OF

PRELIMINARY EVALUATION OF GEOTHERMAL RESOURCES OF THE FRIO FORMATION, MIDDLE TEXAS GULF COAST

BUREAU OF ECONOMIC GEOLOGY

THE UNIVERSITY OF TEXAS
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PRELIMINARY EVALUATION OF GEOTHERMAL RESOURCES OF THE FRIO FORMATION, MIDDLE TEXAS GULF COAST

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OBJECTIVE—TO EVALUATE THE GEOTHERMAL RESOURCES OF THE FRIO FORMATION, MIDDLE TEXAS GULF COAST

Knowledge of the regional sand distribution and its relationship to formation temperature and pressure is a preliminary step in evaluating the geothermal resources of the Frio Formation.

At depths generally greater than 7,000 feet, the sands and shales of the Frio Formation are overpressured and undercompacted. The insulating effect of these overpressured and undercompacted sediments is the accumulation of subsurface heat and, thus, high-temperature water. The local variations of depth to top of geopressure are related to the distribution of sand and shale lithologies and to the location of growth faults. For more information concerning origin of geopressure or high temperatures, see Jones (1970) and Dorfman and Kehle (1974). Bruce (1973) discusses the nature of growth faults in detail. The resource in the geopressured zone consists of high-temperature water with relatively low salinity and with dissolved methane gas.

The objectives of this study were to determine regional sand distribution of the Frio Formation (fig. 1), identify depositional environments, and delineate the geopressured zone and its relationship to sand/shale distribution, growth faults, and fluid temperatures in the Middle Texas Gulf Coast (fig. 2). This study is essentially an extension of that completed earlier for South Texas (Bebout, Dorfman, and Agagu, 1975); all correlation and mapping units are the same as those represented in the South Texas report.

The Energy Research and Development Administration, through the Lawrence Livermore Laboratory, supported this study of the geothermal resources of the Frio Formation in Middle Texas Gulf Coast.

CENOZOIC — TEXAS GULF COAST

AGE	SERIES	GROUP/FORMATION
Quaternary	Recent	Undifferentiated
	Pleistocene	Houston
Tertiary	Pliocene	Goliad
	Miocene	Fleming
		Anahuac
	?—?	
	Oligocene	Frio
		Vicksburg
	Eocene	Jackson
		Claiborne
		Wilcox
		Midway

Figure 1. Tertiary formations—Gulf Coast of Texas. The Frio Formation is shown in the darker pattern; formations summarized in other Bureau reports are shown with the lighter pattern.

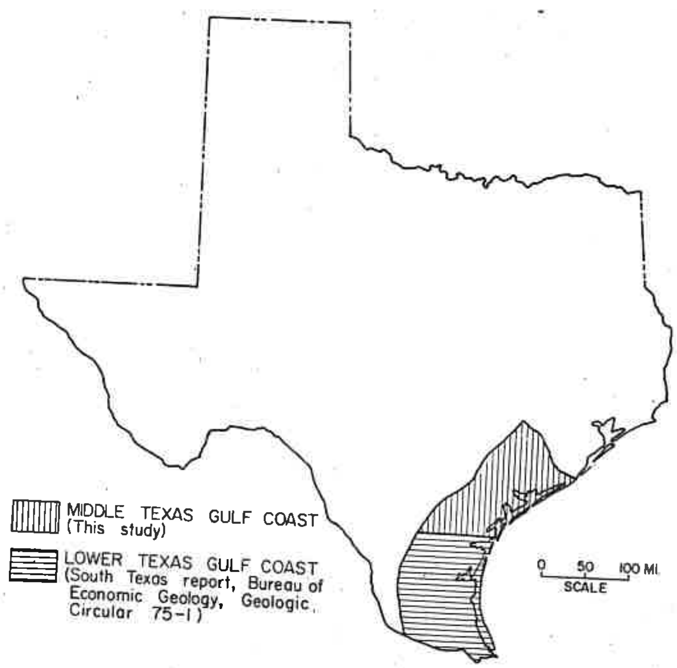

Figure 2. Middle Texas Gulf Coast study area of this report and Lower Texas Gulf Coast area reported on previously by Bebout, Dorfman, and Agagu (1975).

REGIONAL DEPOSITIONAL PATTERNS—MIDDLE TEXAS GULF COAST

The Texas Gulf Coast Tertiary is made up of many terrigenous wedges of sand and shale which thicken downdip into the Gulf.

The Tertiary of the Texas Gulf Coast consists of many wedges of genetically related sands and shales. Each of these wedges thickens and dips in the gulfward direction. Studies resulting from exploration for hydrocarbons have divided the Tertiary into formations based mainly on foraminifer zonation (fig. 3). The Frio is one of the thickest of these formations in the Middle Texas Gulf Coast area and is here considered to be Oligocene in age.

The total thickness of the Frio Formation ranges from about 200 feet near the outcrop to greater than 9,000 feet near the present Gulf Coast (fig. 4). The top of the Frio dips 1/2 to 3 degrees toward the Gulf so that Frio-age sediments which outcrop along a belt approximately 100 miles inland from and parallel to the coast are time equivalent to those which occur 8,000 and 9,000 feet below sea level at the coast (fig. 5).

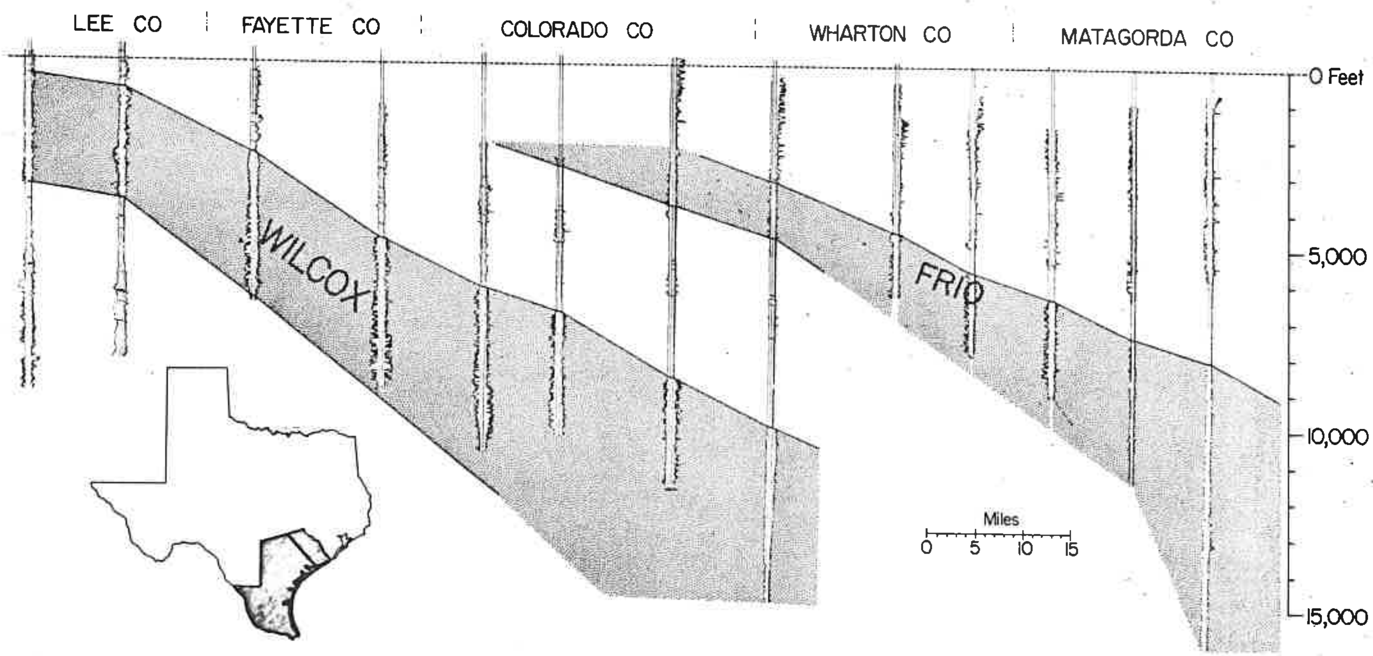

Figure 3. Regional cross section on a sea-level datum showing the offlapping sand/shale packages. Modified from Houston Geological Society (1954) cross section A-A'.

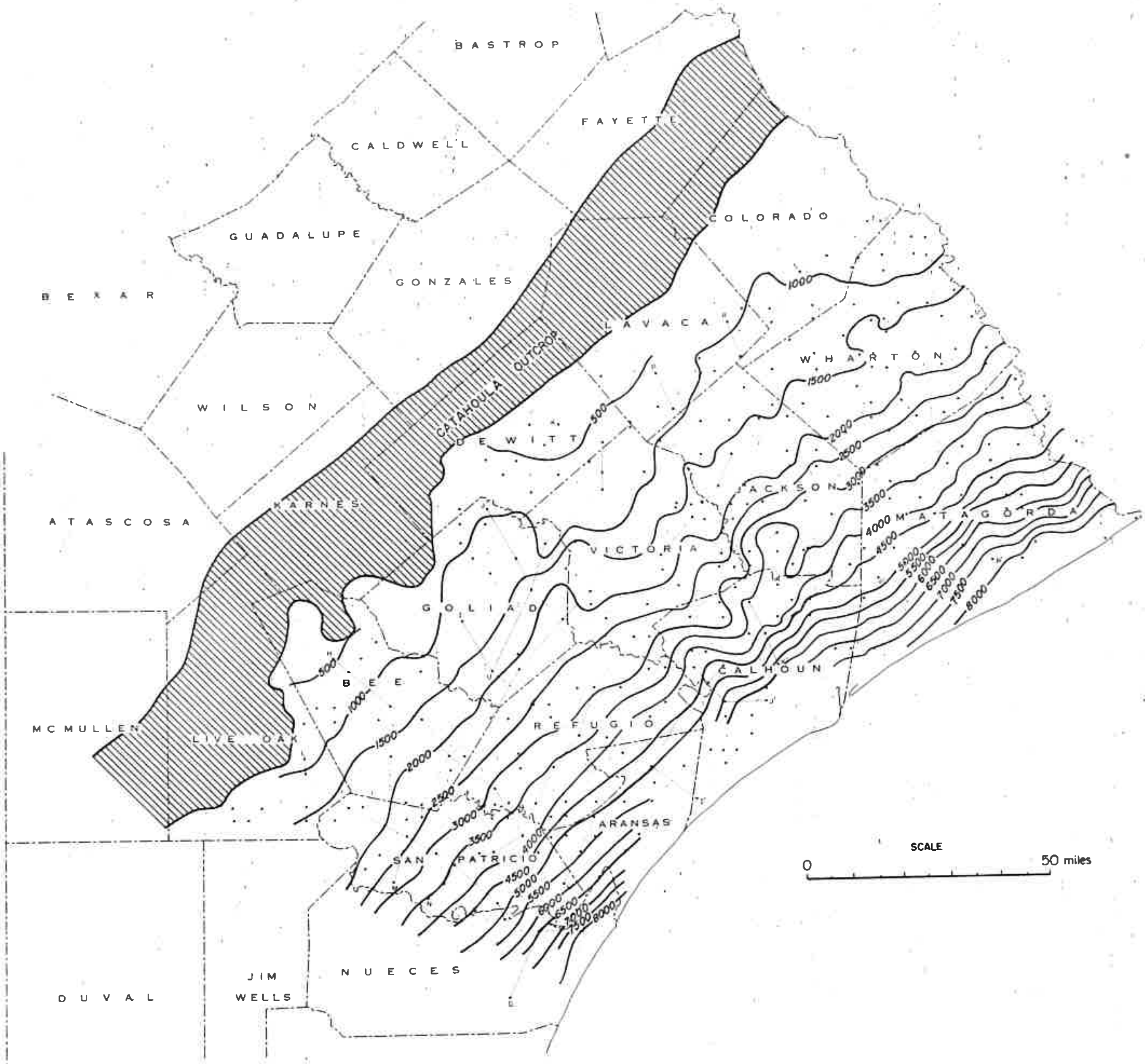

Figure 4. Total thickness of the Frio Formation, Middle Texas Gulf Coast.

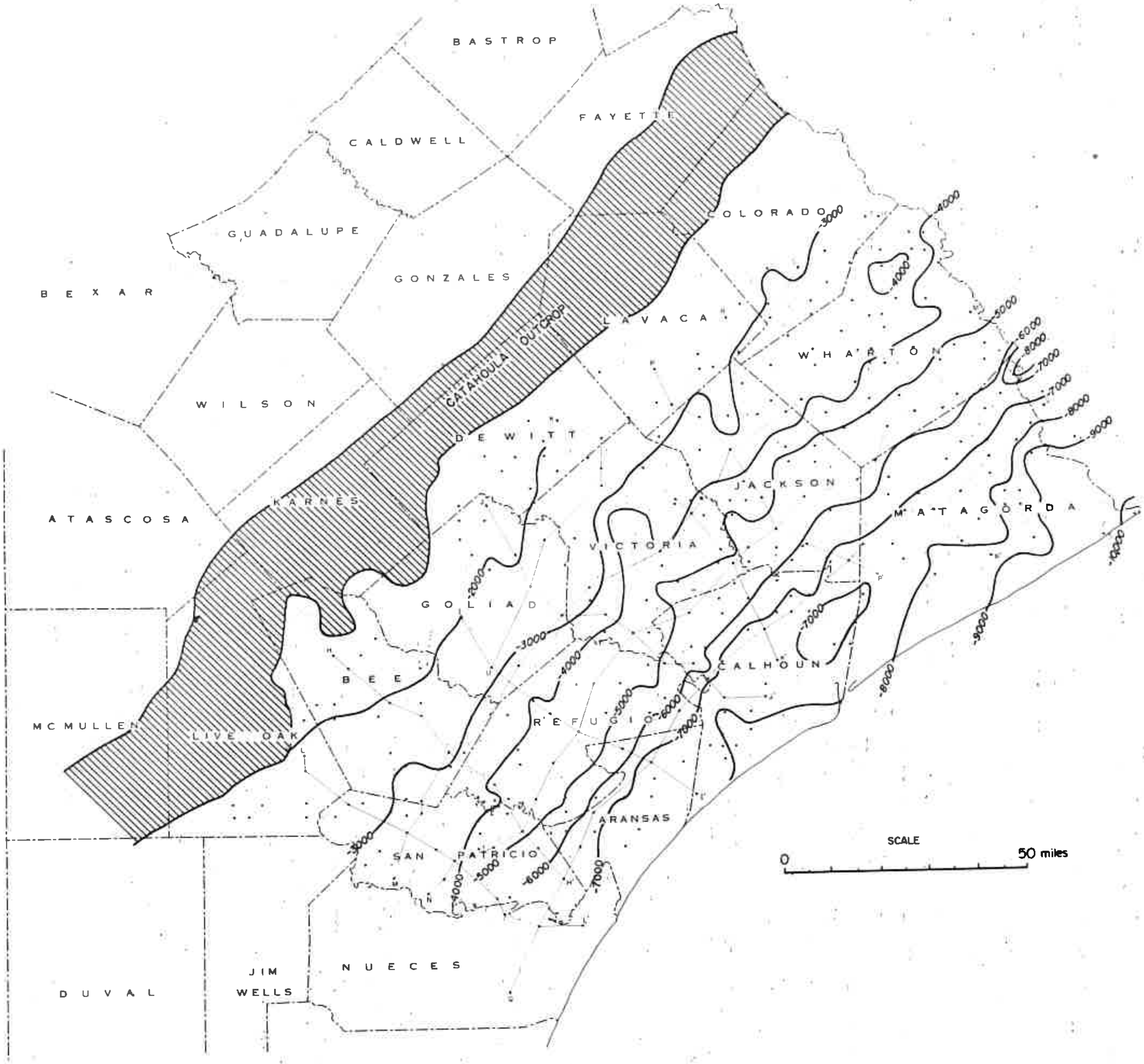

Figure 5. Structure on top of the Frio Formation.

GROWTH FAULTS—CAUSE OF IRREGULAR GULFWARD THICKENING AND LOCAL CHANGES IN DIP

Sediment thickening on the down or coast side of major growth faults interrupts the regularity of downdip thickening toward the Gulf.

Growth faults are contemporaneous structures which occur during sedimentation probably as a result of sediment loading on a soft terrigenous mud substrate. Subsidence along these faults results in the accumulation of abnormally thick bodies of sediment along the down side of the fault; sand bodies along the gulfward side of these faults are displaced downward from their updip equivalent thus forming structural/stratigraphic traps for fluid accumulation. Bruce (1973) has described the manner in which these faults form and the resulting sand/shale configuration. The presence of hydrocarbon reservoirs along the downdip side of these faults has been well known in the petroleum industry for years. The larger growth faults are recognized on seismic sections and by well-log correlation; smaller faults are more difficult to identify.

In South Texas, deltaic and strandplain sand bodies prograded gulfward for considerable distances probably resulting in the formation of several growth faults. Several of these major growth faults have been mapped to the south in Mexico by Busch (1975). To the north in the Middle Texas Gulf Coast, many of the major faults recognized in South Texas die out, and only one main growth fault zone is recognized (fig. 6). Most of the thickening is just gulfward of this main fault and there, for the most part, the sand bodies are stacked one upon the other. The regular gulfward dip of sand bodies is interrupted near the growth faults by counterregional dips resulting from rollover structures.

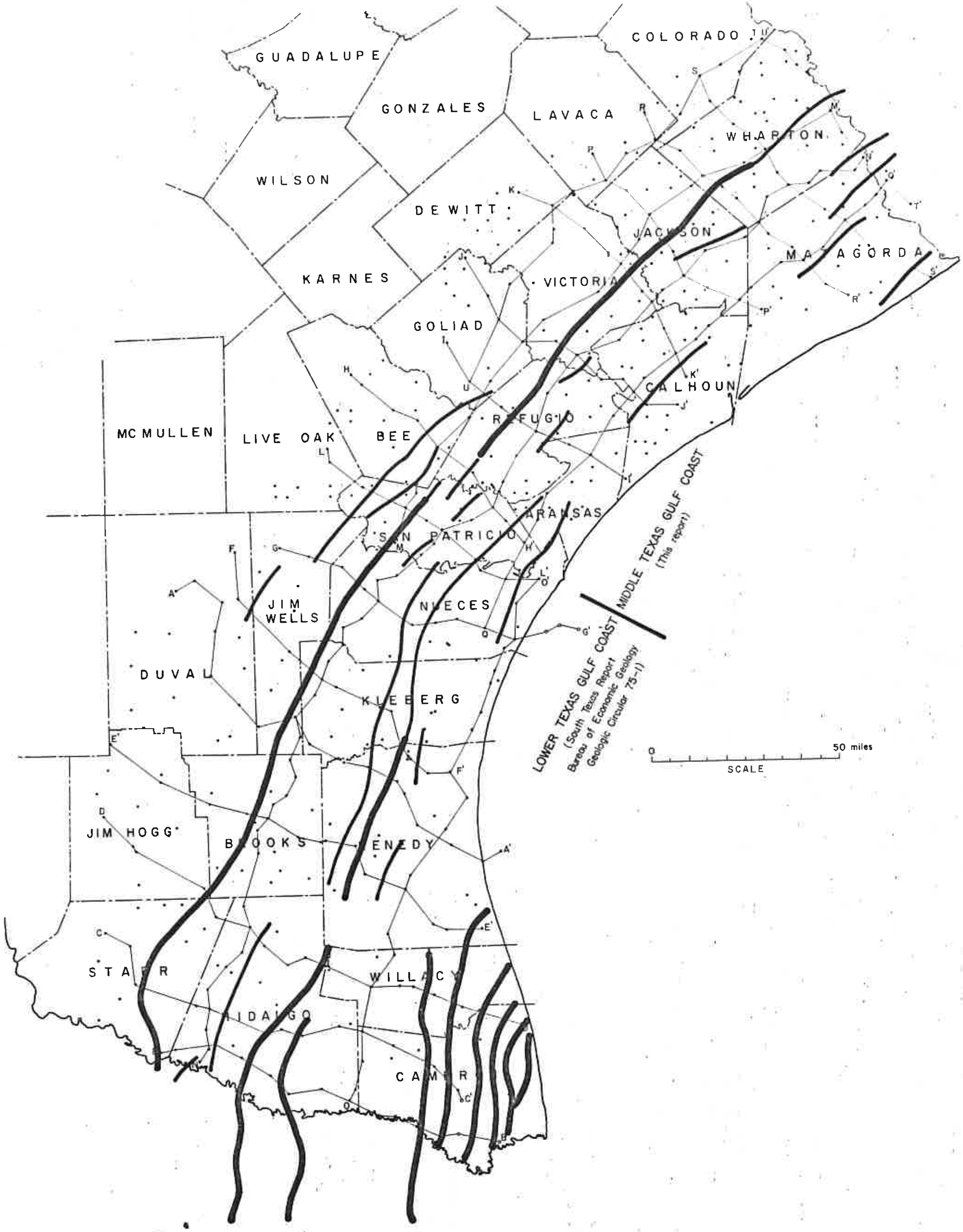

Figure 6. Generalized location of major growth faults along the Middle Texas Gulf Coast (this report), Lower Texas Gulf Coast (Bebout, Dorfman, and Agagu, 1975), and northern Mexico (Busch, 1975).

ELECTRICAL LOGS—THE BASIC CORRELATION TOOL

Regional electrical-log sections provide the basic correlation grid necessary for determining the sand distribution and interpreting the depositional environments.

Obtaining an understanding of the regional sand distribution is an essential step in determining the resource potential of geothermal energy along the Gulf Coast of Texas. This is best accomplished by constructing a network of cross sections using electrical logs to locate major sand bodies. Previous studies of this nature by Fisher and McGowen (1967), Guevara and Garcia (1972), and Bebout, Dorfman, and Agagu (1975) indicate that well spacing of 8 to 10 miles apart is optimal for a regional study. With this in mind, wells selected from the Middle Texas Gulf Coast area were spaced 5 to 10 miles apart (fig. 7). Wherever possible wells which penetrate the entire Frio were selected; in the downdip area, however, many wells do not extend through the whole Frio section.

In the Middle Texas Gulf Coast, the top of the Frio is picked at the occurrence of *Marginulina vaginata* in order to maintain consistency with the top of the formation picked in the South Texas study. In South Texas, the *Marginulina vaginata* zone is high in sand and, because of similar characteristics, is thought to belong to the Frio system. However, this zone becomes less sandy to the north in the Middle Texas Gulf Coast area and lithologically appears to be part of the Anahuac shale wedge. Consequently, in this area the first sand beneath the Anahuac shale wedge contains *Cibicides hazzardi*, a marker which occurs several hundred feet below the top of the Frio in South Texas.

Correlations between wells were accomplished primarily by means of a grid of regional electrical-log cross sections consisting of nine dip and four strike sections (fig. 7). The remaining "infill" wells were then correlated into closest cross sections.

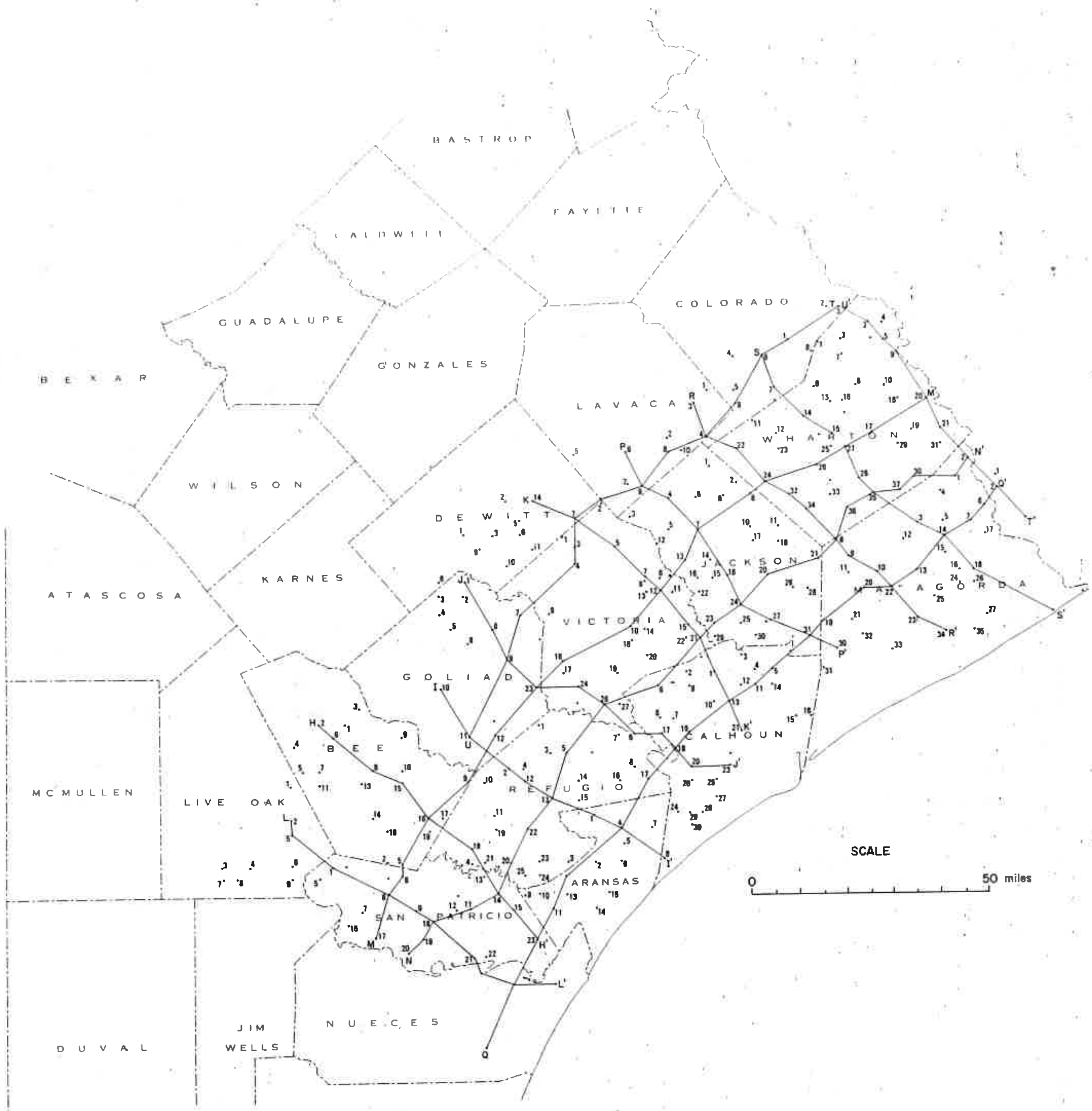

Figure 7. Well-log control and cross sections constructed for the Middle Texas Gulf Coast study.

FRIO SUBDIVIDED ON REGIONAL CROSS SECTIONS

Regional electrical-log cross sections and micropaleontological control provide the basis for subdivision of the Frio into six units.

The entire Frio Formation considered as one depositional unit is too thick to provide meaningful data for sand-facies analysis and interpretation of depositional environments. Therefore, the formation was subdivided into six correlation units using paleontological markers (fig. 8) and major shale breaks. These correlation units are the same as those used for the South Texas study (Bebout, Dorfman, and Agagu, 1975). Several assumptions have been made when establishing the correlations: (1) the Frio thickens downdip and, therefore, each unit should also thicken in a similar manner downdip (exceptions occur locally along growth faults); (2) major shale breaks are more continuous and thus more reliable for correlation than sands; (3) foraminifers used as markers are present only in the marine portion of the units and, although facies control their occurrence, are reliable for identifying major correlation units; (4) along any one correlation unit there is generally one major sand depocenter.

The dip sections (figs. 9 and 10) show a general change from thin, discontinuous sands separated by thick shales in the updip portion of each unit, to a main sand depocenter which extends across only two wells in the center of the sections, and to thick shales with scattered thin sands in the downdip portion. The area of maximum sand deposition did not prograde downdip here as much as it did in South Texas but instead remained in essentially the same location along strike resulting in the vertical stacking of many thick sand bodies. Major shifts in the location of sand depocenters is well illustrated on the strike section (fig. 11), although as a general rule sand/shale facies are more continuous along strike than dip.

In spite of the fact that the main depocenter migrated very little, the major overall pattern of offlapping correlation units is present in the Middle Texas Gulf Coast as it was in the Lower Texas Gulf Coast. This trend is well illustrated by the map showing the updip limit of "T" markers (fig. 12) and is supported by the similar pattern shown on the map of updip limits of marker foraminifers (fig. 13).

SERIES	GROUP/FORMATION	
Miocene	Anahuac	Discorbis nomada Heterostegina texana*
Oligocene	Frio	Marginulina vaginata* Cibicides hazzardi Nonion struma Nodosaria blanpiedi* Textularia mississippiensis Anomalia bilateralis
	Vicksburg	Textularia warreni*

Figure 8. Foraminifer zonation, Texas Gulf Coast Miocene and Oligocene.

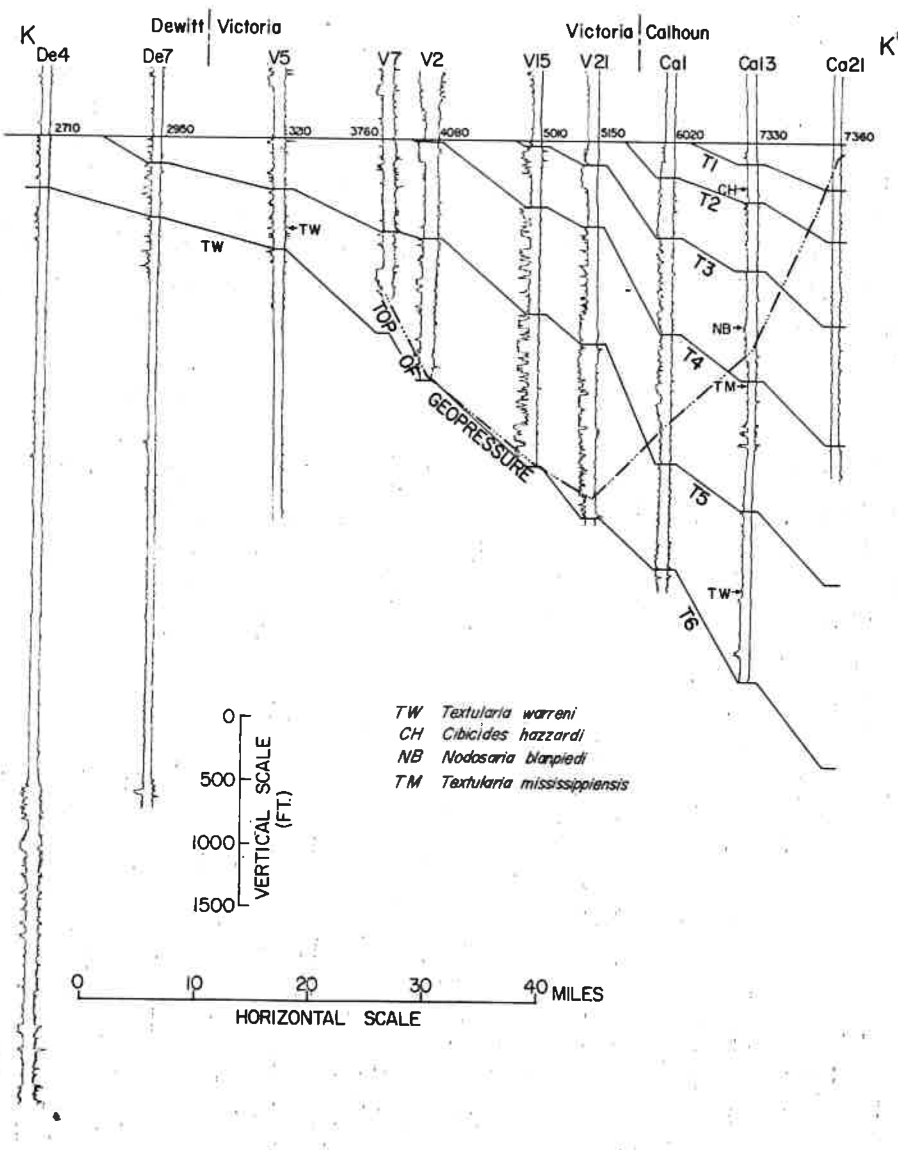

Figure 9. Frio sand distribution along dip section K-K'. The Frio is subdivided into six units indicated by the "T" correlation lines. Occurrence of marker foraminifers is also shown.

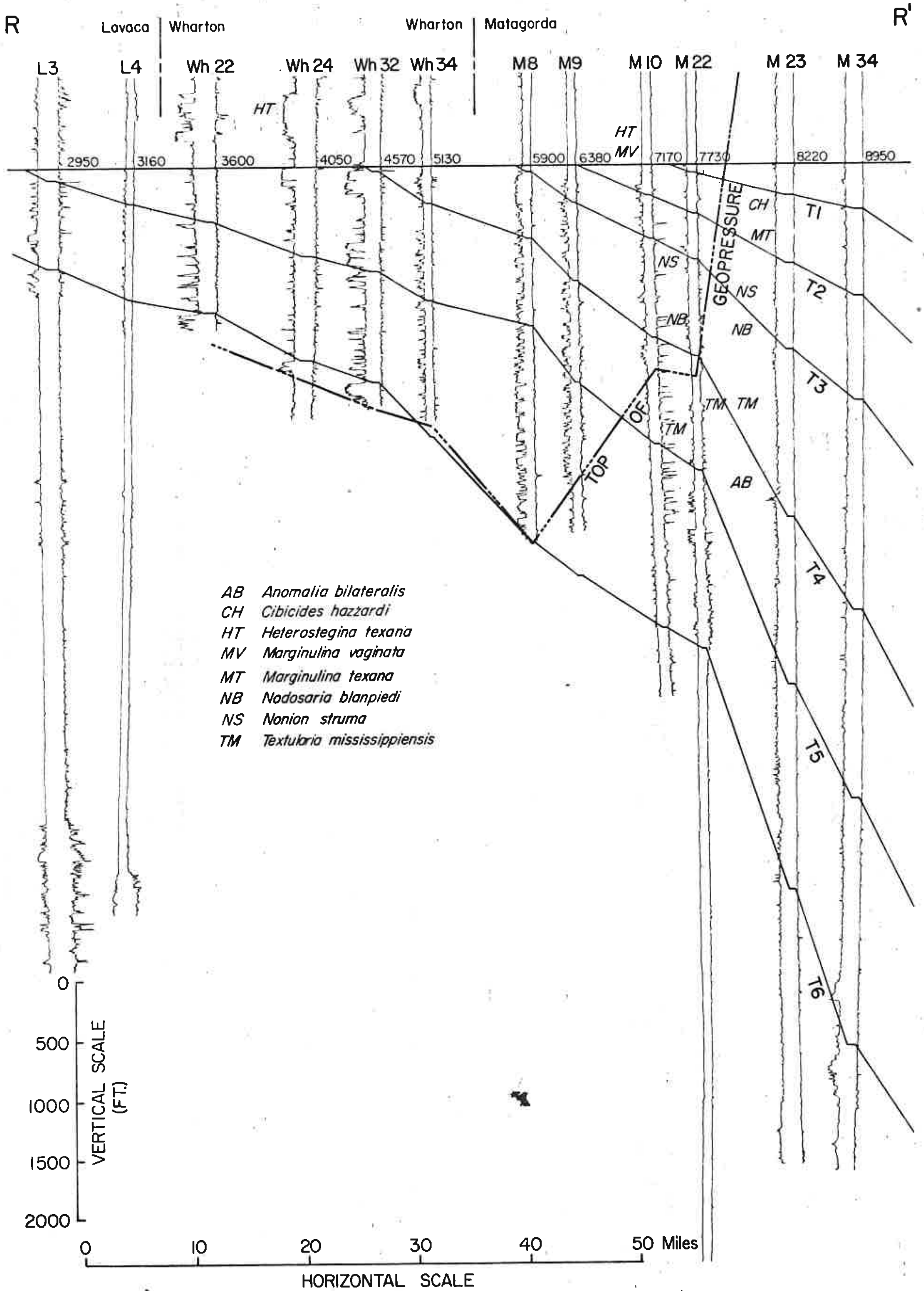

Figure 10. Frio sand distribution along dip section R-R'. The correlation lines which serve to subdivide the Frio are indicated by the "T" markers. Marker foraminifers and persistent shale breaks were used to subdivide the formation into six units.

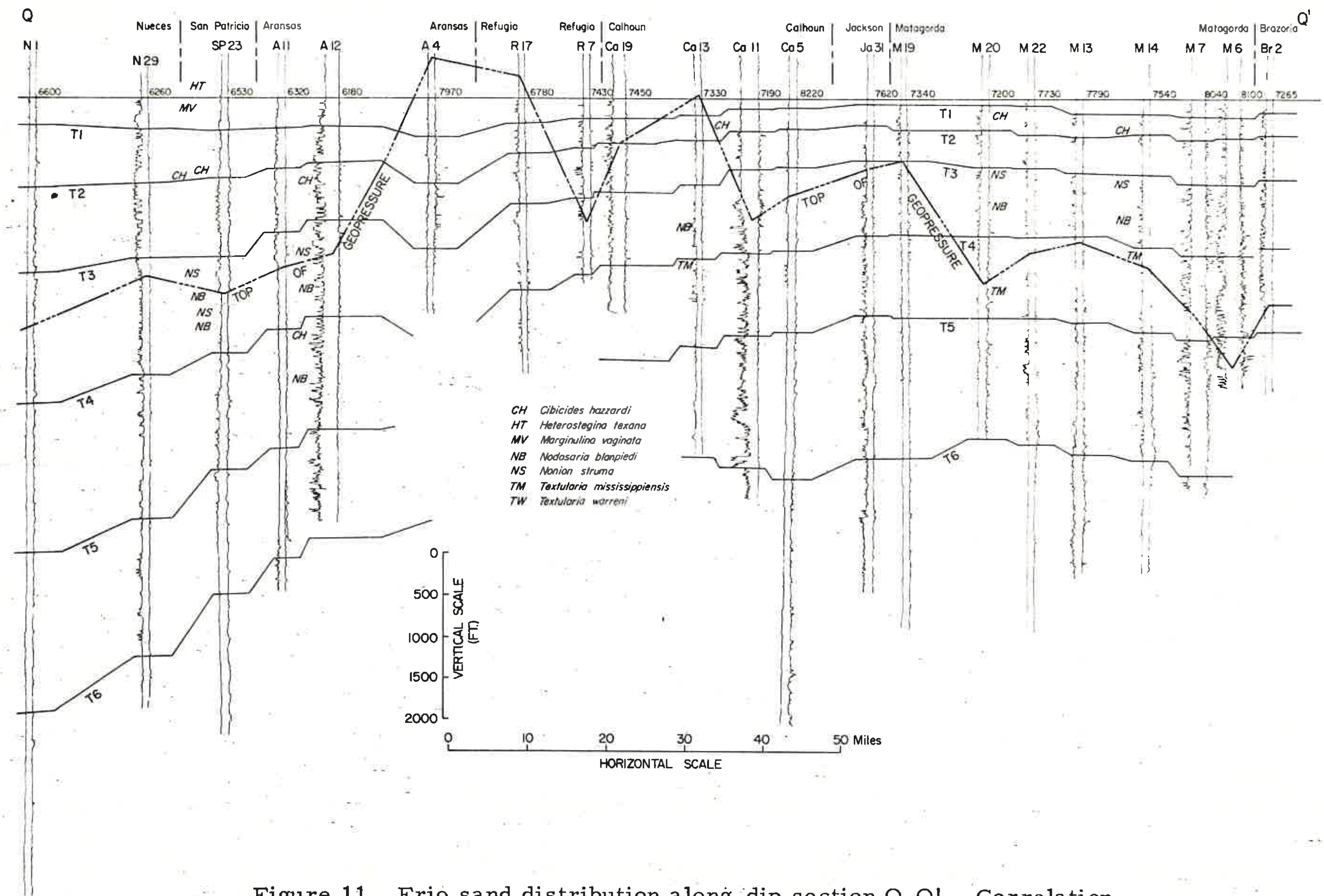

Figure 11. Frio sand distribution along dip section Q-Q'. Correlation lines are based on occurrence of marker foraminifers and persistent shale units.

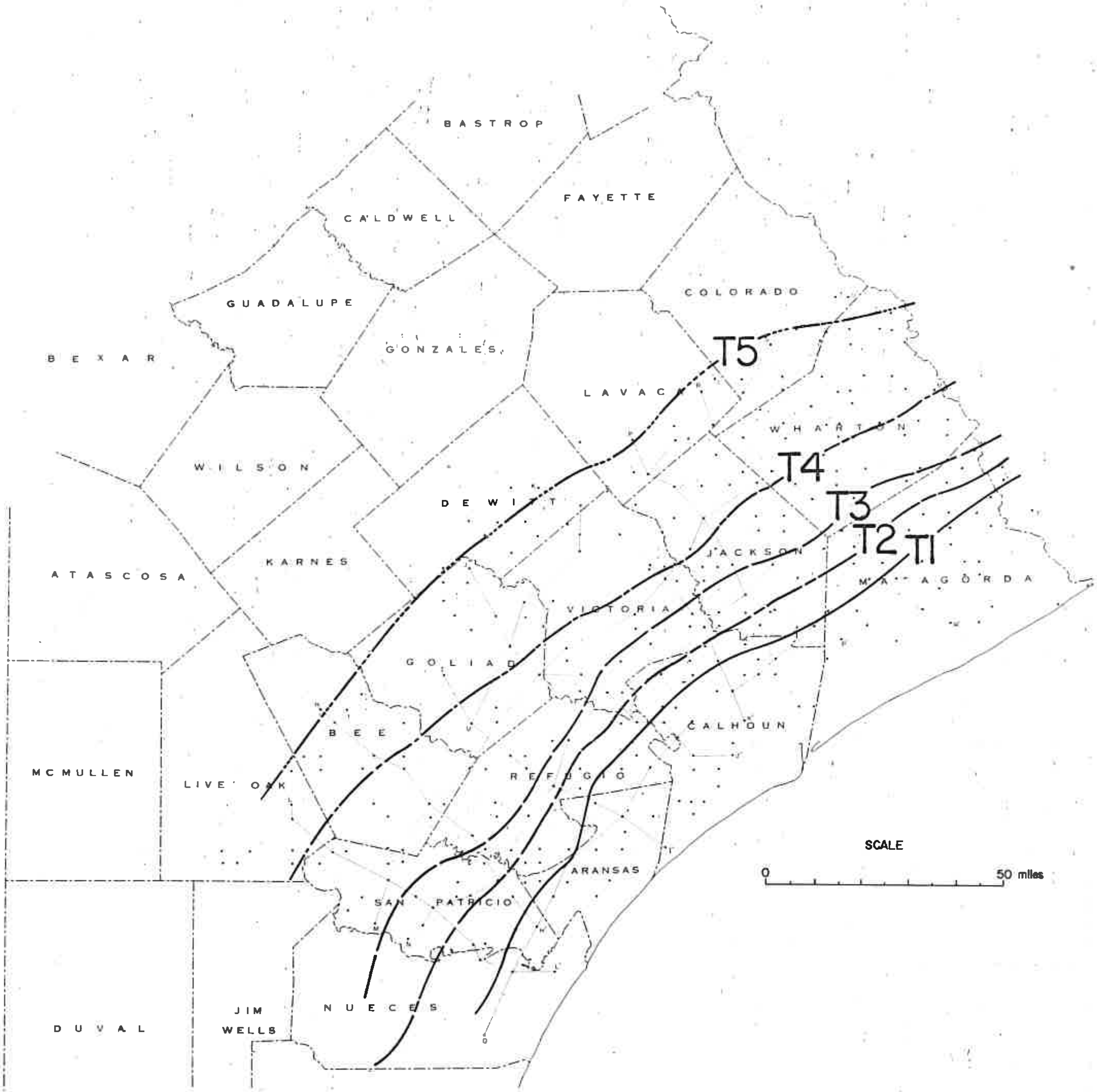

Figure 12. Updip limits of "T" markers.

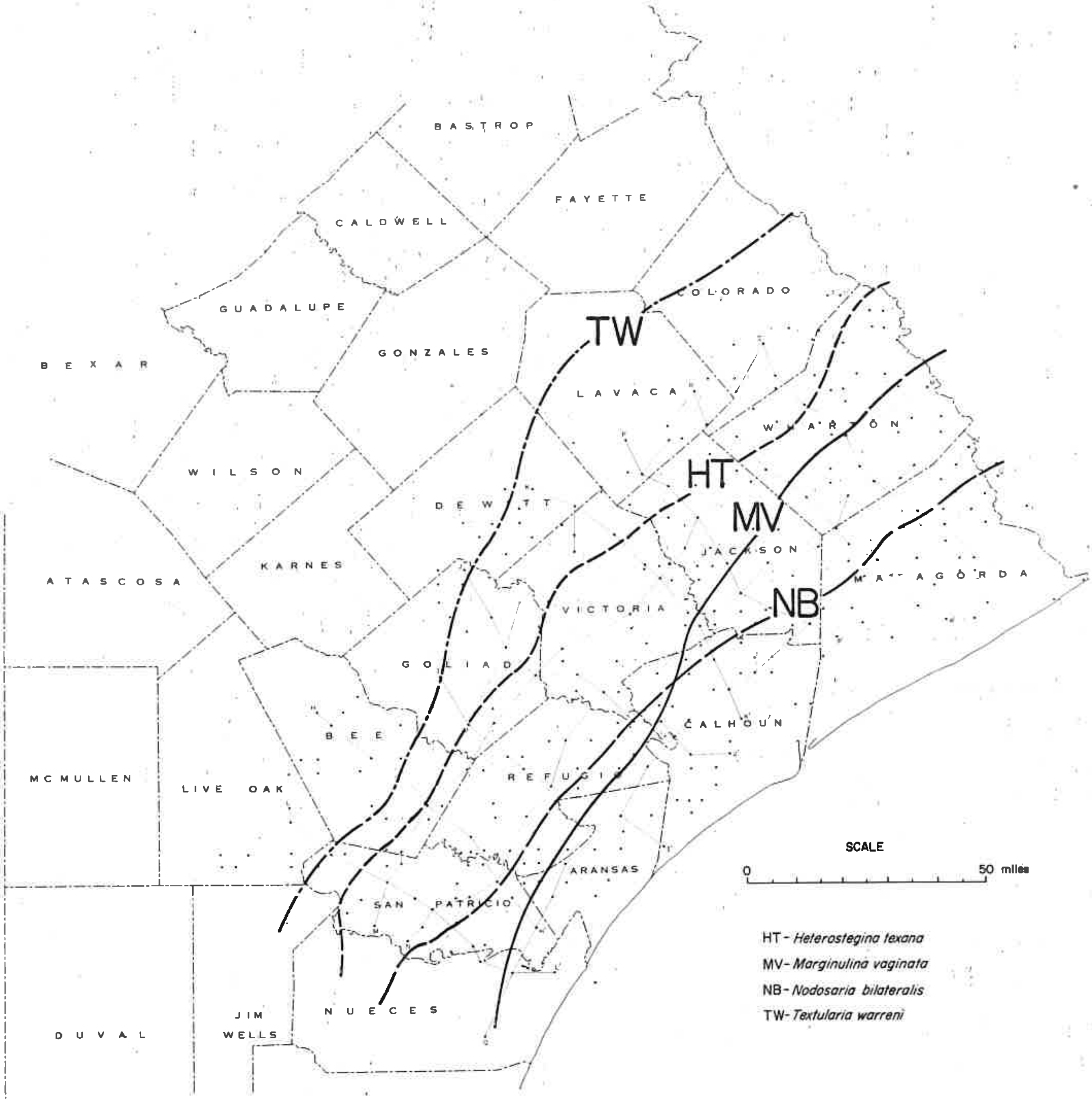

Figure 13. Updip limits of foraminifer markers.

DEPOSITIONAL ENVIRONMENTS DERIVED FROM SAND-PERCENTAGE AND NET-SAND MAPS

Sand-percentage and net-sand maps of each correlation unit aided in the identification of three main depositional environments—fluvial, strandplain, and shelf.

A sand-percentage map, net-sand map, and facies cross section have been constructed for the total Frio (figs. 14 and 15) and for each of the correlation units—T5-T6, T4-T5, T3-T4, T2-T3, T1-T2, and T0-T1 (figs. 16-33). The sand units were identified primarily by a high negative spontaneous potential response on the electrical logs. However, in the geopressure zone the SP response is commonly subdued because of the presence of fresher water, higher temperatures, and modifications in drilling procedures; here the gamma-ray log was commonly used to identify the sands.

The sand distribution as shown on the maps, vertical and lateral facies relationships, and sediment characteristic as interpreted from electrical-log response were features used to interpret the depositional environments within these Frio correlation units. Three gross depositional environments are recognized—fluvial plain, strandplain, and shelf. The fluvial plain consists of a broad area on the updip portion of the maps and cross sections made up predominantly of shale; scattered sand bodies are thin and discontinuous and are concentrated in dip-oriented trends. This area under the influence of fluvial processes is extensive in the lower units (T5-T6, T4-T5) but becomes narrower in the upper units. Units T1-T2 and T0-T1 do not show dip-oriented sand bodies. The lack of fluvial sand bodies in the uppermost correlation units may be the result of truncation of these units by the overlying Anahuac transgression. However, the sand-percentage maps for T1-T2 and T0-T1 show a decrease in sand content to the north suggesting the absence of fluvial feeder systems. This is also indicated on the map showing the updip limits of foraminifers (fig. 13) by the landward encroachment of the *Marginulina vaginata* marker in the low-sand areas.

The strandplain environment consists of a narrow band 10 to 15 miles wide oriented parallel to strike. It is made up of thick sands 40 to several hundred feet thick and separated by thin shales 10 to 50 feet thick. Very little basinward progradation of these thick sands took place throughout the entire Frio Formation, possibly because of contemporaneous movement along the large growth fault just landward of the main sand depocenter. On the other hand, this lack of progradation, the stacking of sand bodies, and the high sand/shale ratio may be due to the low sediment supply suggested by the lack of dip-oriented feeder systems in this area. These sand bodies are dominantly strike oriented and probably accumulated as a complex of beach ridges and barrier islands.

Gulfward of the strandplain sands the section changes abruptly into shelf sediments consisting predominantly of shale with mostly thin sands 10 to 30 feet thick. The configuration of the sands in the shelf environment is difficult to determine because of the lack of adequate well control. However, local thicker sand bodies which are probably reworked from the strandplain system do occur here.

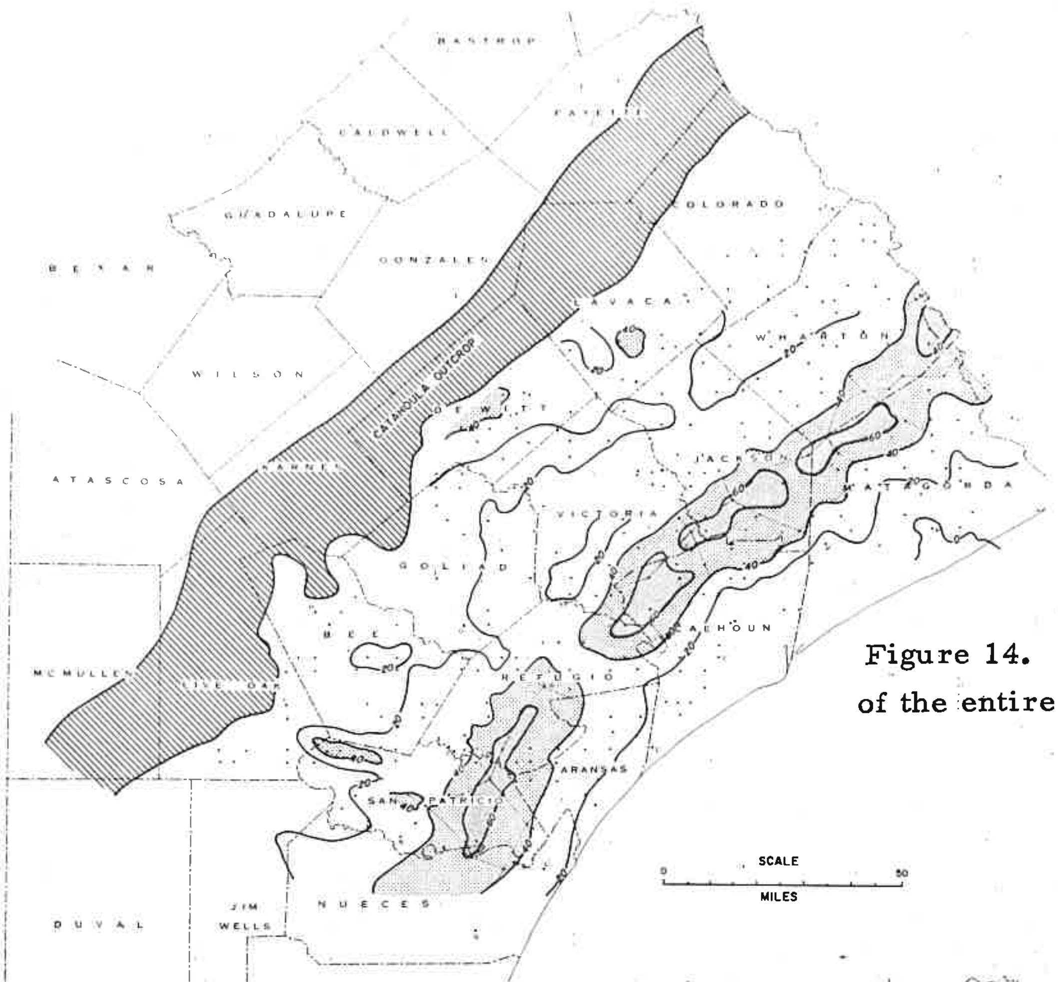

Figure 14. Sand percentage of the entire Frio Formation.

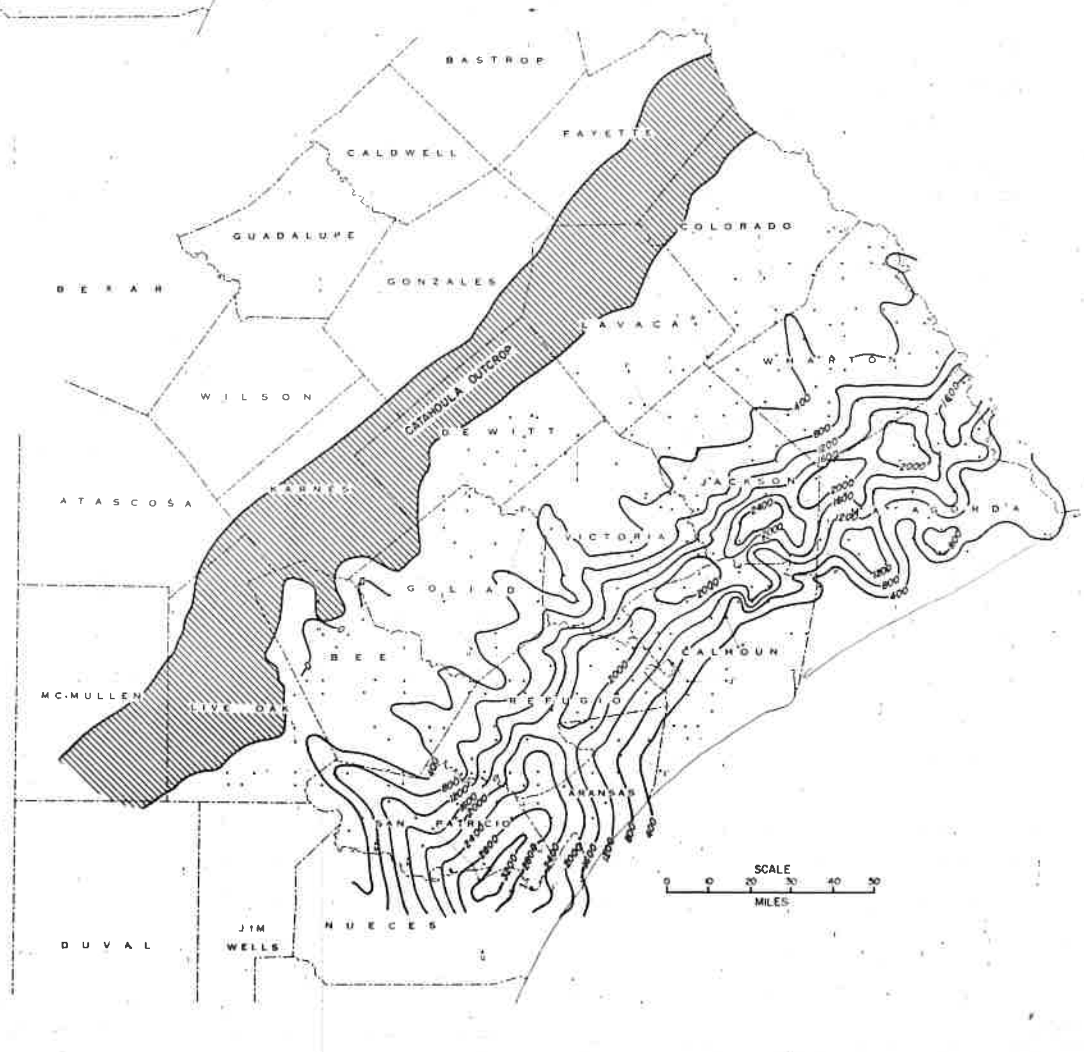

Figure 15. Net sand of the entire Frio Formation.

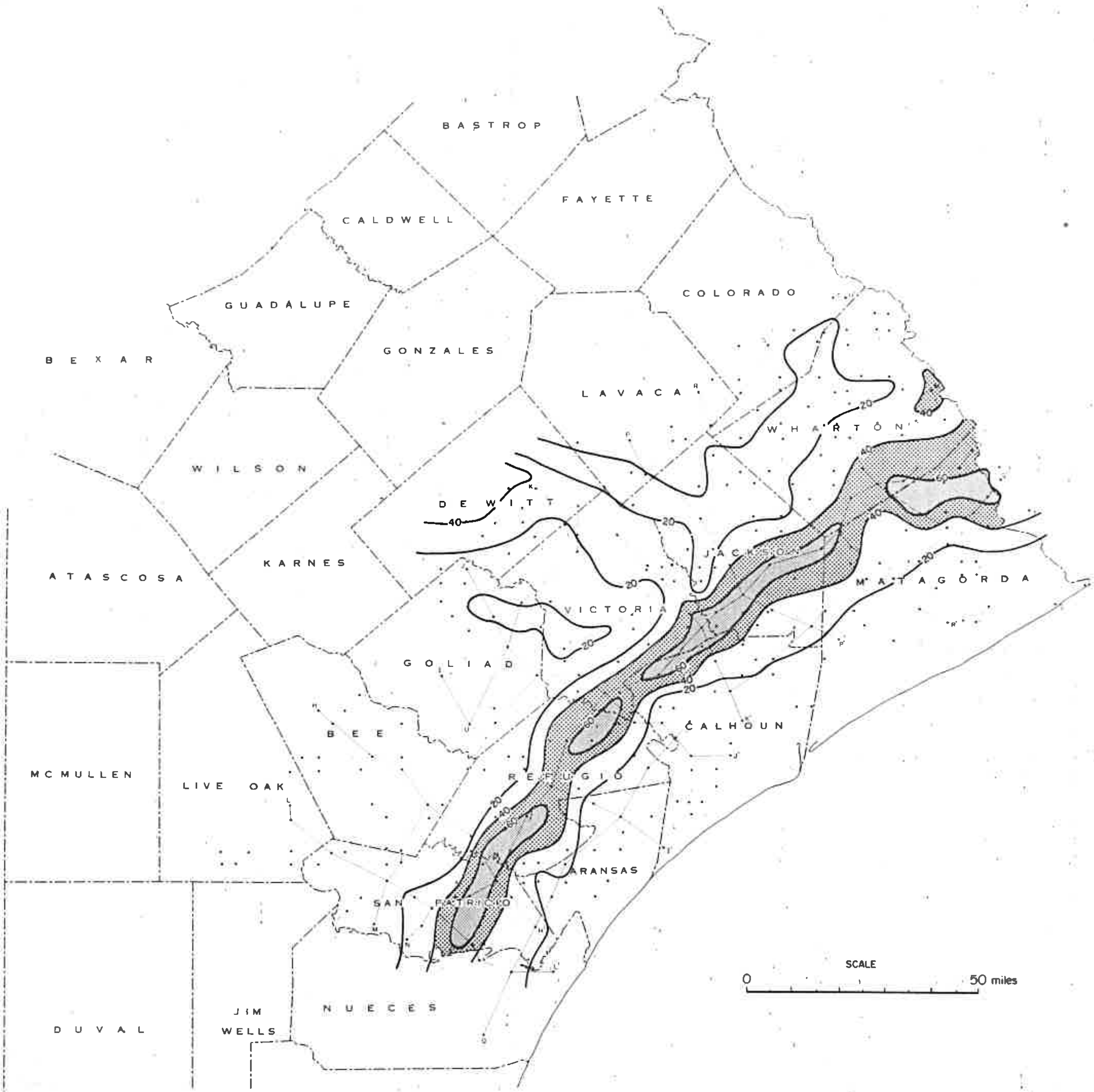

Figure 16. Sand percentage in unit T5-T6.

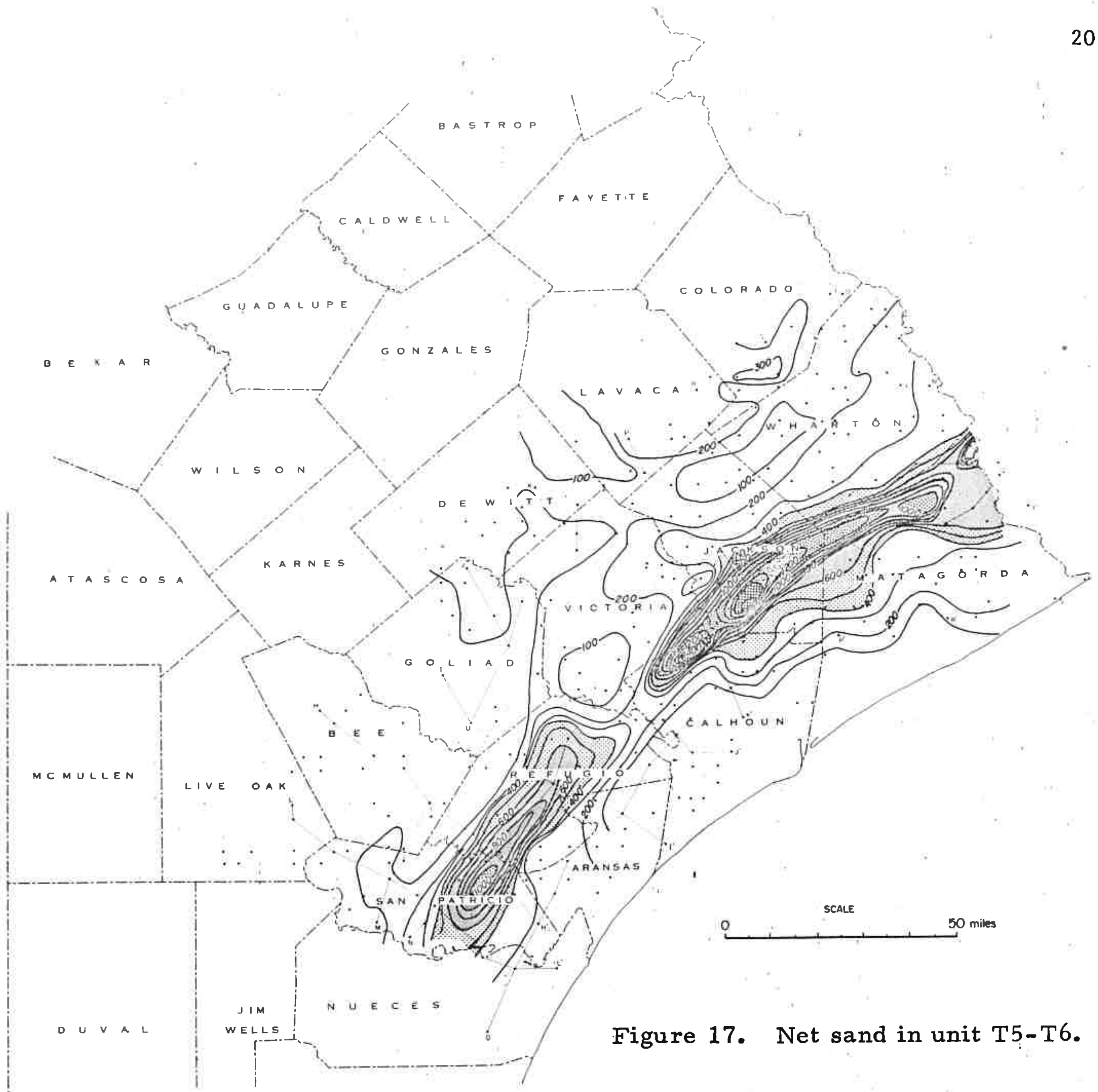

Figure 17. Net sand in unit T5-T6.

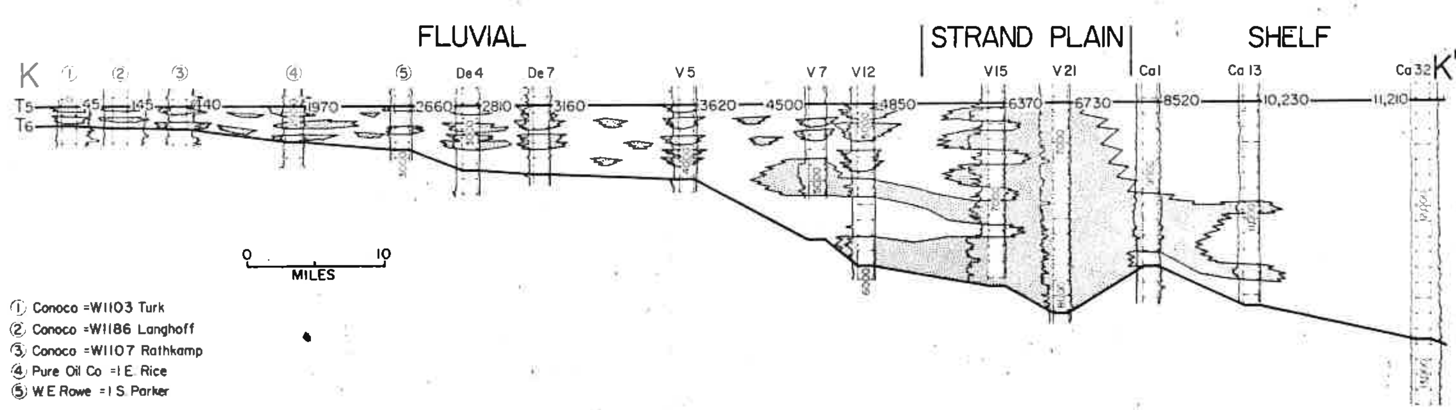

Figure 18. Sand distribution and interpreted depositional environments in unit T5-T6 along section K-K'.

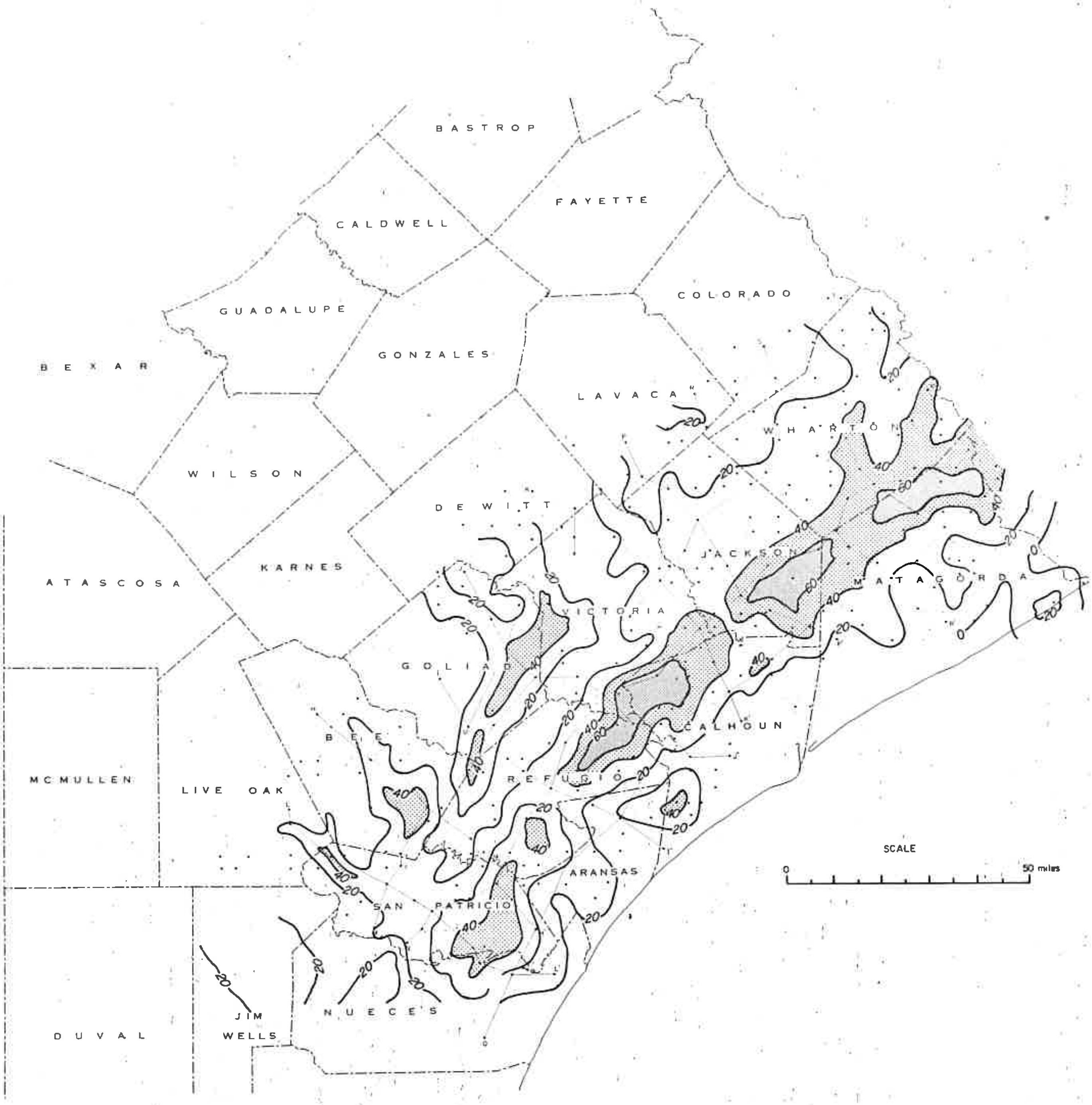

Figure 19. Sand percentage in unit T4-T5.

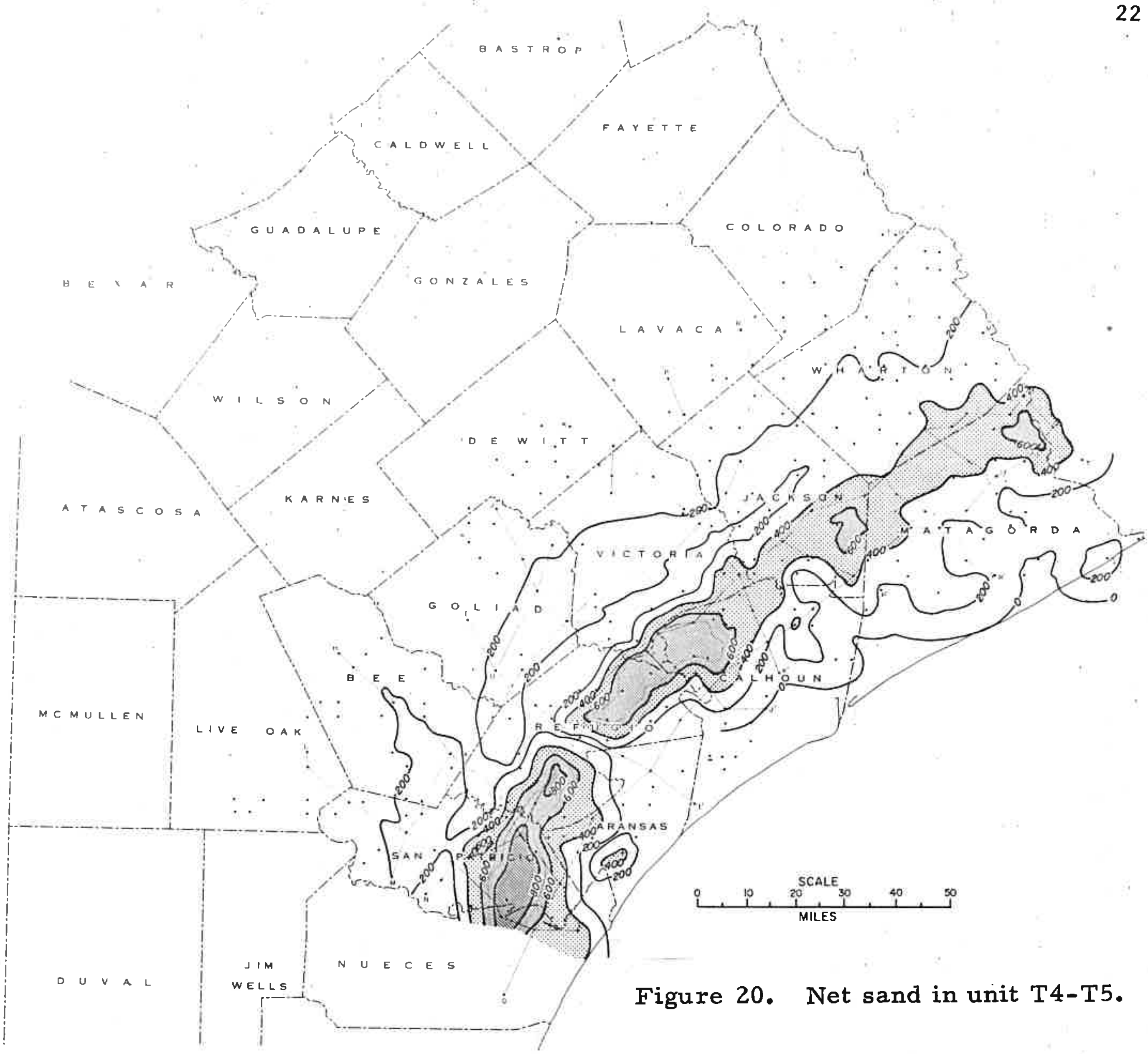

Figure 20. Net sand in unit T4-T5.

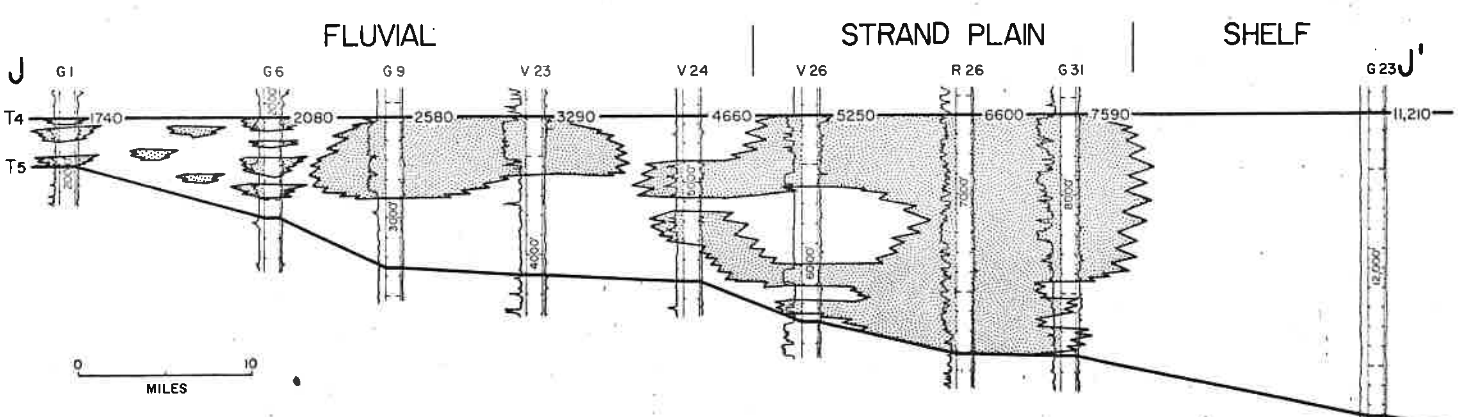

Figure 21. Sand distribution and interpreted depositional environments in unit T4-T5 along section J-J'.

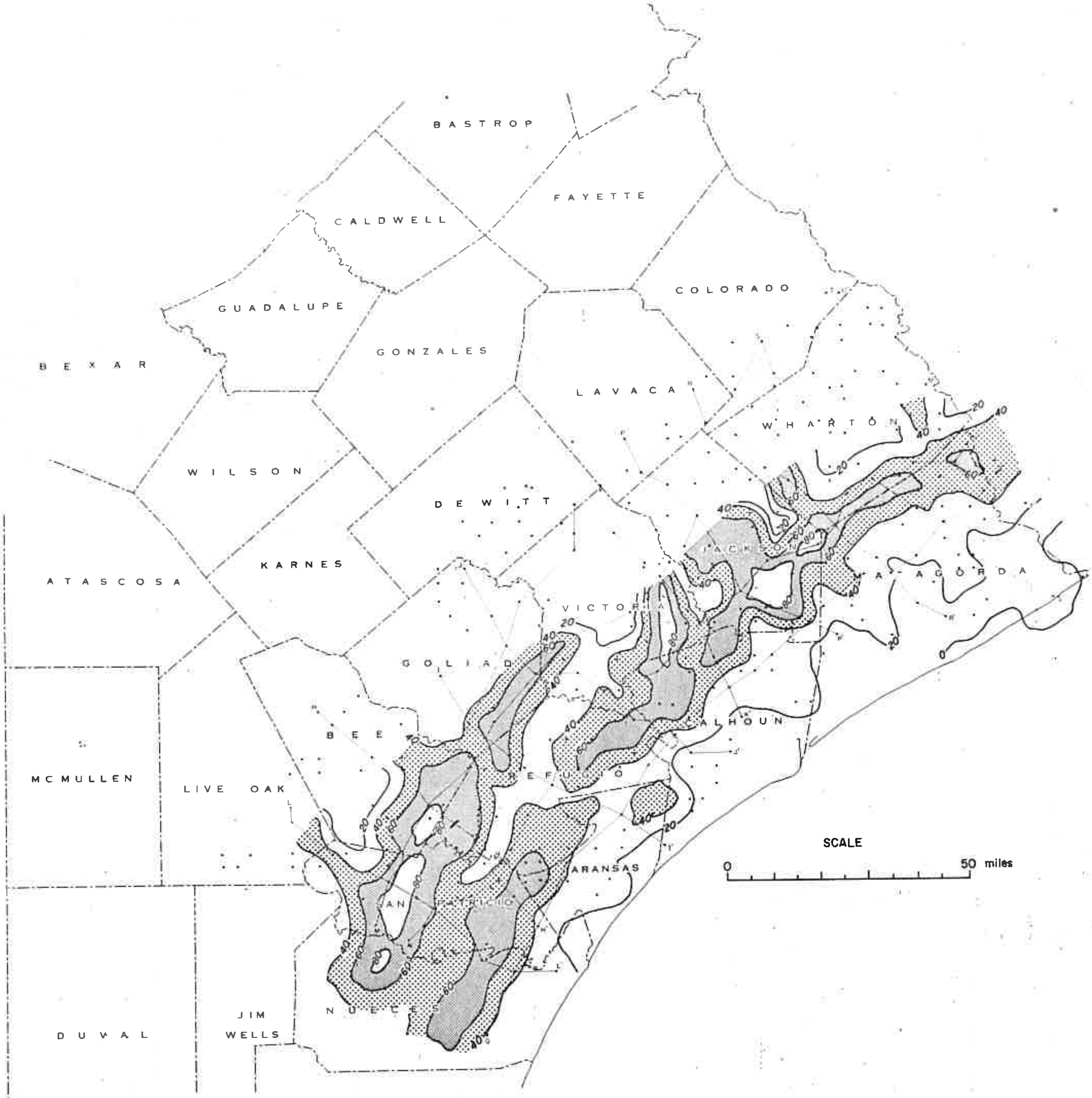

Figure 22. Sand percentage in unit T3-T4.

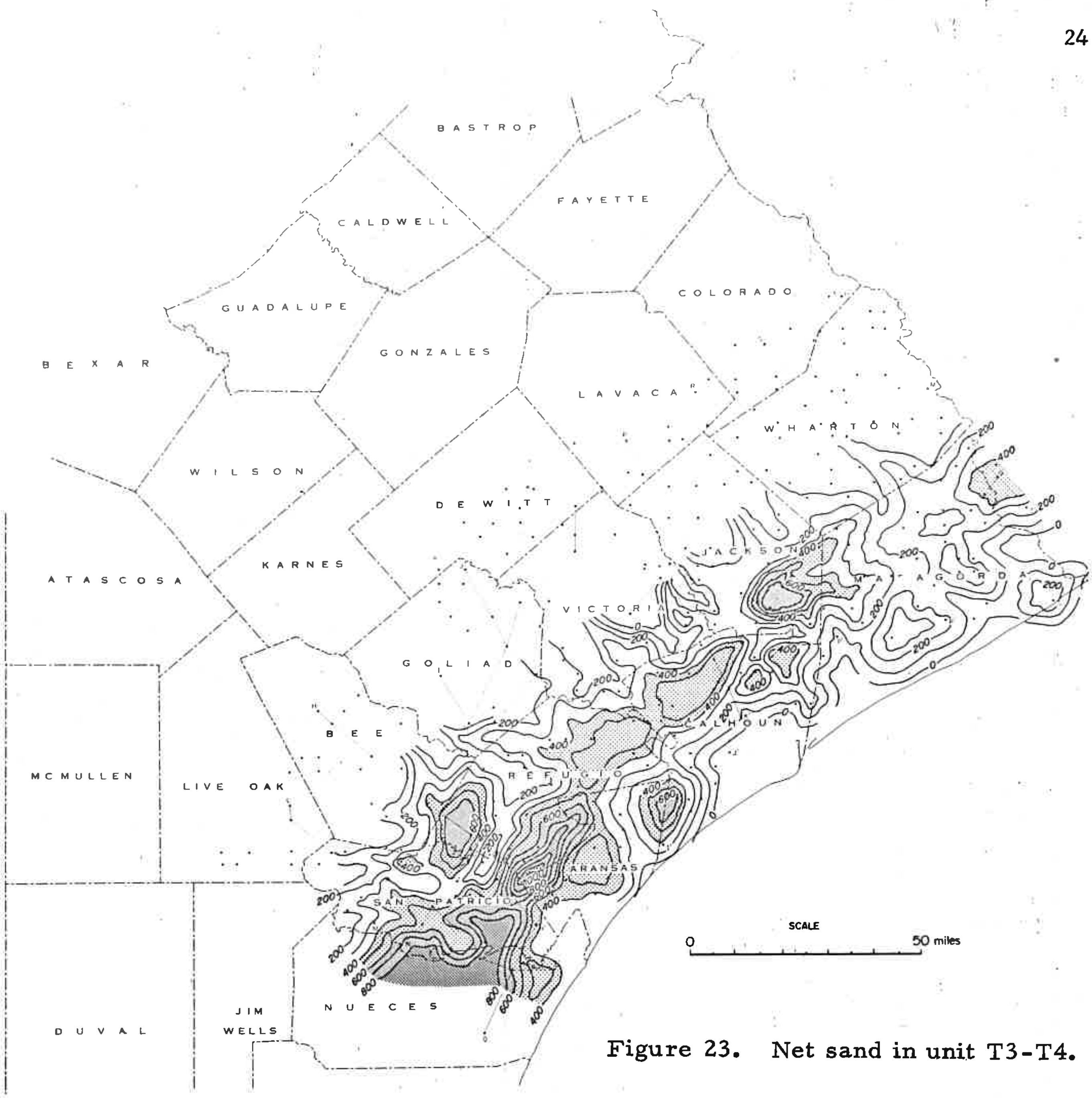

Figure 23. Net sand in unit T3-T4.

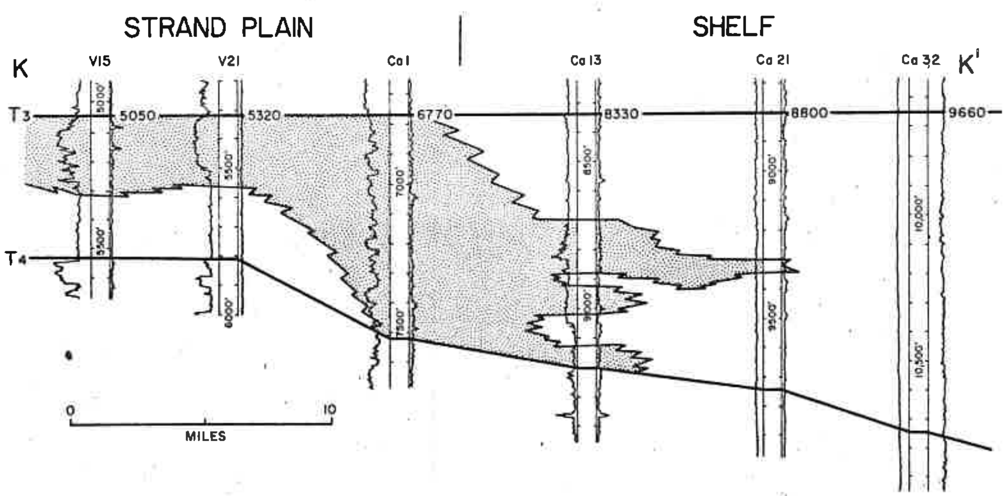

Figure 24. Sand distribution and interpreted depositional environments in unit T3-T4 along section K-K'.

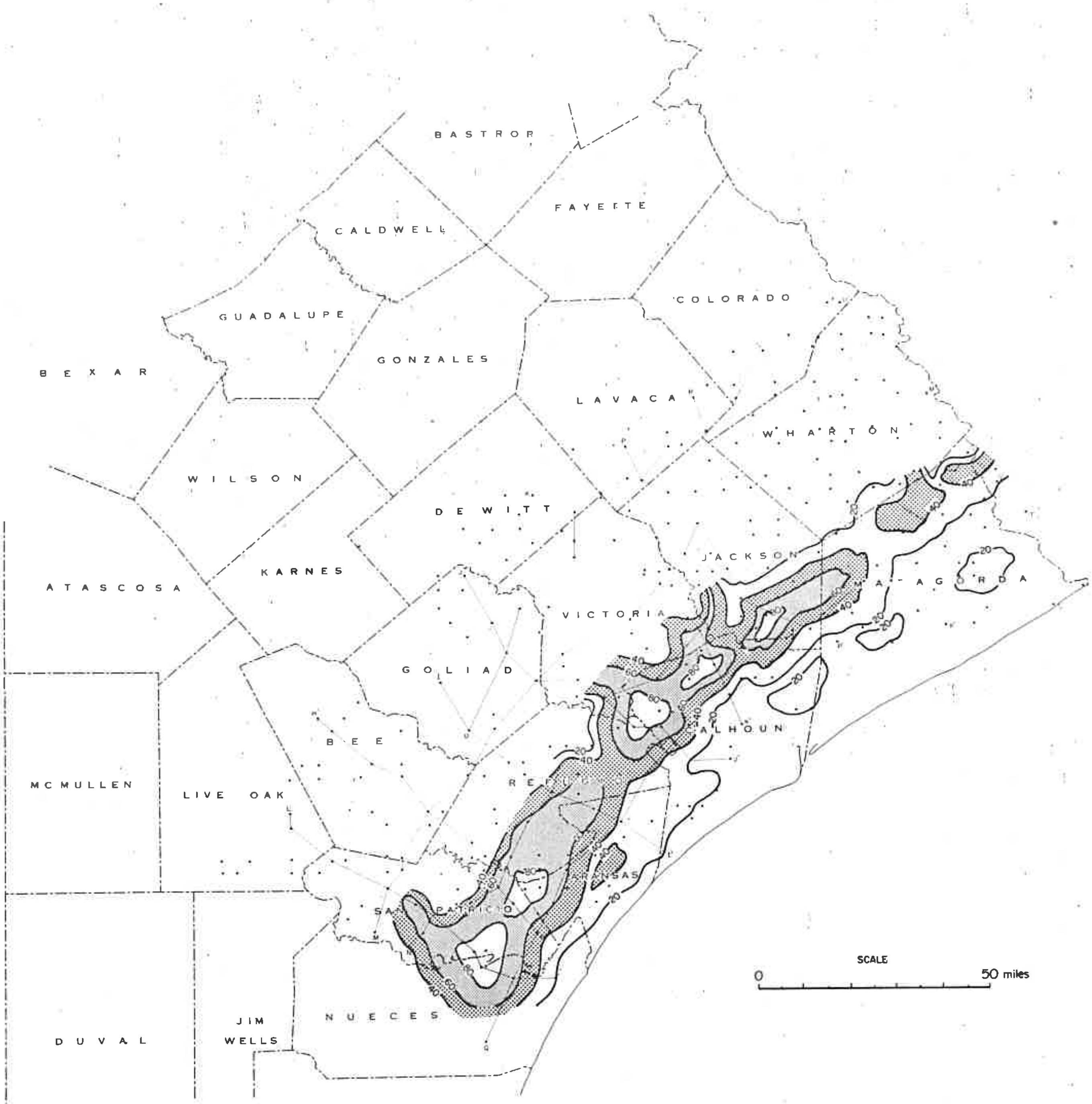

Figure 25. Sand percentage in unit T2-T3.

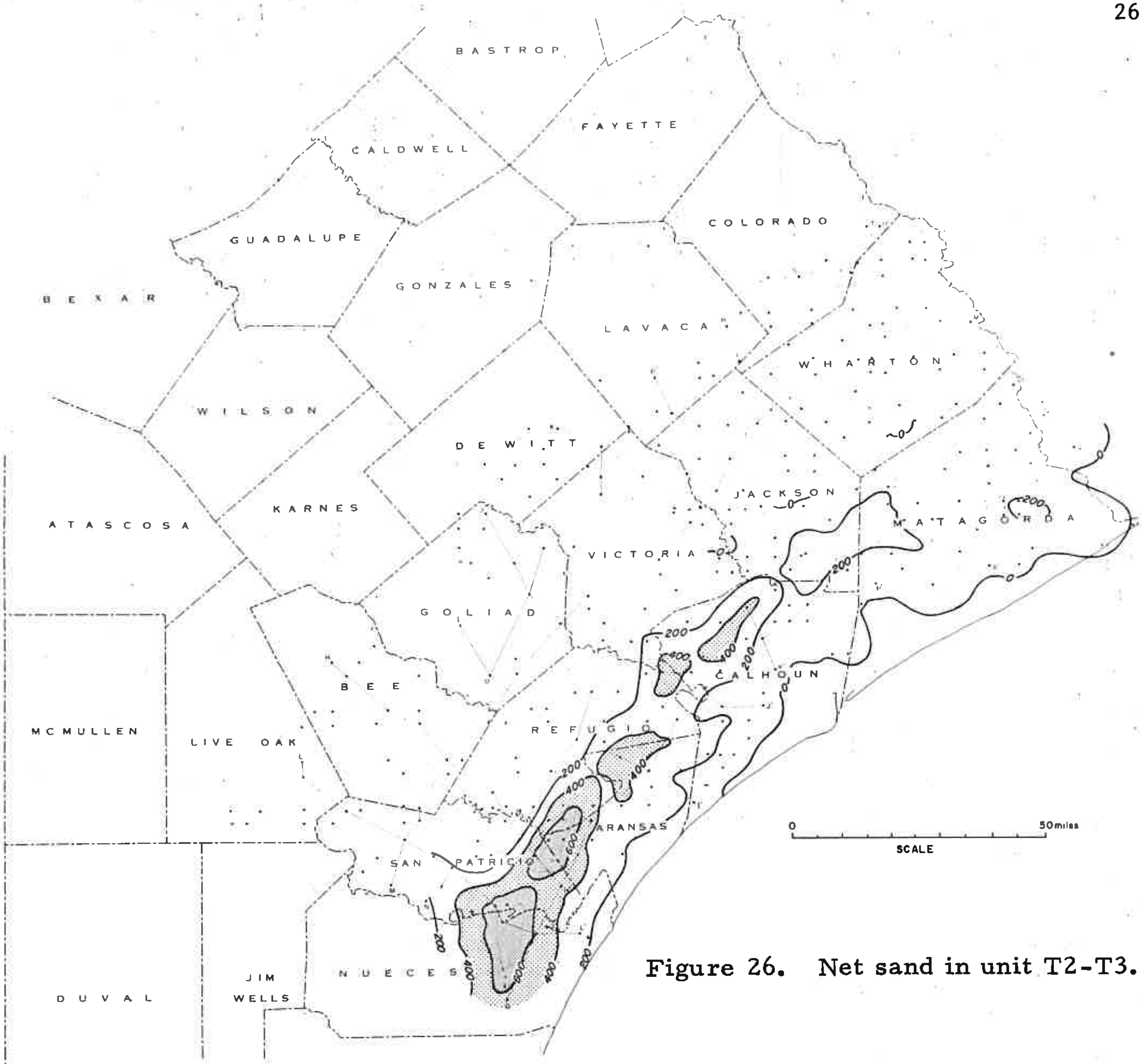

Figure 26. Net sand in unit T2-T3.

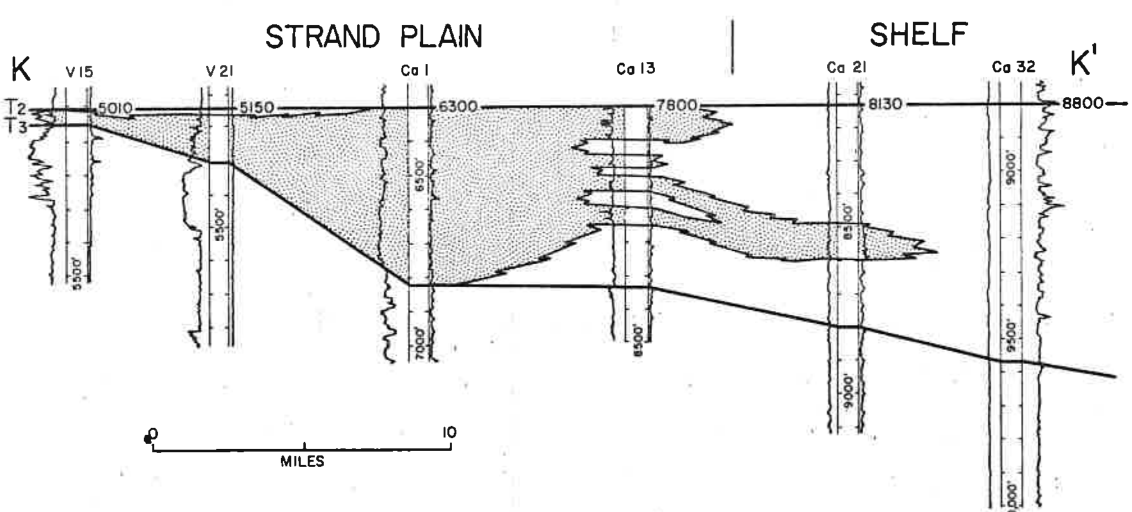

Figure 27. Sand distribution and interpreted depositional environments in unit T2-T3 along section K-K'.

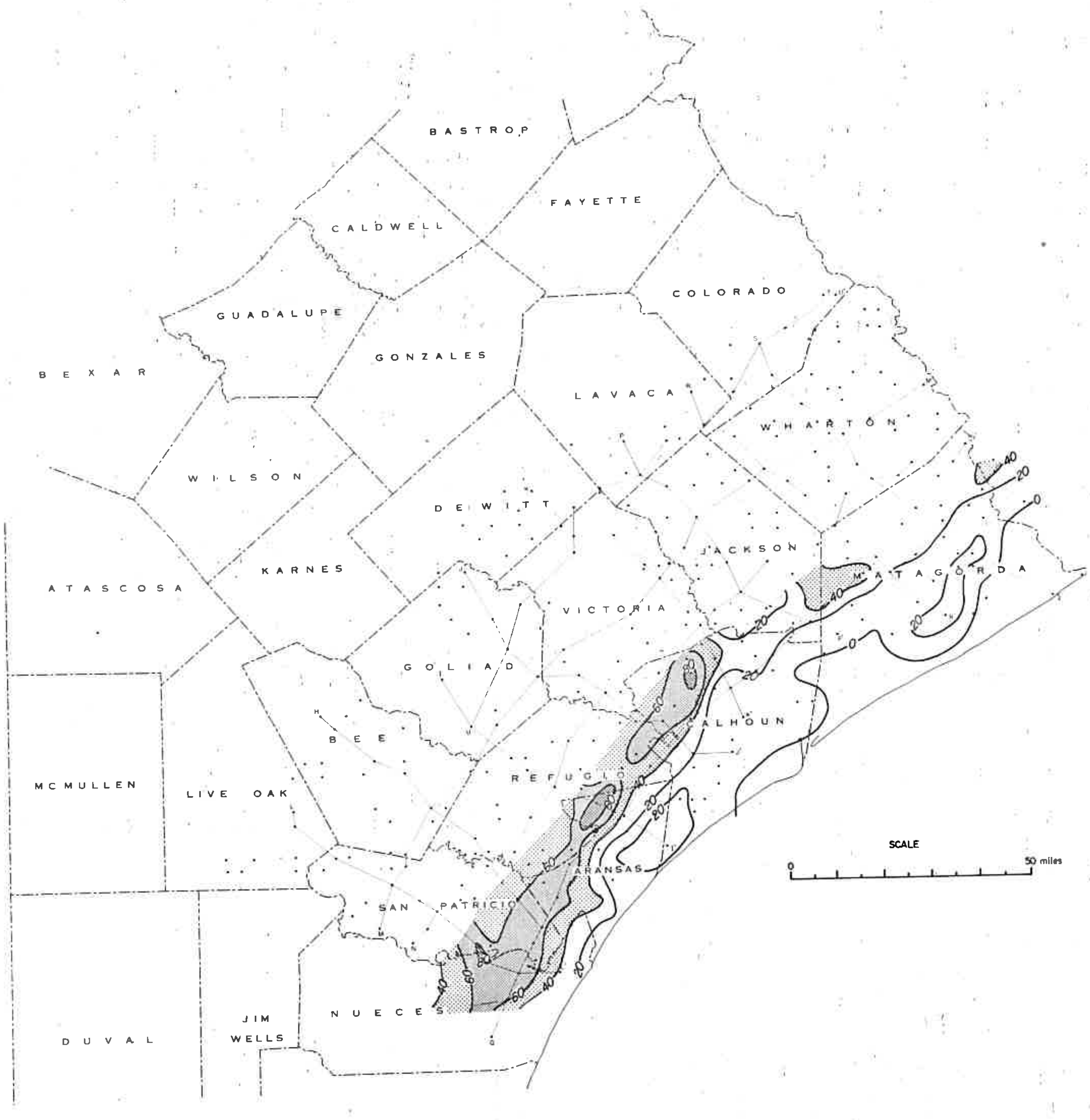

Figure 28. Sand percentage in unit T1-T2.

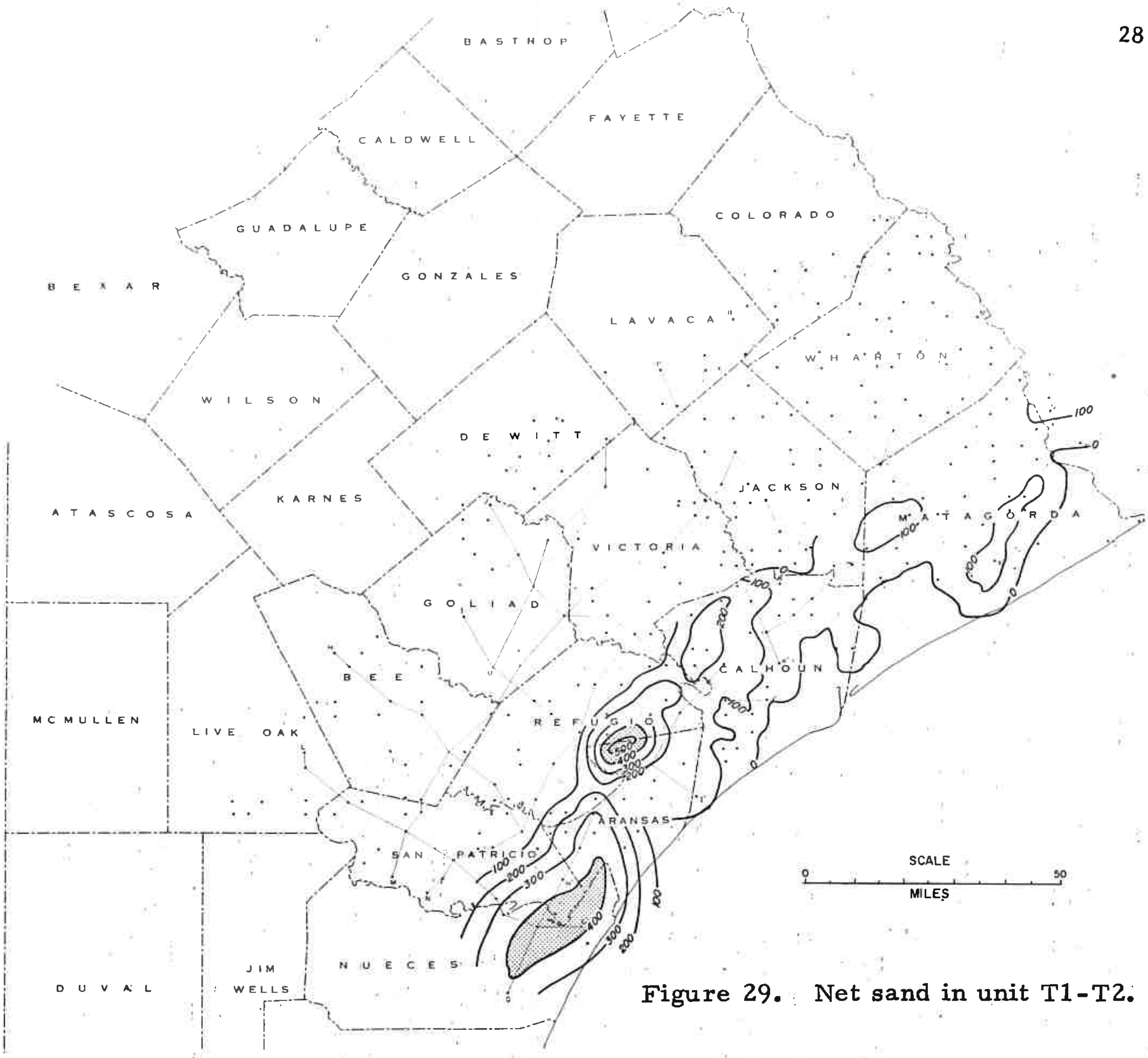

Figure 29. Net sand in unit T1-T2.

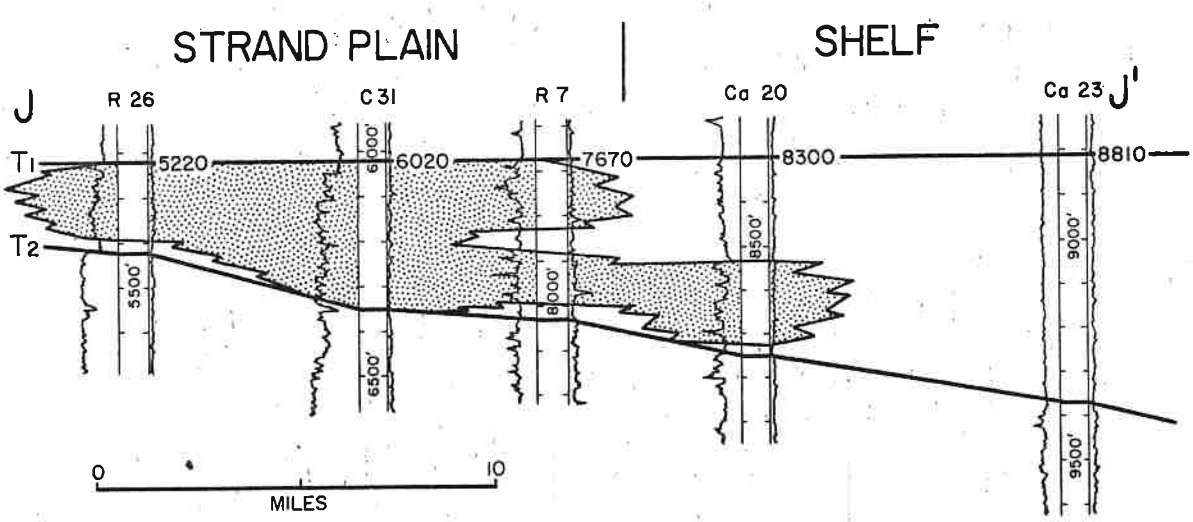

Figure 30. Sand distribution and interpreted depositional environments in unit T1-T2 along section J-J'.

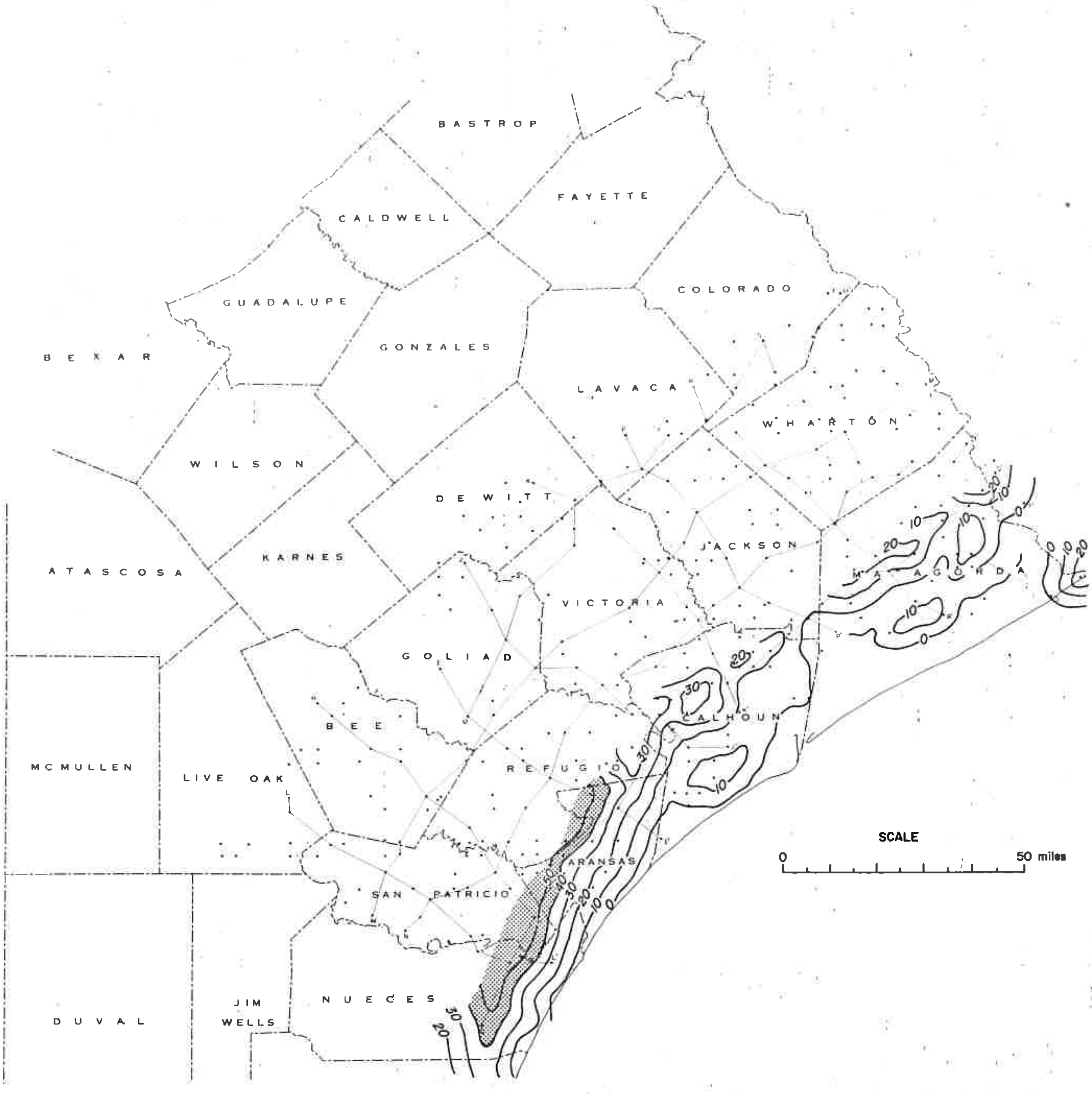

Figure 31. Sand percentage in unit T0-T1.

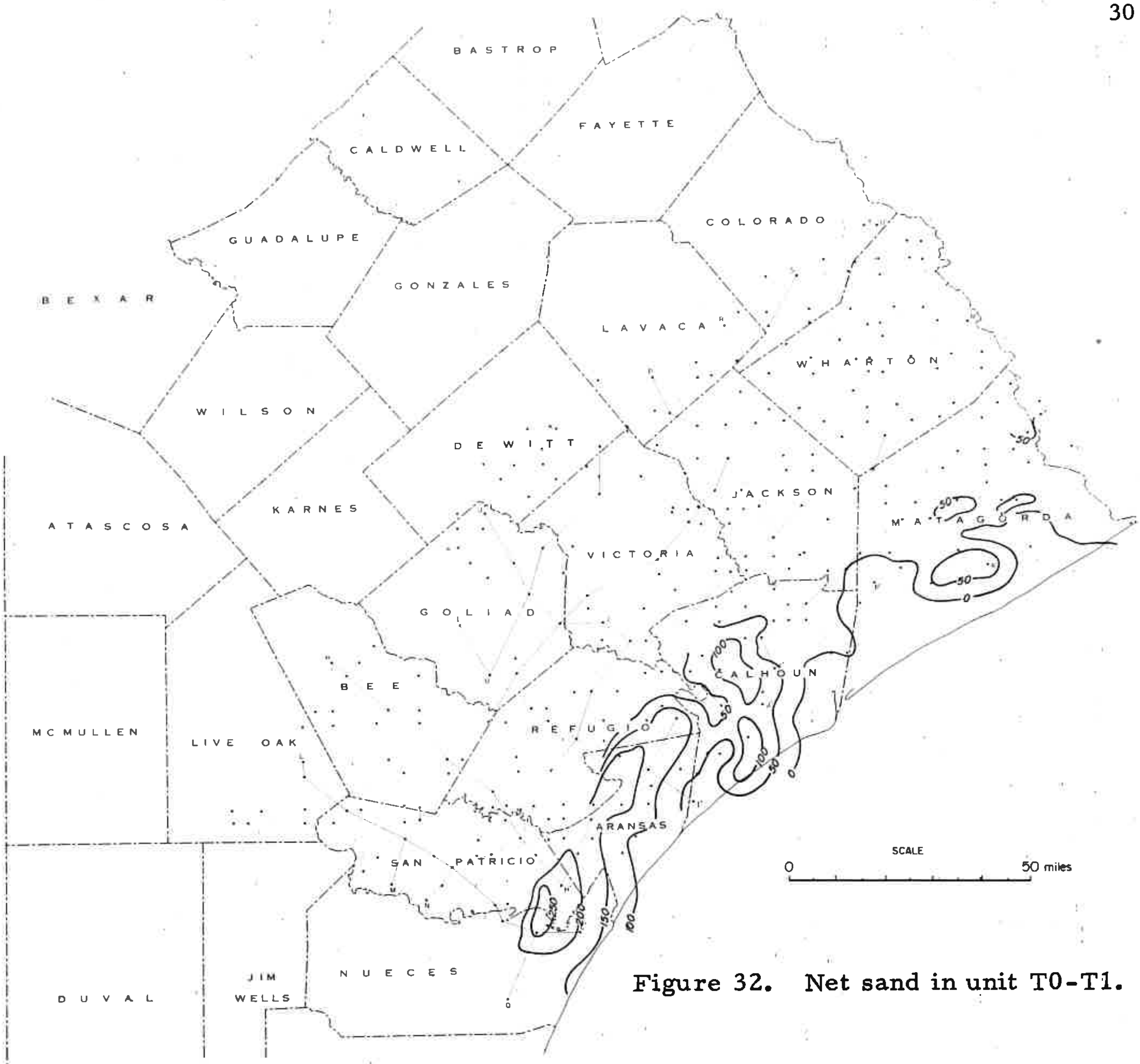

Figure 32. Net sand in unit T0-T1.

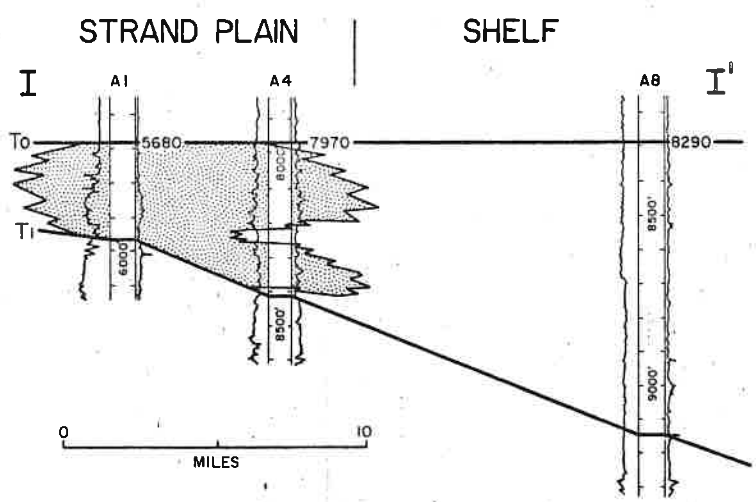

Figure 33. Sand distribution and interpreted depositional environments in unit T0-T1 along section I-I'.

GEOPRESSURED FRIO RELATED TO SAND DISTRIBUTION

Along the Middle Texas Gulf Coast, only the sands seaward of the main sand depocenter in the shelf environment occur beneath the top of geopressure.

Geopressure is defined as the zone in which the subsurface fluid pressure significantly exceeds that of the normal hydrostatic pressure of 0.464 psi/ft (Jones, 1969). For this study, 0.7 psi/ft is considered to indicate geopressure. The top of geopressure is picked from various criteria shown on the electrical logs such as gradual reduction in the negative self-potential deflection, increase in drilling mud weight above 13.5 lbs/gal, location of the intermediate casing point, and reduction of the density and resistivity of the shale.

In the Middle Texas Gulf Coast area, the top of geopressure occurs between -7,000 and -11,000 feet (fig. 34). The shallowest occurrence of geopressure corresponds to thick shale sections beneath the Frio updip from the major strike-oriented sands. Throughout the area of occurrence of major strandplain sediments, the top of geopressure occurs in shallow troughs at subsea depth ranging from -8,500 to -9,000 feet, resulting in the top of geopressure being located beneath the sand sections. This relationship, as noted in the South Texas study (Bebout, Dorfman, and Agagu, 1975), is characteristic of strandplain sediments primarily because of lack of effective shale seals, allowing fluid leakage from the reservoir and displacing the top of geopressure downward. Downdip of the strandplain trend, the top of geopressure occurs within the section of thick shale and thin sands of the Frio shelf sediments.

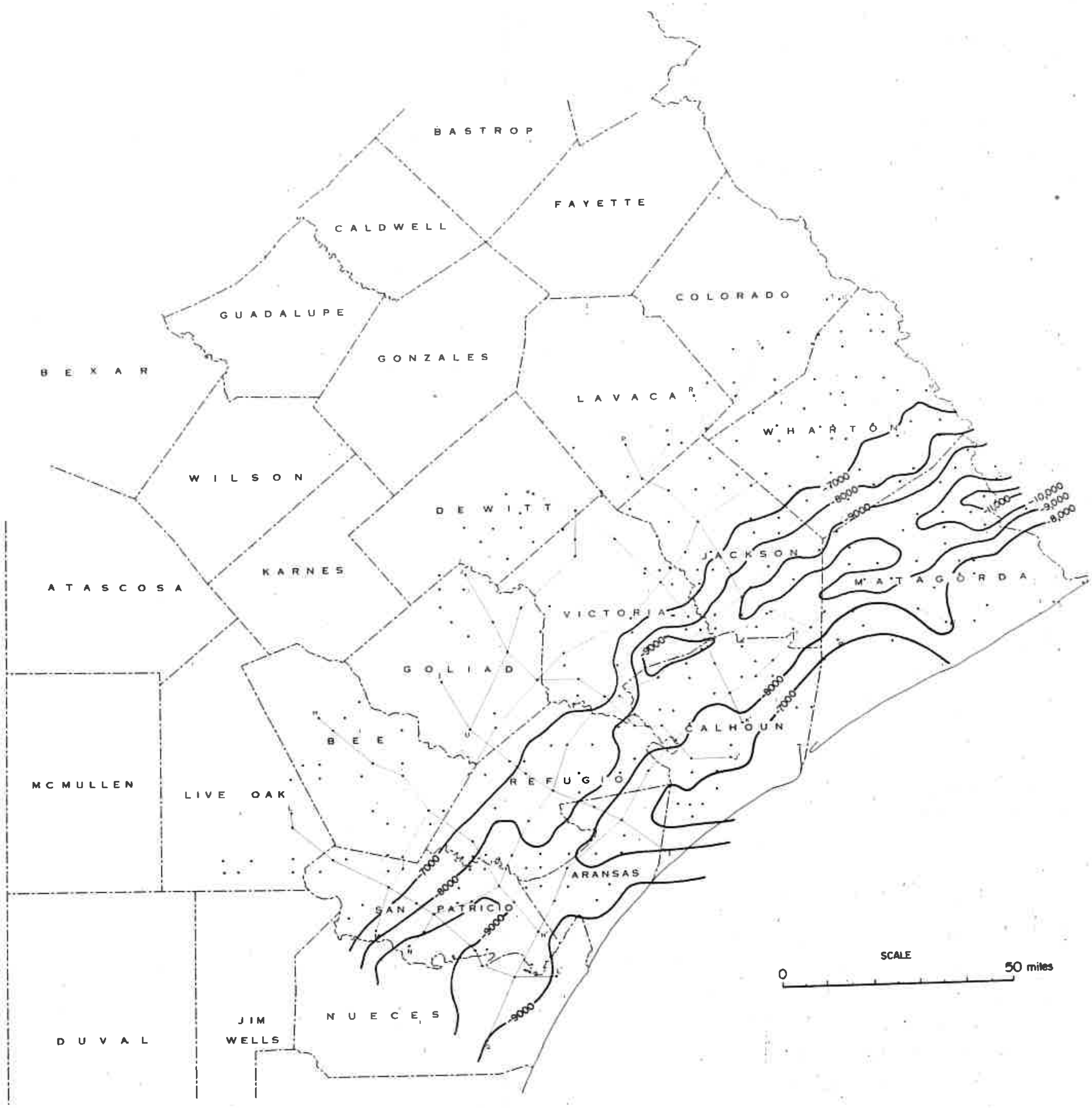

Figure 34. Top of geopressure, Middle Texas Gulf Coast.

ISOTHERMAL MAPS

Isothermal maps constructed from well-log bottom-hole temperatures indicate low temperatures within high-sand areas and steepening of geothermal gradients below 225°F in downdip Frio sections.

Isothermal maps have been constructed for units T5-T6, T4-T5, and T3-T4 (figs. 35-37), based on uncorrected well-log bottom-hole temperatures. These temperatures were not measured under stable hole conditions and are expected to be slightly lower than the actual subsurface temperature. Because of the difficulty encountered in correcting temperatures, it is not felt that this procedure is necessary for the gross evaluations required here. Data points for these isothermal maps are sparse because there is commonly only one temperature reading per well in the Frio interval; consequently, the data density is approximately one-third that used in the preparation of other maps.

From these isothermal maps (used with the sand-distribution maps), three observations can be made: (1) fluid temperatures within the main sand depocenter are generally lower than 200°F, (2) the temperature gradient steepens at temperatures above 225°F, principally in the thick shale section downdip from the major sand depocenter, and (3) temperatures higher than 250°F occur only in the shelf environment where the sand bodies are relatively thin.

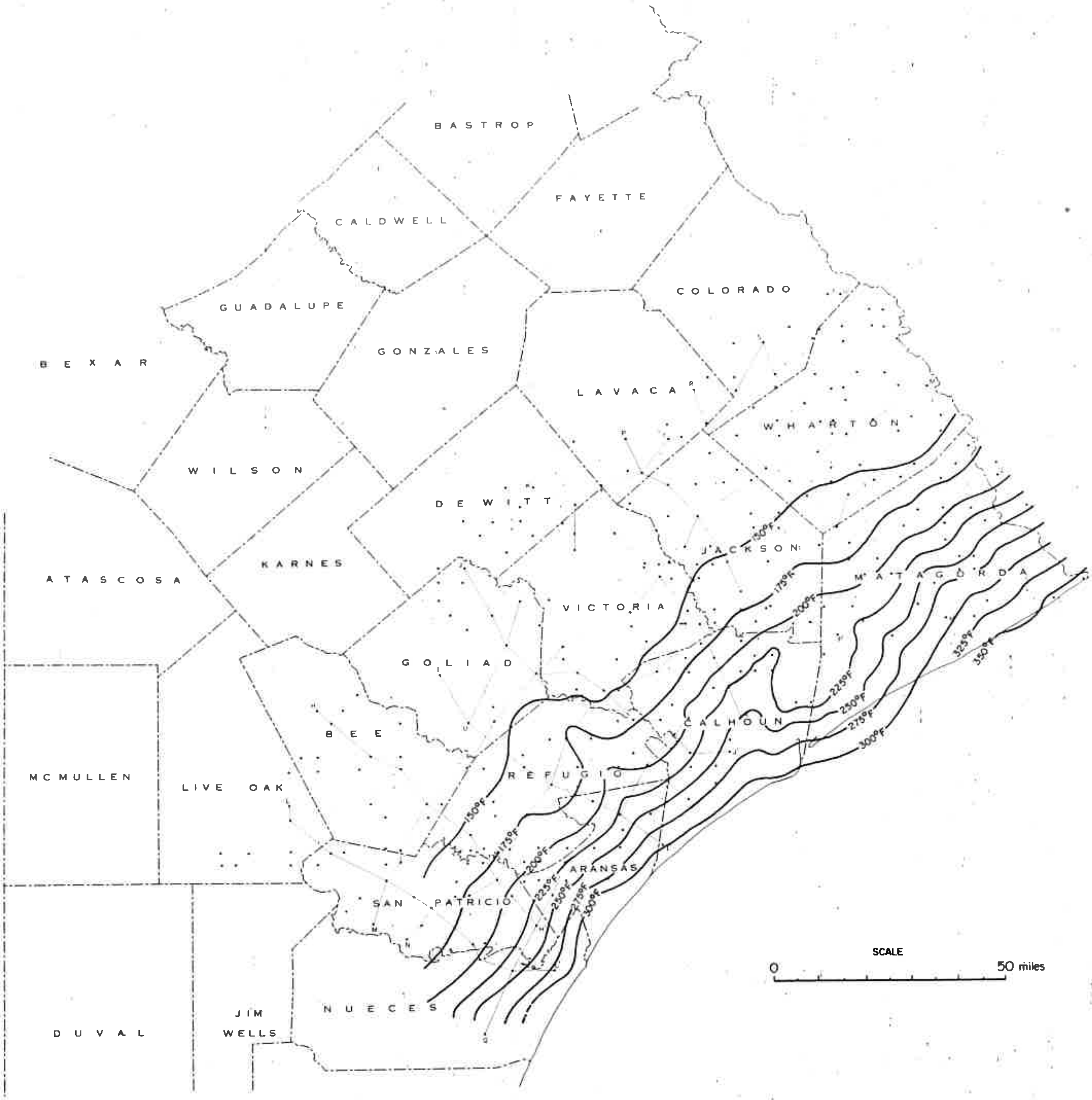

Figure 35. Isothermal map—unit T5-T6.

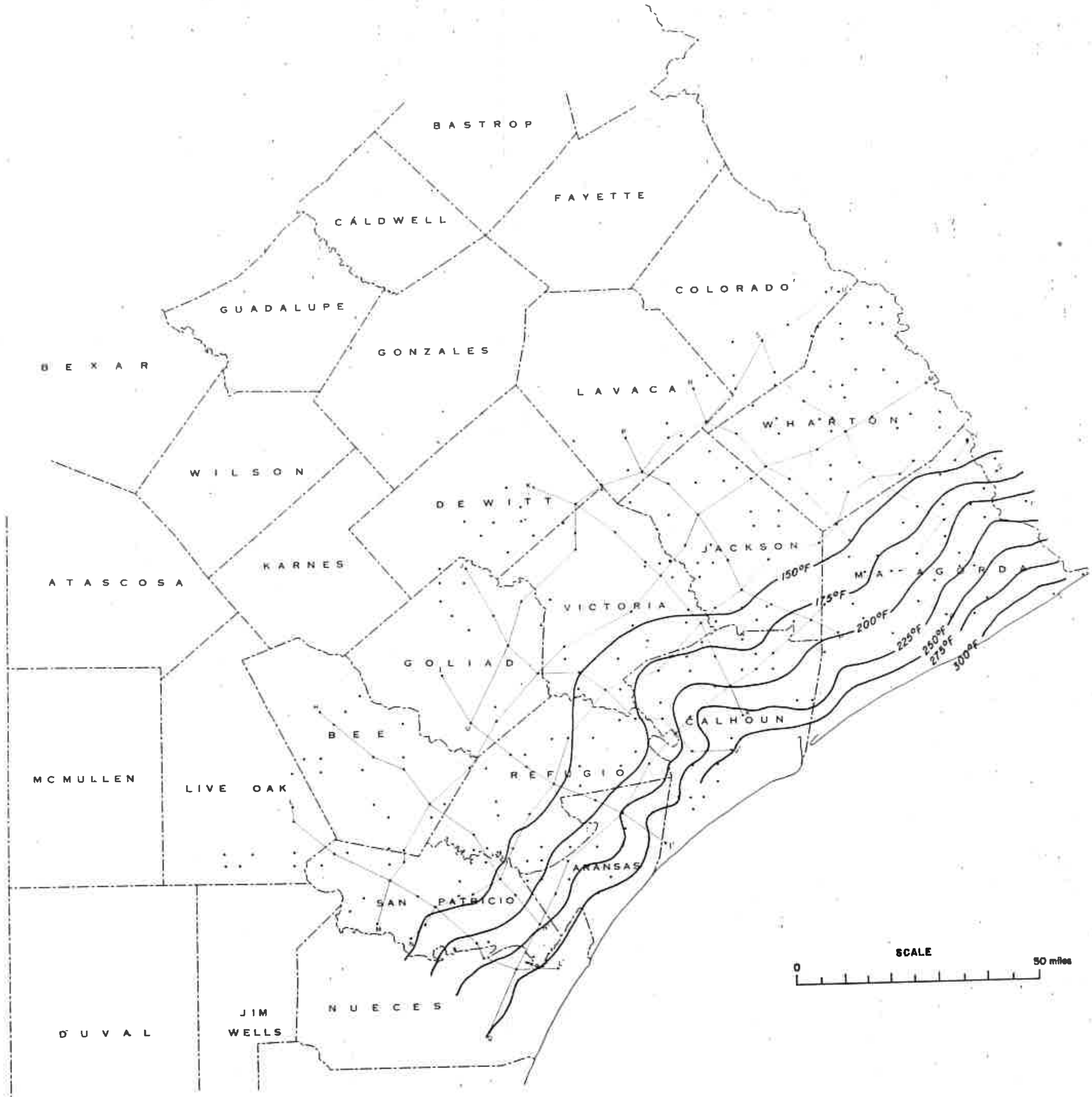

Figure 36. Isothermal map—unit T4-T5.

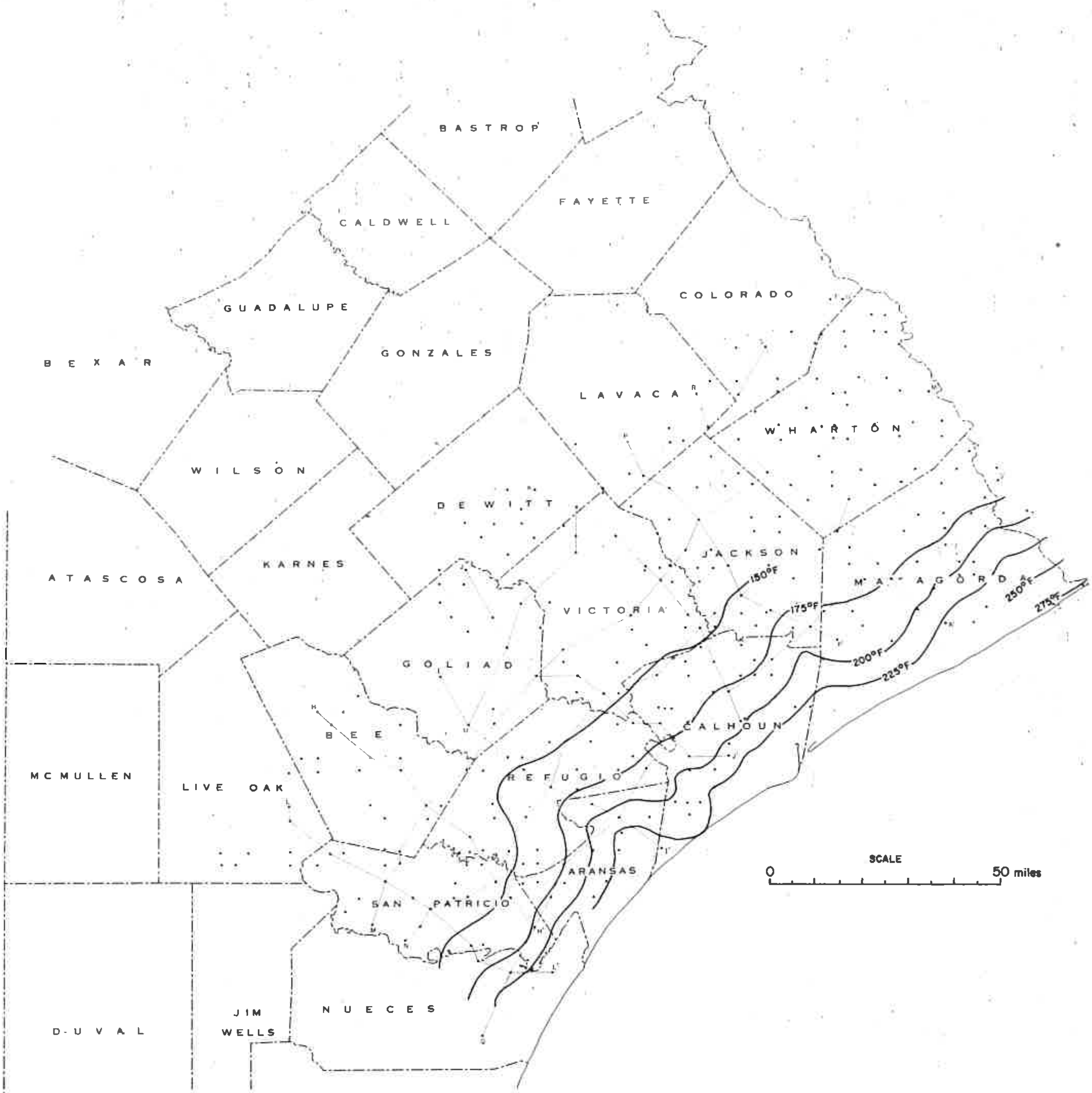

Figure 37. Isothermal map—unit T3-T4.

CONCLUSIONS AND POTENTIAL GEOTHERMAL FAIRWAYS

From this study of the Frio of the Middle Texas Gulf Coast, three areas (gulfward of the main sand depocenter) have been identified as potential geothermal prospects.

Frio sand along the Middle Texas Gulf Coast was deposited in three main depositional environments: fluvial, strandplain, and shelf. The fluvial environment consists of a relatively narrow fluvial plain crossed by sand-filled dip-oriented feeder channels. The strandplain environment comprises many thick strike-oriented sand bodies which are stacked one upon the other along a narrow band 10 to 15 miles wide. The shelf environment is composed primarily of shale with thin sands of local lateral distribution.

Some gross conclusions can be drawn concerning the geothermal potential of these major depositional systems. The sands of the fluvial system are thin and discontinuous and have fluid temperatures too low to be prospective. The strandplain sands are thick and extensive but, like the fluvial system, have fluid temperatures too low to be prospective. Most of the sands in the shelf system are thin, and lateral continuity is not known largely because of the lack of control; however, some of the sand bodies are thick enough and contain water temperatures high enough to be considered prospective.

Arbitrary criteria for geopressured geothermal sand reservoirs, based on preliminary reservoir studies, indicate that a minimum volume of 7.5 cubic miles and a minimum temperature of 275°F should be used in delineating prospective areas for detailed studies. This aquifer volume corresponds with a sand thickness of 200 feet over an area of 200 square miles; however, increases in sand thickness will substantially reduce the area required. Within the limits of these minimum standards we have identified three areas which merit further study to delineate potential geothermal reservoirs (fig. 38). All of these areas are gulfward of the main sand depocenter in the shelf environment.

Area 1. The vicinity of the intersection of Aransas, San Patricio, and Nueces Counties, including most of Corpus Christi Bay. The sand bodies considered here occur between -10,000 and -16,000 feet, are more than 500 feet thick, and are known to occur over an area of at least 200 square miles. Recorded fluid bottom-hole temperatures are between 300 and 320°F.

Area 2. South-central Matagorda County. This sand body is known to extend over an area of 100 square miles at -15,700 feet, is 200 feet thick, and has fluid temperatures greater than 300°F. Although this sand body appears not to meet the minimum requirement of 200 square miles, the actual boundaries of the prospective reservoir have not yet been delineated by well control.

Area 3. Northeast Matagorda County. This sand body is recognized in only one well where it occurs at -13,700 feet, is 150 feet thick, and has fluid temperatures of approximately 300°F. The lateral extent of this sand is unknown because of lack of control.

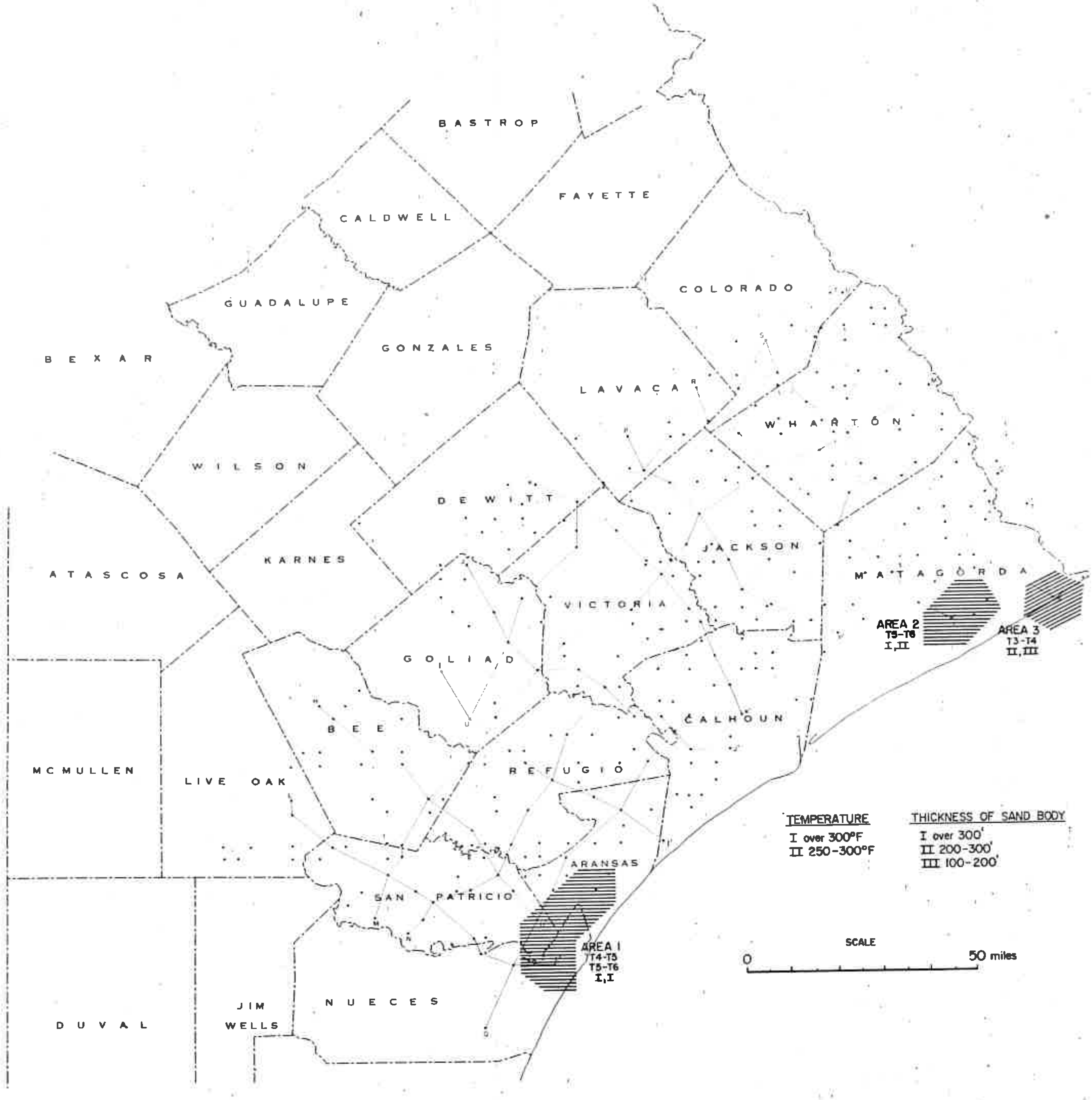

Figure 38. Potential geothermal fairways, Middle Texas Gulf Coast.

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