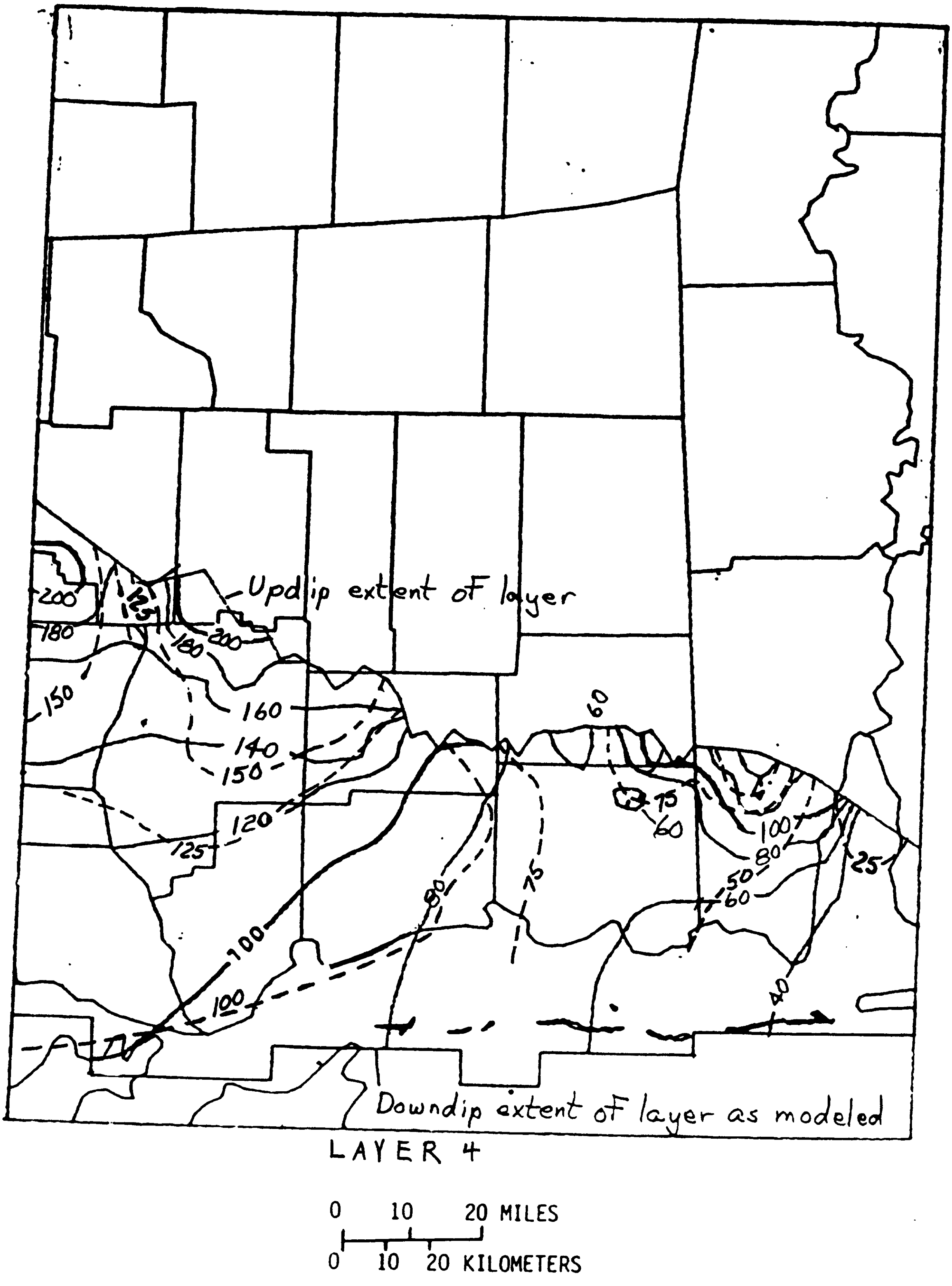
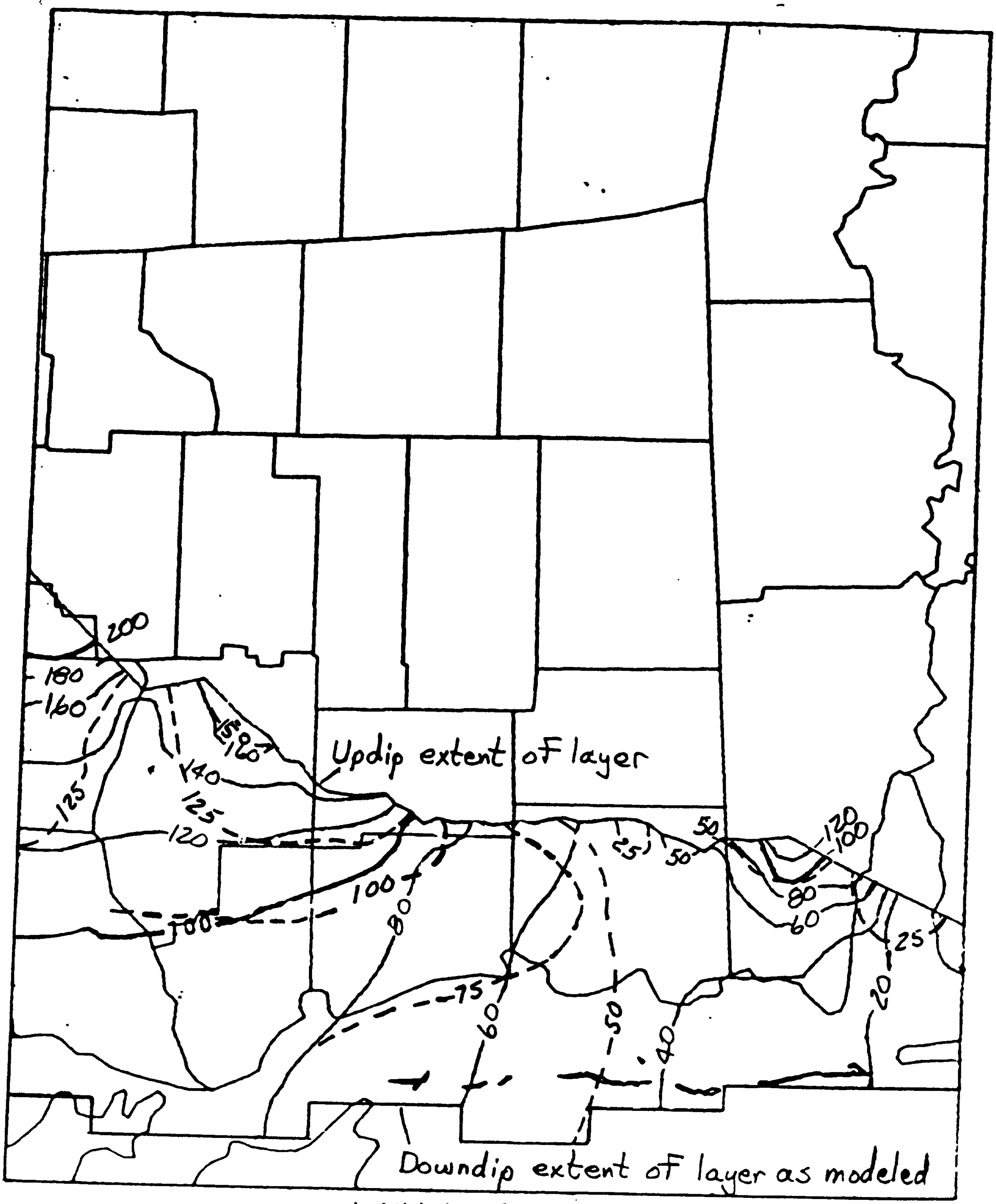


Figure 35.--Continued



LAYER 5

0 10 20 MILES
0 10 20 KILOMETERS

Figure 35.-- Continued

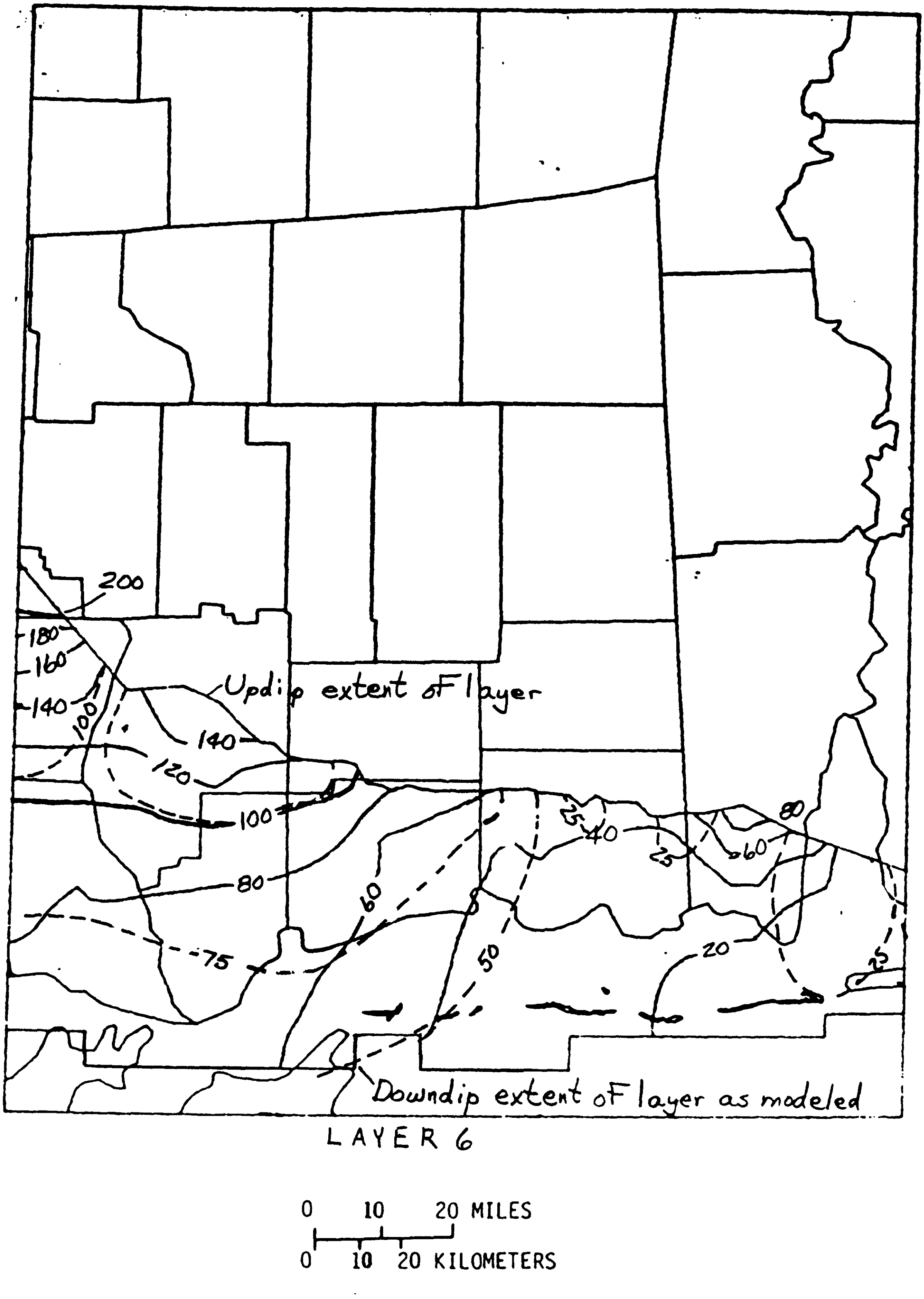
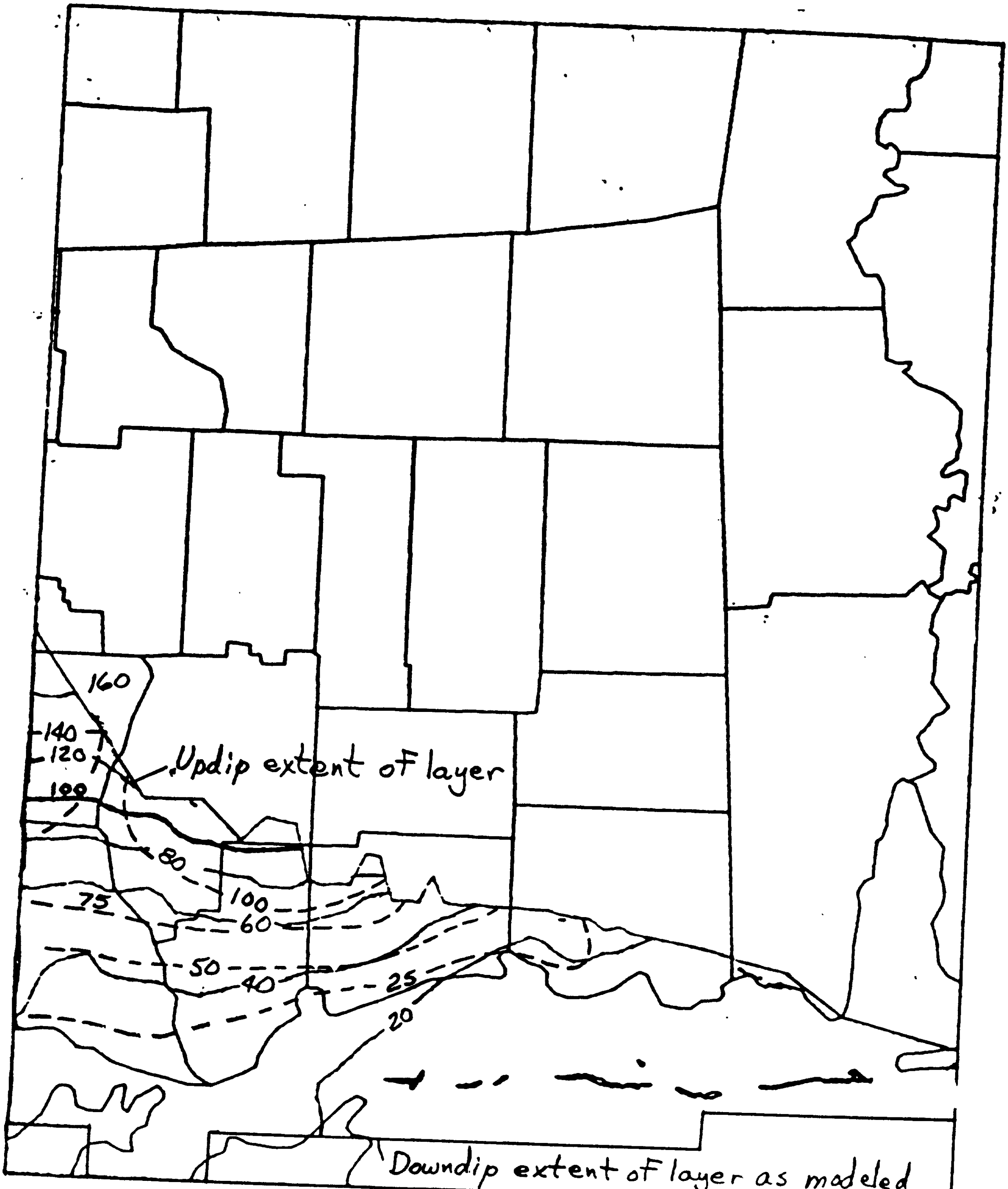


Figure 35. -- Continued



LAYER 7

0 10 20 MILES
0 10 20 KILOMETERS

Figure 35.--Continued

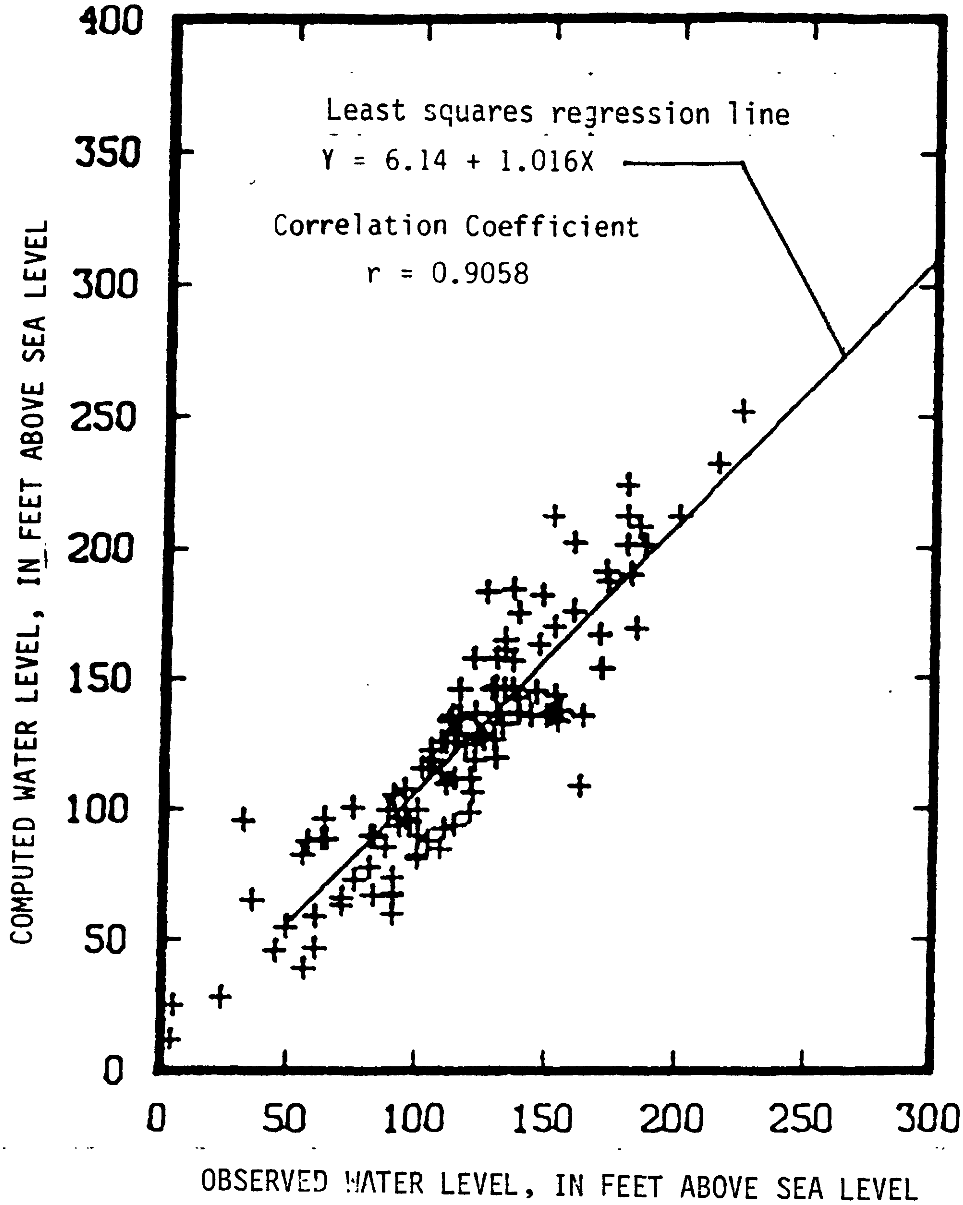


Figure 36.--Relation of observed and computed water levels in selected wells as computed by the steady-state model.

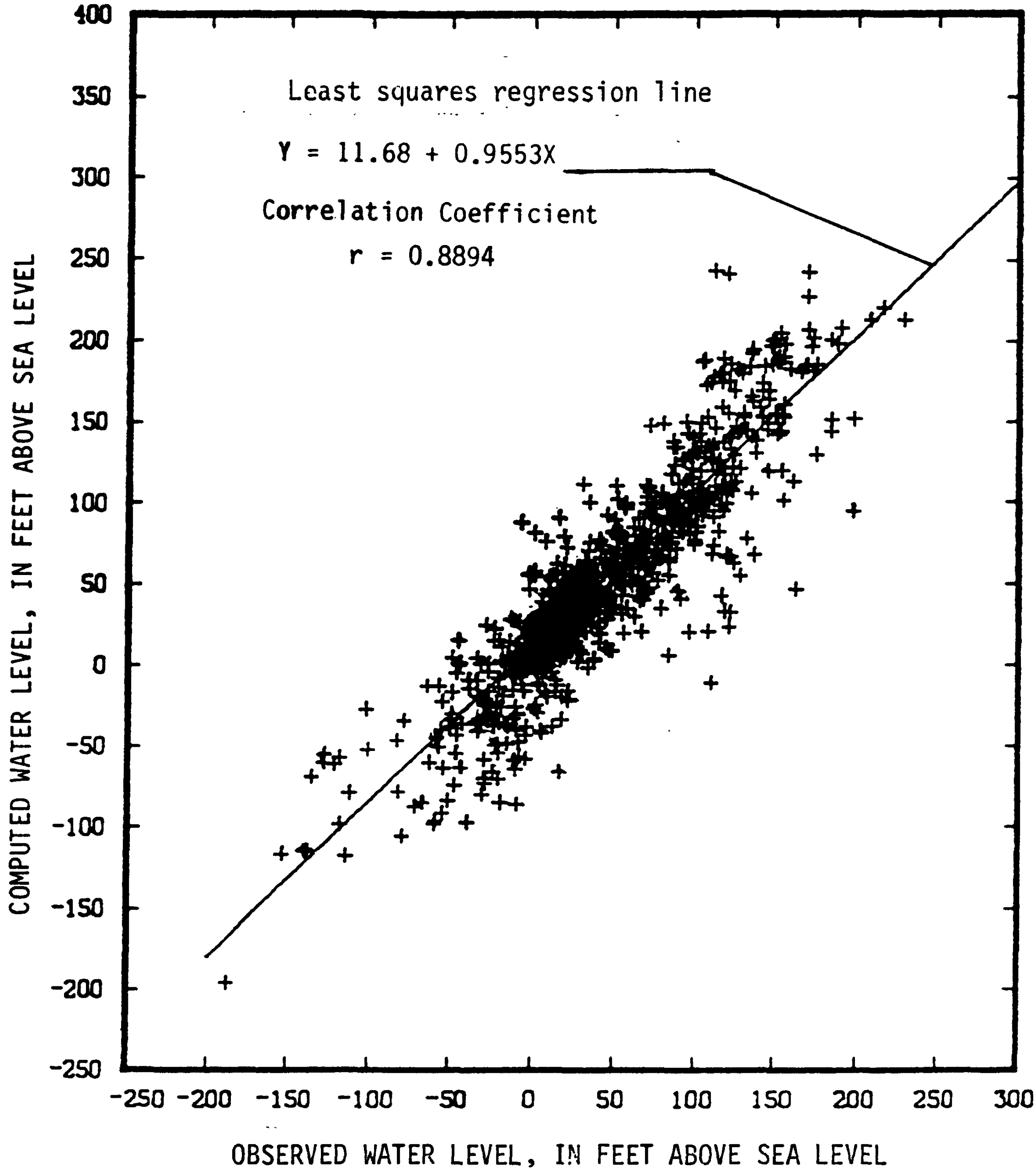


Figure 37.--Relation of observed and computed water levels in selected wells as computed by the transient-flow model.

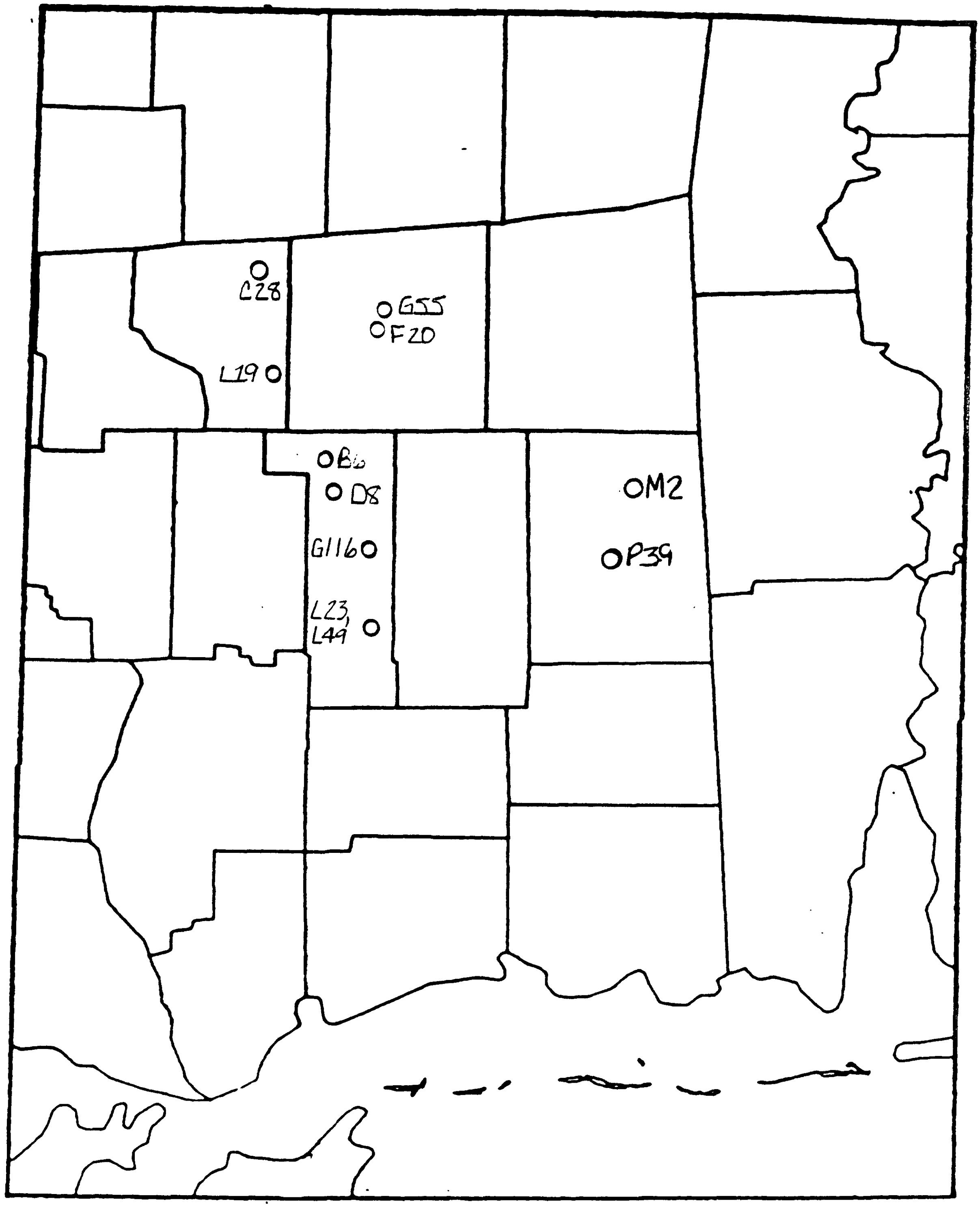
The title and explanation below apply to the following seven pages which make up this multipage illustration.

EXPLANATION

● OBSERVATION WELL--Hydrograph shown in figure 39

○ OBSERVATION WELL--Hydrograph not shown in figure 39

Figure 38.--Locations of water-level observation wells in hydrologic layers.



Layer 1

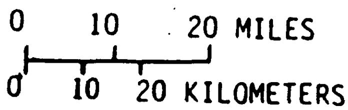
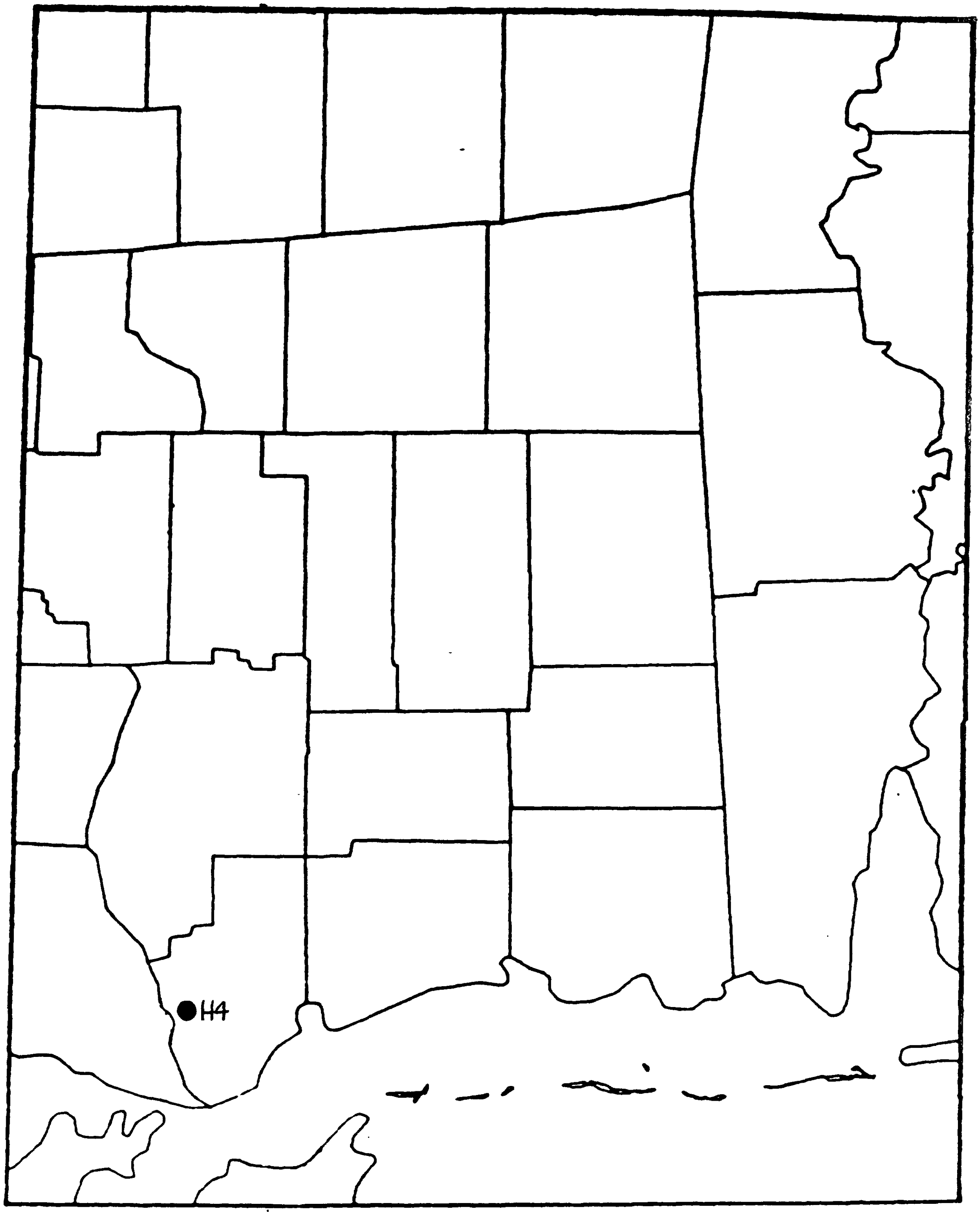


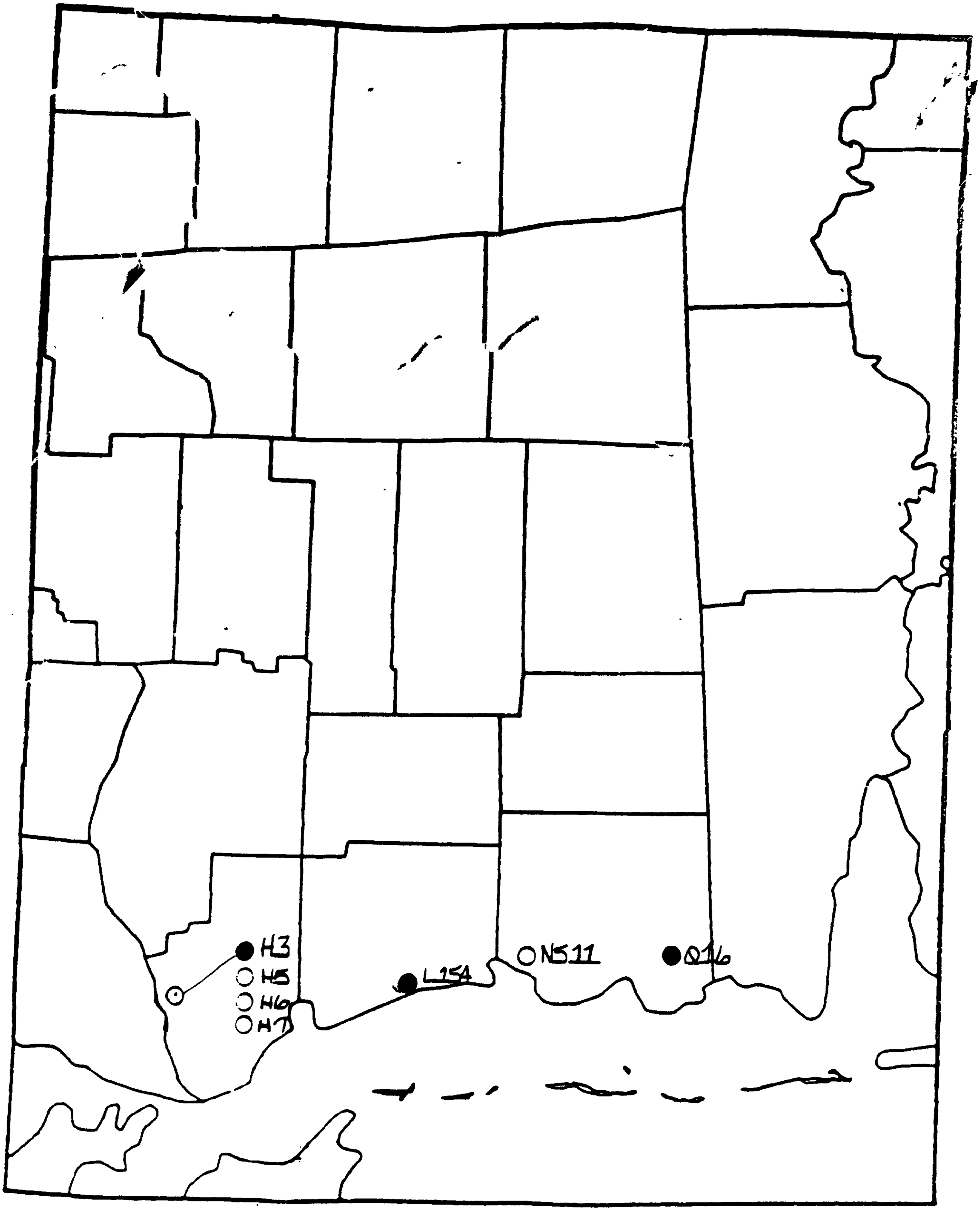
Figure 38. -- Continued



Layer 2

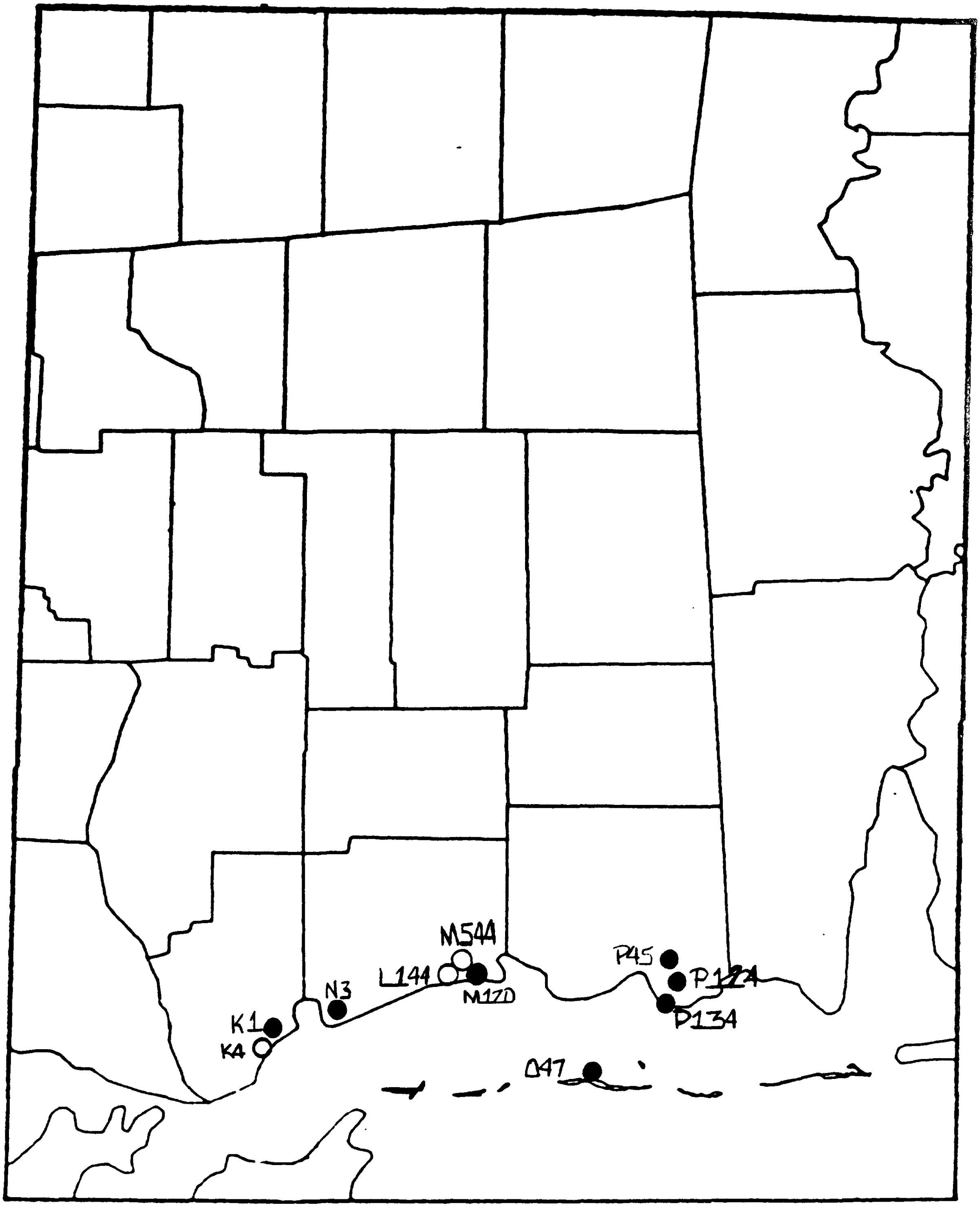
0 10 20 MILES
0 10 20 KILOMETERS

Figure 38.-- Continued



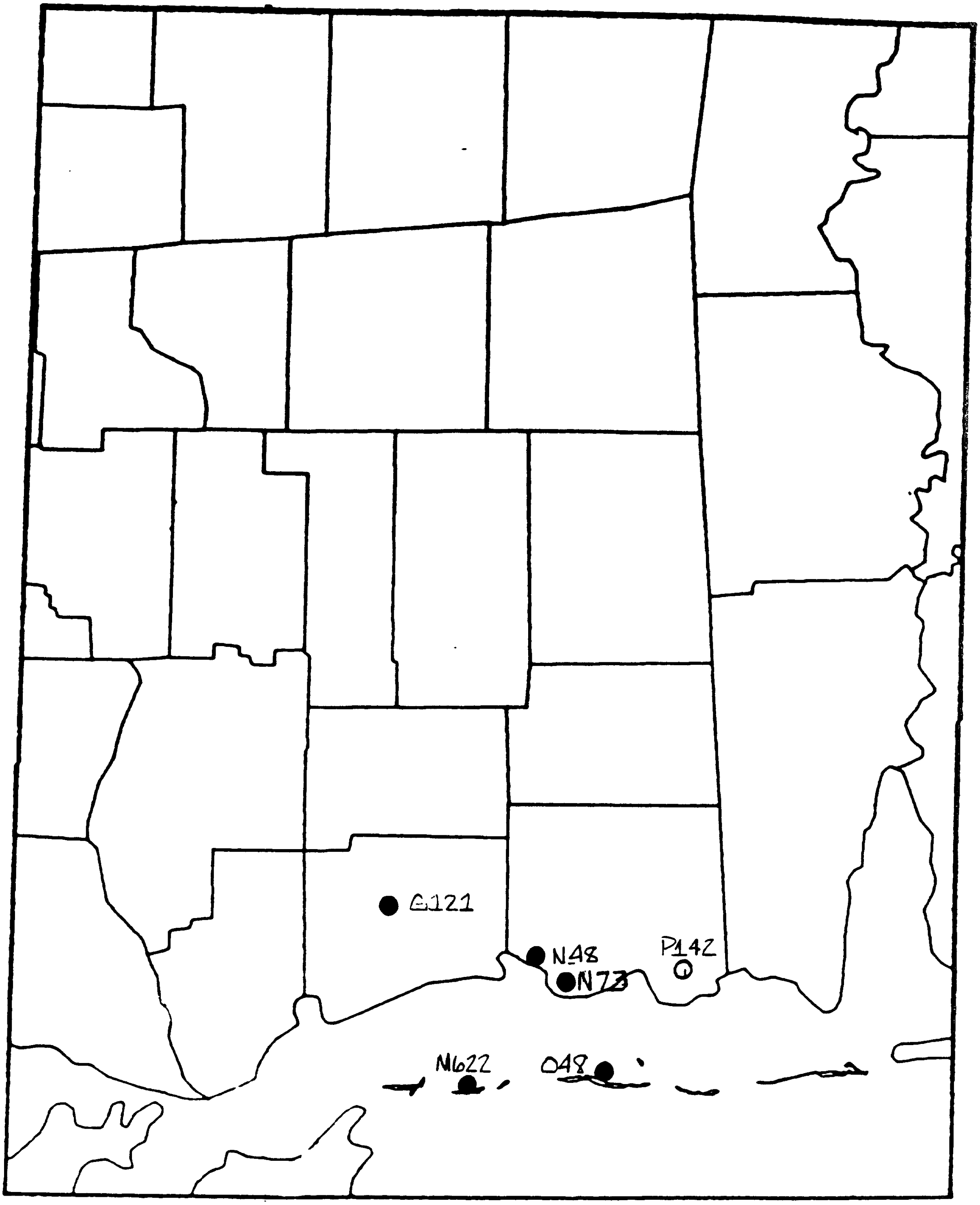
Layer 3

Figure 38.--Continued



Layer 4

Figure 38.--Continued



Layer 5

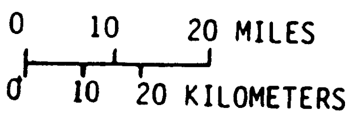
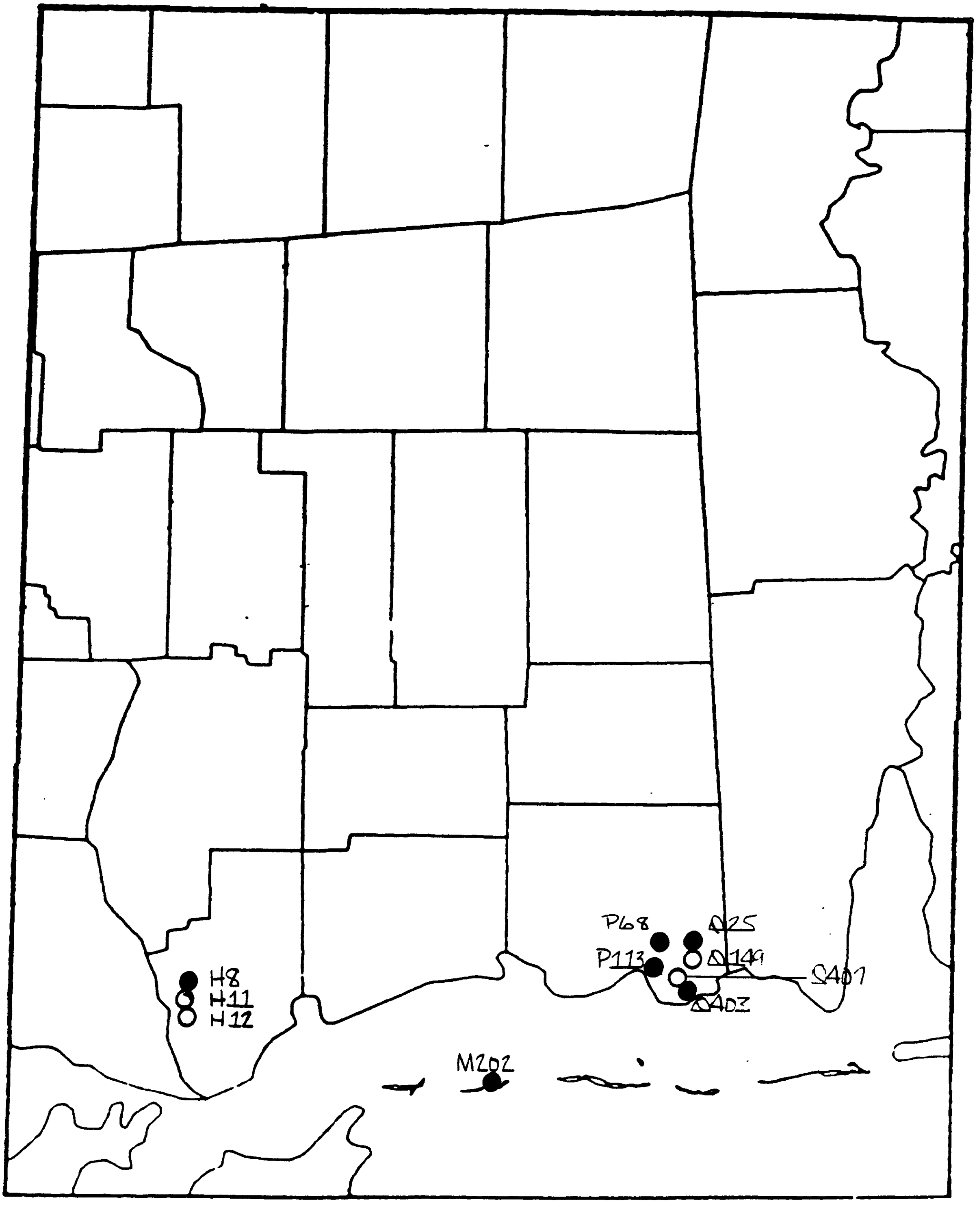


Figure 38. -- Continued



Layer 6

0 10 20 MILES
0 10 20 KILOMETERS

Figure 38.--Continued

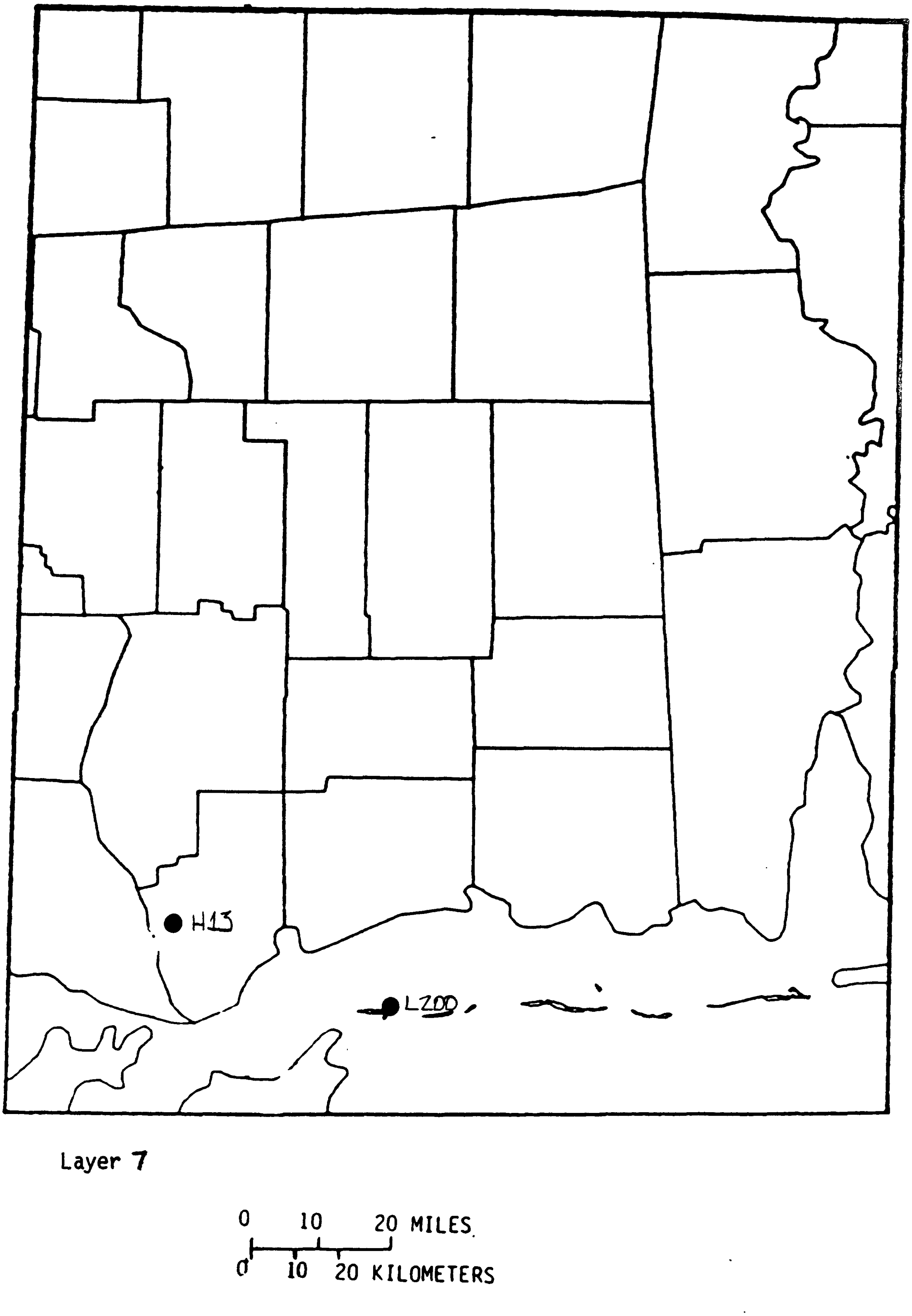


Figure 38. -- Continued

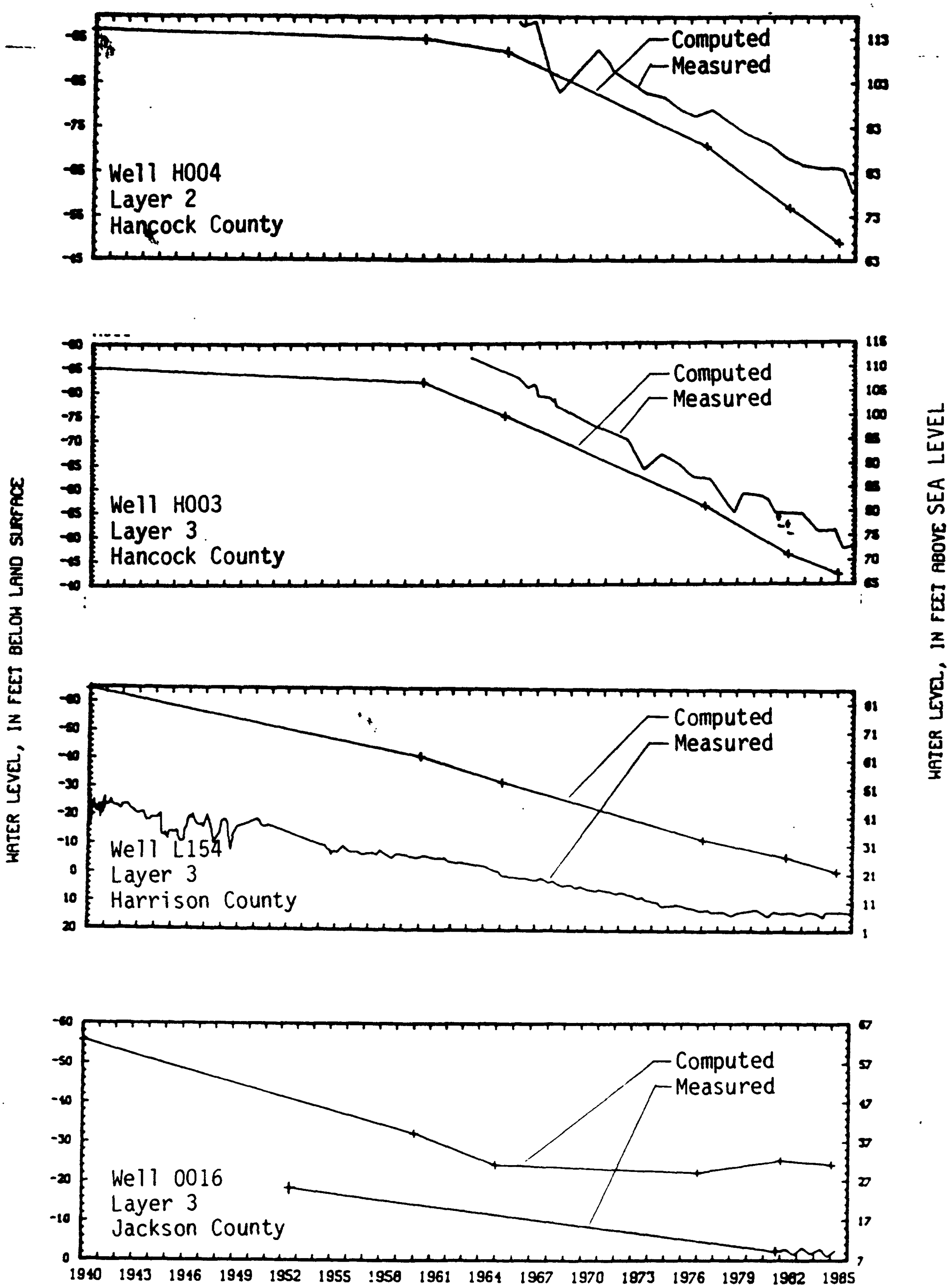


Figure 39.--Comparison of observed and computed water levels in selected wells.

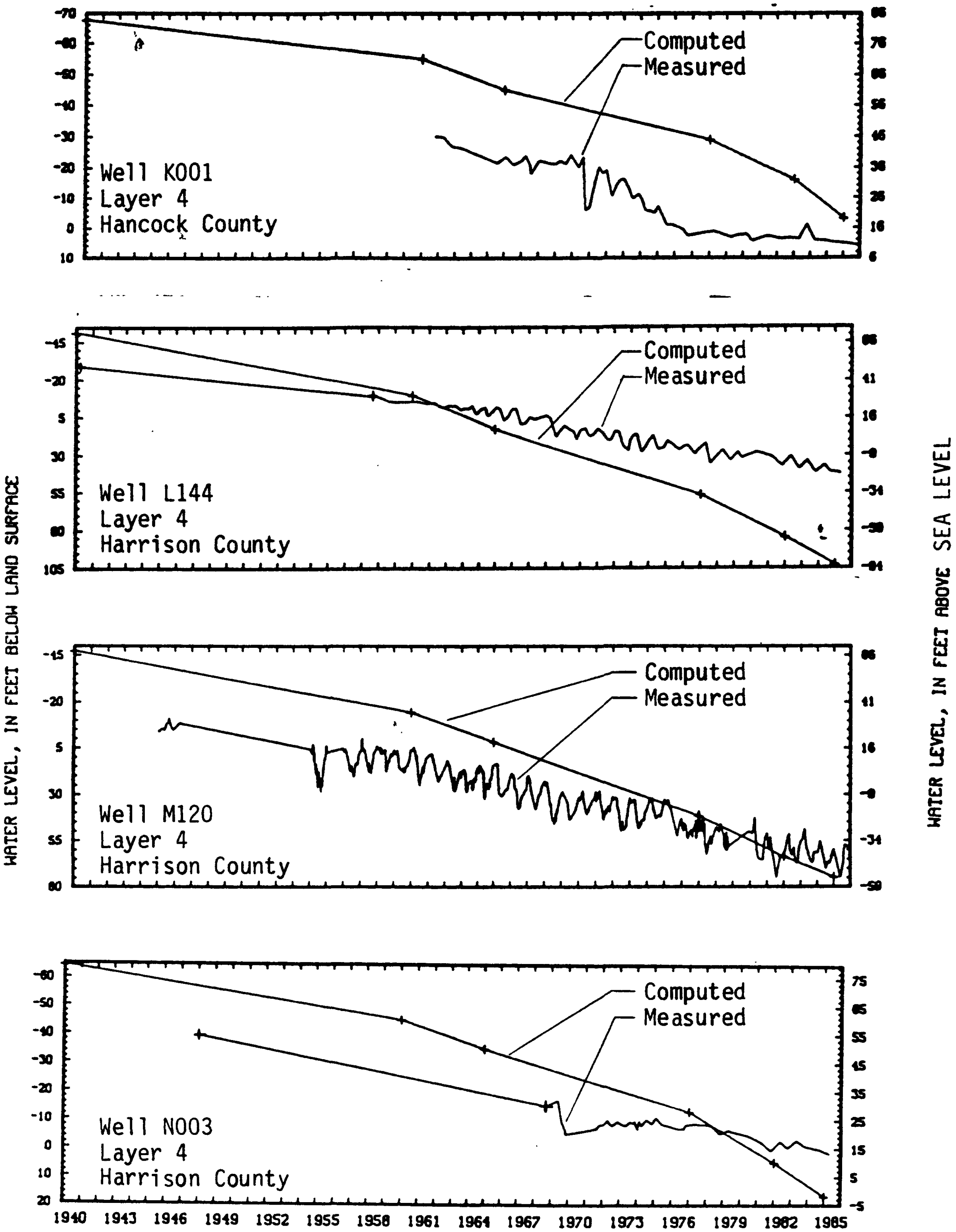


Figure 39.--Comparison of observed and computed water levels in selected wells.--Continued

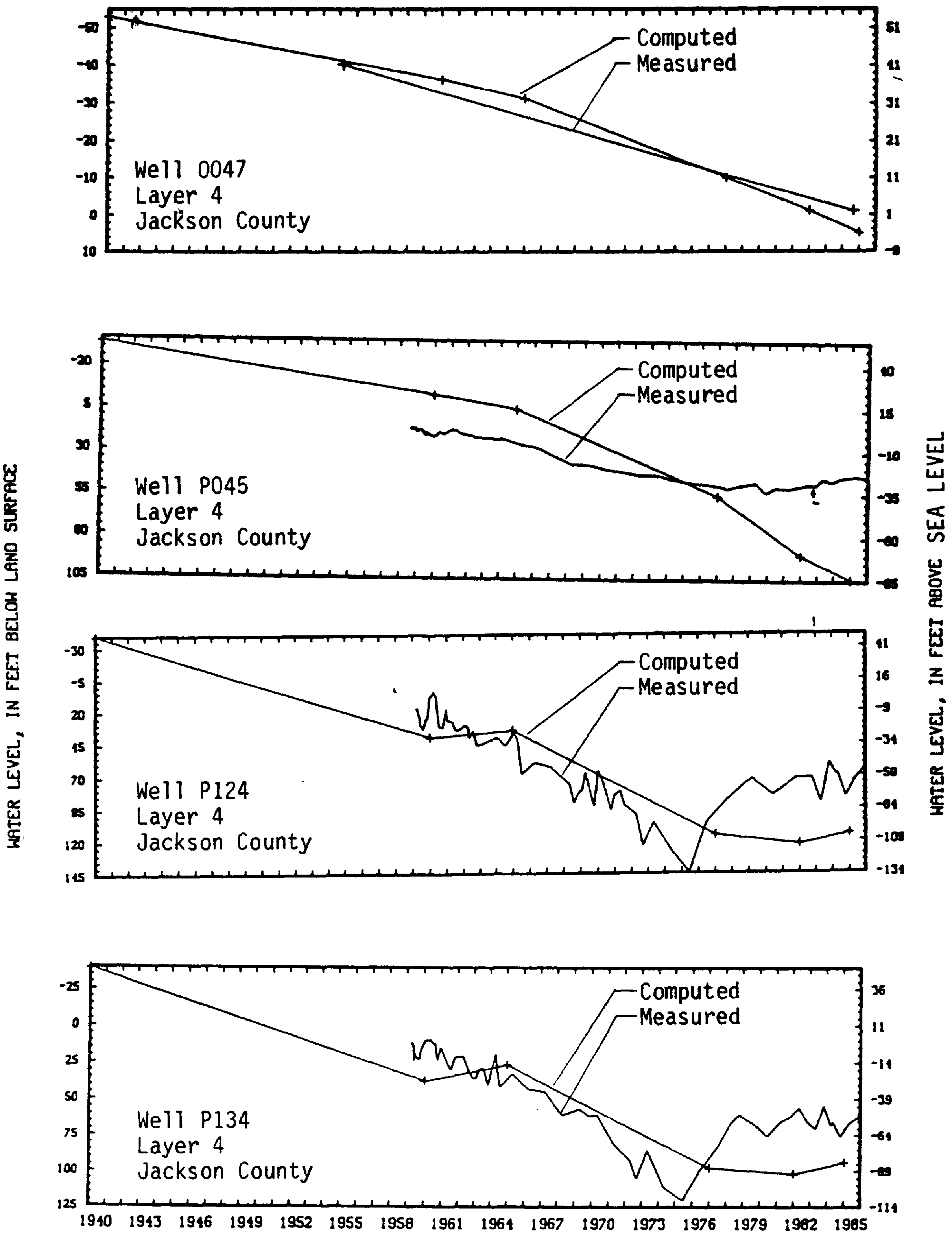


Figure 39.--Comparison of observed and computed water levels in selected wells.--Continued

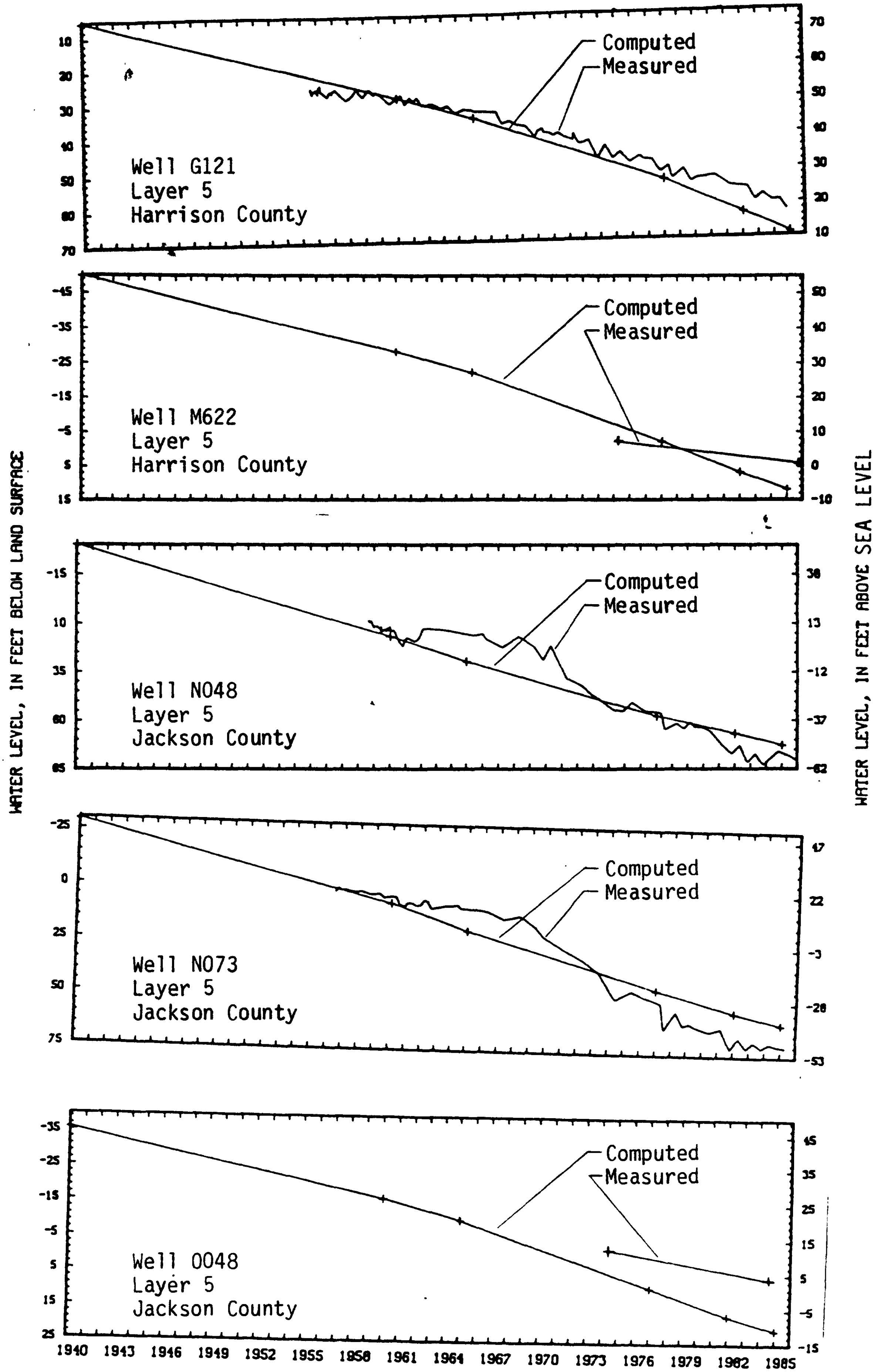


Figure 39.--Comparison of observed and computed water levels in selected wells.--Continued

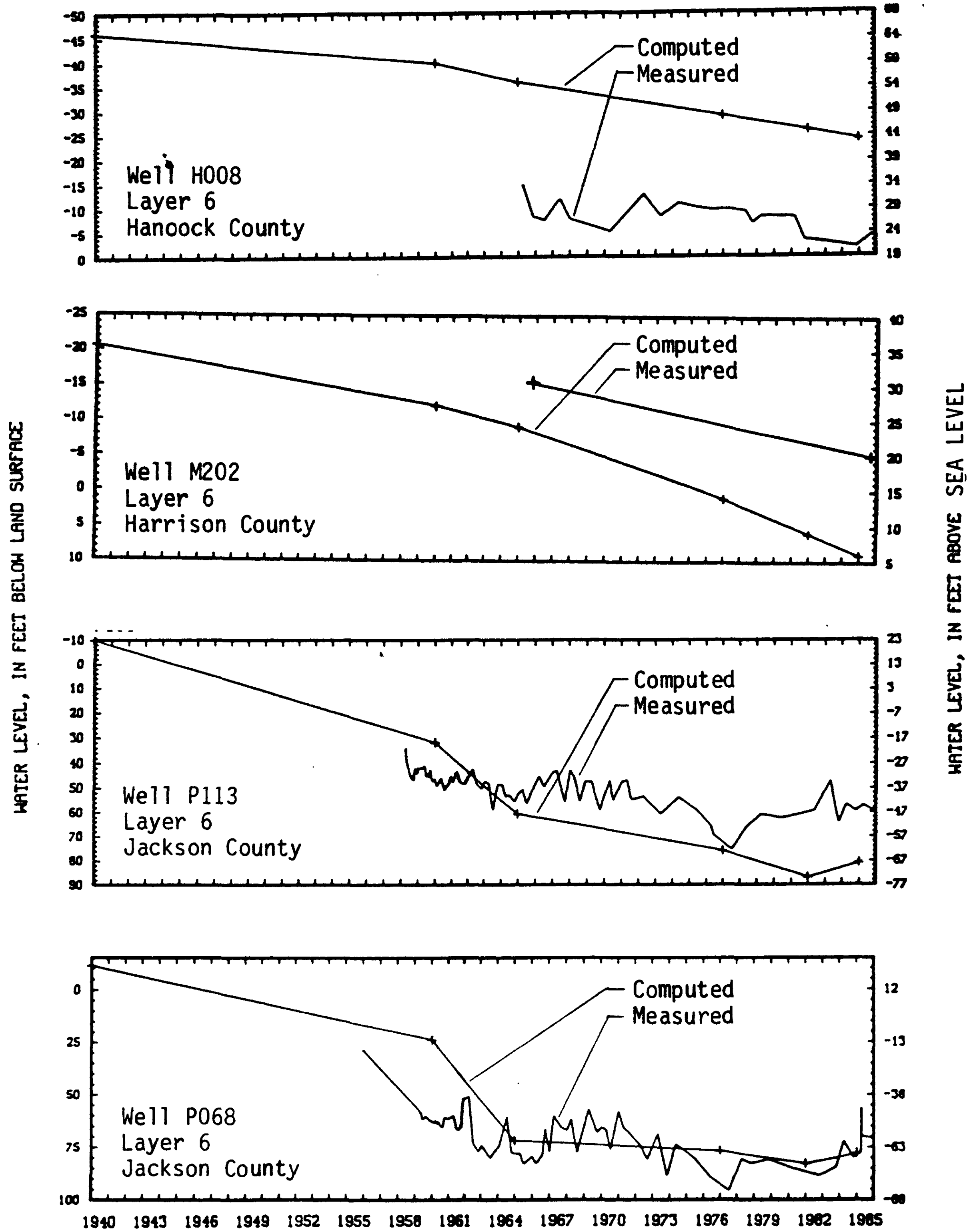


Figure 39.--Comparison of observed and computed water levels in selected wells.--Continued

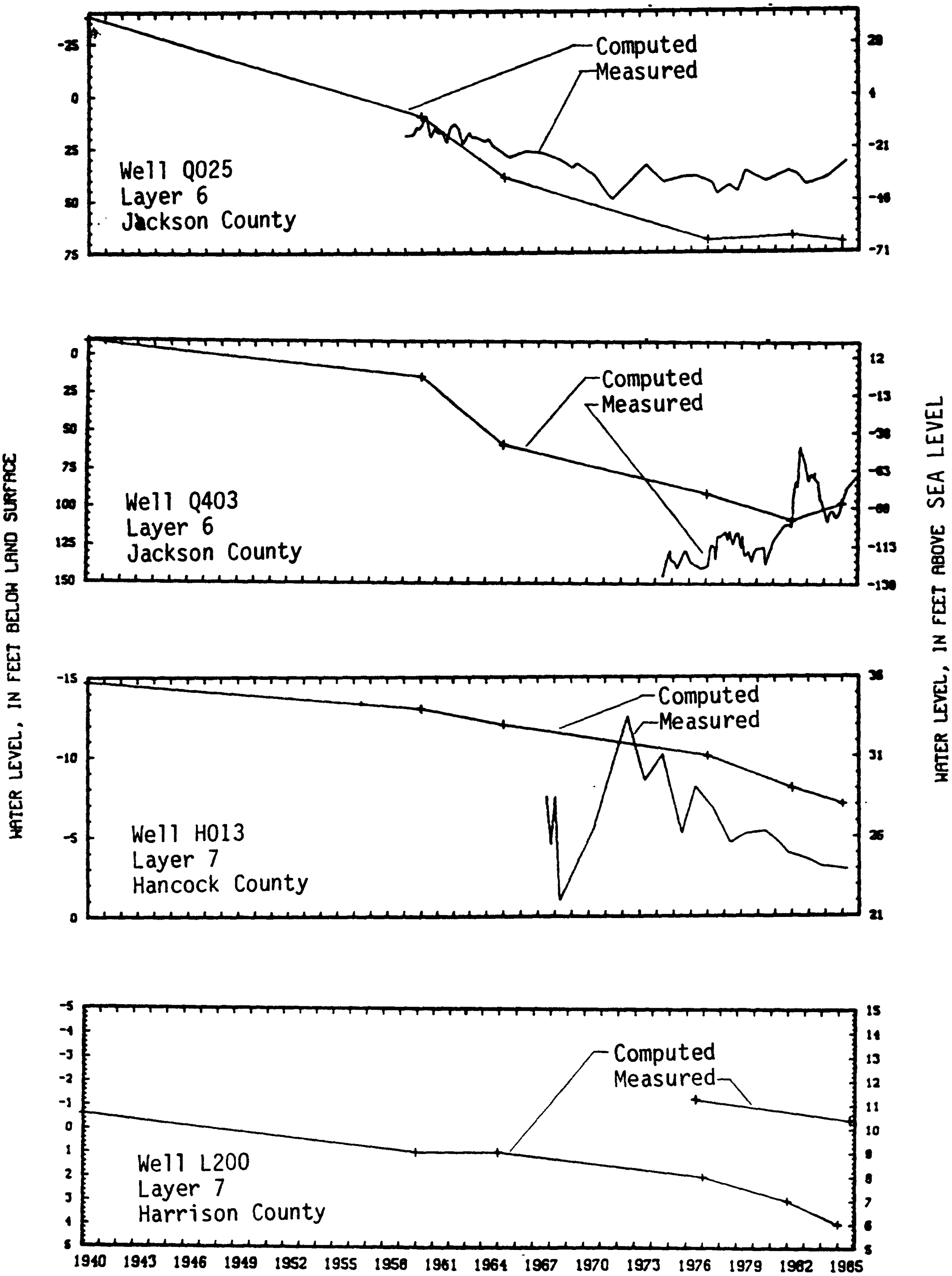


Figure 39.--Comparison of observed and computed water levels in selected wells.--Continued

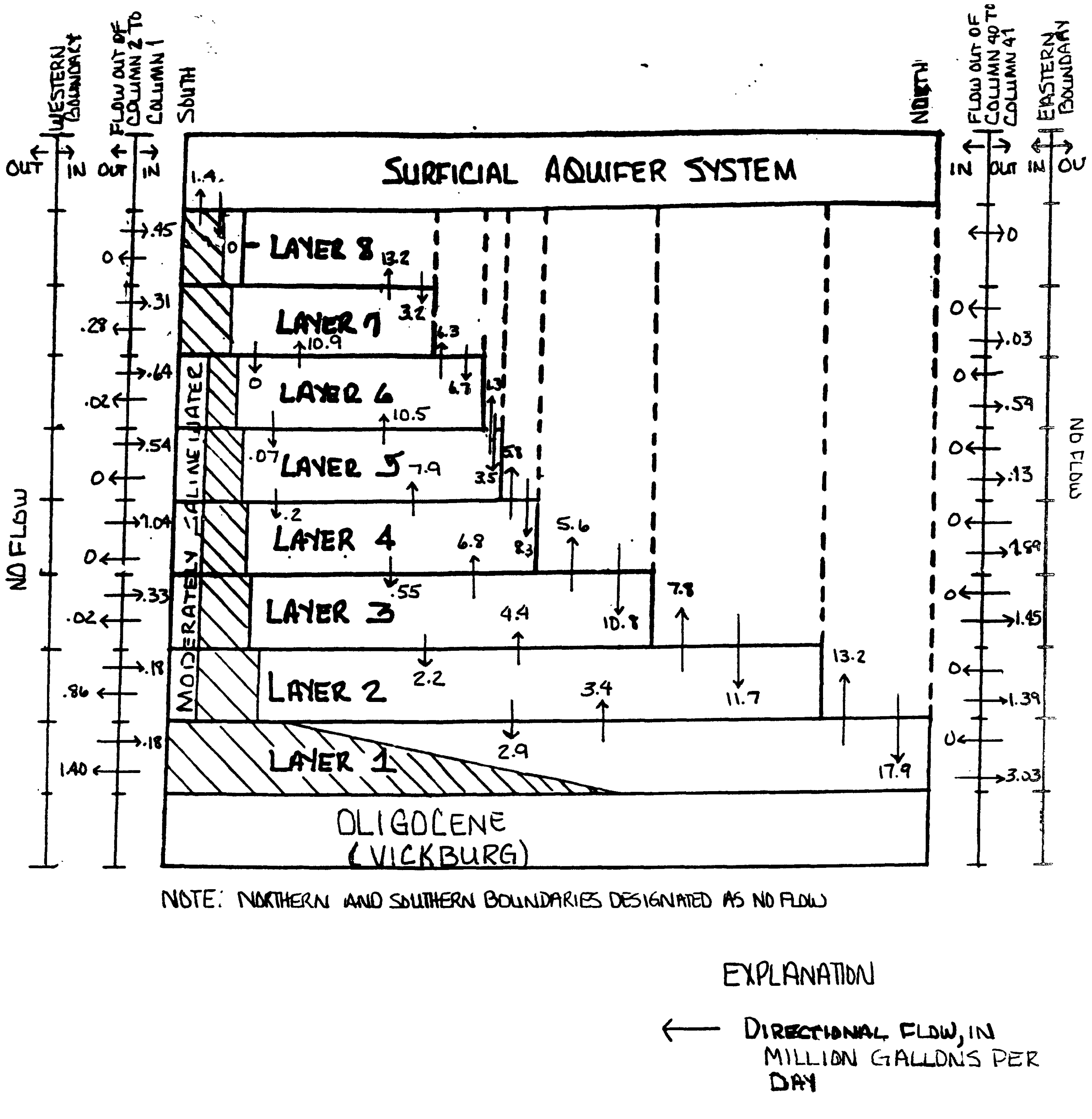


Figure 40.--Schematic diagram of flow simulated by predevelopment model.

consistently less than 1.0 inch per year (fig. 41). Only a small amount of water entering the Miocene aquifer system through the subcrop continues beyond the subcrop. Most subcrop recharge circulates within the subcrop area and discharges locally to the surficial aquifer system.

The flow budget terms during the first and last stress periods of the 1940-85 transient simulation are summarized in table 3 and in a schematic of flow in 1985 (fig. 42). Several generalizations can be made about the changes in the flow system from predevelopment to the 1940-60 stress period and to the 1982-85 stress period:

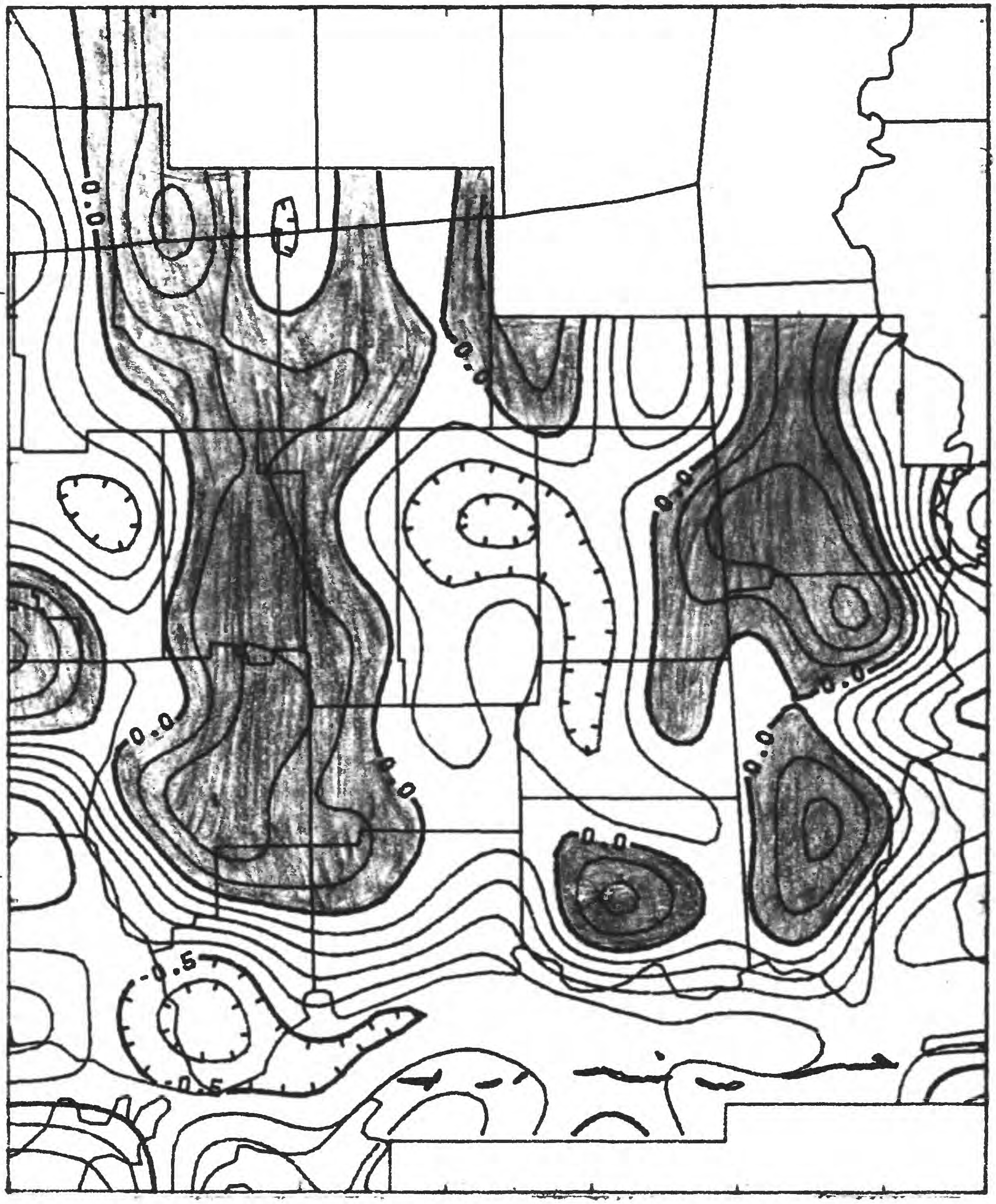
- Ground-water withdrawals increased, dramatically in many areas.
- Significant amounts of water were removed from storage.
- Water-level declines have resulted in the capture of significant amounts of water from the surficial aquifer system, changing some discharge areas to recharge areas.
- Fluxes between layers generally have increased.
- Amount of water lost through the western boundary has increased, because water flows to pumping centers in southeastern Louisiana.
- Flow through the eastern boundary has changed only slightly.

Sensitivity Analysis

Sensitivity of the model to changes in the values of the hydraulic parameters that were varied during model calibration was analyzed for three reasons: 1) a measure of the degree of error introduced into the model as a result of using possibly erroneous estimates of parameter values was needed, 2) knowledge of the relative importance of the various parameters can guide future investigators toward a better understanding of the flow system and, 3) a measure of the validity of the calibration process can be obtained. A calibration-derived estimate of a given hydraulic parameter is more likely to be reliable if the model is sensitive to changes in that parameter. The converse is true of calibration-derived parameters to which the model shows little sensitivity. The response of the transient model to both lower and higher values than the calibration-derived values of several hydraulic parameters (horizontal hydraulic conductivity of aquifer materials, and vertical hydraulic conductivity and specific storage of confining materials) was evaluated at three nodes considered to be representative of the system.

Two of the nodes for which model sensitivity was evaluated are in pumping centers (layer 4 at Biloxi and layer 6 at Bayou Casotte). The third node evaluated is in the subcrop of layer 6 in northern Jackson County, outside the area of significant ground-water withdrawals. A sharp contrast exists between the pronounced model sensitivity in the highly stressed parts of the flow system and the lower sensitivity in those areas more distant from pumping (figs. 43-45). In general, model sensitivity is greater during transient simulation.

Simulated heads at the two highly stressed nodes increase as much as 125 feet with increasing values of horizontal hydraulic conductivity of aquifer materials. However, simulated heads at the node distant from



EXPLANATION

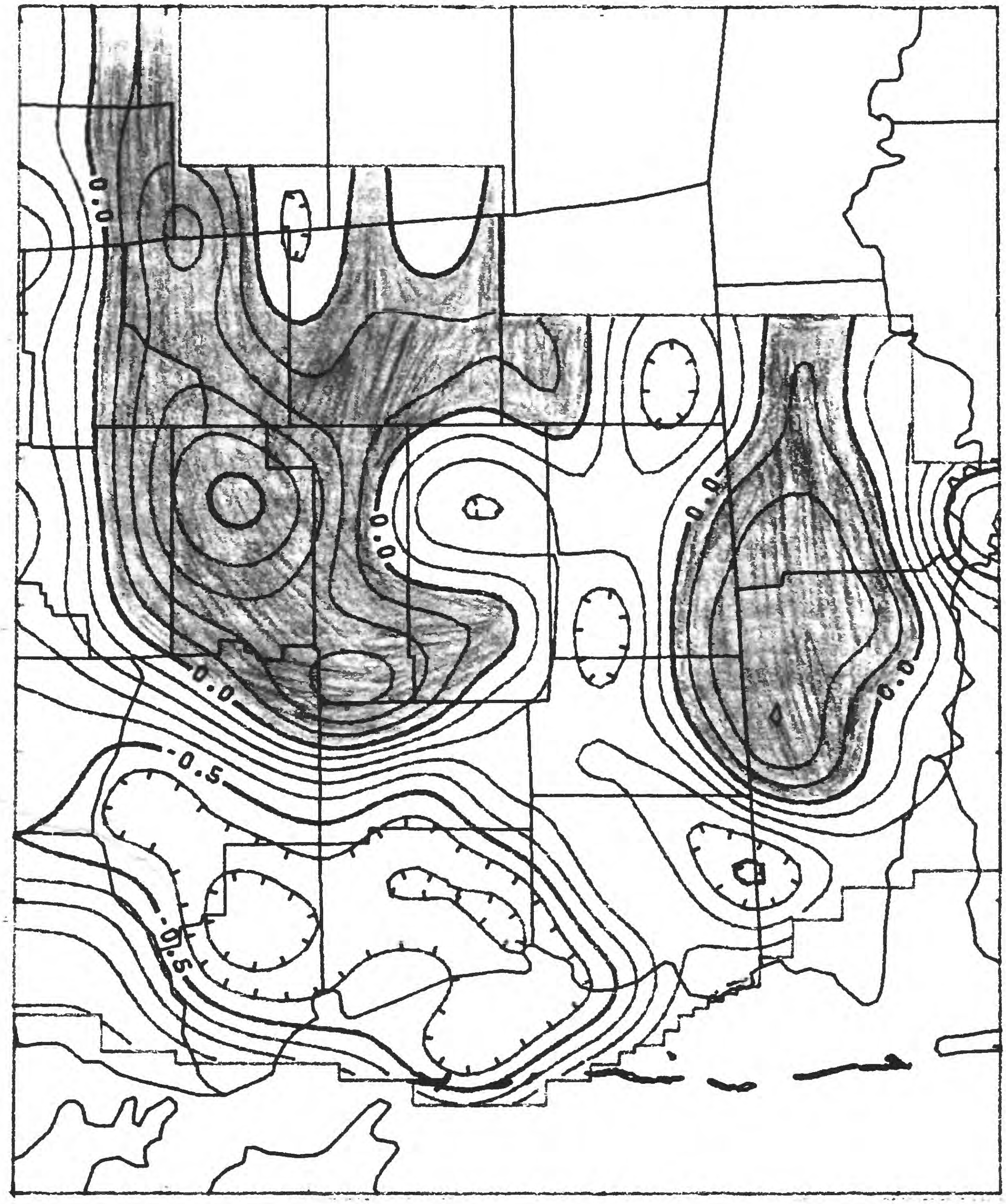
0 10 20 MILES
0 10 20 KILOMETERS

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

— 0.0 — LINE OF EQUAL VALUE--Shows flux in inches per year in the surficial aquifer. Contour interval 0.1 inch

Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.



EXPLANATION

0 10 20 MILES

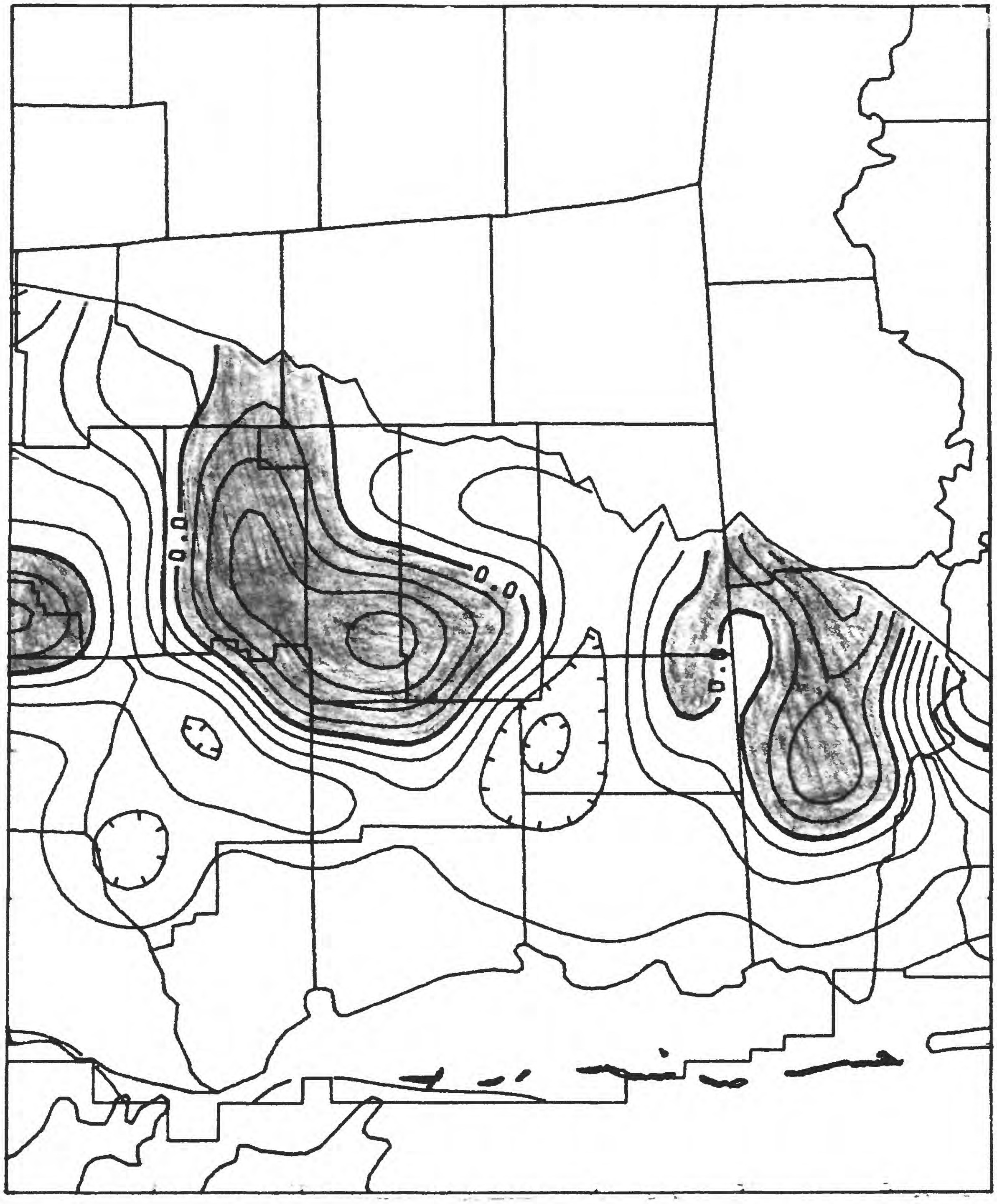
0 10 20 KILOMETERS

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 1. Contour interval 0.1 inch

Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.--Continued



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

0.0 LINE OF EQUAL VALUE--Shows flux in inches per year in layer 2. Contour interval 0.1 inch

0 10 20 MILES
0 10 20 KILOMETERS

Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.--Continued

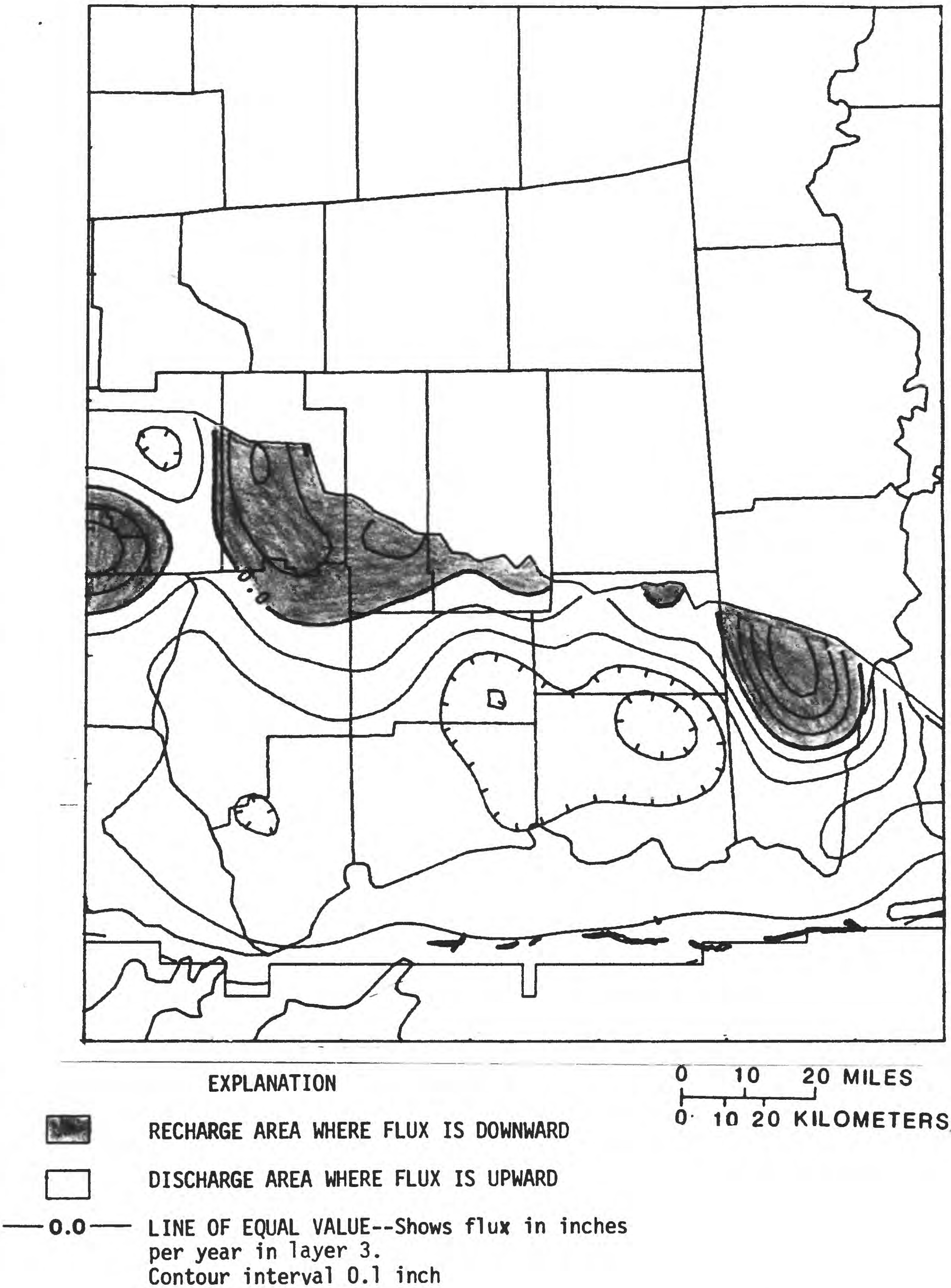
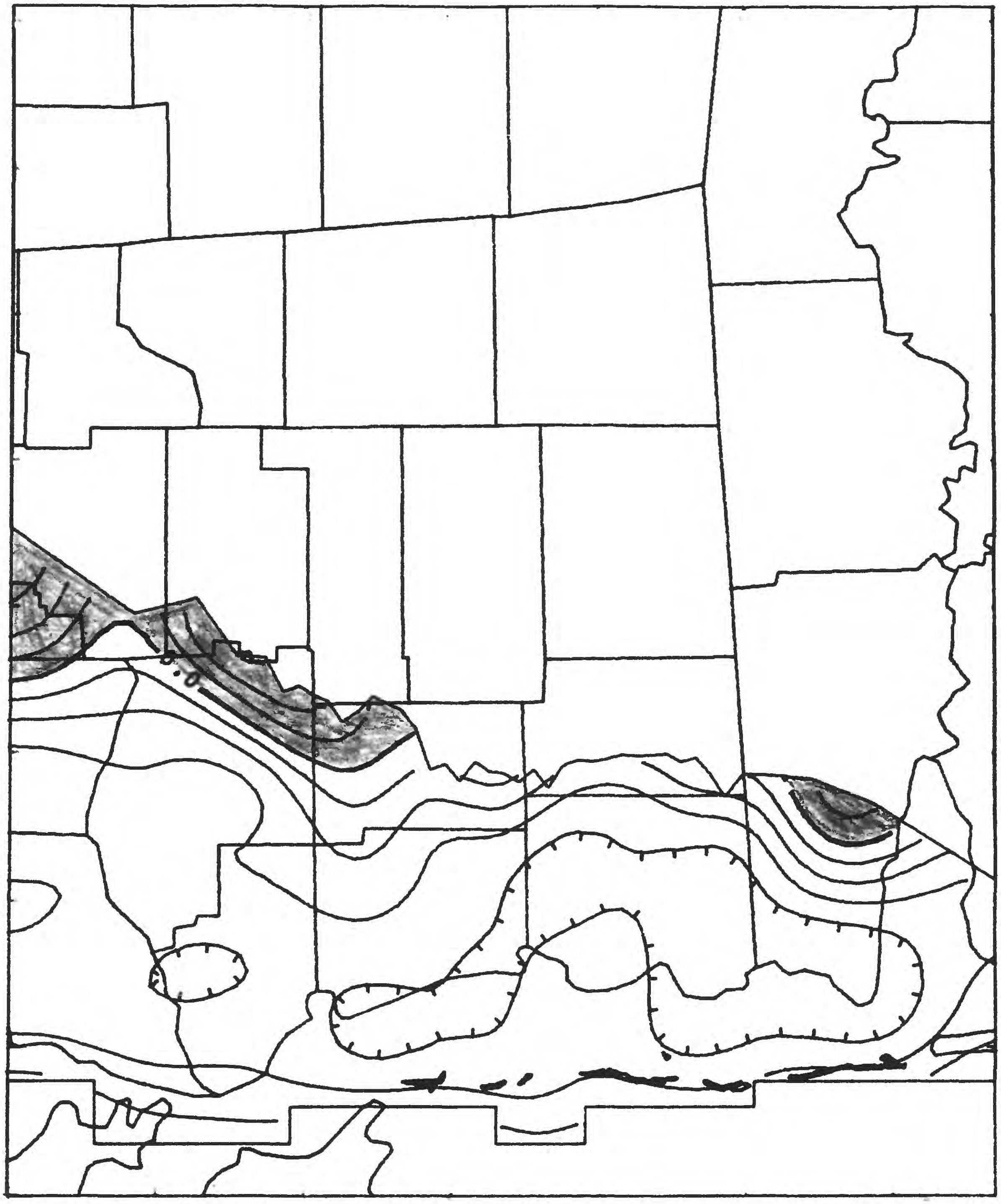
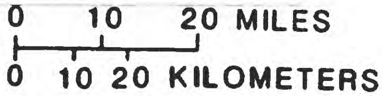


Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.--Continued



EXPLANATION

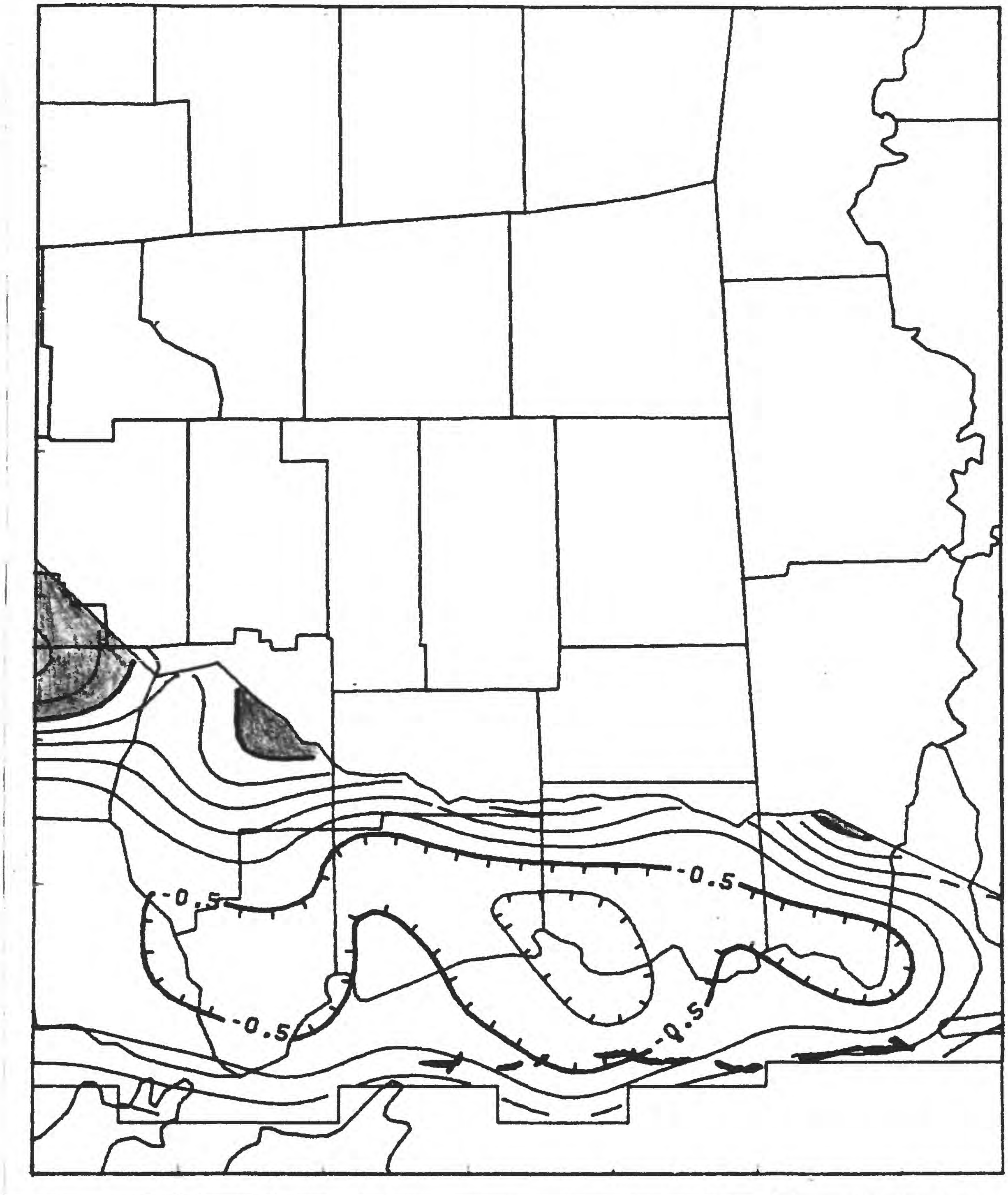


RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 4.
Contour interval 0.1 inch

Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.--Continued



EXPLANATION

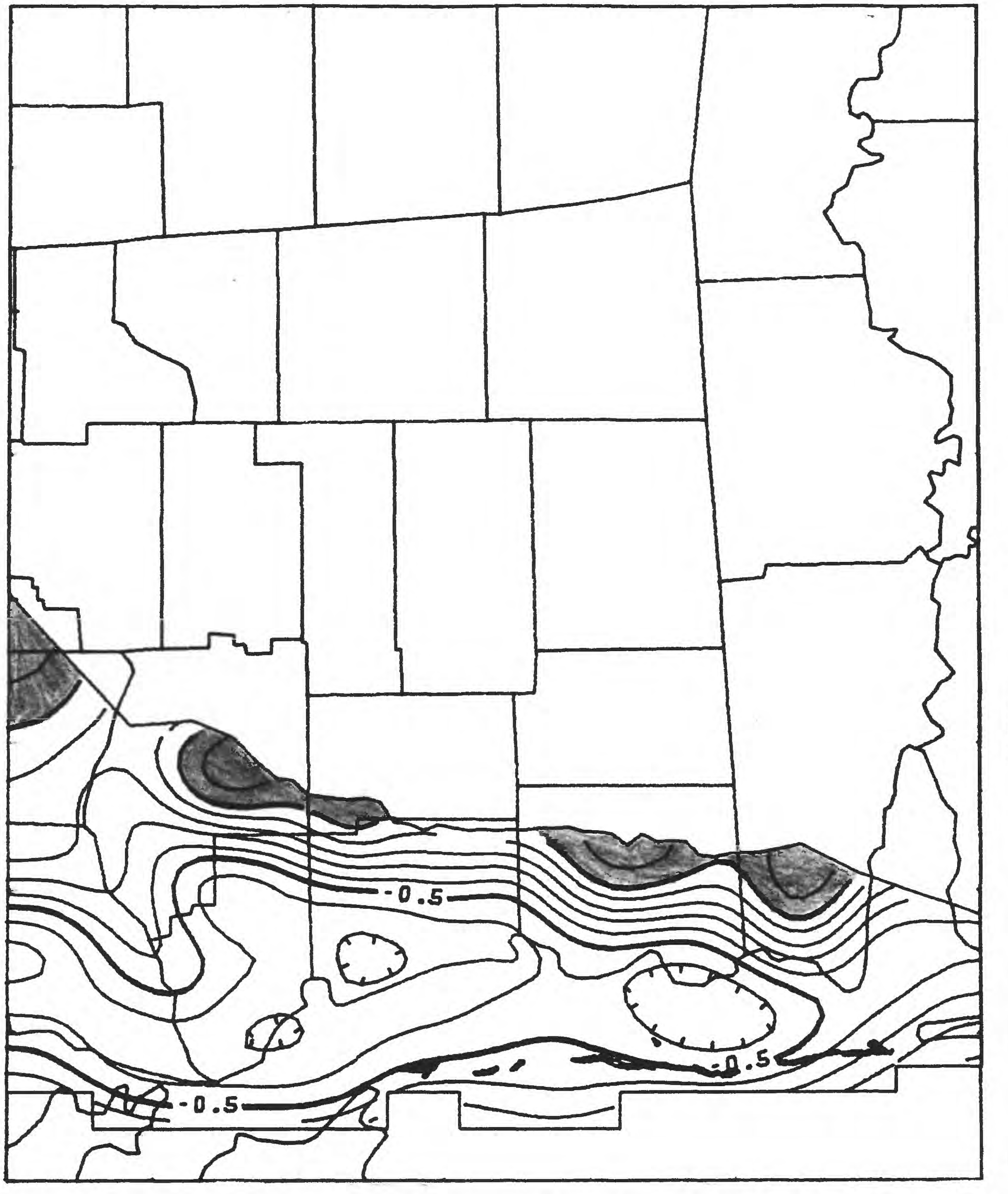
0 10 20 MILES
0 10 20 KILOMETERS

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 5.
Contour interval 0.1 inch

Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.--Continued



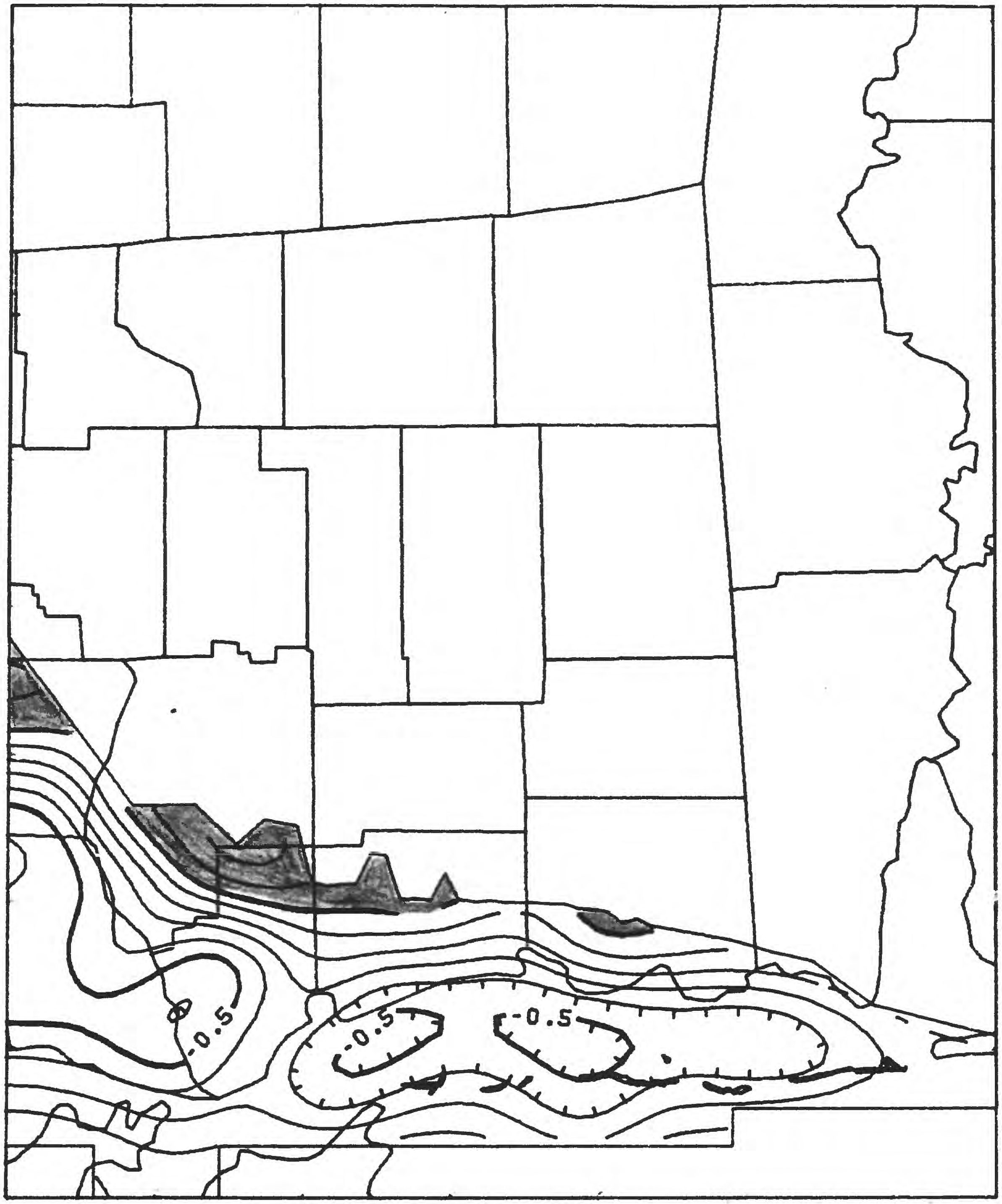
EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 6.
Contour interval 0.1 inch

Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.--Continued



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

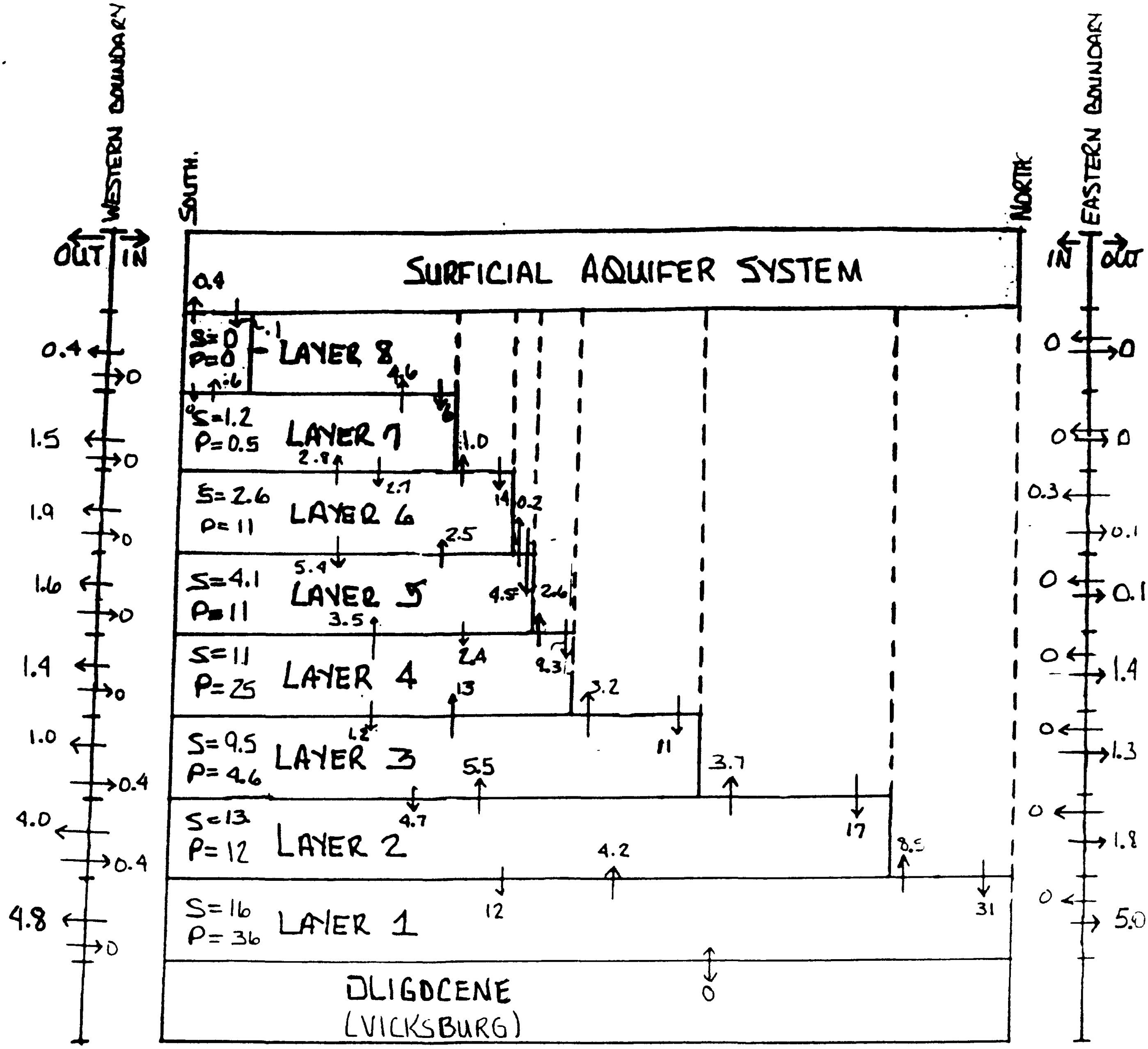
DISCHARGE AREA WHERE FLUX IS UPWARD

—— 0.0 —— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 7. Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 41.--Flux through the top surface of each layer during predevelopment as calculated by the steady-state model.--Continued



Note: Northern and southern boundaries are designated as no flow.

EXPLANATION

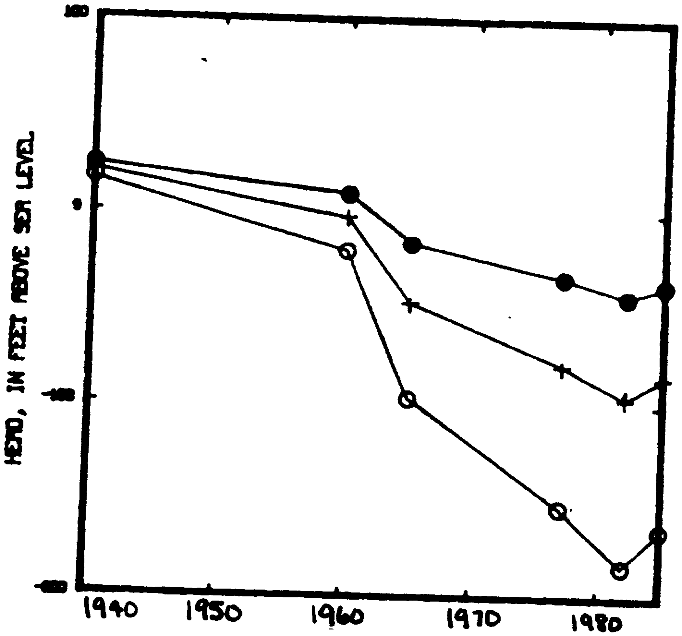
Flow, in million gallons per day

← DIRECTIONAL

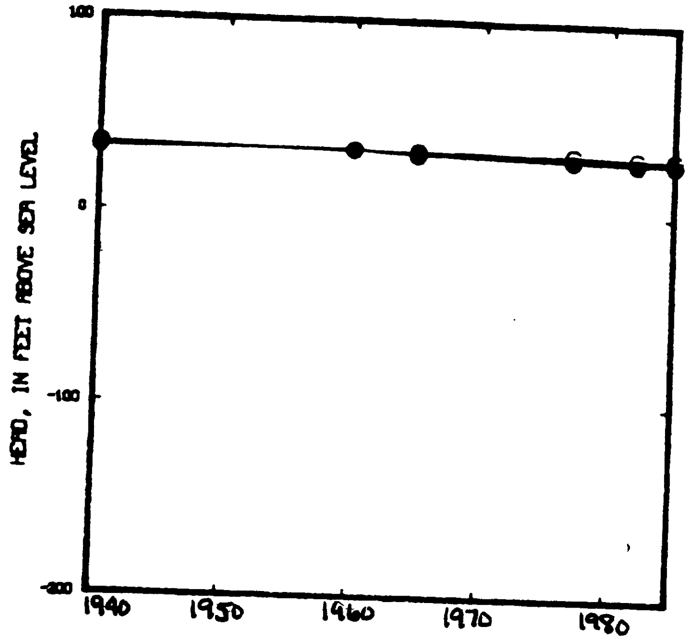
S STORAGE, FROM

P PUMPAGE

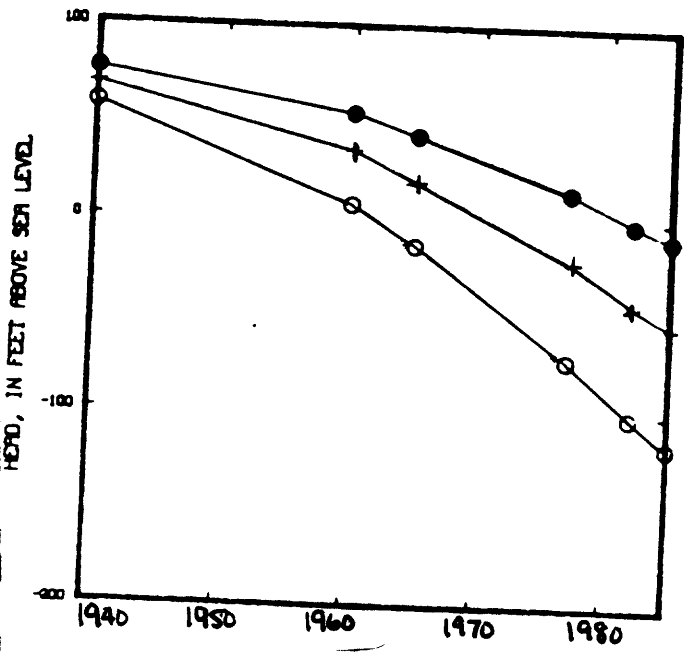
Figure 42.--Schematic diagram of flow simulated by the transient-flow model for the period 1982-85.



Bayou Casotte, Layer 6,
(Node 25,35)



Northern Jackson County, Layer 6,
(Node 12,31)



Biloxi, Layer 4,
(Node 22,22)

EXPLANATION

VALUE OF HORIZONTAL HYDRAULIC CONDUCTIVITY OF AQUIFER MATERIALS USED IN TRANSIENT SIMULATION:

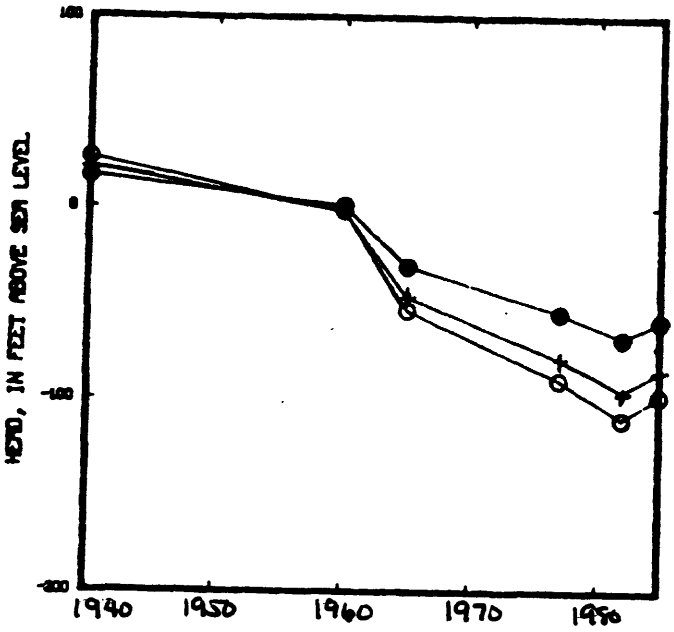
● K_H times 2

\+ K_H

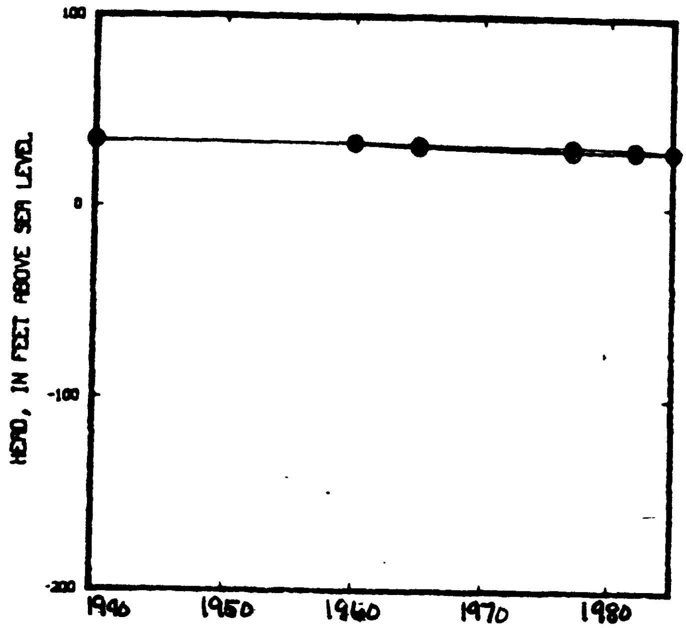
○ K_H divided by 2

WHERE K_H = CALIBRATION-DERIVED PARAMETER VALUE

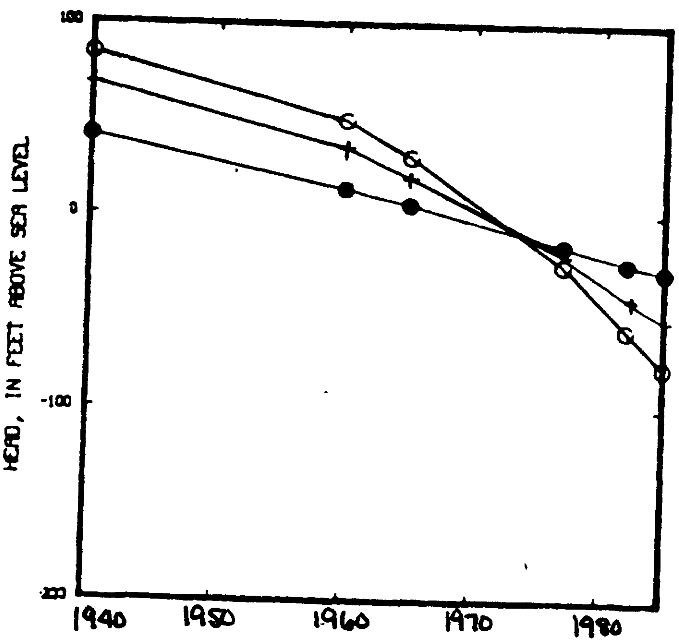
Figure 43 -Analysis of model sensitivity to changes in horizontal hydraulic conductivity of aquifer materials.



Bayou Casotte, Layer 6,
(Node 25,35)



Northern Jackson County, Layer 6,
(Node 12,31)



Biloxi, Layer 4,
(Node 22,22)

EXPLANATION

VALUE OF VERTICAL HYDRAULIC CONDUCTIVITY OF CONFINING MATERIALS USED IN TRANSIENT SIMULATION:

● K_V times 10

+ K_V

o K_V divided by 10

WHERE K_V = CALIBRATION-DERIVED PARAMETER VALUE

Figure 44 --Analysis of model sensitivity to changes in vertical hydraulic conductivity of confining materials.

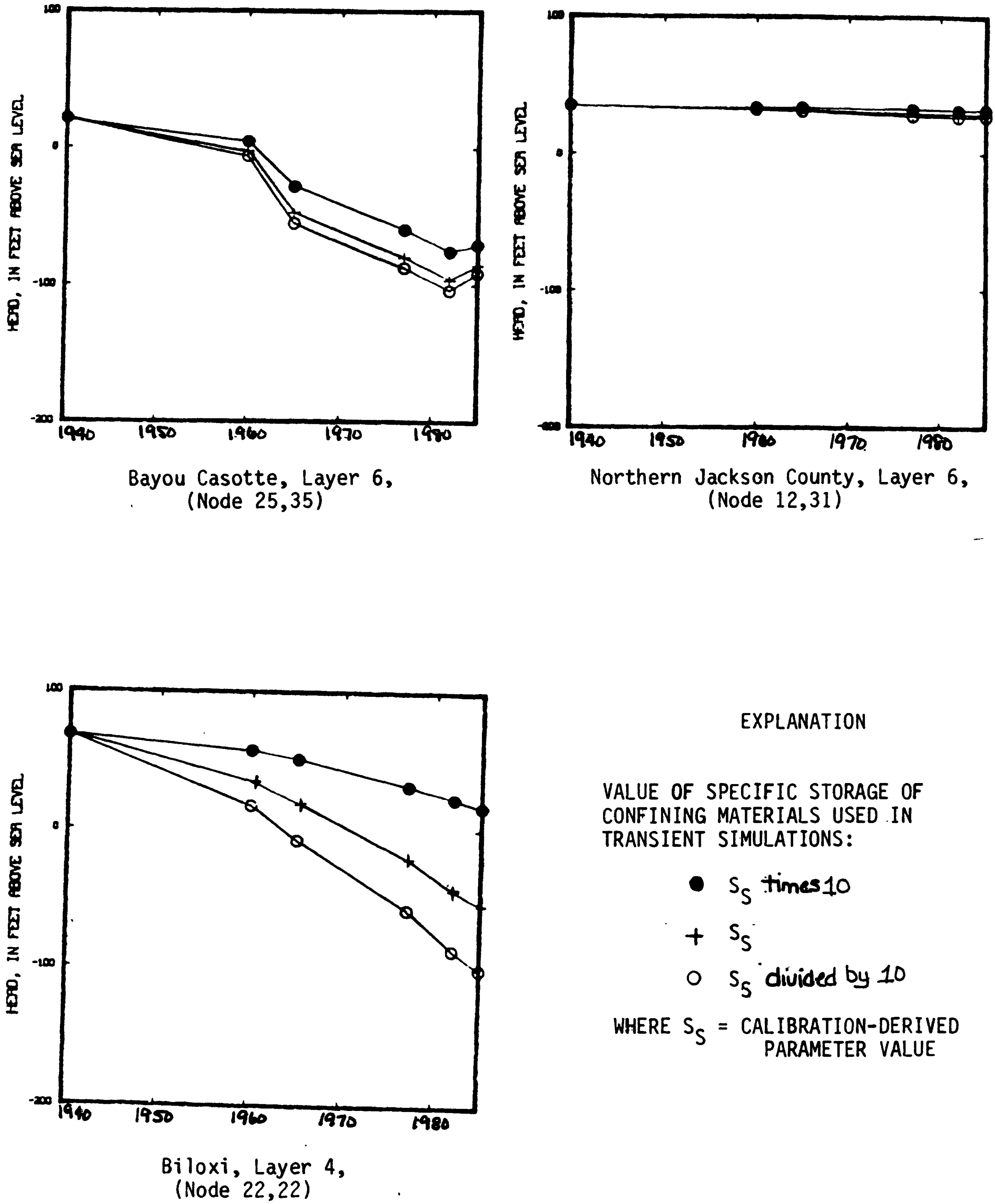


Figure 45 --Analysis of model sensitivity to changes in specific storage of confining materials.

pumping showed very little response to increasing horizontal hydraulic conductivity (fig. 43).

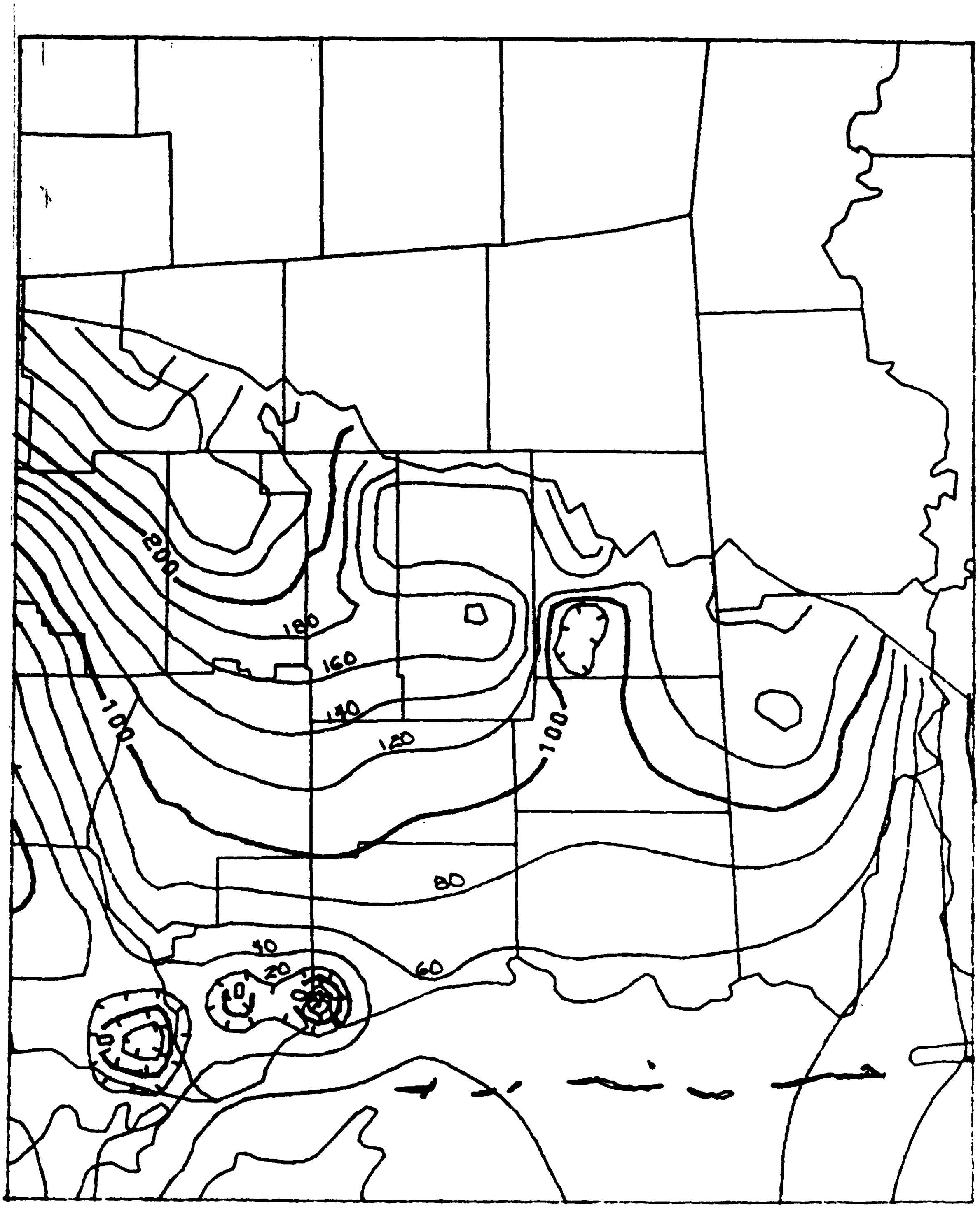
As with horizontal hydraulic conductivity, transient-model sensitivity to vertical hydraulic conductivity of confining materials (fig. 44) in the subcrop node is not pronounced. Within the highly stressed nodes, simulated heads are much more sensitive to changes in this hydraulic parameter (as much as 50 feet).

Water levels in the highly stressed nodes are sensitive (differences as much as 120 feet) to changes in specific storage, whereas, the subcrop node shows little sensitivity (fig. 45). The sensitivity of the node in layer 6 at Bayou Casotte is lower than that of the node in layer 4 at Biloxi because of the relative importance of horizontal flows at the two nodes. The proximity of layer 6 at Bayou Casotte to the subcrop area allows for steep hydraulic gradients and results in high horizontal flows from the subcrop to the pumping centers. Thus, storage effects at this location are less important to the local flow budget than where the subcrop recharge source is more distant.

SIMULATED EFFECTS OF ANTICIPATED GROUND-WATER WITHDRAWALS

The effects of projected ground-water withdrawals on the water levels and quality of water in the aquifers along the Mississippi Gulf Coast were a primary concern of this study. To address this concern, the numerical model was used to evaluate the effects of a 1.5 percent anticipated annual increase in ground-water withdrawals (Charles Branch, Mississippi Bureau of Land and Water Resources, oral commun., 1987) along the Gulf Coast between 1985 and 2005 (potentiometric maps, fig. 46).

The specified eastern and western boundary heads of the transient model were based on extrapolations of current trends (hydrograph, fig. 31). The effect of these extrapolations on the model-projected potentiometric surfaces (fig. 46) were evaluated by two predictive simulations with markedly different eastern and western boundary heads. The two boundary head conditions used in the sensitivity analysis are 1) 1983 east and west boundary heads are maintained throughout predictive simulations, and 2) rate of decline of east and west boundary heads is twice that used in the predictive model (fig. 31). These two conditions bracket the best estimate of east and west boundary heads in the predictive model (fig. 31). Head distributions generated by the predictive simulations show negligible sensitivity in the areas of primary concern (figures 46, 47, and 48). A full set of potentiometric maps for 2005 for the two sensitivity simulations was made and none of them showed noticeable difference in heads east of the Hancock-Harrison County line. Changes in heads along the eastern boundary had no noticeable effect on any of the potentiometric maps of the various layers. Changes in heads along the western boundary were greater than those in the east and heads near the western boundary were affected more. Two of these potentiometric maps that showed the greatest water-level change in response to boundary head change were for

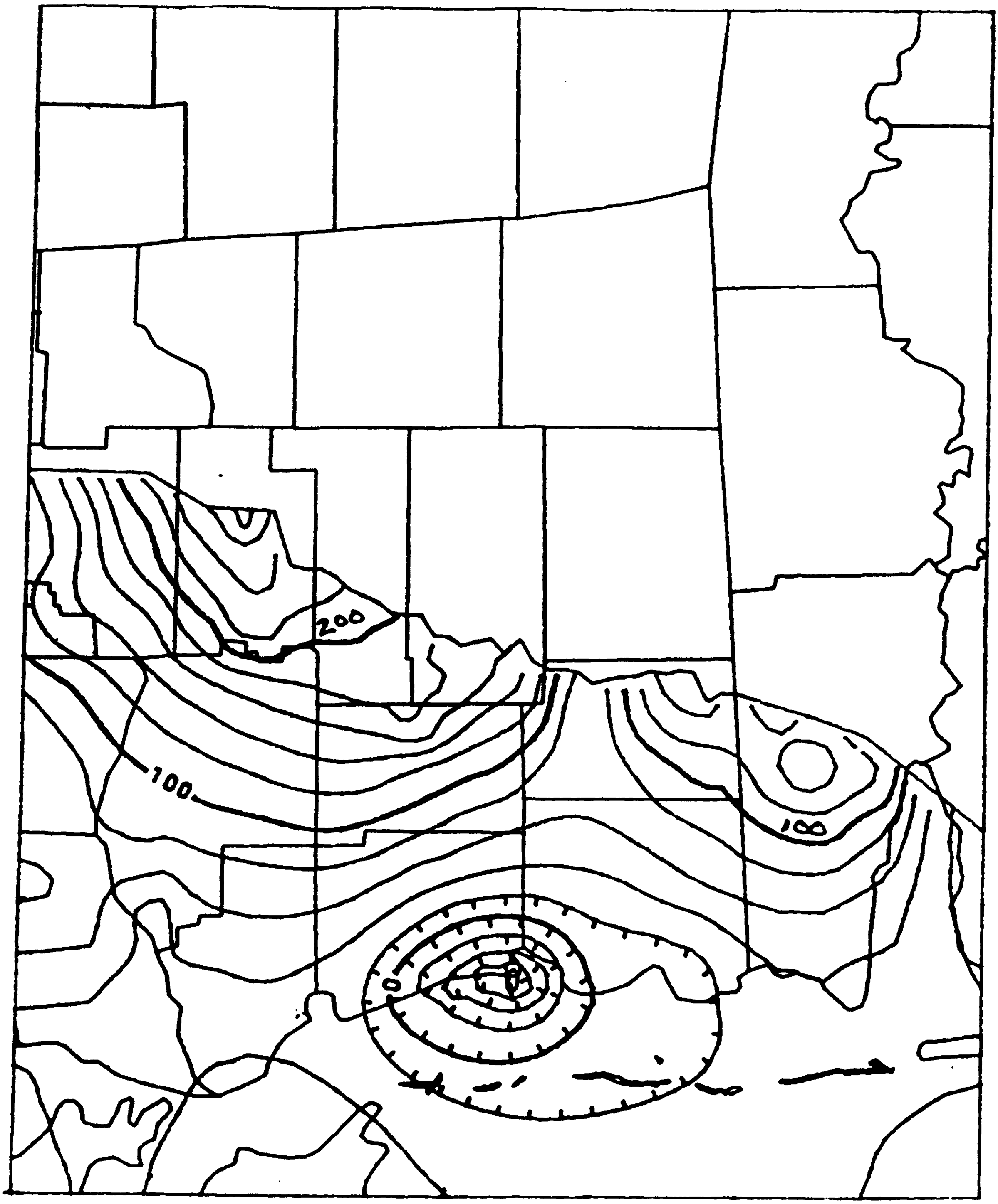


EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

—— 100 —— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 2. Contour interval 20 feet. Datum is sea level

Figure 46.--Potentiometric surface for selected layers as simulated by the transient-flow model for the year 2005.

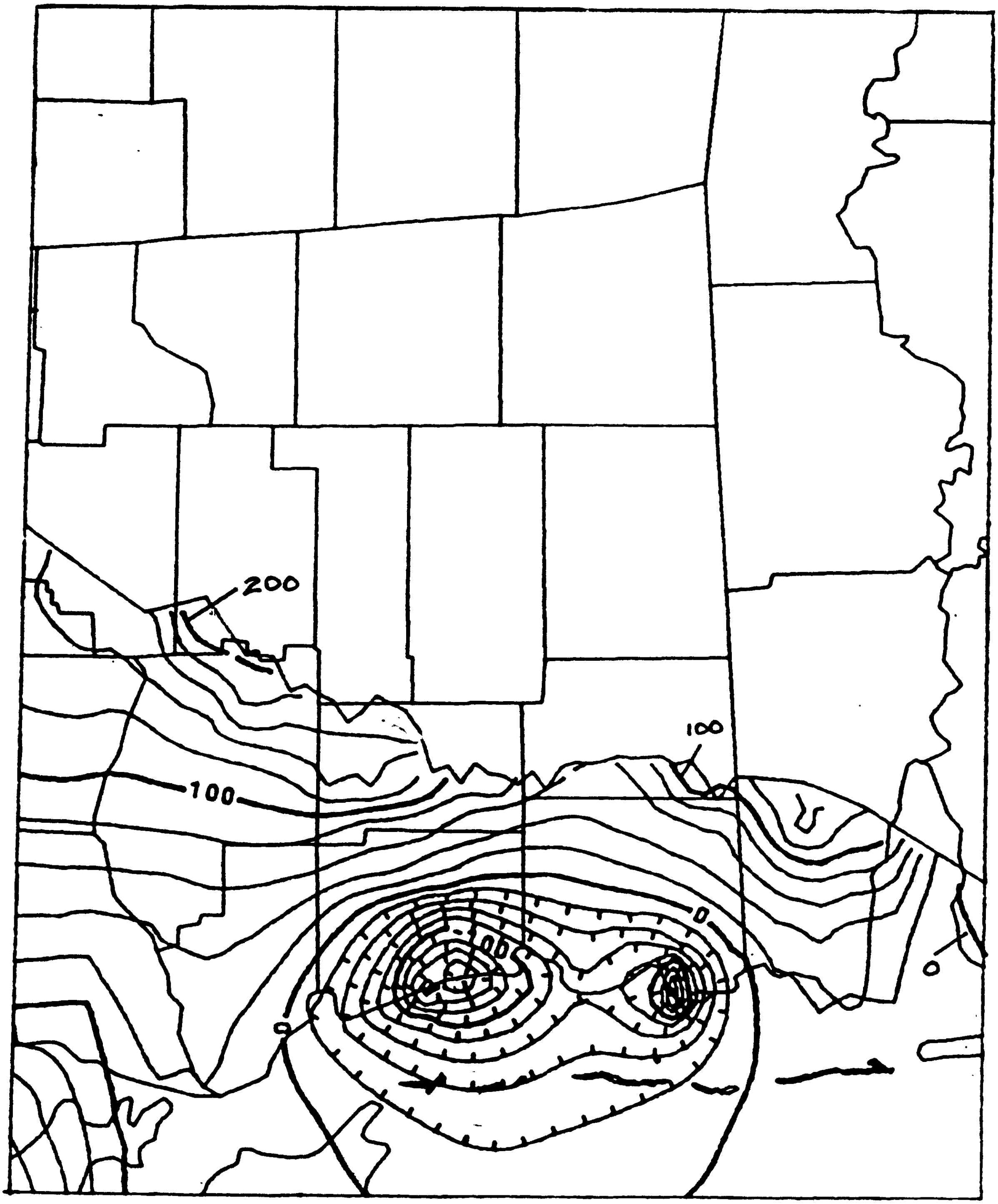


EXPLANATION

—— 100 —— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 3. Contour interval 20 feet. Datum is sea level

0 10 20 MILES
0 10 20 KILOMETERS

Figure 46.--Potentiometric surface for selected layers as simulated by the transient-flow model for the year 2005.--Continued

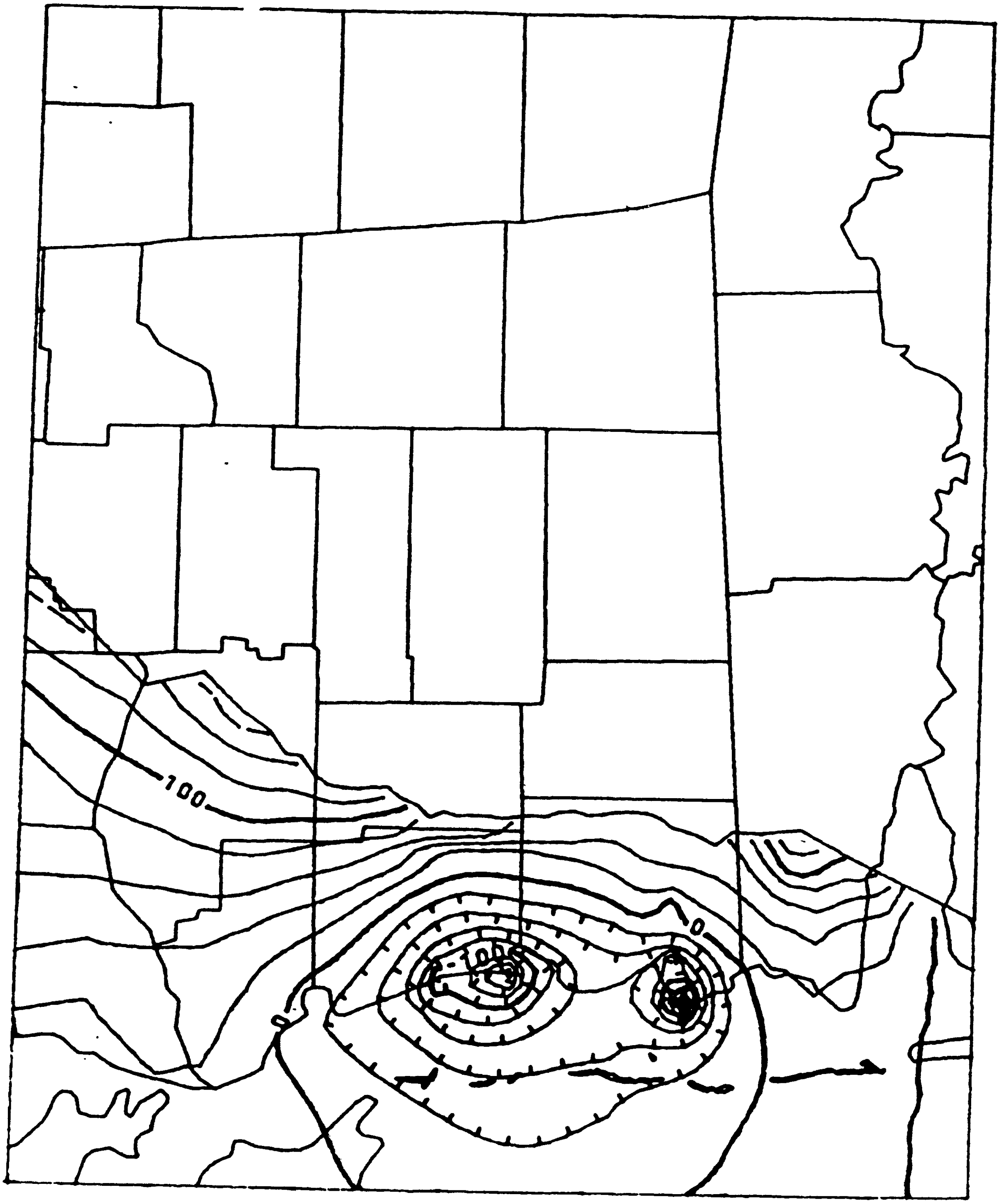


EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

—— 100 —— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 4. Contour interval 20 feet. Datum is sea level

Figure 46.--Potentiometric surface for selected layers as simulated by the transient-flow model for the year 2005.--Continued

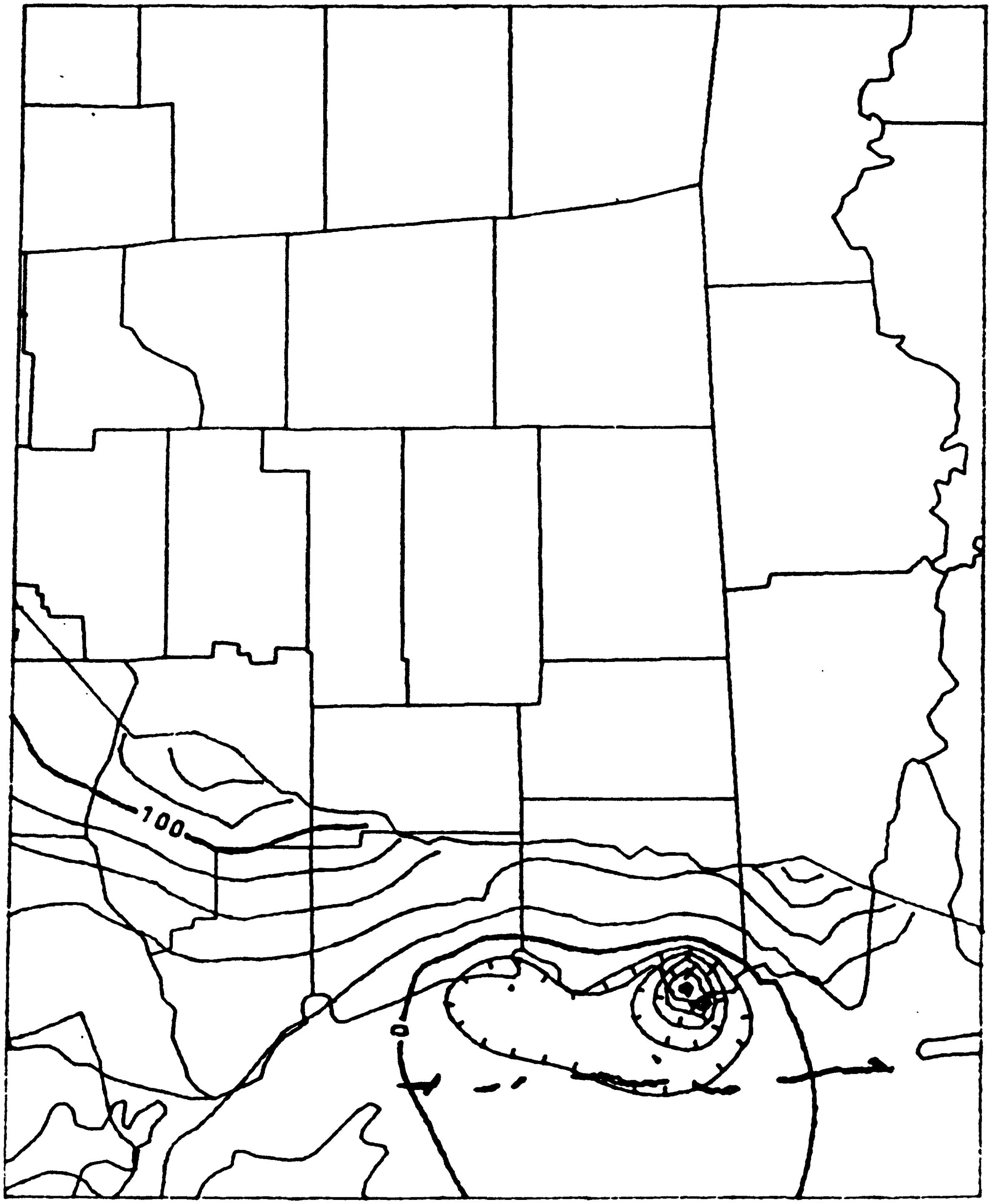


EXPLANATION

—— 100 —— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 5. Contour interval 20 feet. Datum is sea level

0 10 20 MILES
0 10 20 KILOMETERS

Figure 46.--Potentiometric surface for selected layers as simulated by the transient-flow model for the year 2005.--Continued

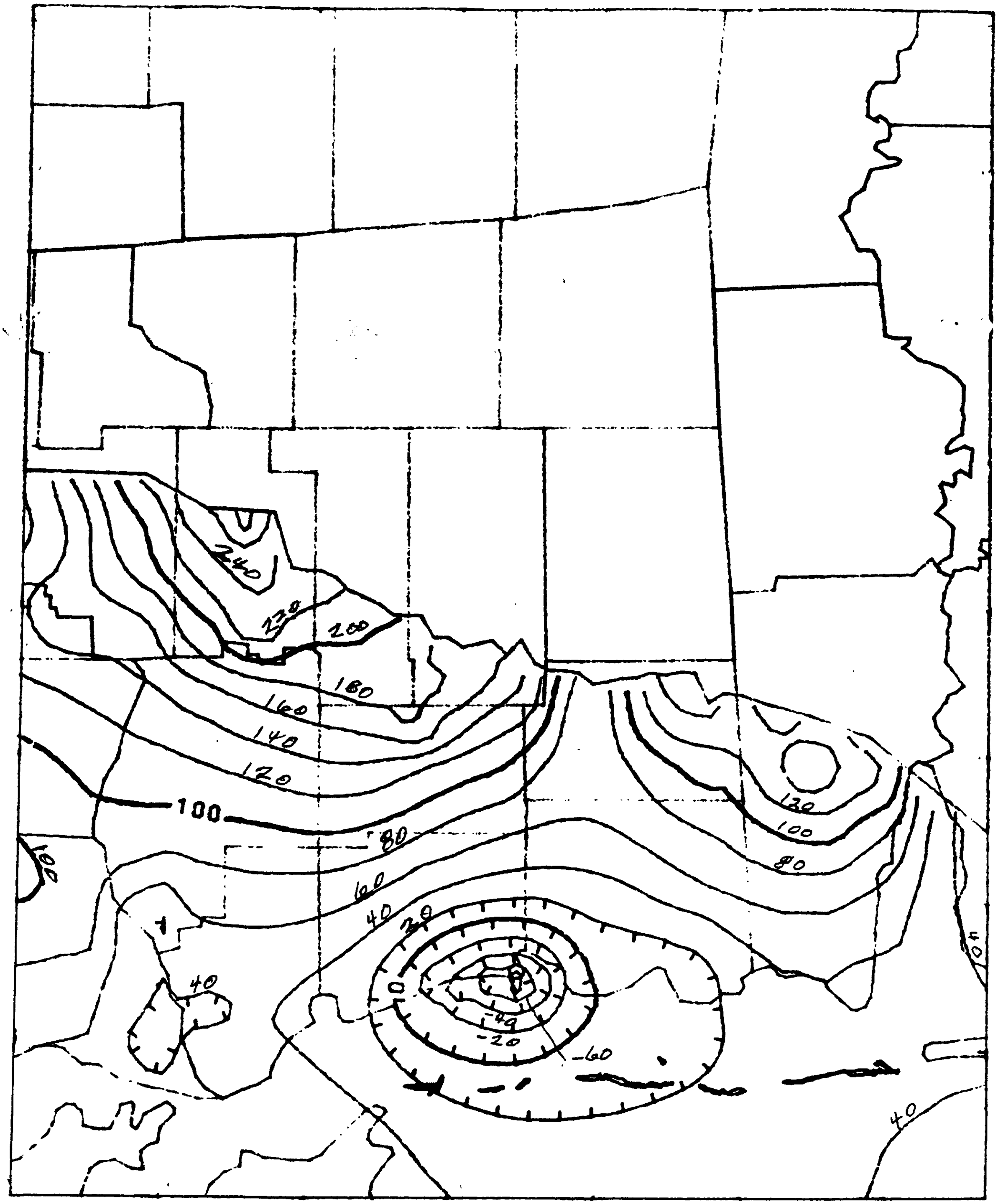


EXPLANATION

—— 100 —— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface of layer 6. Contour interval 20 feet. Datum is sea level

0 10 20 MILES
0 10 20 KILOMETERS

Figure 46.--Potentiometric surface for selected layers as simulated by the transient-flow model for the year 2005.--Continued



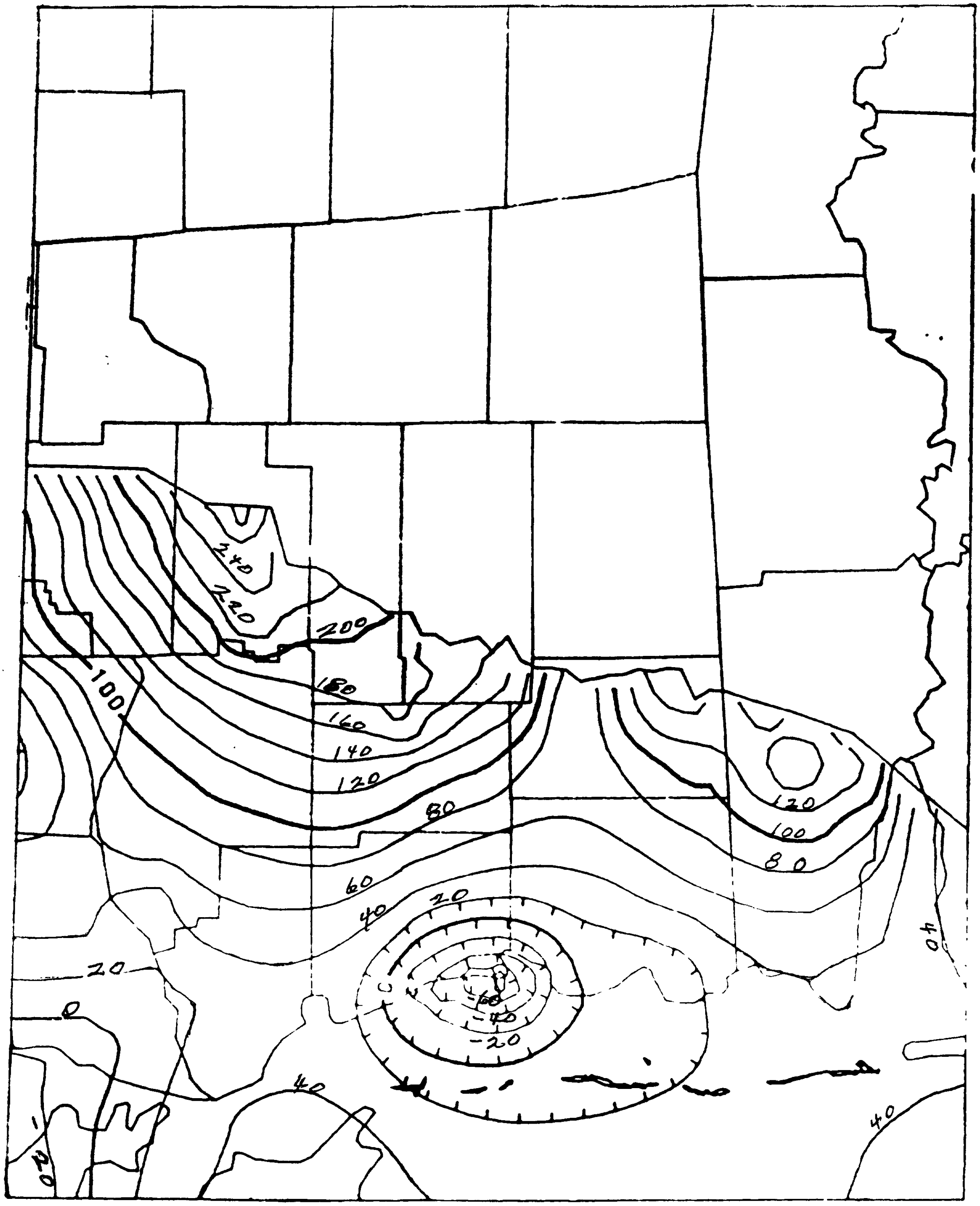
EXPLANATION

—— 100 —— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface.
Contour interval 20 feet.
Datum is sea level.

0 10 20 Miles

0 10 20 Kilometers

Figure 47.--Potentiometric surface for layer 3 for the year 2005, assuming no water-level change in nodes along the western boundary between 1983 and 2005.



EXPLANATION

—— 100 —— POTENTIOMETRIC CONTOUR--Shows altitude of potentiometric surface.
Contour interval 20 feet.
Datum is sea level.

0 10 20 Miles
0 10 20 Kilometers

Figure 48.--Potentiometric surface for layer 3 for the year 2005, assuming twice as much water-level decline as in the predictive model (fig. 46) in the specified nodes along the western boundary between 1983 and 2005.

layer 3 and are shown in figures 47 and 48. Thus, specification of the lateral boundary heads based on extrapolations of current heads should not significantly affect the results in the area of concern.

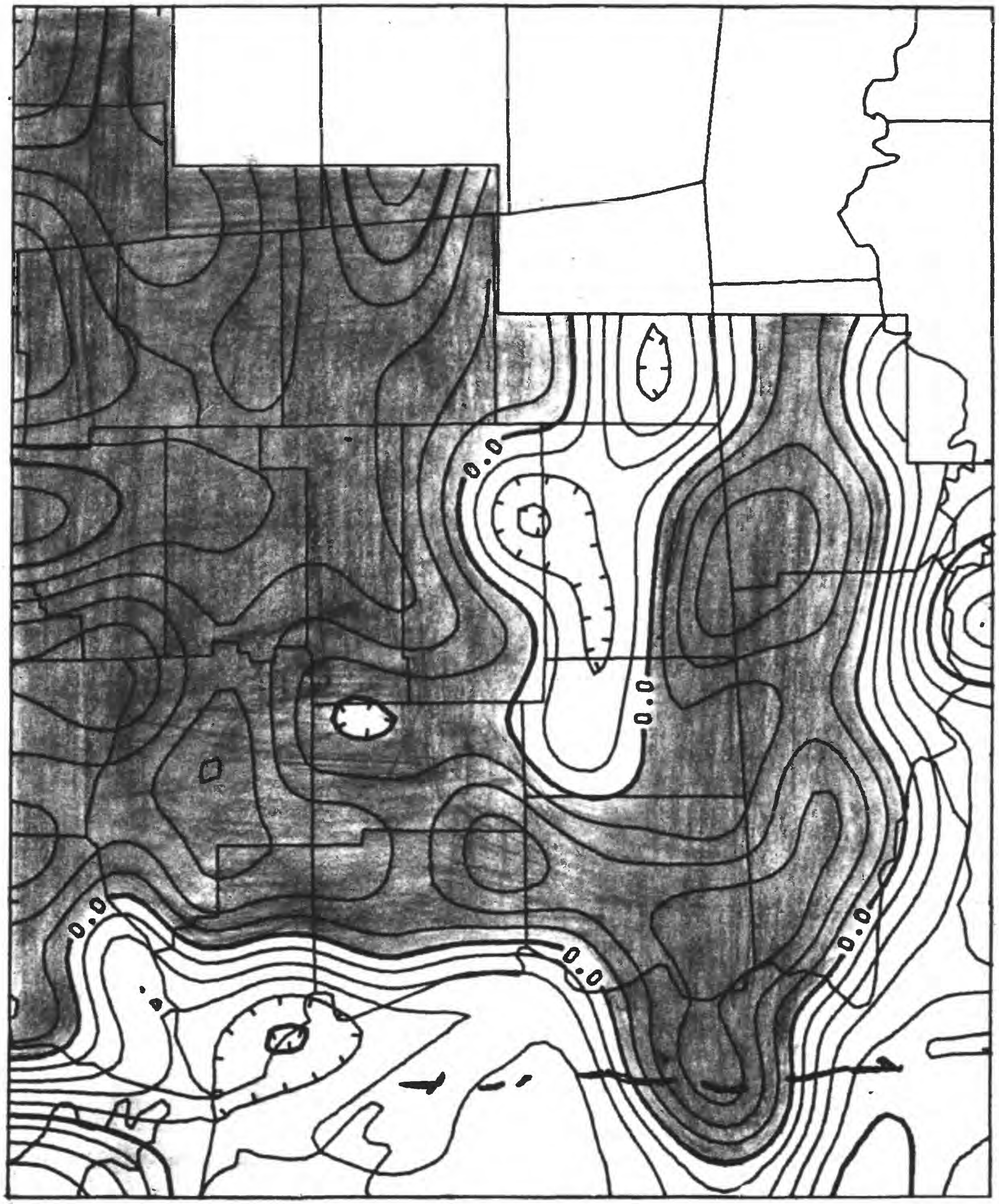
Model-projected potentiometric surfaces (fig. 46) for the various layers for the year 2005 were simulated assuming a 1.5 percent annual increase in withdrawals. Generally, depressions within the potentiometric surfaces will be larger and deeper compared to the 1985 surfaces. In the Biloxi-Gulfport area, the maximum water-level decline is projected to be about 50, 135, and 100 feet for layers 3, 4, and 5, respectively. Maximum drawdown in the Pascagoula area is projected to be about 30 and 40 feet for layers 4 and 6, respectively. Water levels in the subcropping parts of the model layers are projected to be relatively unchanged. In much of the western part of the coastal area and in areas more than 10 miles north of the coast, projected declines by the year 2005 generally are less than 20 feet in all layers.

Significant changes in the direction and magnitude of vertical flow (figs. 41, 49, and 50) from 1900 to 1985 and to 2005 have and will result from increased ground-water development. Large amounts of water will be captured from the surficial aquifer system as shown in a schematic (fig. 51). Pumping will also induce significant changes in the flow budget among layers (table 3) and between the layers and the surficial aquifer system.

The most critical ground-water withdrawal and water-quality problems along the coast are in the Pascagoula area. Seven of the eight aquifer layers of the Miocene aquifer system and the surficial aquifer occur at this location. To better describe the flow system in this area, water budgets for each layer in a 27-node segment of the numerical model (columns 33-35 and rows 19-26) were projected for the period 2000-05.

Projected water budgets for each layer in the Pascagoula area indicate that in 2005 most of the pumpage in the area will be from layers 6 and 4 (11.76 and 6.07 Mgal/d), respectively. Combined pumpage from the other layers will be 1.19 Mgal/d. Net flows to layer 5 will occur from all directions. Transmissivity of layer 5 in the Pascagoula area is low, and the small pumpage of 0.65 Mgal/d will cause water levels in layer 5 to be lower than in the adjoining layers. Net flows to layers 4 and 6 will be positive from all directions, except for vertical flows to layer 5. About 0.38 Mgal/d will flow from layer 3 to layer 4. Dissolved-solids concentrations in layer 3 are greater than 1,000 mg/L, and thus, any upward flow of water from layer 3 will tend to contaminate the water in layer 4. In layers 3 through 7, flow will be toward the Pascagoula area from all horizontal directions, threatening the pumping center by saltwater encroachment from the south (fig. 21).

The model projects that a small amount of water will be coming from storage in the period 2000-05; in the Pascagoula area, only 0.5 Mgal/d will be supplied from storage.



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

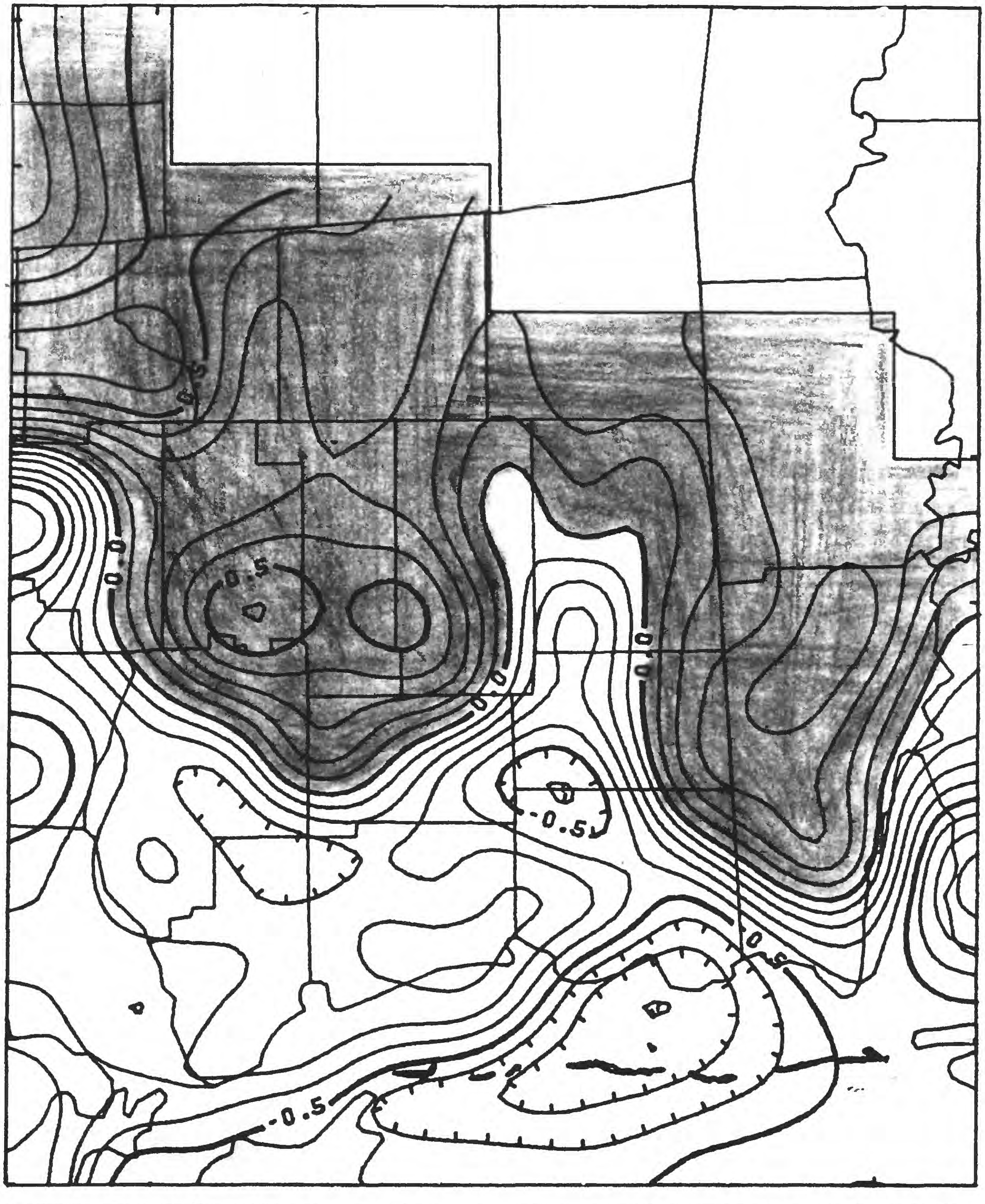
DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in the surficial aquifer. Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 49.--Flux through the top surface of each layer during 1982-85.



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

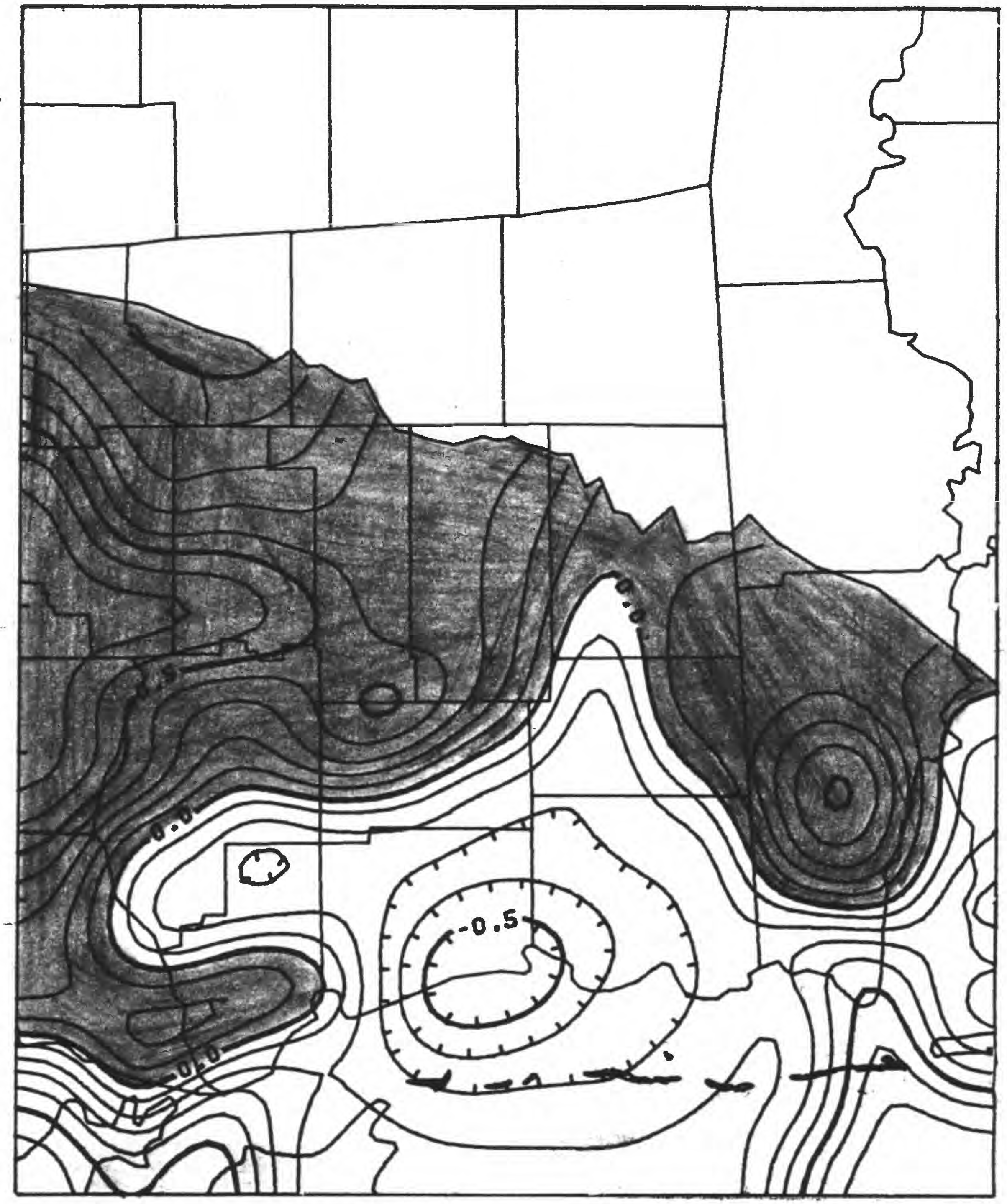
DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 1. Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 49.--Flux through the top surface of each layer during 1982-85.--Continued



EXPLANATION

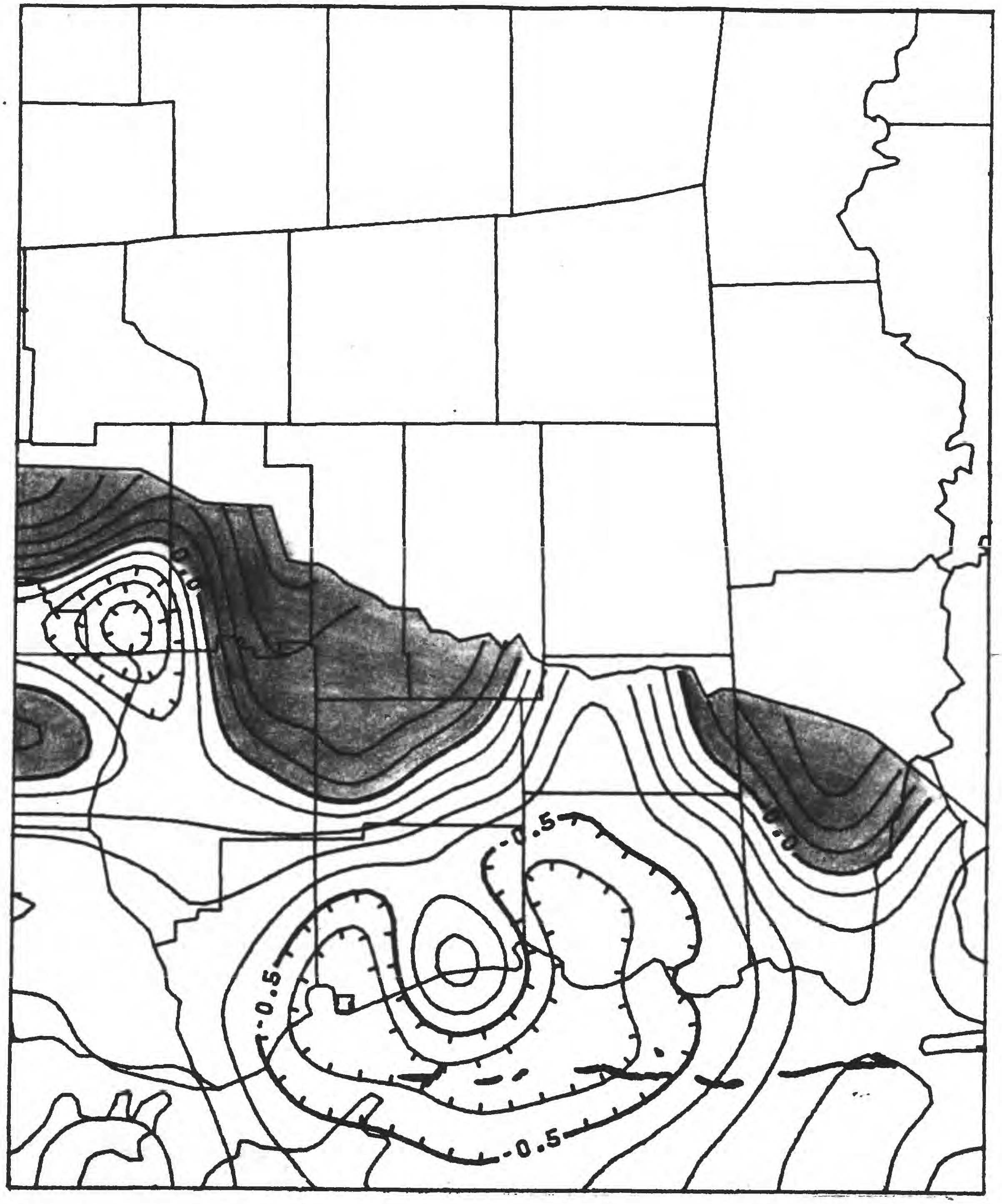
RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 2. Contour interval 0.1 inch

0 10 20 MILES
0 10 20 KILOMETERS

Figure 49.--Flux through the top surface of each layer during 1982-85.--Continued



EXPLANATION

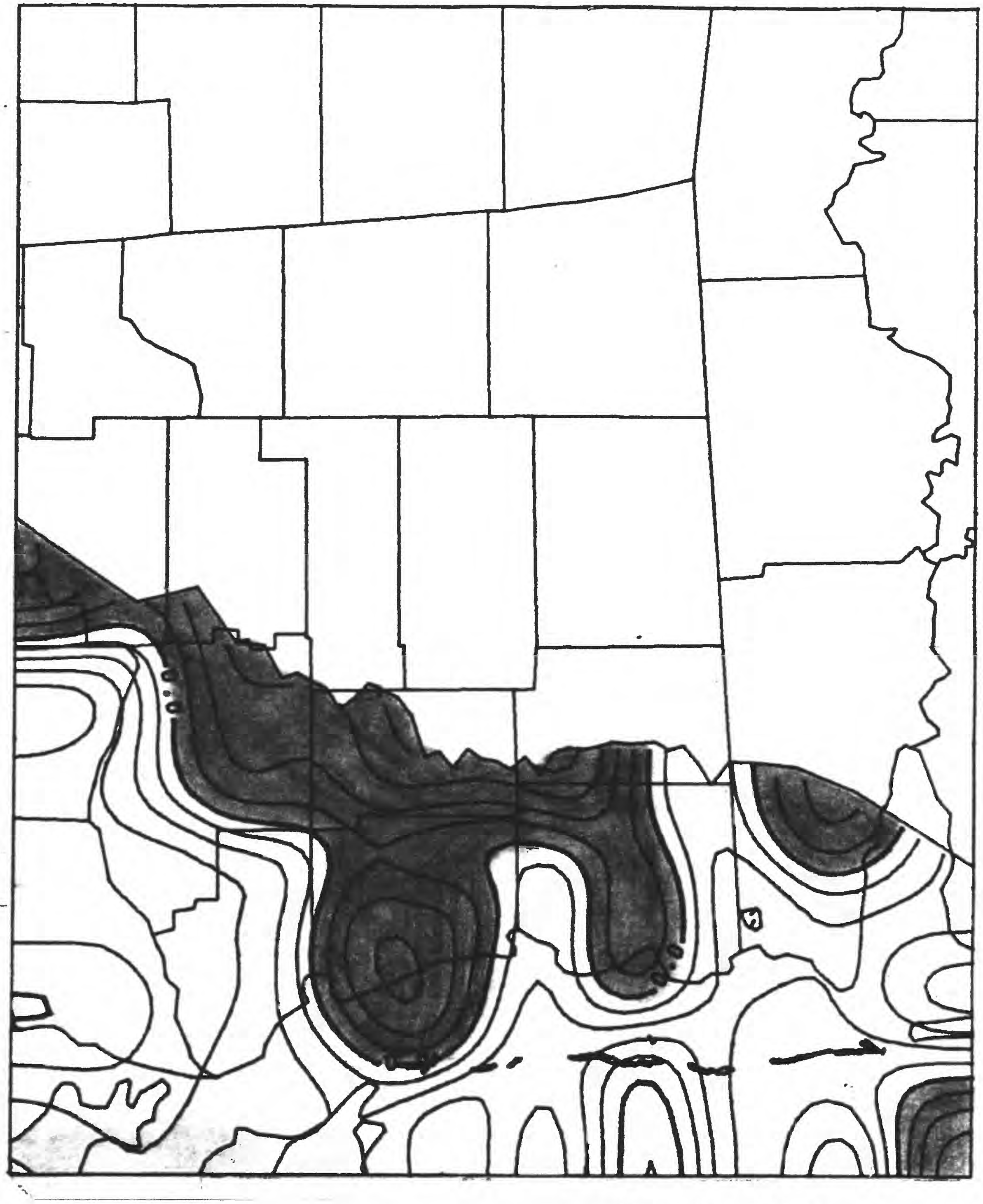
RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 3.
Contour interval 0.1 inch

0 10 20 MILES
0 10 20 KILOMETERS

Figure 49.--Flux through the top surface of each layer during 1982-85.--Continued



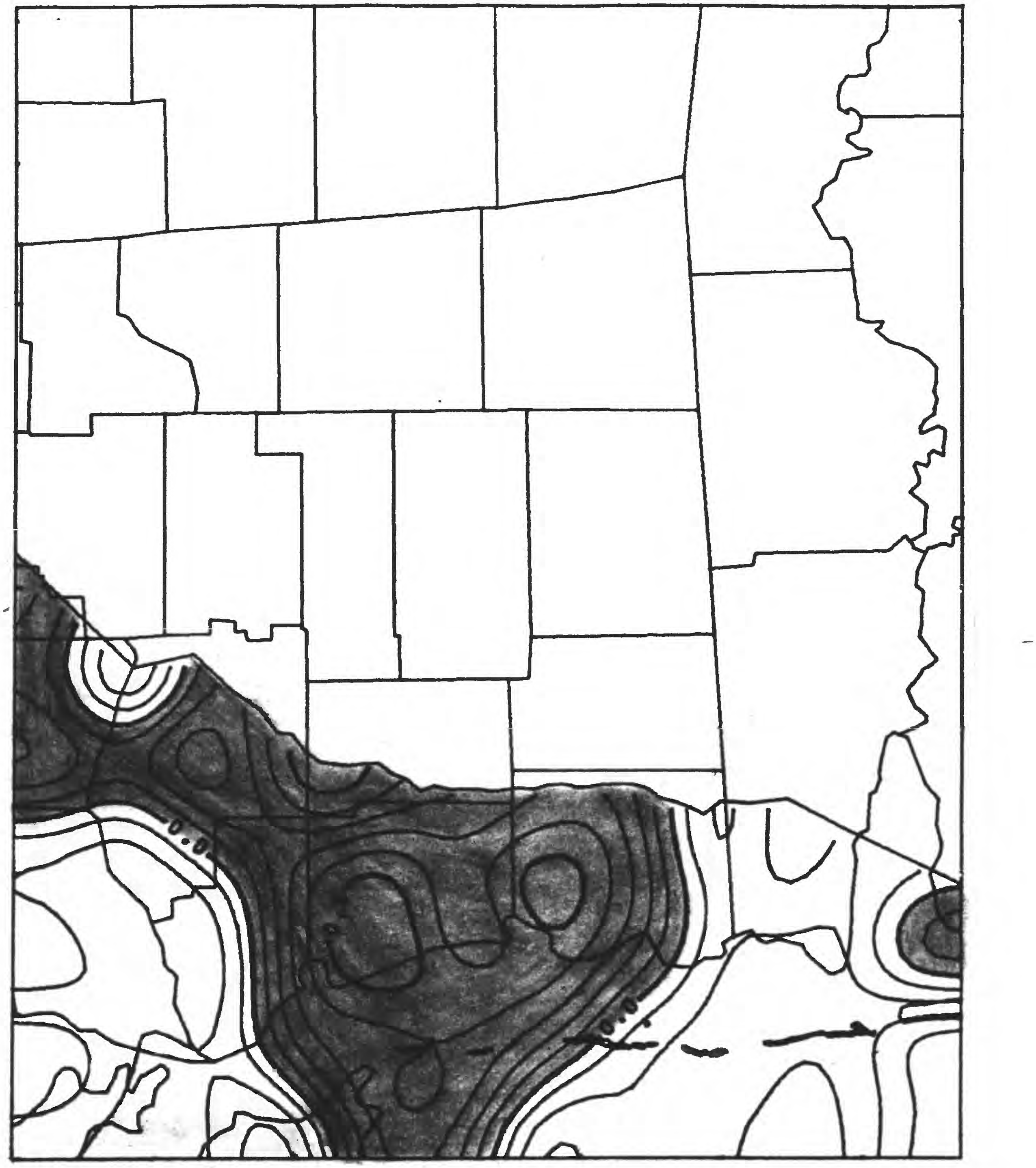
EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 4. Contour interval 0.1 inch

Figure 49.--Flux through the top surface of each layer during 1982-85.--Continued



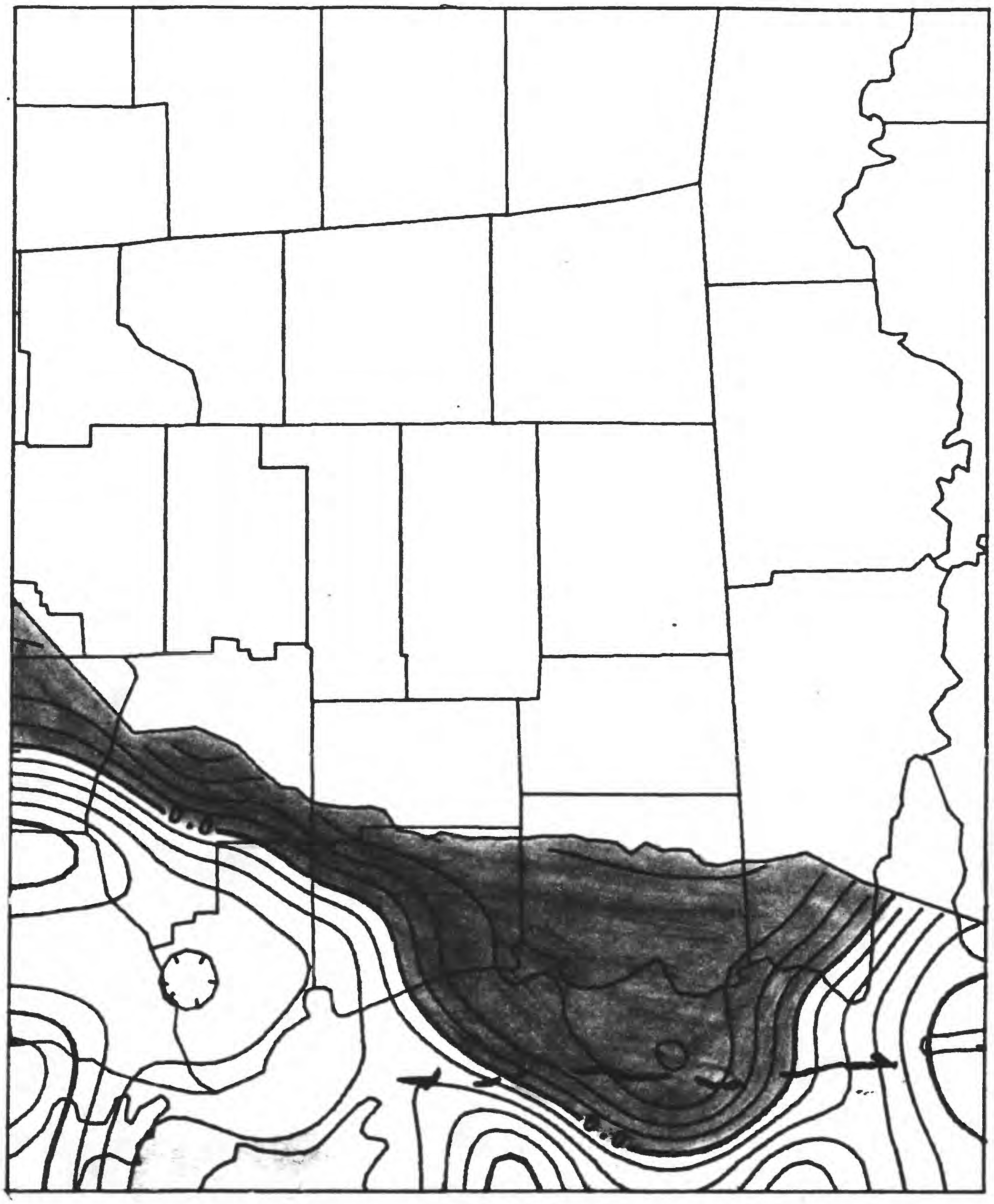
EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 5.
Contour interval 0.1 inch

Figure 49.--Flux through the top surface of each layer during 1982-85.--Continued



EXPLANATION

0 10 20 MILES
0 10 20 KILOMETERS

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 6.
Contour interval 0.1 inch

Figure 49.--Flux through the top surface of each layer during 1982-85.--Continued

EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

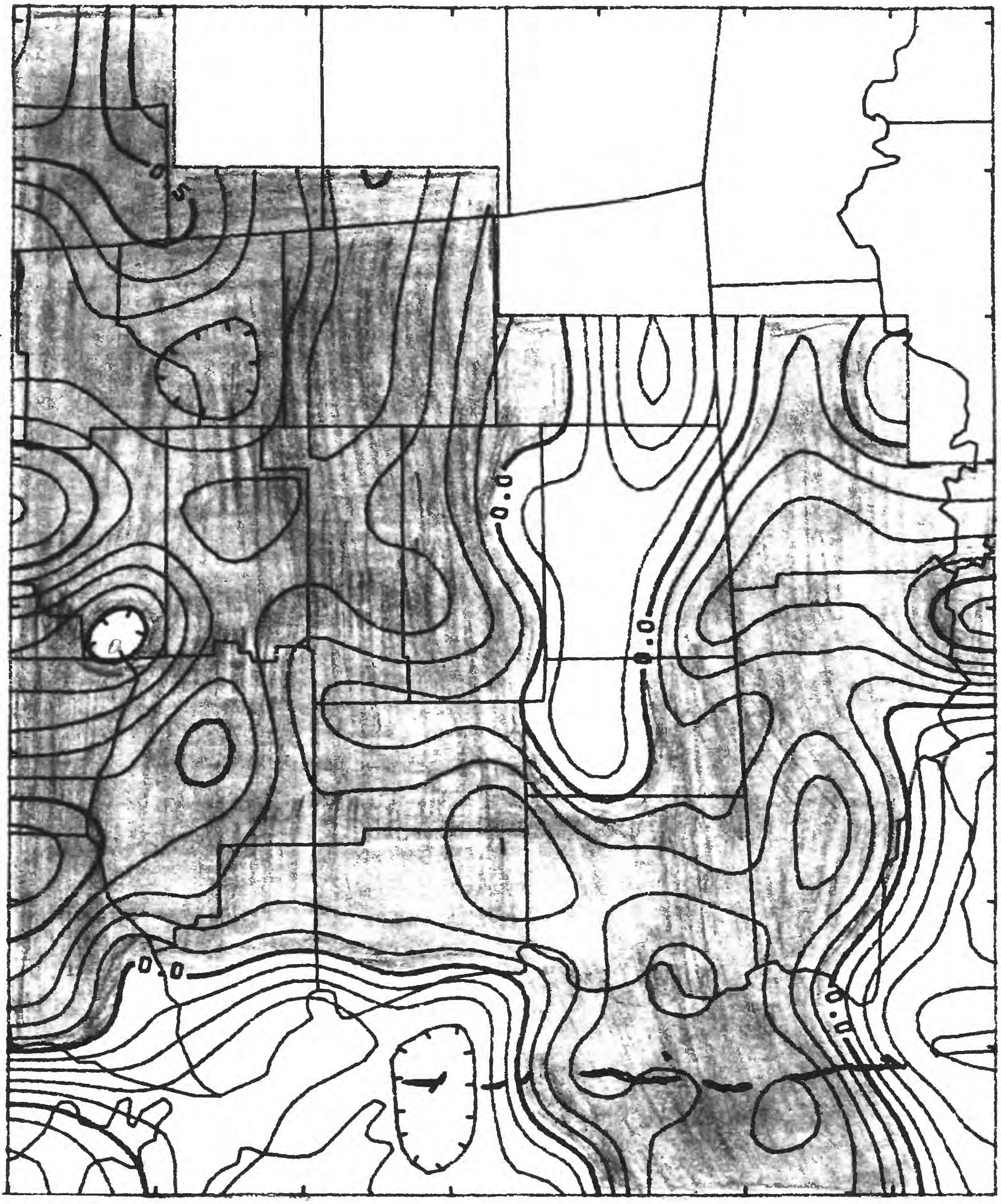
DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 7. Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 49.--Flux through the top surface of each layer during 1982-85.--Continued



EXPLANATION

0 10 20 MILES

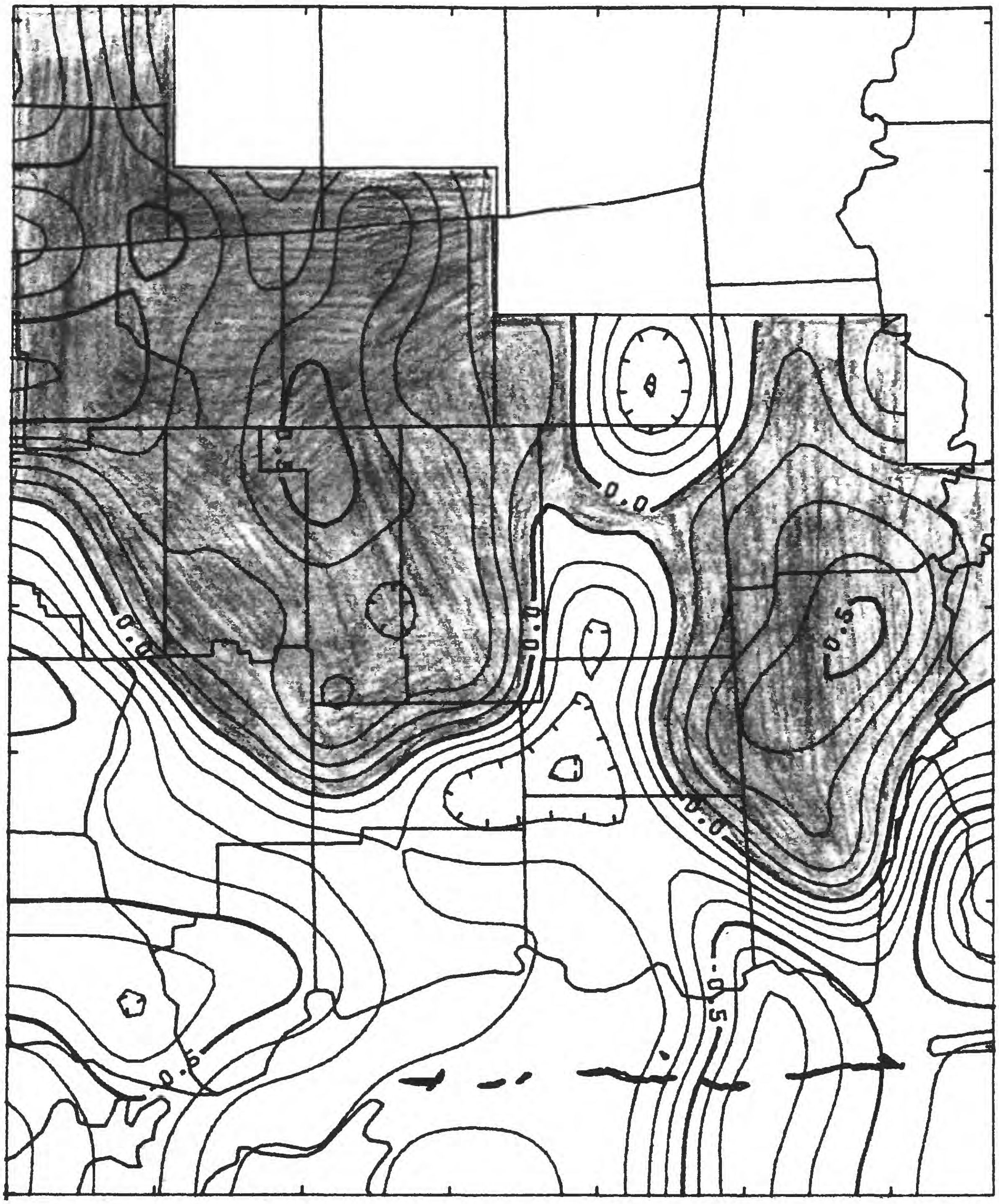
0 10 20 KILOMETERS

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in the surficial aquifer. Contour interval 0.1 inch

Figure 50.--Flux through the top surface of each layer during 2000-05.



EXPLANATION

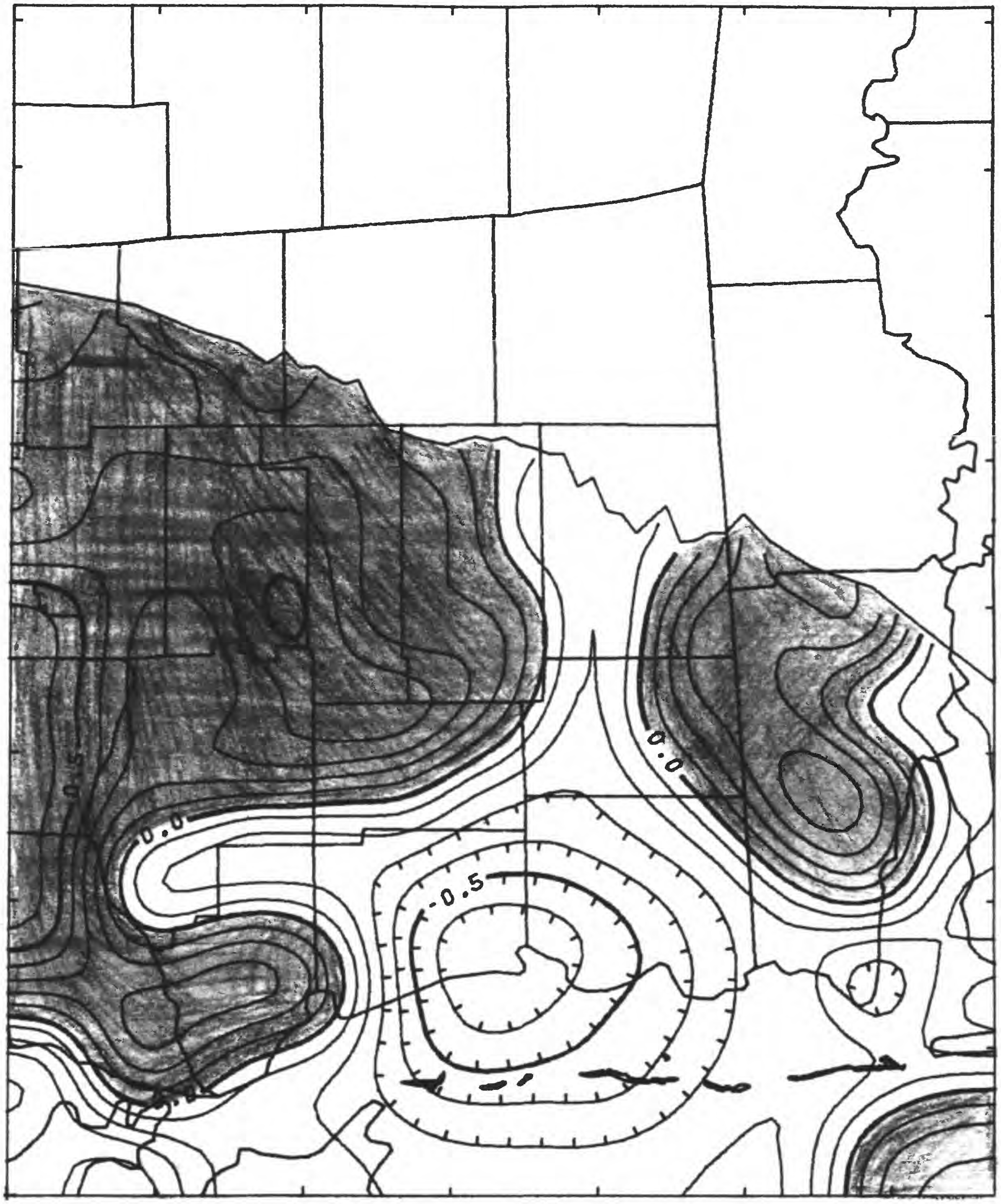
0 10 20 MILES
0 10 20 KILOMETERS

RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 1.
Contour interval 0.1 inch

Figure 50.--Flux through the top surface of each layer during 2000-05.--Continued



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

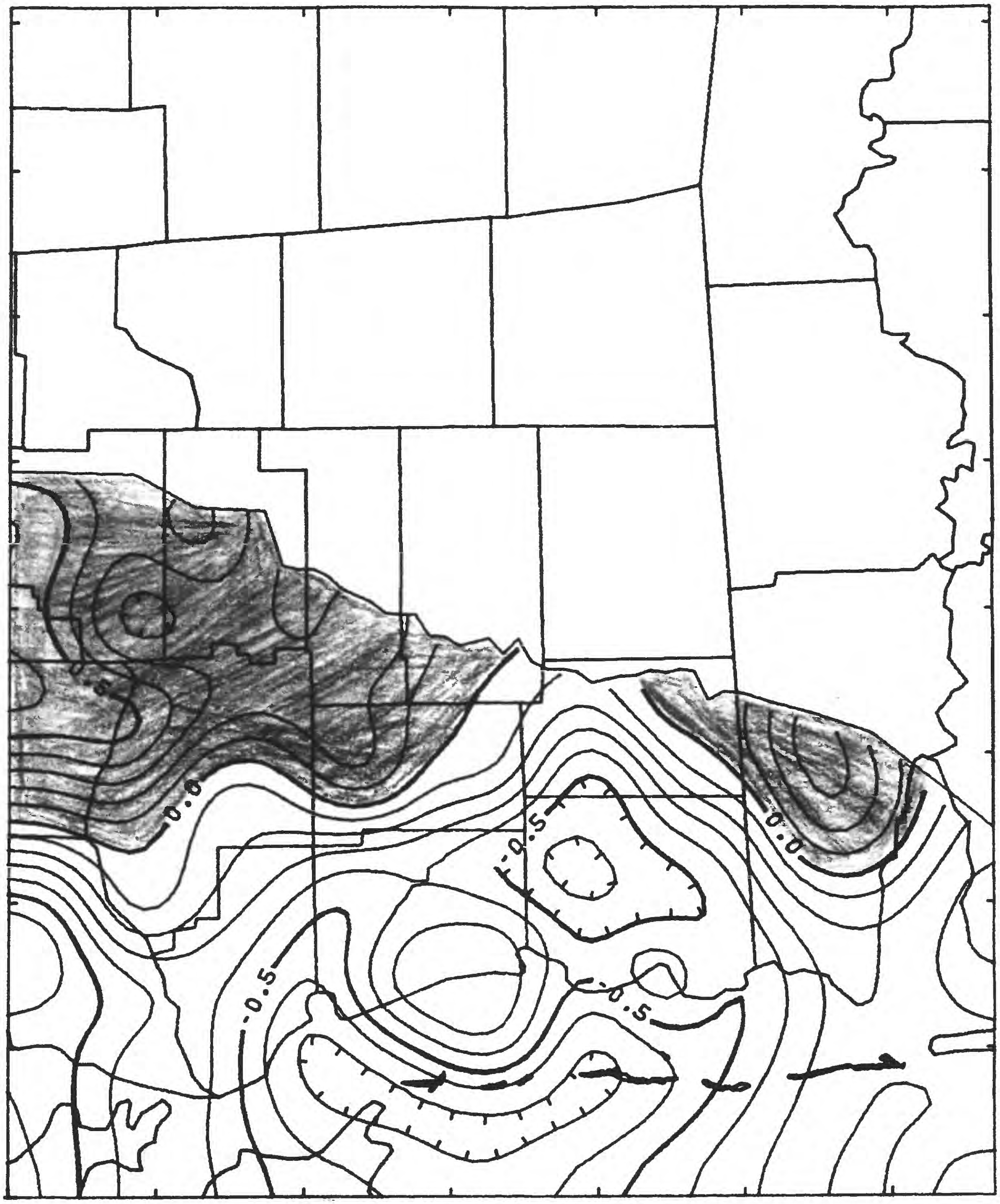
DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 2.
Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 50.--Flux through the top surface of each layer during 2000-05.--Continued



EXPLANATION

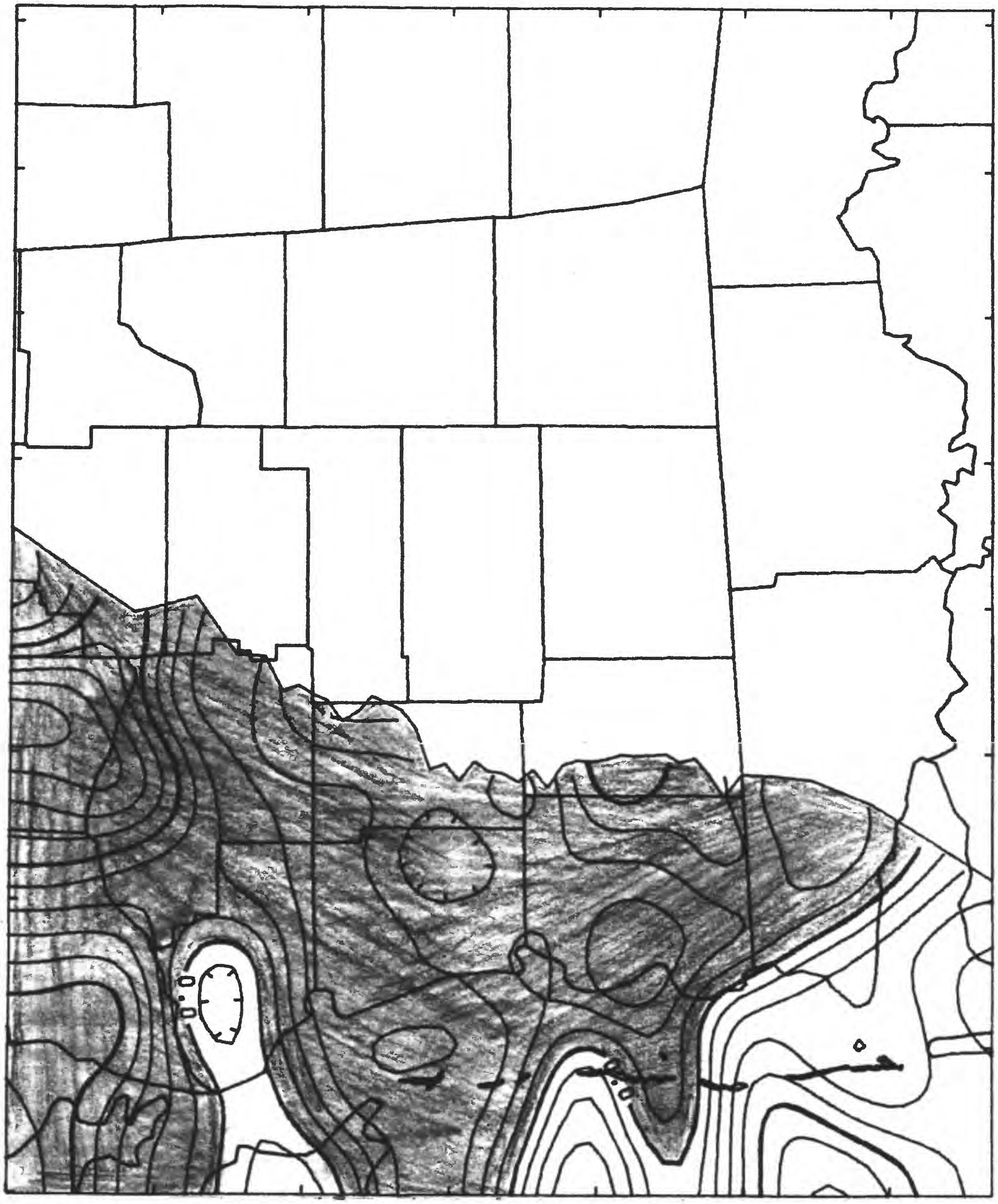
RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 3. Contour interval 0.1 inch

0 10 20 MILES
0 10 20 KILOMETERS

Figure 50.--Flux through the top surface of each layer during 2000-05.--Continued



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

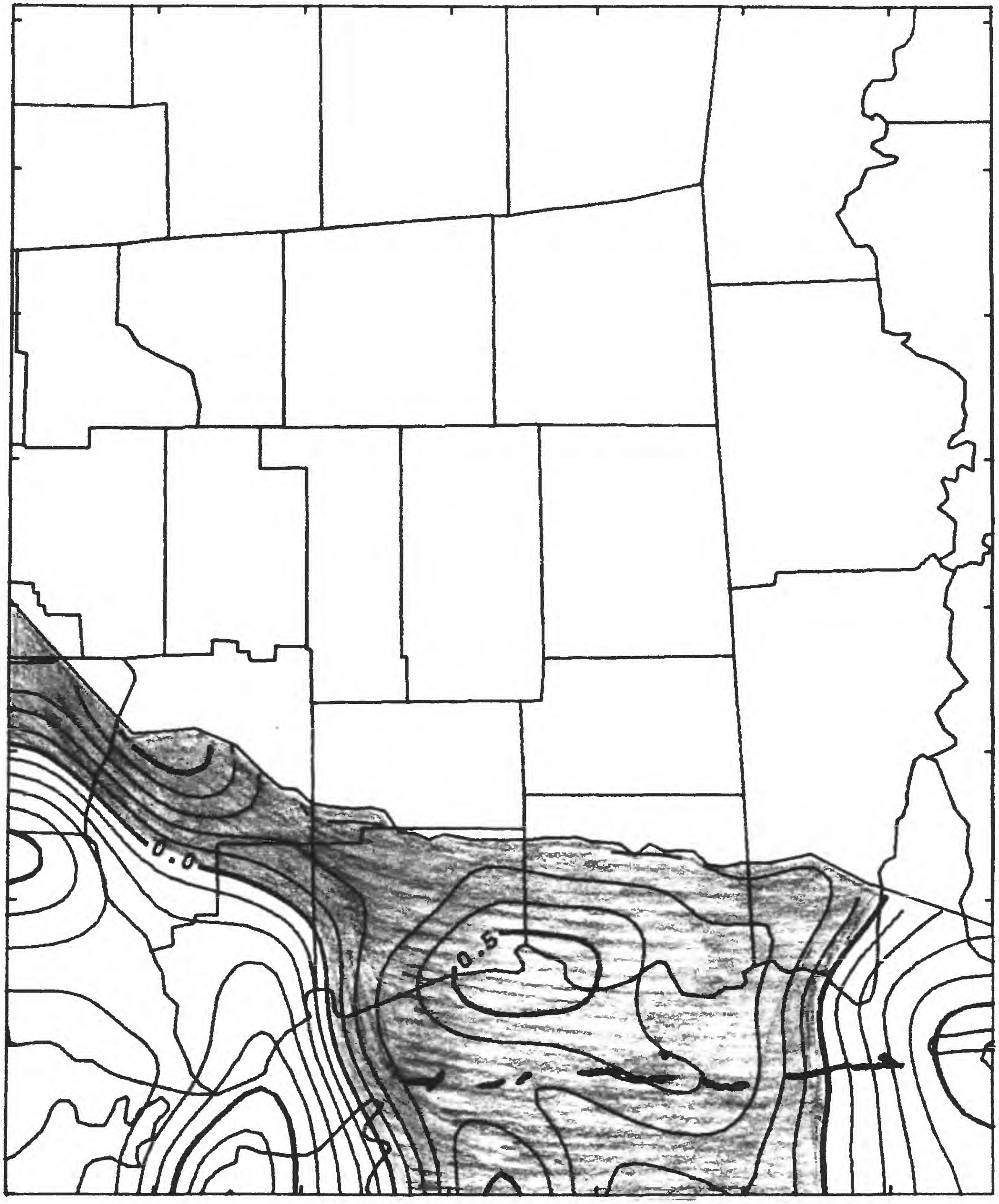
DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 4. Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 50.--Flux through the top surface of each layer during 2000-05.--Continued



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

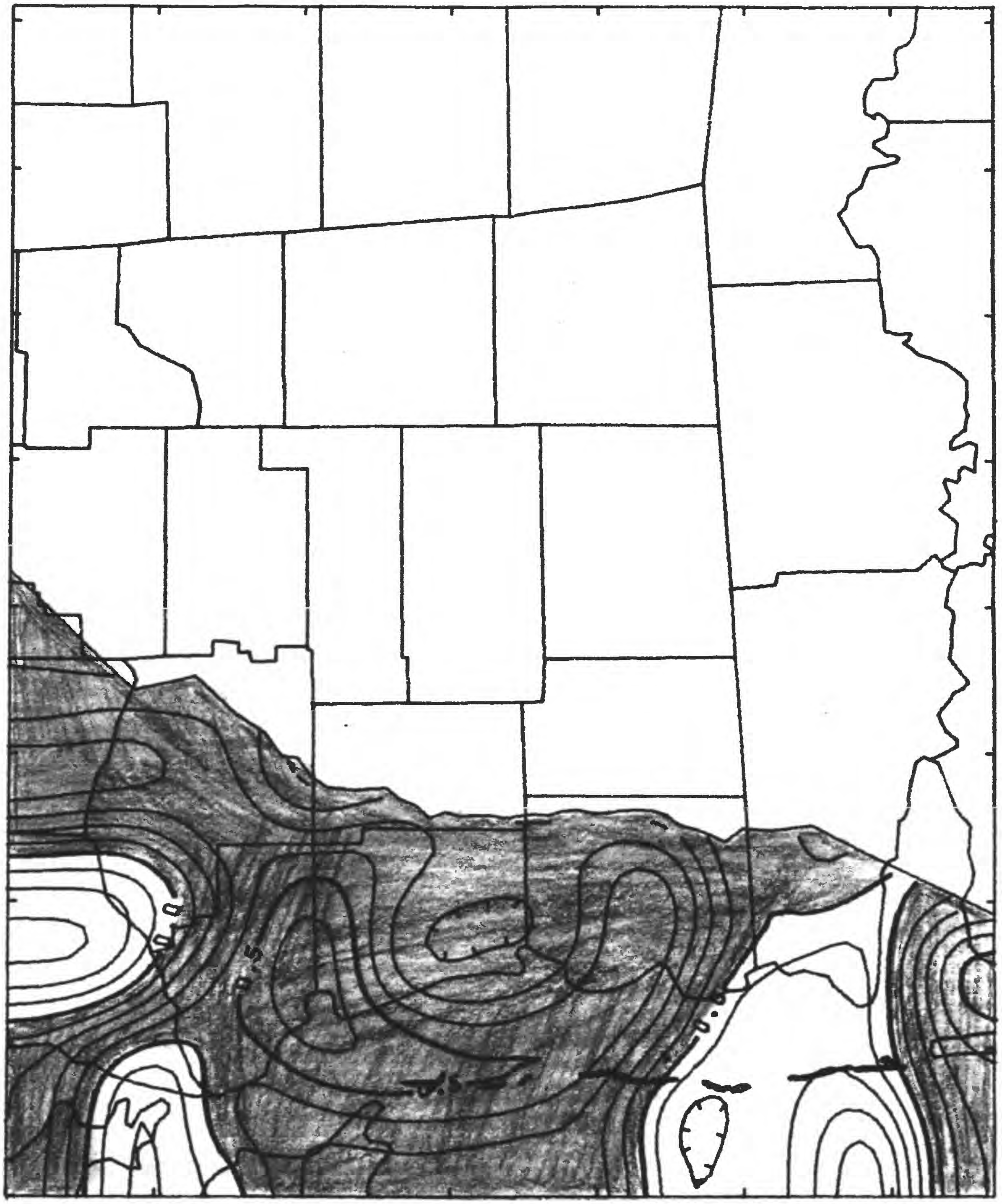
DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 5.
Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 50.--Flux through the top surface of each layer during 2000-05.--Continued



EXPLANATION

RECHARGE AREA WHERE FLUX IS DOWNWARD

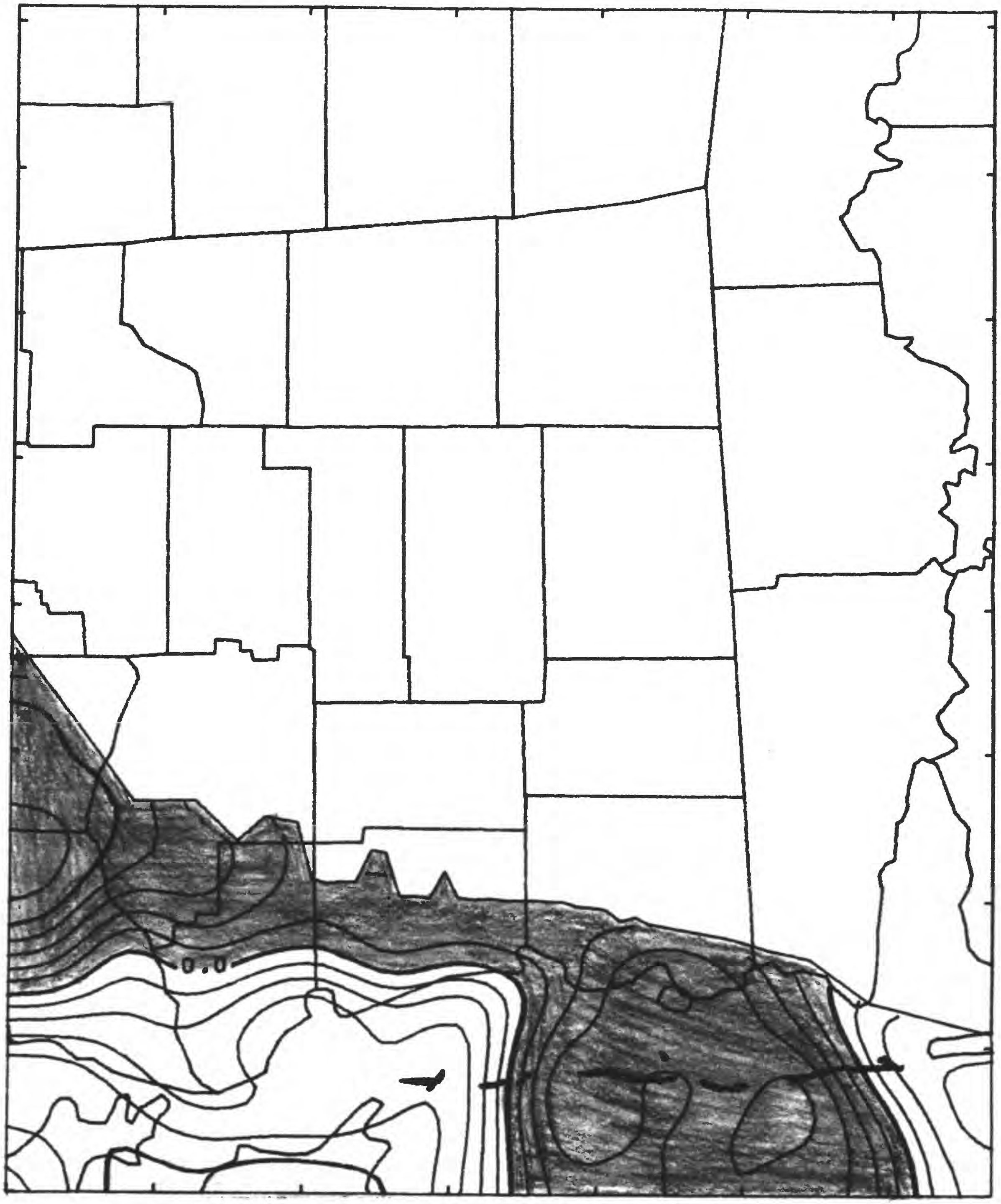
DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 6. Contour interval 0.1 inch

0 10 20 MILES

0 10 20 KILOMETERS

Figure 50.--Flux through the top surface of each layer during 2000-05.--Continued



EXPLANATION

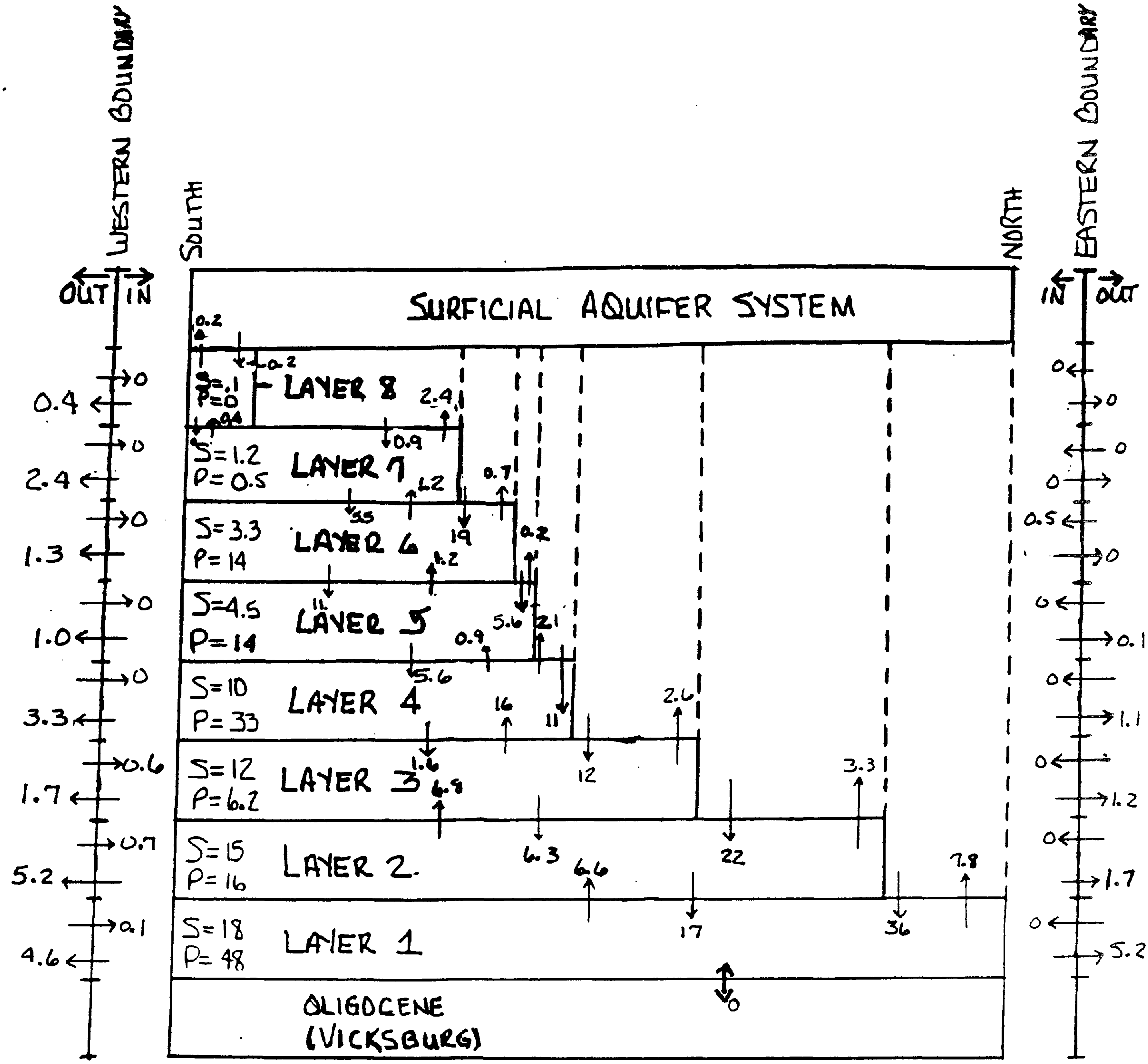
RECHARGE AREA WHERE FLUX IS DOWNWARD

DISCHARGE AREA WHERE FLUX IS UPWARD

—0.0— LINE OF EQUAL VALUE--Shows flux in inches per year in layer 7.
Contour interval 0.1 inch

0 10 20 MILES
0 10 20 KILOMETERS

Figure 50.--Flux through the top surface of each layer during 2000-05.--Continued



Note: Northern and southern boundaries are designated as no flow.

EXPLANATION

Flow, in million gallons per day

← DIRECTIONAL

S STORAGE, FROM

P PUMPAGE

Figure 51.--Schematic diagram of flow simulated by the transient-flow model for the period 2000-05.

Table 3.--Components of simulated flow in the transient model.
[in million gallons per day]

Component of flow	Layer 1			Layer 2			Layer 3			Layer 4			Layer 5			Layer 6			Layer 7			Layer 8		
	Stress Period			Stress Period			Stress Period			Stress Period			Stress Period			Stress Period			Stress Period			Stress Period		
	1940-60	1982-85	2000-05	1940-60	1982-85	2000-05	1940-60	1982-85	2000-05	1940-60	1982-85	2000-05	1940-60	1982-85	2000-05	1940-60	1982-85	2000-05	1940-60	1982-85	2000-05	1940-60	1982-85	2000-05
Storage, from	3.7	15.8	18.0	1.9	13.5	15.3	2.9	9.4	11.9	2.7	10.6	10.0	1.6	4.0	4.5	1.3	2.6	3.3	0.3	1.1	1.2	0.0	0.0	0.1
Storage, to	.0	.3	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.1	.0	.0	.0	.0	.0	.0	.0
Pumpage	11.6	35.9	47.6	1.8	12.0	16.0	3.1	4.7	6.2	5.9	24.6	32.7	6.2	10.7	14.2	3.6	10.9	14.4	.0	.4	.5	.1	.0	.0
Surficial layer, from	20.7	30.5	36.3	12.8	16.7	21.5	10.3	10.9	12.1	7.9	9.4	11.1	3.5	4.5	5.6	8.0	14.0	18.5	3.6	6.0	8.7	.0	.1	.2
Surficial layer, to	9.8	8.4	7.8	4.4	3.7	3.3	3.8	3.2	2.6	3.4	2.6	2.1	.6	.2	.2	2.3	1.0	.7	8.8	4.6	2.4	.8	.4	.2
Base of layer, to	-	-	-	2.3	4.2	6.6	3.8	5.5	6.8	8.0	12.5	15.5	7.6	3.5	.9	5.4	2.5	1.2	6.7	2.8	1.2	.8	.6	.4
Base of layer, out	-	-	-	6.8	12.2	17.3	3.4	4.7	6.3	1.1	1.2	1.6	.3	2.4	5.6	.9	5.4	11.1	.2	2.7	5.5	.0	.0	.0
Top of layer, in	6.8	12.2	17.3	3.4	4.7	6.3	1.1	1.2	1.6	.3	2.4	5.6	.9	5.4	11.1	.2	2.7	5.5	.0	.0	.0	-	-	-
Top of layer, out	2.3	4.2	6.6	3.8	5.5	6.8	8.0	12.5	15.5	7.6	3.5	.9	5.4	2.5	1.2	6.7	2.8	1.2	.8	.6	.4	-	-	-
Western boundary, out	.5	.0	.1	.3	.4	.7	1.6	.4	.6	1.2	.0	.0	.0	.0	.0	.0	.0	.0	.1	.0	.0	.4	.0	.0
Western boundary, in	3.3	4.7	4.6	1.9	4.0	5.2	.1	1.0	1.7	.3	1.4	3.3	1.2	1.6	1.0	1.2	1.8	1.3	.7	1.5	2.4	.3	.4	.4
Eastern boundary, in	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.0	.3	.5	.0	.0	.0	.0	.0	.0
Eastern boundary, out	4.7	5.0	5.2	1.8	1.8	1.7	1.4	1.3	1.2	1.7	1.4	1.1	.0	.1	.1	.1	.1	.0	.1	.0	.0	.0	.0	.0

The error introduced by ignoring dispersive and density effects on movement of the freshwater-saltwater interface was evaluated by D.C. Dial and D.M. Sumner (U.S. Geological Survey, written commun., 1987) for the New Orleans, La., area, which is hydrogeologically similar to the area under study. In that study, the observed movement of the saltwater front between 1960 and 1982 in the "700-foot" sand at New Orleans agreed favorably with the calculated movement. Average flow velocity is given by the Darcy equation (Lohman, 1972):

$$v = \frac{KI}{p},$$

where

v = ground-water velocity,

K = horizontal hydraulic conductivity of the aquifer,

I = potentiometric head gradient at the location of the saltwater front, and

p = porosity of aquifer.

The projected position of the saltwater front within each layer can be estimated by using this equation. The value of hydraulic conductivity used will depend on the spatial scale involved. Regionally valid values of hydraulic conductivity derived from model calibration generally are lower than the values associated with local sand beds. If the saltwater front is relatively close to a pumping center, the ground-water withdrawals probably are from a local sand bed containing the front, and a local aquifer-test-derived value of horizontal hydraulic conductivity should be used. Conversely, where movement of the front is of a more regional nature, calibration-derived values of horizontal hydraulic conductivity should be used to estimate the movement.

Average porosity of sand beds in the Gulf Coast strata varies with depth of burial from 33.6 percent at land surface to 32.3 percent at a depth of 2,000 feet (Wallace and others, 1979). A porosity value of 33 percent was used for this study.

This analysis assumes that the effects of hydrodynamic dispersion and nonuniform water density have a negligible effect on the movement of dissolved constituents. Dispersion will cause an acceleration of front movement compared to the simplified nondispersive analysis. Saltwater generally is located downdip from freshwater sources or in strata underlying freshwater. Therefore, the lower elevation of the denser saltwater will retard encroachment rates compared to those estimated if a uniform density is assumed.

The potential for contamination of freshwater aquifers by saltwater was evaluated on the basis of Darcian estimates of ground-water velocities and estimates of the present (1985) location of the saltwater fronts (figs. 21, and 23-26). This analysis indicated that the most serious threats of saltwater contamination are in layers 4, 5, and 6 in the Pascagoula area and in layers 3 and 4 in the Biloxi Bay area in Biloxi.

Available data indicate that the base of layer 4 currently contains saltwater in the southern edge of Pascagoula, and that the top of the layer is salty about half a mile farther south. If the estimated locations of the saltwater fronts (fig. 19) are accurate, saltwater can be expected to contaminate the southernmost wells in layer 4 in Pascagoula in less than 10 years. It is also possible that the saltwater in layer 4 at the southern edge of Pascagoula is due to upward leakage from the underlying aquifer, which is the intrepretation of the data shown in figure 24. If this is true, the saltwater front could be more than half a mile southeast of the pumping center and could take much more than a decade to reach the center. However, upward leakage of saltwater from the underlying aquifer could be expected to continue to contaminate the freshwater in the base of layer 4 in the areas of greatest pumping. Another possible source of present contamination to layer 4 at this location is from the surficial aquifer by way of abandoned wells or faulty well casings. In this immediate area, the surficial aquifer is salty (Wasson, 1978).

The saltwater front in layer 5 is probably at the southern edge of the well field in the southeastern part of Pascagoula. Dissolved-solids concentrations increase from about 700 mg/L in the northern end of this field to about 1000 mg/L in the southern end of the field, which indicates that the freshwater-saltwater interface is at or near the southern edge of the well field. Water from these wells will become saltier with time as pumping continues.

In layer 6 the saltwater front is probably 2 or 3 miles southeast of downtown Pascagoula but less than a mile southeast of the Bayou Casotte industrial complex (fig. 21). In layer 6, the downdip saltwater front can be expected to reach the southernmost wells in the Bayou Casotte industrial complex in less than a decade but probably will take several decades to reach the southernmost municipal-supply wells in Pascagoula. Additionally, some data indicates that part of layer 6 beneath the flood plains of the Pascagoula and Escatawpa Rivers, north of Pascagoula and Moss Point, has been contaminated by saltwater from the tidal reaches of those streams. Prior to the large water-level declines in this area, freshwater discharged from layer 6 by way of the surficial aquifer to the Pascagoula River, but the gradient has now been reversed.

At Biloxi, layers 3 and 4 have areas of salty or nearly salty water. Layer 3 (the 1,200-foot sand in Biloxi) is salty in the Pascagoula area, along the coast between Pascagoula and Biloxi, and in the area of Biloxi Bay (fig. 23). The downdip extent of saltwater in layer 3 in the Biloxi Bay area is poorly defined and additional observation wells are needed to adequately describe the saltwater problem in this layer in this area. Figures 17 and 24 show higher chloride values in layer 4 in the Biloxi Bay area than in adjoining areas, but not nearly as high as in layer 3 in the same area (fig. 23). Layer 5 (the 600-foot sand in Biloxi) appears to be safe from saltwater intrusion in the near future (fig. 25). West of Gulfport, the freshwater section is relatively thick, and except in the southwestern corner of Hancock County, the saltwater front is several miles offshore. Most production wells in this area are screened above the base of freshwater, and saltwater contamination of these producing sands is not expected to be a problem in the near future.

In estimating the time of arrival of the saltwater front in any of the layers, the most uncertain factor is the present location of the freshwater-saltwater interface. Additional water-level and water-quality data from wells at strategic locations in various aquifers would help to define the locations of the interfaces and to monitor the movement of the interface toward pumping centers. The interface is relatively close to some pumping centers. A more detailed study of these areas will be necessary to adequately describe for water planners the present extent of saltwater in the various layers of the Miocene aquifer system. Figures 23 through 26 and figure 21 would serve as guides to the areas where more observation wells and more hydrologic data are needed.

SUMMARY

Intense development of the Miocene aquifer system for water supplies along the Mississippi Gulf Coast has resulted in large water-level declines and has altered the ground-water flow patterns in most areas. Water levels in some Miocene aquifers have declined about 2 feet per year since 1940 and water-level declines exceed 100 feet (80 feet below sea level) in large areas along the coast. Concern for the aquifer system's ability to meet the increasing demand for water and the potential for contamination of the freshwater aquifers by saline water prompted this study.

The Miocene and younger interbedded and lenticular sands and clays crop out in southern Mississippi and dip to the south and southwest. These sediments do not fit the concept of layered geology but do exhibit large vertical variations in head and locally respond to stresses as separate aquifers. An analysis of well-completion data along the Gulf Coast indicated that an aquifer system with eight layers having surfaces based primarily on the dip or slope of the base of the mappable Miocene would best represent the vertical heads in the Miocene aquifer system.

Recharge to the Miocene aquifer system primarily is from the surficial aquifer system, which is recharged by precipitation. Water in the Miocene aquifer system generally moves to the south and southeast along the bedding planes toward the Mississippi Gulf Coast, where the water is either withdrawn by wells, discharges to the gulf, or gradually percolates upward through the overlying layers into shallower layers. The downdip location of the freshwater-saltwater interface is not well defined in some areas in each of the eight layers. The interfaces probably were static prior to development. Drawdowns caused by large ground-water withdrawals in some areas probably have resulted in the gradual movement of saltwater toward the pumping centers.

Most of the water in the Miocene aquifer system in the area is a sodium bicarbonate type. In the northern third of the study area, water is fresh to the base of the Miocene sediments. Water from some aquifers in the Pascagoula-Moss Point area and in the Biloxi-Ocean Springs area is marginally fresh because of the proximity of the freshwater-saltwater interface and (or) the upward leakage of saline water from deeper aquifers.

The effects of an expected 1.5 percent annual increase in ground-water withdrawals from 1985 through the year 2005 were evaluated by means of a quasi three-dimensional numerical model of the ground-water flow system. An eight-layer model incorporating available geohydrologic data was developed and calibrated by adjusting hydraulic parameters until a reasonable match between computed and measured water levels in 1940, 1960, 1965, 1977, 1982, and 1985 was obtained. The calibration-derived parameter values were 5 ft/d (oldest layer) to 40 ft/d (youngest layer) for horizontal hydraulic conductivity of aquifer material, 1×10^{-4} ft/d for vertical hydraulic conductivity of confining material, and $1 \quad 10^{-5}$ ft^{-1} for specific storage of confining material. A sensitivity analysis indicated that the model-computed water levels were relatively sensitive to changes in vertical and horizontal hydraulic conductivity and to storage in the areas heavily stressed by pumping. These water levels were much less sensitive to changes in areas more remote from the pumping centers.

The results of model projections indicate that water-level declines generally would be largest in the Biloxi-Gulfport area. Layer 4, which corresponds to the 900-foot sand at Gulfport, is expected to have additional water-level declines of 135 feet by the year 2005. In the Biloxi-Gulfport area, additional declines of 100 feet in layer 5 (600-foot sand) and 50 feet in layer 3 (1,200-foot sand) are also projected. In the Pascagoula area, model projections of additional water-level declines are 40 feet in layer 6 (400-foot sand) and 30 feet in layer 4 (800-foot sand). In much of the western part of the coastal area and in areas more than 10 miles north of the coast, projected declines by the year 2005 generally are less than 20 feet in all layers.

The potential for contamination of freshwater aquifers by saltwater was evaluated on the basis of analytically estimated ground-water velocities and estimates of the present (1985) location of the saltwater fronts. The most serious threats of saltwater contamination are in layers 4, 5, and 6 (the 800-, 600-, and 400-foot sands) in the Pascagoula area. Available data indicate that the base of layer 4 currently is salty in the southern edge of Pascagoula, and that the top of the layer contains saltwater about half a mile farther south. The saltwater front in layer 5 is believed to be at the southern edge of the well field in the southeastern part of Pascagoula. In layer 6 the saltwater front is believed to be 2 or 3 miles southeast of downtown Pascagoula but less than a mile southeast of the Bayou Casotte industrial complex. If the estimated locations of the saltwater fronts are accurate, saltwater can be expected to contaminate the southernmost wells in layers 4 and 5 in Pascagoula in less than 10 years. In layer 6, the downdip saltwater front can be expected to reach the southernmost wells in the Bayou Casotte industrial complex in less than a decade but will probably take several decades to reach the southernmost municipal-supply wells in Pascagoula. Some evidence exists, however, that parts of layer 6 beneath the flood plains of the Pascagoula and Escatawpa

Rivers, north of Pascagoula and Moss Point, have been contaminated by saltwater from the tidal reaches of these streams.

A potential problem with saltwater moving into freshwater sands also exists in layer 3 (1,200-foot sand) in the eastern part of Biloxi. Water in this aquifer is salty in the Pascagoula area, along the coast between Pascagoula and Biloxi, and in the area of Biloxi Bay. Layer 5 (the 600-foot sand), appears to be safe from saltwater intrusion in the near future. West of Gulfport the freshwater section is relatively thick, and except in the southwest corner of Hancock County, the saltwater front is several miles offshore. Most production wells in this area are screened above the base of freshwater, and saltwater contamination of these producing sands is not expected to be a problem in the near future.

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