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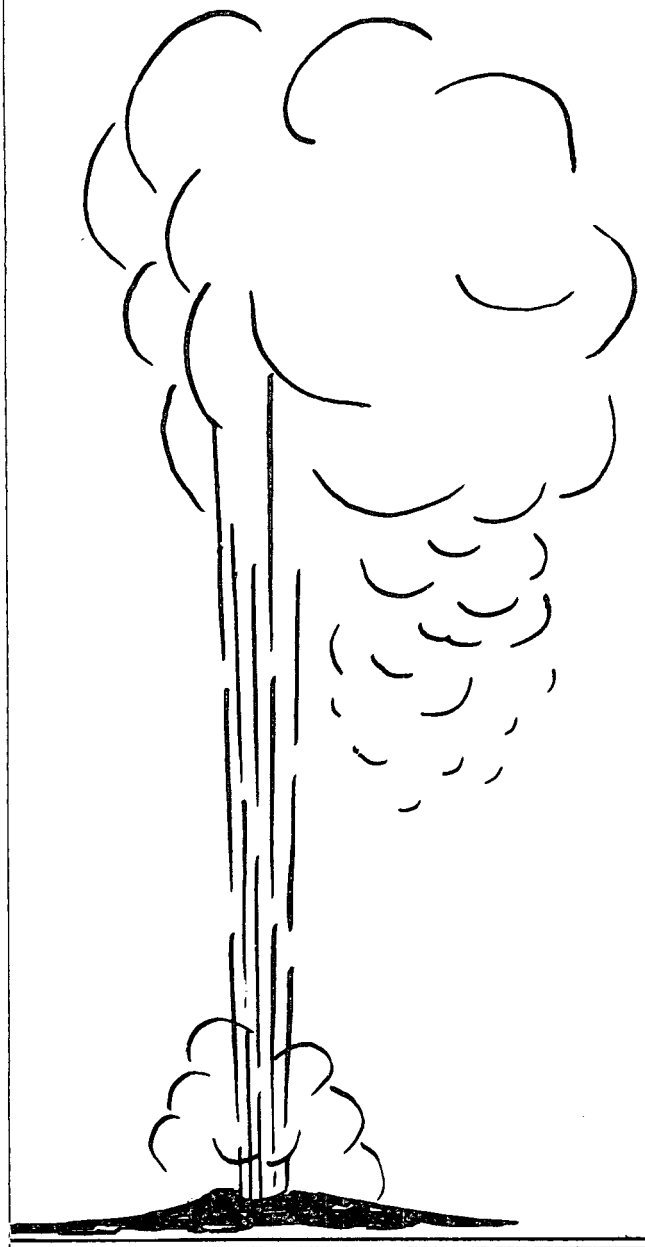

GEOPRESSURED-GEOTHERMAL TEST OF THE EDNA DELCAMBRE NO. 1 WELL, TIGRE LAGOON FIELD, VERMILION PARISH, LOUISIANA: GEOLOGY OF THE TIGRE LAGOON FIELD, PLANULINA BASIN

By
Paul H. Jones

October 1978

Work Performed Under Contract No. EY-76-S-05-4937

McNeese State University
Lake Charles, Louisiana

MASTER

U. S. DEPARTMENT OF ENERGY

Geothermal Energy

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GEOLOGY OF THE TIGRE LAGOON FIELD, PLANULINA BASIN

October, 1978

FINAL REPORT

Prepared by

McNeese State University

Lake Charles, Louisiana 70609

for

MASTER

DEPARTMENT OF ENERGY

DIVISION OF GEOTHERMAL ENERGY

under

DOE CONTRACT NO. EY-76-S-05-4937

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I. SUMMARY

Geology and Hydrology of the Tigre Lagoon Gas Field
Eastern Vermilion Parish, Louisiana

The Tigre Lagoon Gas Field in east-central Vermilion Parish, Louisiana, occupies a complexly faulted northwest-southeast trending structure. As mapped on the top of the Planulina zone, it is about 4 miles long and 2 miles wide, and is located about 4 miles due west of Avery Island salt dome. Nonassociated gas is produced from several high-pressure conventional reservoirs formed by extensive sand-bed systems in the geopressure zone. In the field area, geopressure occurs below a depth of about 12,000 ft.; the geopressure seal is a shale bed only 300 to 500 ft. thick.

The depth-pressure gradient in the Coastal States Gas Producing Company Edna Delcambre Well No. 1 was 0.52 psi/ft. at 12,070 ft., and 0.86 psi/ft. at 12,410 ft. when the well was drilled late in 1967. Formation fluid pressures responsible for these gradients were 6,300 psi at 12,070 ft. and 10,600 psi at 12,410 ft.; a pressure differential of 4,300 psi occurs in a depth interval of 340 ft., reflecting a fluid-pressure gradient of about 12.6 psi/ft. The Coastal States Edna Delcambre Well No. 4, less than a thousand feet north of well no. 1, blew out and cratered in 1969 from a depth of about 14,000 feet.

The gas reservoirs of the Tigre Lagoon Field, formed by a narrow roll-over fold, are located immediately southwest from a major growth fault that is the landward boundary of a lower Miocene depositional basin. Subsidence occurred as the basin was rapidly filled by deltaic, coastal, and

nearshore marine sediments. These deposits were capped by a transgressive marine shale that can be identified in drill cuttings by a Planulina marker fossil. The Tigre Lagoon rollover anticline is cut diagonally by arcuate branch faults which die out westward at distances of 2 to 3 miles. At least 5 widespread sand-bed aquifers, probably formed by the winnowing action of waves in ancient coastal lakes, occur between depths of 12,500 and 14,000 ft. These sand beds range in thickness up to about 250 ft. in the eastern part of the Planulina basin, but generally are no more than 100 ft. thick; their areal extent is commonly greater than 50 mi^2. The hydraulic continuity of these aquifers regionally is interrupted by fault displacements and, except to the westward, fluid movement is much influenced by geologic structure.

Natural gas in the producing reservoirs at Tigre Lagoon is not associated with oil. The solubility of natural gas (methane) in water of moderate to low salinity is very great at the elevated pressures and temperatures of the geopressure zone; each barrel of water rising from depths of 15,000 to 20,000 ft. in the Planulina basin may, at low salinity, contain up to 100 cubic ft. of methane. As the pressure and temperature of the rising water are reduced along the path of flow, and the salinity is increased by hyperfiltration as water escapes through the shale-bed "seal," methane comes out of solution; released vapor-phase gas accumulates in structural traps and forms commercial reservoirs. By referring to Table 3, it can be seen that a pressure drop from 16,000 to 6,000 psi, at $400^{o}F$, for example, reduces methane solubility in fresh water by 52 cf/bbl; a temperature drop from 400° to $200^{o}F$, at 10,000 psi, reduces it by 49 cf/bbl.

The Tigre Lagoon structure has been a focus of water flow from deep in the Planulina basin for millions of years, with continuing leakage into the overlying hydropressure zone--mainly by movement up fault planes when fluid pressure exceeds rock pressure. The clay-bed seal is thin and the pressure differential across it is large; even today the fluid pressure is very close to the fracture pressure required for leakage up growth faults and branch faults. Hyperfiltration of saline formation water that seeps through the clay-bed seal as a consequence of the great pressure differential has concentrated the dissolved solids in the uppermost aquifers of the geopressure zone, where water salinities locally exceed 100,000 mg/l. As water salinity is increased, methane solubility is substantially reduced--as much as 30 percent if salinity is raised from 10,000 to 100,000 mg/l. The combined effects of pressure, temperature, and water salinity changes have resulted in methane exsolution and accumulation in the Tigre Lagoon structure, and commercial gas reservoirs are found in 6 of the uppermost 8 sand-bed aquifers in the geopressure zone.

Coastal States Gas Producing Company's Edna Delcambre Well No. 1 was recompleted in 1977 to produce waters from the first and third aquifers below the top of the geopressured zone and measure their methane content. Neither of these sand-bed aquifers are known to form commercial natural gas reservoirs. Recompletion and production tests were designed to enable collection of formation water within the well at depths near aquifer depth; to enable continuous sampling of produced fluids at the well head under controlled rates of flow, at measured pressures; and to monitor the rate of sand influx through perforations at selected flow rates.

Hydrologic data obtained from the tests lead to the following interpretations and conclusions:

1. All formation waters in tested aquifers are at saturation in situ; vapor phase gas is also present, as dispersed bubbles that become entrained in the flow to the well during flow tests.
2. The gas-water ratio of produced water is highly sensitive to flow rate; for aquifer no. 1, it increased from 16.8 cf/bbl at a flow rate of 1,165 bbl/day to 64.2 cf/bbl at 7,599 bbl/day. Data for aquifer no. 3 are not usable because there is a zone of free gas a few feet thick at its top.
3. Formation water salinity maps reflect long-term leakage through the Tigre Lagoon pressure seal from a rather broad area, as a marked increase in salinity is evident near its crest--a consequence of hyperfiltration of water leaking through the clay-bed seal.
4. Upwarps of isothermal surfaces reflect the upward movement of hot water, indicating that the southern part of the Tigre Lagoon structure has long been a zone of leakage from the geopressured zone.
5. Aquifer maps, structural maps, and geologic sections, show that the combination of subsurface conditions that result in the natural ex-solution of dissolved methane, and the trapping of vapor phase gas to form commercial reservoirs, do not favor the large-scale production of water necessary for commercial geopressured geothermal resources development.
6. Both of the aquifers tested could be developed, using water-well technology and equipment, to produce at least 50,000 bbl/day of

geothermal brine with free gas. At these flow rates, the gas water ratio should exceed 50 cf/bbl initially, gradually falling to about 18 cf/bbl in 5 to 10 years: this ratio should hold for the remainder of the well life.

Geologic and hydrologic studies made in the Tigre Lagoon Field area, together with interpretation of data obtained from the flow tests in the recompleted Coastal States Edna Delcambre No. 1 Well, provide the basis for identification and assessment of aquifer systems, and the mapping of conditions in those systems most favorable for resource development. Criteria to be used in site selection will differ, depending upon the product to be developed: for geothermal resources, wells should produce from thick, highly permeable aquifers of broad (regional) extent, in which little or no structural deformation has occurred; for natural gas, wells should tap moderately thick, regionally extensive aquifers and be drilled on structural highs, preferably a few thousand feet from hydraulic barriers (faults or pinchouts) which restrict flow and amplify head declines caused by fluid withdrawals from producing wells.

II. INTRODUCTION

The area of this investigation is in coastal southwestern Louisiana. (See Figure 1.) It covers about 200 mi^2 of low prairie and coastal marsh, and is bounded on the south by the Intracoastal Waterway. It occupies all or parts of townships 13 and 14 south, ranges 3, 4, and 5 east, and includes six important oil and gas fields in addition to Tigre Lagoon. The City of Lafayette, the center of the oil industry in southern Louisiana, is about 20 miles to the north; Abbeville, about 10 miles to the west, and New Iberia, about the same distance to the east, are growing industrial and trade centers historically keyed to agriculture.

Characteristic features of the area that led to consideration of a well here for testing, to investigate and assess the dissolved natural gas in formation waters of geopressure zone include the following:

1. Sufficient control, in the form of well logs and structure maps, to provide a basis for subsurface studies of aquifer conditions.
2. Several (at least eight) areally extensive sandstone aquifers in the geopressure zone above a depth of 15,000 ft., of sufficient thickness to be likely sources for production through wells at rates up to about 10,000 barrels per day (bpd).
3. A thin (300 to 500 ft.) pressure transition zone, the pressure seal being a mappable transgressive marine shale.
4. Very high fluid pressures and moderately high temperatures in the geopressured aquifer systems.
5. Two sandstone aquifers near the top of the geopressure zone in which no commercial gas reservoirs are known to occur, and from which no conventional gas production has been recorded.

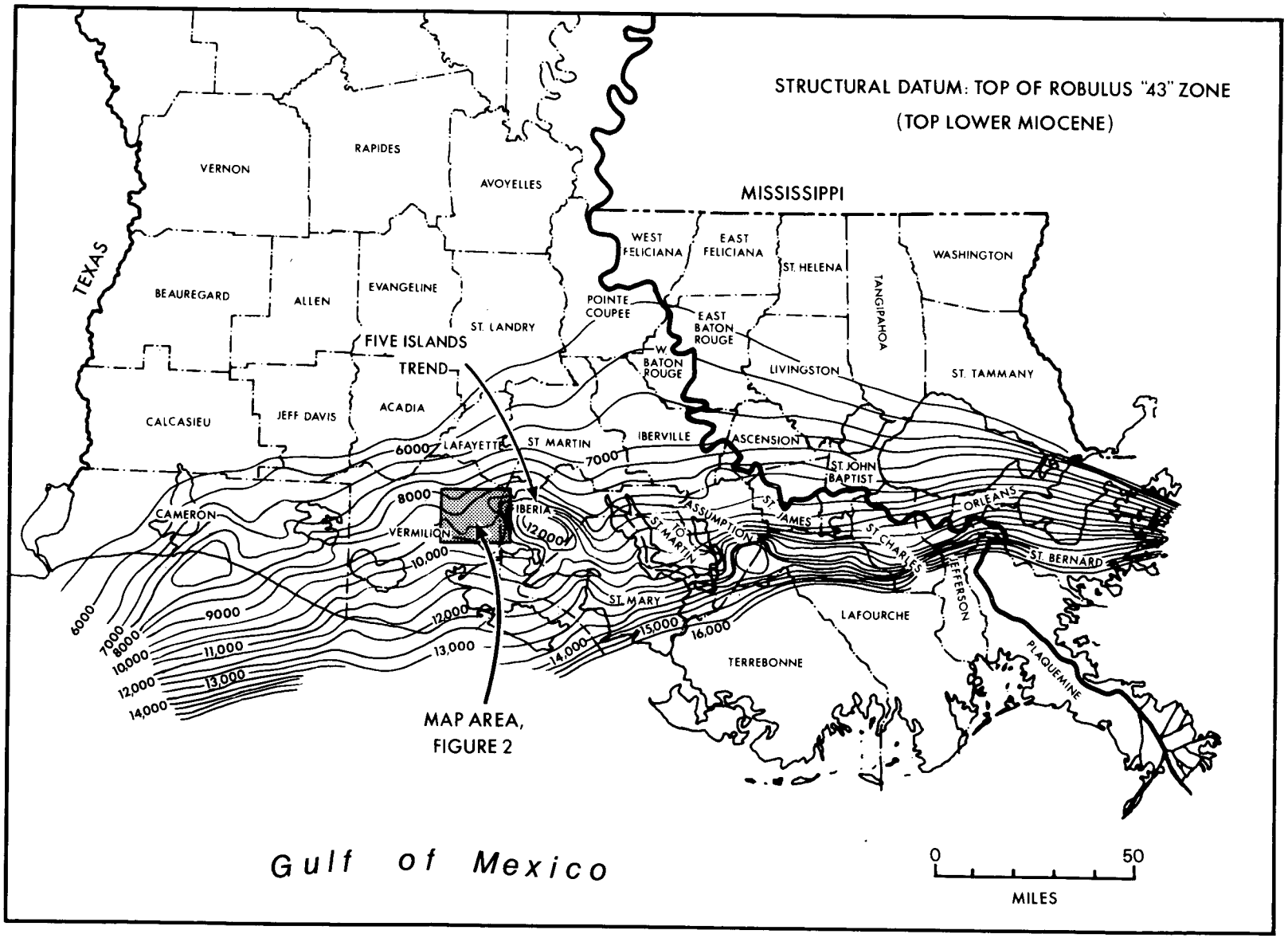

FIGURE 1. Depth of Occurrence of Lower Miocene Deposits in South Louisiana.

This investigation of the geology and hydrology of the Tigre Lagoon Gas Field area was made in support of a field test program, in which water was produced from two aquifers near the top of the geopressure zone, using the Coastal States Gas Producing Company's Edna Delcambre Well No. 1 in section 5, township 14 south, range 5 east. The purpose of this investigation was to describe the aquifer systems as they occur in the subsurface, including their thickness, structural attitude, and deformation by faulting; their texture, porosity, and permeability; and the temperature, pressure, and salinity of the water they contain. All of these characteristics must be known in considerable detail if the yield characteristics and dissolved gas content of formation waters are to be estimated, and the development plans are to be formulated for production of geothermal and dissolved gas resources.

In this investigation it has been possible to identify and map, in the study area, the target aquifers, and to describe local structural deformation using geologic sections; to map the top of the geopressure zone and two isothermal surfaces; and to map in a generalized way, the salinity of aquifer waters. Insufficient information is available to describe their porosity, texture, and permeability; but some data are presented on the lithology, porosity, and permeability of sandstones between depths of 7,486 and 13,778 ft., based upon study of sidewall cores taken from the Coastal States Edna Delcambre Well No. 1.

Records and subsurface information used in the preparation of this report included electric logs for 49 wells; structural control from published maps, and from the Hearings file of the Louisiana Department of Conservation; and core data and a structure map provided by Coastal

States Gas Producing Company. Technical references consulted included those listed at the end of the report.

Calculation of the dissolved methane resource and estimation of recoverable natural gas from the aquifer systems described were not objectives of this study. However, the information developed here, together with certain reasonable assumptions, can be used to make such estimates. Guidelines are suggested, and test data are interpreted in terms useful in making the calculations.

The general title for all the reports issued on this project is Geopressured-Geothermal Test of the Edna Delcambre No. 1 Well, Tigre Lagoon Field, Vermilion Parish, Louisiana. The subtitles are as follows:

1. Well Completion, Testing, and Production Data Analysis by OHRW.*
2. Analysis of Water and Dissolved Natural Gas by McNeese State University.
3. Geology of the Tigre Lagoon Field, Planulina Basin by McNeese State University.

* Osborn-Hodges-Roberts-Wieland Engineering Corporation.

III. GEOLOGY

Coastal Louisiana has been an area of rapid deltaic deposition, much as it is today, for more than 40 million years. Contemporaneous subsidence, continuing today at natural rates of perhaps one foot in 100 years at the inner edge of the coastal marsh, has resulted in cyclic marine transgressions related to changes in the location and rate of sediment deposition by the ancestral Mississippi River and its sister streams. As a consequence, the vertical sequence of depositional types in any locality ranges from alluvial to deltaic, delta flank or delta front, coastal marsh or coastal lakes, beach or strand line, or shallow marine or continental shelf in endless repetition (Lowman, 1949, p. 1939-1997). Depositional sequences are complicated by the effects of erosion and redeposition, and by vertical structural movements--mainly downwarp by contemporaneous faulting controlled by differential compaction related to the subsurface distribution of sediment types, and local upwarp by shale or salt diapirism (Krumbein, Sloss, and Dapples, 1949, p. 1859-1891). Sediments are mainly clay and sand; clay beds are largely made up of the swelling varieties of clay minerals--montmorillonite and illite, and sands are generally quartzose, with silt, lignite, marl, shell, chalk, and lime nodules common. Regionally, and vertically through depths ranging up to 20,000 ft. or more in Vermilion Parish, these sediments form monotonously similar sequences indistinguishable from one another except by their microfauna--the occurrence and abundance of foraminifera and ostracoda species within them (New Orleans Geological Society, 1962; Lafayette Geological Society, 1962). According to Hardin (1962), the total thickness of the Cenozoic deposits in Vermilion Parish may exceed 50,000 ft.

The geology of the deposits of interest in this investigation is excellently described by Meyerhoff and others (1968, p. 482-483), who state that "In the central and western parts of South Louisiana early Miocene history began with a moderate (marine) transgression. The Abbeville (outer neritic facies) was overlain by the marine Planulina sequence. A subsequent period of alternating small transgressions and regressions was terminated by a transgressive phase, the farthest updip Miocene transgression in South Louisiana." It was during this terminal marine transgression that the clay-bed seal of the geopressure zone in the Tigre Lagoon Gas Field was deposited. Crouch (1959, p. 1283-1292) estimates that "the greatest aggregate thickness of lower Miocene strata. . . is about 15,000 ft. in Cameron and Vermilion Parishes."

The deposits consist of light to dark-gray, grayish-green, and greenish-gray waxy shale; quartzose sandstone, fine to very fine grained, poorly to well-sorted, light gray to light brownish gray, calcareous, slightly to moderately glauconitic; lignite in stringers, with abundant lignite fragments in carbonaceous shale; and gray to buff, slightly calcareous siltstone. These deposits are distributed in depositional basins in which stacked sequences of sand and shale beds have thickness of 1,000 ft. or more; individual sand beds may range upwards of 500 ft. in thickness, but they are generally less than 200 ft. thick.

Sand beds in the Tigre Lagoon Gas Field area range in thickness from a few feet to about 240 ft.; most of them are 30 to 100 ft. thick. Core data porosity ranges from 5 to 30 percent, and permeability ranges from less than 10 to more than 400 millidarcys (md). (See Table 1.) The sand

TABLE 1

Porosity and Permeability of Sandstones

(Sandstones Penetrated by the Coastal States Edna Delcambre No. 1 Well, Tigre Lagoon Field. Data from Sidewall Cores by Core Labs, Inc.)

Depth of Sample (ft)	Porosity (percent)	Permeability (millidarcys)	Remarks
7,486	17.7	0.1	shaly, calcareous
8,030	25.8	52.0	shaly, fossiliferous
8,060	17.3	0.2	very shaly
8,065	20.8	5.8	shaly
8,069	22.8	3.8	shaly
8,098	19.7	0.3	shaly, calcareous
11,561	27.8	120.0	silty
11,562	25.8	150.0	silty
11,570	30.0	130.0	silty, calcareous
11,572	25.3	100.0	silty, calcareous
11,573	27.9	140.0	silty, calcareous
12,190	19.9	80.0	calcareous
12,191	19.8	3.6	shaly
12,212	20.1	60.0	very calcareous
12,213	23.3	28.0	very calcareous
12,215	21.0	42.0	shaly, calcareous
12,233	31.2	115.0	calcareous

TABLE 1 (continued)

Porosity and Permeability of Sandstone

(Sandstone Penetrated by the Coastal States Edna Delcambre No. 1 Well, Tigre Lagoon Field. Data from Sidewall Cores by Core Labs, Inc.)

Depth of Sample (ft)	Porosity (percent)	Permeability (millidarcys)	Remarks
13,346	16.5	4.6	hard, limey
13,358	23.0	9.4	shaly, limey
13,362	27.1	400.0	limey
13,367	25.3	130.0	limey
13,383	28.3	670.0	slightly shaly
13,387	23.5	85.0	slightly shaly
13,394	23.7	95.0	limey
13,402	30.1	1,485.0	clean sand
13.411	26.7	310.0	slightly shaly
13,515	16.9	0.6	very shaly
13,535	20.7	19.0	shaly, limey
13,536	25.5	72.0	slightly shaly
13,571	24.0	70.0	limey
13,713	14.4	0.1	very shaly
13,719	26.5	460.0	clean sand
13,720	16.1	5.8	hard, limey
13,778	28.6	210.0	slightly shaly

grains are well sorted, and grain diameter seldom exceeds 0.3 mm. The areal extent of individual sand beds, as deposited, may be hundreds of square miles; the depocenters in which they occur are commonly bounded by faults on their landward margins, and the sand beds pinchout into shale on the gulfward margins.

The geologic structure of the area reflects mainly the gulfward downwarp of deposits on the northern flank of the Gulf Coast geosyncline (Barton, Ritz, and Hickey, 1933). Figure 1, a map of the foraminiferal marker, Robulus "43" (the top of lower Miocene deposits in southern Louisiana), shows a pronounced gulfward steepening in the dip of beds. In southern Pointe Coupe Parish, the dip is about 40 ft. per mile; in northern Vermilion Parish, it averages about 100 ft. per mile, and in southeastern St. Mary Parish, it exceeds 200 ft. per mile.

The most conspicuous structural feature in south-central Louisiana is the downwarp that parallels the Five Islands Trend (Fig. 1); this is considered to be a result of the salt flowage that produced the domes known as the Five Islands. Avery Island, one of these, lies only 4 miles east of the Tigre Lagoon structure. Faulting associated with dome formation had profound effects on contemporaneous deposition, and the eastward end of the Planulina basin is marked by the Avery Island Salt Dome.

As indicated by the flattening of dip on the Robulus "43" marker across the map area, Figure 1, the underlying deposits become quite stable by the end of lower Miocene time. The structure map, Figure 2, based upon faunal markers some 2,000 to 3,000 ft. below the Robulus "43" marker, shows that deformation by faulting contemporaneous with deposition was widespread

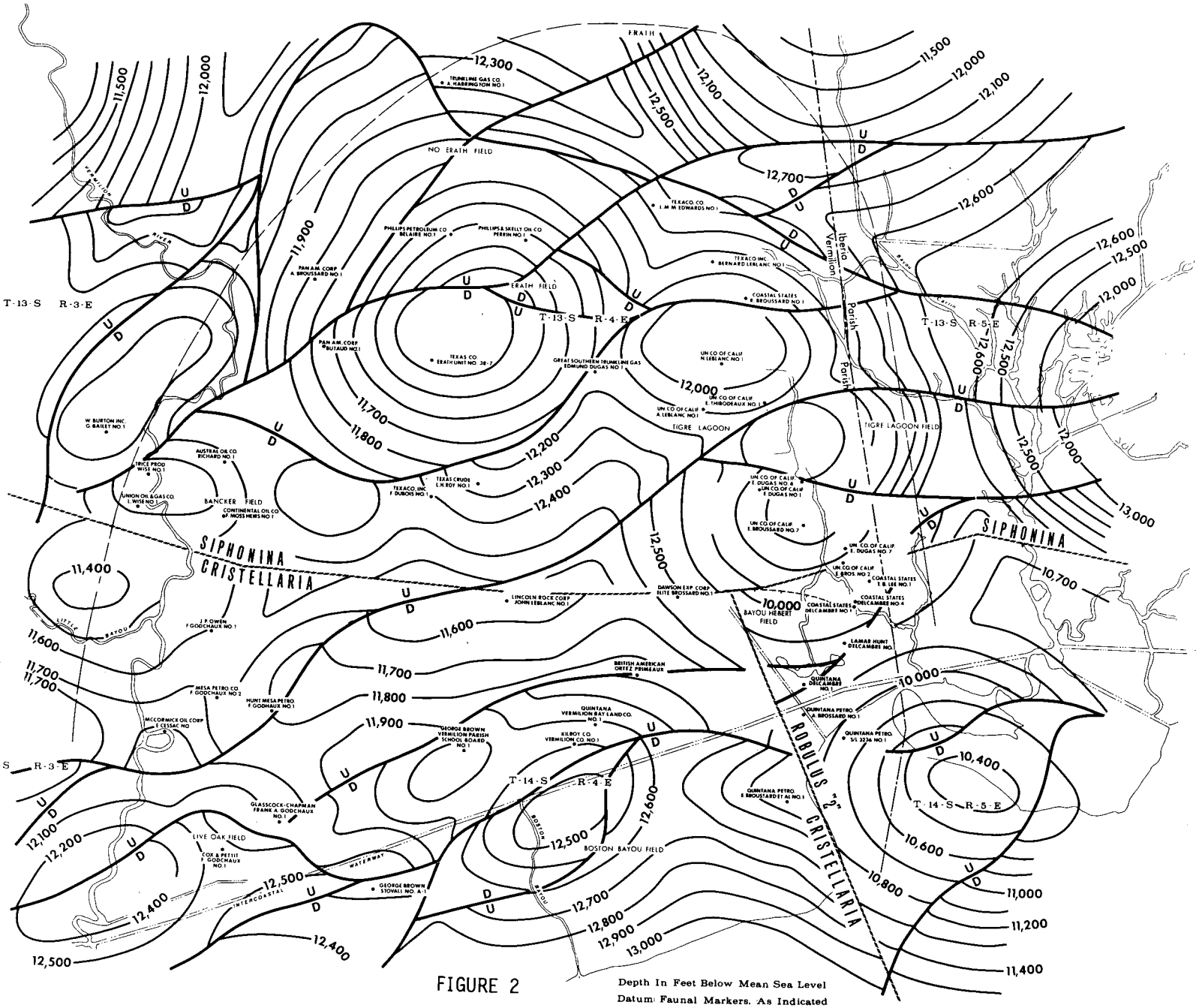

FIGURE 2

Depth In Feet Below Mean Sea Level
Datum: Faunal Markers, As Indicated
GEOLOGIC STRUCTURE OF DEPOSITS,
PLANULINA BASIN, EASTERN VERMILION PARISH, LOUISIANA

during lower Miocene time. Such faulting is termed "growth faulting" in southern Louisiana (O'Camb, 1961); it is characterized by marked thickening of correlative beds across the fault, on the downthrown side.

As shown on Figure 2, the principal growth faults cross the study area sinuously from southwest to northeast and, except to the northeast of Tigre Lagoon Field, the downthrown blocks are gulfward. Displacement across faults at the top of the lower Miocene sequence ranges from a few feet to a few hundred feet except near Avery Island, where it exceeds 1,000 feet. It increases with depth in the lower Miocene, and faults with displacements greater than 5,000 ft. can be traced through these deposits for distances of 50 miles or more along east-west trends (Meyerhoff and others, 1968, p. 483).

Structural features of the Tigre Lagoon Gas Field evidenced by mapping the top of the "Planulina 6" sand are shown in Figure 3. The major fault of the structure parallels the Vermilion-Iberia Parish line, almost north-south, for several miles, turning westward at the northern end along the southern boundary of township 13 south. Three large branch faults arc westward into the basin and die out in a few miles. To the south, a major growth fault branches north-westward from the Tigre Lagoon fault beneath Vermilion Bay. These faults are all collapse features at the eastern margin of the lower Miocene Planulina depocenter.

Three geologic cross sections, Figures 4, 5, and 6, show the effects of faults on the structural attitude and areal continuity of sand-bed aquifers No. 1 and No. 3. Section A-A' (Fig. 4), trending north-south through the center of the Vermilion Parish sub-basin (see inset map) is

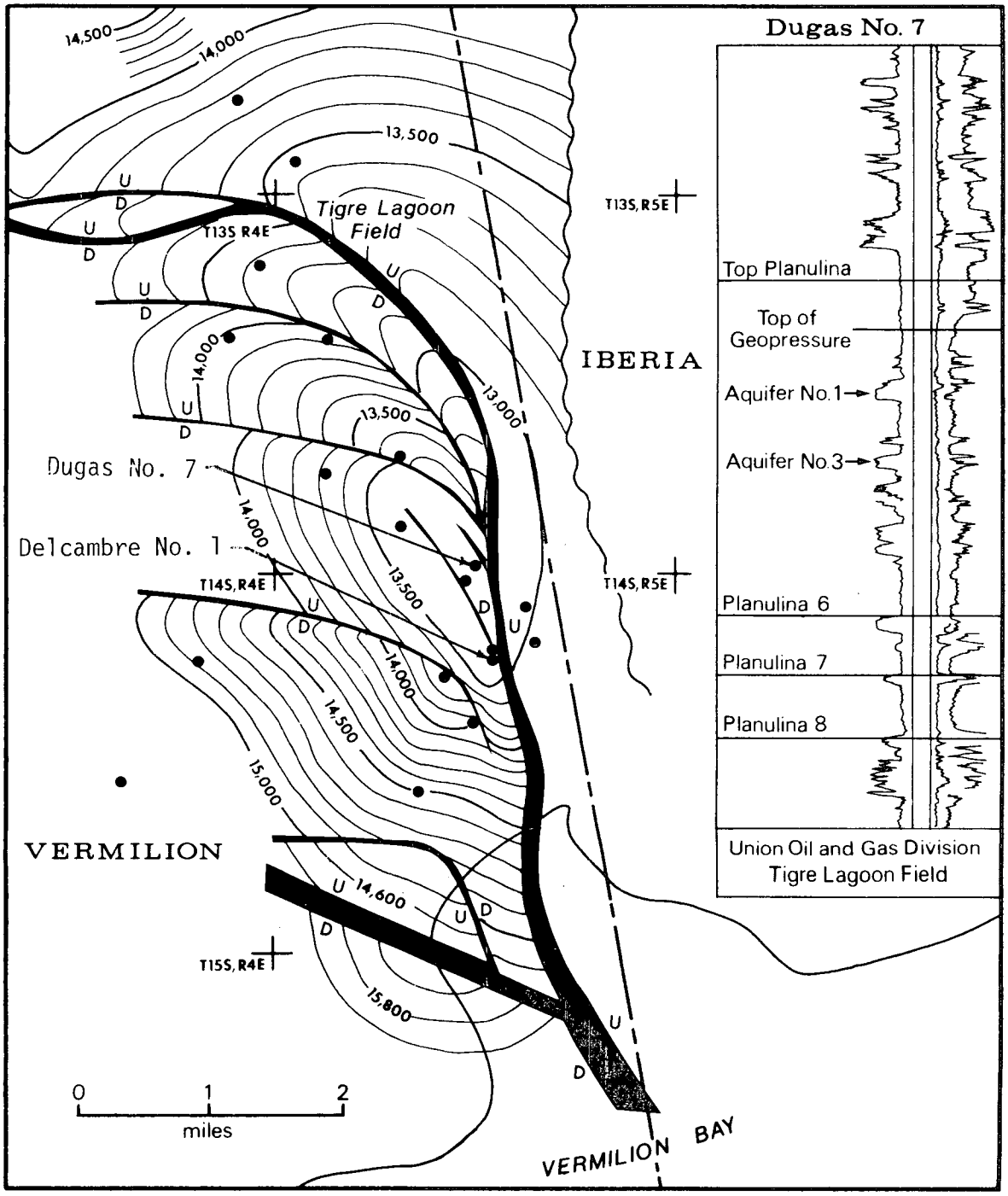

FIGURE 3. Geologic Structure, Tigre Lagoon Field, Planulina Basin.

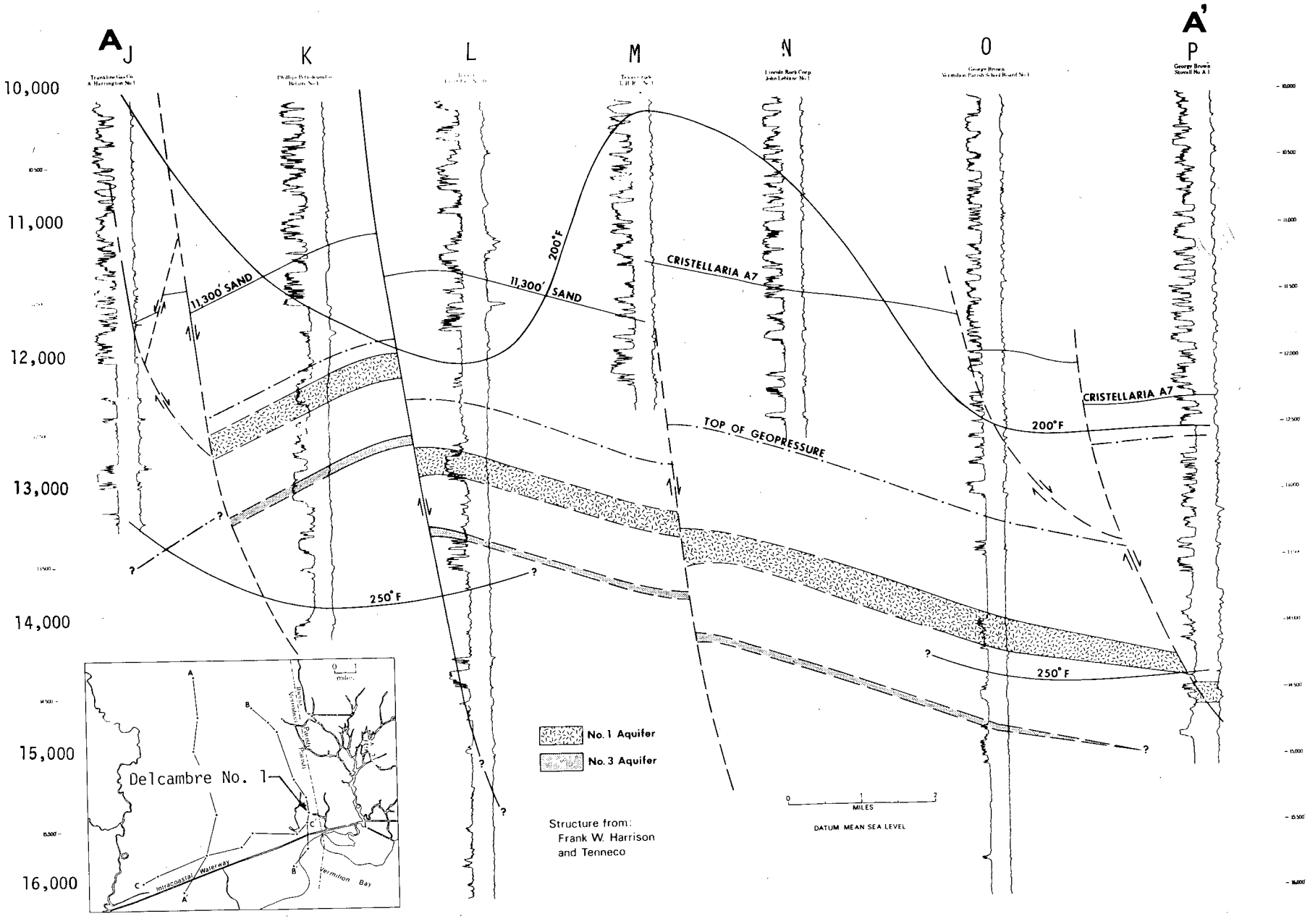

FIGURE 4. Geologic cross section A-A' showing structural conditions, the depth of the geopressure zone, and the depth ofs of the 200° and 250°F isothermal surfaces in the western part of the study area.

FIGURE 4 LEGEND

J. Trunkline Gas Co., A. Harrington No. 1

K. Philips Pet. Co., Belaire No. 1.

L. Texas Co., Erath Unit No. 38-7.

M. Texas Crude, L. H. Roy No. 1.

N. Lincoln Rock Corp., John Leblanc No. 1.

O. George Brown, Vermilion Parish School Board No. 1.

P. George Brown, Stovall No. A-1.

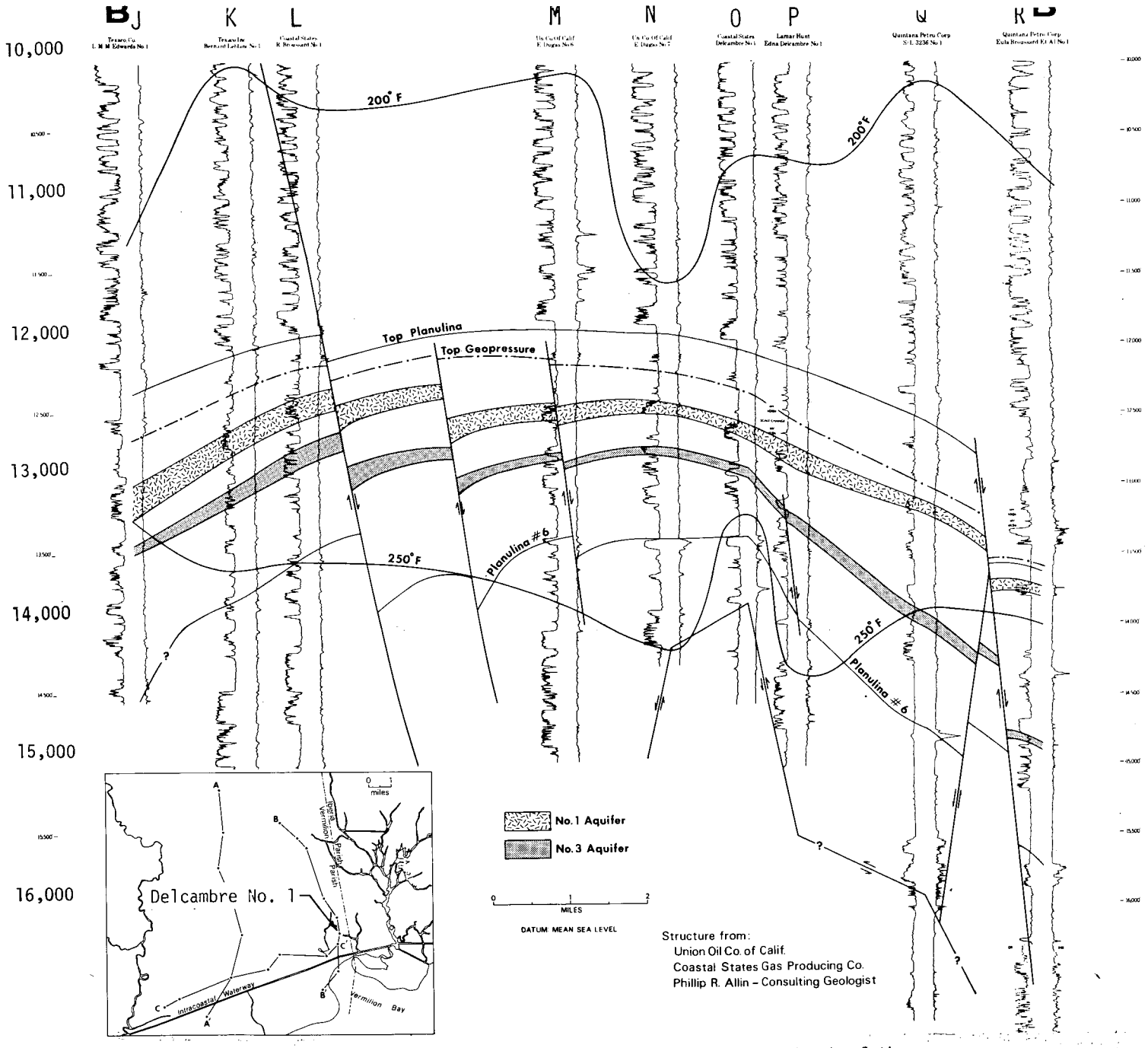

FIGURE 5. Geologic cross section B-B' showing structural conditions, depth of the geopressure zone, and depths of the 200° and 250°F isothermal surfaces in the eastern part of the study area.

FIGURE 5 LEGEND

J. Texaco Co., L.M.M. Edwards No. 1.

K. Texaco Inc., Bernard Leblanc No. 1.

L. Coastal States, R. Broussard No. 1.

M. Union Oil Co. of Calif., E. Dugas No. 6.

N. Union Oil Co. of Calif., E. Dugas No. 7.

O. Coastal States, E. Delcambre No. 1*.

P. Lamar Hunt, E. Delcambre No. 1.

Q. Quintana Petrol. Corp., S/L 3236, No. 1.

R. Quintana Petrol. Corp., Eula Broussard et al No. 1.

* Test well used in this study.

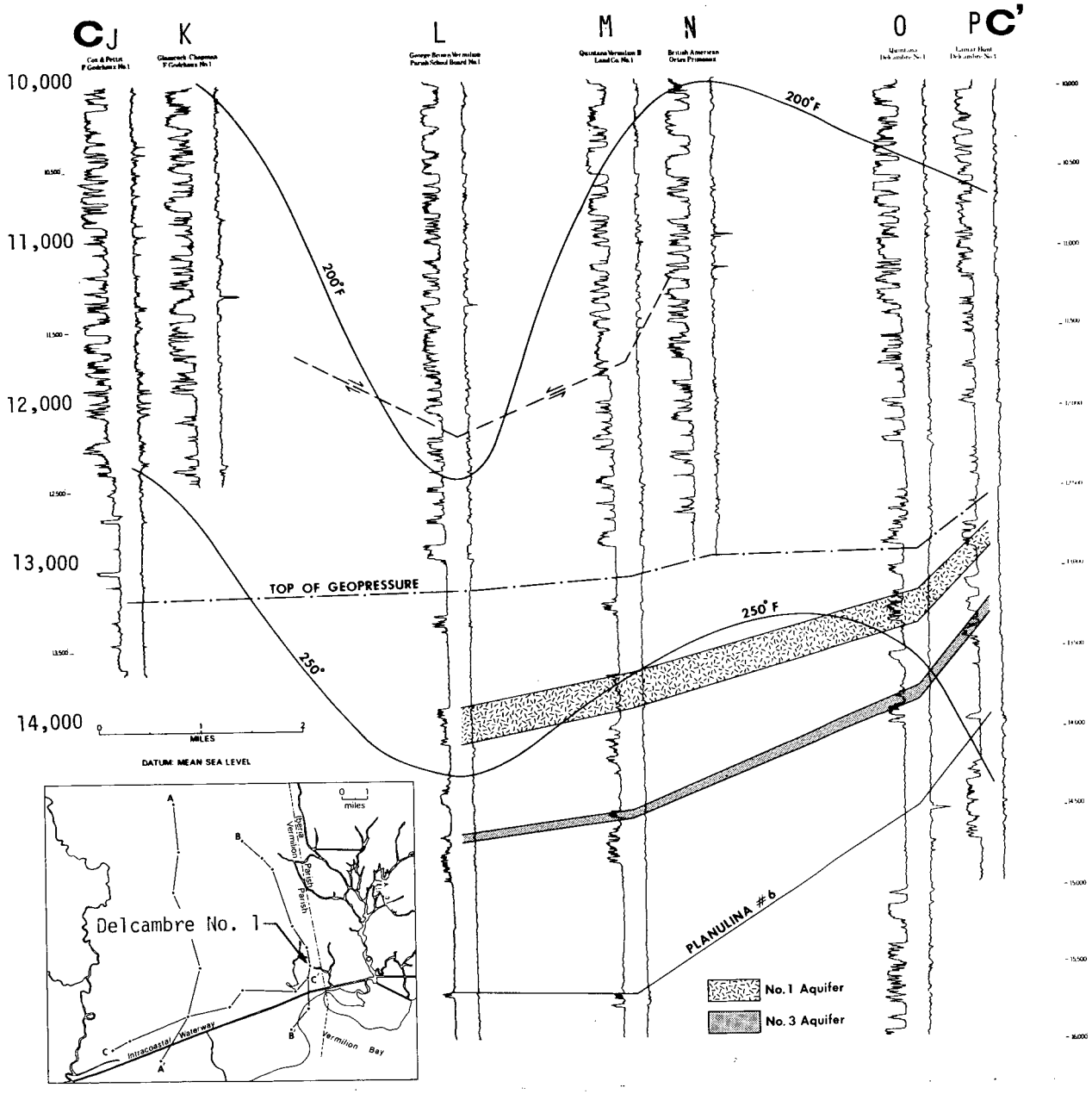

FIGURE 6. Geologic cross section C-C' showing structural conditions, the depth of the geopressure zone, and the depths of the 200° and 250°F isothermal surfaces in the southern part of the study area.

FIGURE 6 LEGEND

J. Cox & Petit, F. Godchaux No. 1

K. Glasscock--Chapman, F. Godchaux No. 1.

L. George Brown, Vermilion Parish School Board No. 1.

M. Quintana, Vermilion B. Land Co. No. 1.

N. British American, Ortez Primeaux.

O. Quintana, Delcambre No. 1.

P. Lamar Hunt, Delcambre No. 1.

a classic example of growth-fault deformation in southern Louisiana where no effects of diapiric structure are evidenced.

The geologic sections B-B' (Fig. 5) crosses the eastern part of the study area from north to south. It passes through the fault-truncated eastern end of the Tigre Lagoon rollover. The most important structural condition shown on this section is the upward die-out of growth faults in, or reduced displacement on them in the thick shale blanket that marks the top of the Planulina zone. Increasing displacement with depth is evident on the Planulina No. 6 marker.

Also evident on this section is the abundance of sand beds in the geopressure zone, and the increasing thickness of sand beds above a depth of 15,000 ft. northward from Union Oil Company of California, E. Dugas Well No. 6. That well penetrates about 700 ft. of sand between depths of 14,000 and 15,000 ft.

The geologic section C-C' (Fig. 6) crosses the southern part of the study area a mile or so north of the Intracoastal Waterway. Structurally, it reflects downwarp of the depocenter westward from its eastern margin; no faults are shown in the geopressure zone, but this is because no structural control on deformation in this depth range was available. A westward decrease in the number and thickness of sand beds below a depth of about 15,000 ft. is apparent.

Electric logs for the 49 wells listed in Table 2 were used in studies of the geologic structure, areal extent, and thickness of the two sand-bed aquifers tested by the Edna Delcambre Well No. 1. Figure 7 shows the generalized depth of occurrence of the top of the No. 1 sand-bed aquifer.

TABLE 2

LOCATIONS AND IDENTIFICATIONS OF WELLS

Location	Section	Total Depth	Well Identification
T13S,R3E	63	16,114	Continental Oil Co. Frank D. Moss Heirs #1
	73	15,000	Union Oil & Gas Co. of La. Leonard M. Wise #1
	57	14,120	Austral Oil Co. Ursin Richard Estate #1
	62	12,390	Trice Prod. & Christie, Mitchell & Mitchell Wise #1
	62	10,955	Trice Prod. & Christie, " (side track hole) " "
	58	13,291	W.T. Burton Ind., Inc. George Bailey et al #1
	21	15,985	The Texas Co. Erath Unit #38-7
	15	13,702	Phillips Petr. Co. & Skelly Oil Co. Perrin Unit #1
T13S,R4E	45	12,800	Pan American Petr. Corp. A Butand #1
	11	14,507	Texaco Inc. Lula Mae Moss Edwards #1
	41	14,016	Phillips Petr. Co. Belaire #1
	49	16,000	Texaco Inc. & Gordon St., Inc. Bernard LeBlanc #1
	40	13,180	Trunkline Gas Co. et al Adam Harrington #1
	33	12,306	Texas Crude & Nicklos Drlg. Ludie Hulin Roy Well #1
	43	13,518	Pan American Petr. Corp. A. Broussard #1
	33	17,100	Texaco Inc. Felicien Dubois #1

TABLE 2 (continued)

Location	Section	Total Depth	Well Identification
	24	11,804	Union Oil Co. of Calif. N. J. LeBlanc #1
	25	11,680	Union Oil Co. of Calif. A. D. LeBlanc #1
	23	12,003	Great Southern Trunkline Gas Edmund J. Dugas #1
T13S,R5E	32	14,246	Union Oil Co. of Calif. E. Dugas #7
	18	15,197	Coastal States Gas Producing Co. Rene Broussard #1
	31	14,907	Union Oil Co. of Calif. Edmond Dugas #6
	31	11,793	Union Oil Co. of Calif. Elia Dugas #1
	31	8,370	Union Oil Co. of Calif. Big 3-2SUF: E.E. Broussard #7
	42	10,483	Union Oil Co. of Calif. Emile Thibadeaux Heirs #1
	83	14,513	Mesa Petroleum Co. F. A. Godchaux #2
T14S,R3E	79	14,323	McCormick Oil & Gas Corp. & Apache Explor. Corp E. Cessac #1
	83	12,582	J. P. Owen et al Frank Godchaux #1
	88	13,660	Edwin L. Cox & R. C. Pettit F. Godchaux #1
	14	13,007	Kilroy Co. of Texas Vermilion Bay Land Co. Well #1
	19	12,500	Glassock-Chapman Inc., Chambers & Kennedy, Frank A. Godchaux #1
T14S,R4E	1	16,489	Damson Exploration Corp. Elite Broussard Nunez et al #1
	14	17,773	Quintana Pet. Corp (sidetrack hole) Vermilion Bay Land Co. #1

TABLE 2 (continued)

Location	Section	Total Depth	Well Identification
	11	13,011	British American Oil Producing Co. Ortez Primeaux #1
	3	12,502	Lincoln Rock Corp. John N. LeBlanc #1
	29	15,048	George R. Brown (Formerly: Phillips Petrl. Co.) Stovall #A-1
	18	17,466	Hassie Hunt Trust Mesa Petrl. F. A. Godchaux #1
	16	16,223	George R. Brown, Vermilion Parish School Board #1
	8	16,817	Quintana Petroleum Corp. L. Delcambre #1
	5	11,662	Union Oil Co. of Calif. Emila Broussard #2
	19	16,946	Quintana Petroleum Corp. Eula Broussard et al #1
	17	15,212	Quintana Petroleum Corp. A. Broussard #1
T14S,R5E	17	16,833	Quintana Petroleum Corp. S/L 3236 #1
	5	15,414	Coastal States Gas Producing Co. & Preston Oil Co. Edna Delcambre #2
	8	15,005	Lamar Hunt Edna Delcambre #1
	5	12,844	Coastal States Gas Producing Co. Edna Delcambre et al #4A
	5	13,983	Coastal States Gas Producing Co. Edna Delcambre et al #4
	5	14,512	Coastal States Gas Producing Co. & Preston Oil Co. Edna Delcambre et al #1
	5	13,743	Coastal States Gas Producing Co. & Columbia Gas Development T. B. Lee #1

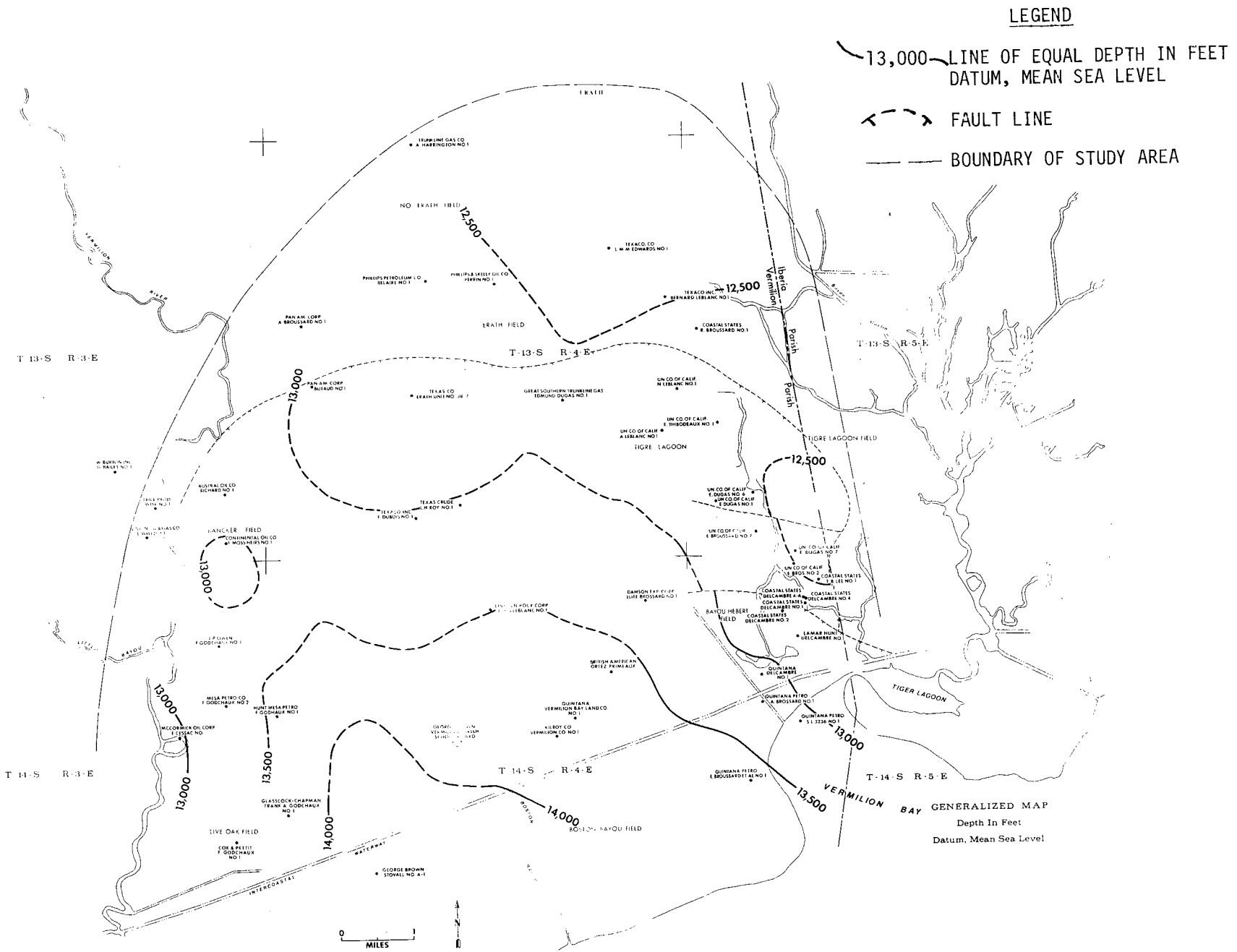

FIGURE 7. Depth of occurrence of the No. 1 sand-bed aquifer in the geopressure zone.

The bed dips gulfward at a rate of about 200 ft. per mile through the center of the study area, with marked uplifts to both the east and the west--reflecting structures related to producing oil and gas fields. Figure 8 is a thickness map of the No. 1 sand-bed aquifer; the area of occurrence of maximum thickness (greater than 220 ft.) coincides with the axis of basin downwarp. However, the westward thickening of the sand bed suggests that subsidence during deposition was less rapid along the eastern boundary fault than to the west.

Figure 9 shows the depth of occurrence of the No. 3 sand-bed aquifer, and its area of pinchout westward. The bed dips gulfward about 300 ft. per mile along the axis of the basin downwarp, through the center of the study area. The relative uplift on the eastern margin is even greater than on the overlying No. 1 sand-bed aquifer. The thickness of the No. 3 sand-bed aquifer (Fig. 10) is greatest along the eastern growth-fault boundary, suggesting that deposition may have come from a river system entering the area from the northeast. Marked thickening adjacent to and on the downthrown side from the eastern boundary fault (Fig. 3) is evident.

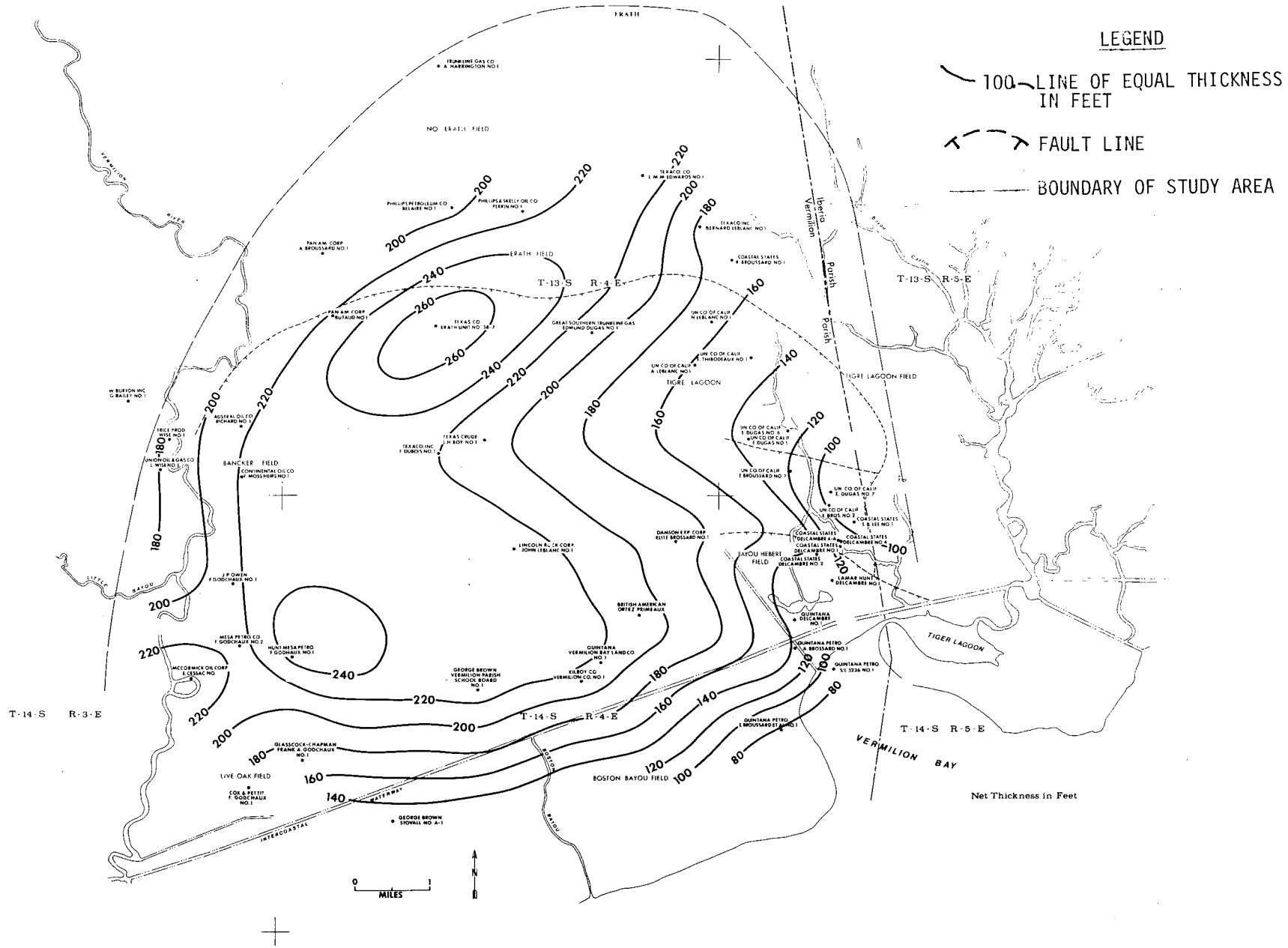

FIGURE 8. Thickness of the No. 3 sand-bed aquifer.

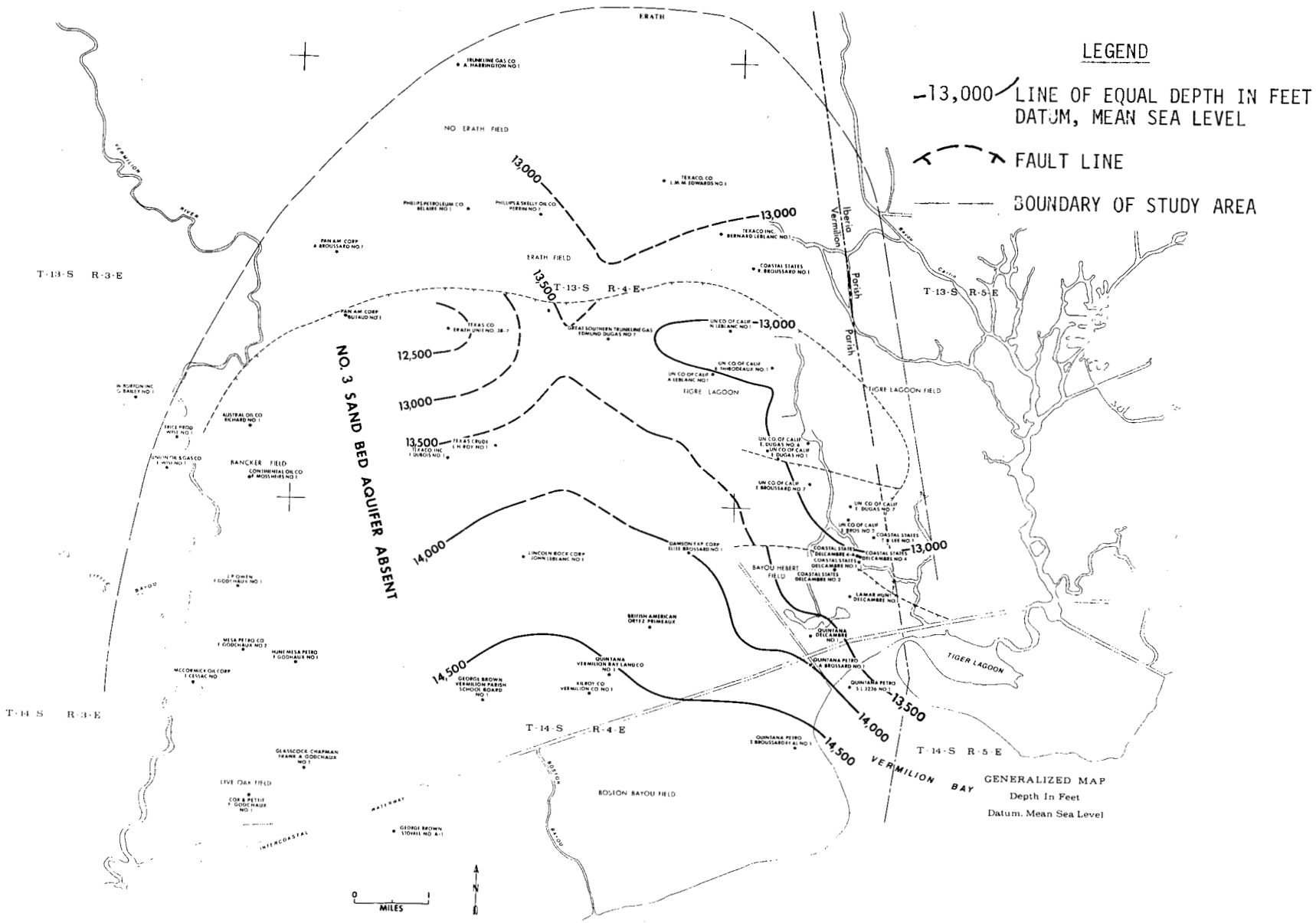

FIGURE 9. Depth of occurrence of the No. 3 sand-bed aquifer in the geopressure zone.

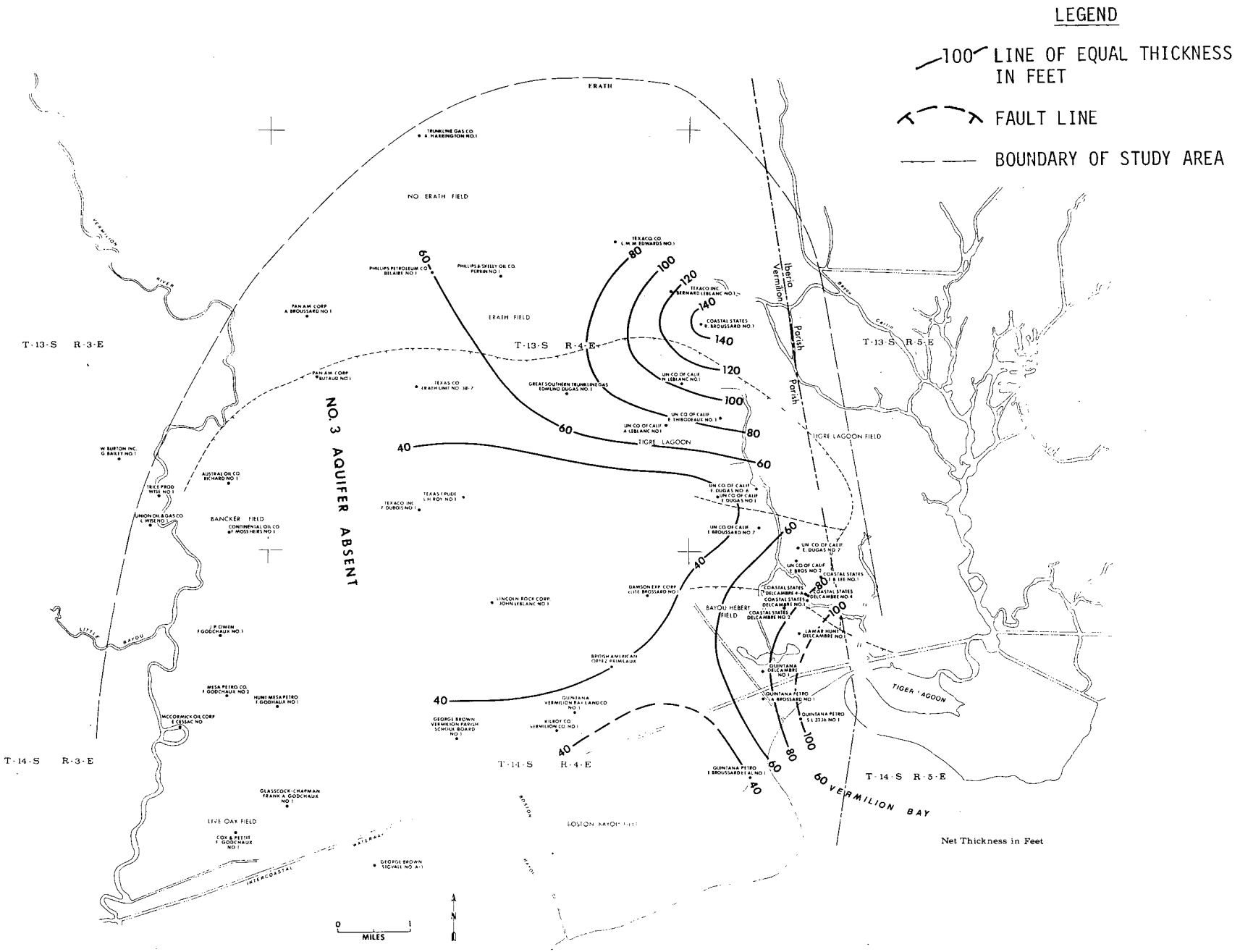

FIGURE 10. Thickness of the No. 3 sand-bed aquifer.

IV. HYDROLOGY

The depth of occurrence of the geopressure zone, where fluid pressure reflects part or all of the weight of overlying sediments, is shown in Figure 11. Depth determinations at the locations of all wells for which data were used (Table 2), were based upon electric-log information. The amplified short normal resistivity curve readings were analyzed using the method of Hottman and Johnson (1965, p. 717-722), which provide approximate fluid pressure in "clean" shale beds, indicating the fluid pressure in adjacent sand beds. These values were converted to equivalent mud weight required to balance these pressures at the measurement depths, and compared with well-log heading mud-weight figures for each run. The top of the geopressure zone was found to occur within the marine shale that marks the top of the Planulina zone, as an abrupt decrease downward in the apparent log resistivity recorded on the long normal curve, generally from about 1.2 ohm meters to 0.6 ohm meters over a depth interval of about 500 ft. Mud weights were increased from about 12.5 to as much as 18.2 pounds per gallon (ppg) over this same depth interval.

The depth to the top of the geopressure zone ranges from about 11,900 ft. in the North Erath Field (T 13 S, R 4 E) to about 13,900 ft. in the Boston Bayou Field (T 14 S, R 4 E). In the Tigre Lagoon Field its depth ranges from 12,100 to 12,300 ft. On the geologic section A-A' (Fig. 4) the vertical displacement of the top of the geopressure zone across the southern boundary fault is about 700 ft., somewhat more than the displacement of marker beds. On section B-B' (Fig. 5) the maximum

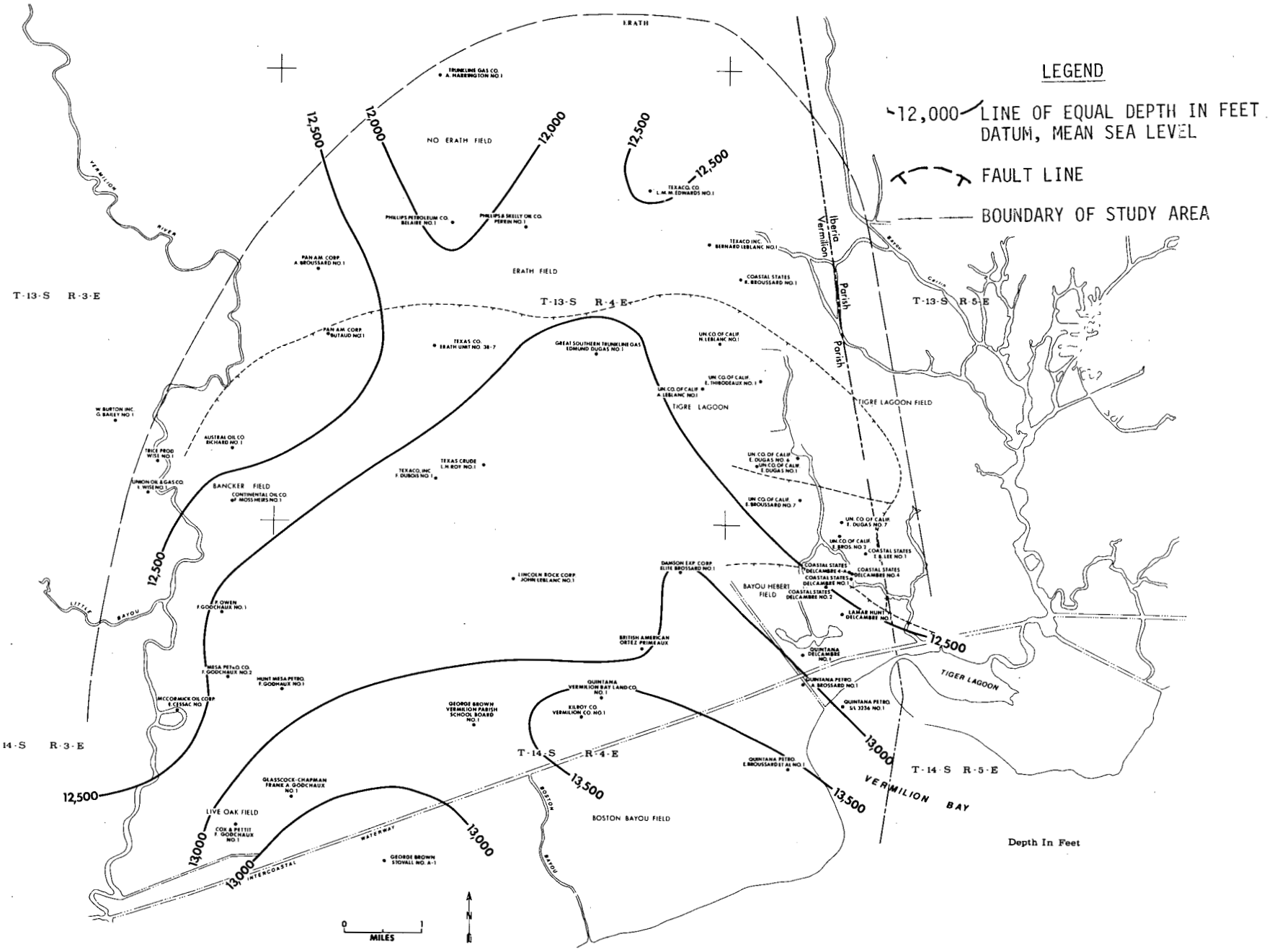

FIGURE 11. Depth of occurrence of the geopressure zone.

displacement is about 300 ft., also on the southern boundary fault. Section C-C' (Fig. 6) shows no deep basin faults, and the top of geopressure zone follows the base of the main sand series of the hydropressure zone. Although pressure gradients exceed 0.8 pounds per square inch per foot of depth (psi/ft) in much of the study area, there are no indications of appreciable water escape rates in the study area.

The isothermal maps show the depth of occurrence of the 200°F (Fig. 12) and 250°F (Fig. 13) isothermal surfaces. These maps are based upon bottom-hole temperatures recorded for each logging run on the headings of electric logs of wells listed in Table 2. Recorded nonequilibrium temperatures at indicated depths were corrected to equilibrium temperatures using the correction chart developed by the American Association of Petroleum Geologists in its Geothermal Survey of North America (Kehle, 1972). Geothermal gradients for each well were calculated for incremental depths --from the land surface to the depth reached by the first logging run, and between depths reached in successive runs. A reference land surface temperature of 70°F was used. Depth-temperature gradients plotted for two wells in the study area are shown in Figures 14 and 15. Interpolated depths at which the 200°F and 250°F isothermal surfaces occur on depth-temperature graphs for each of the 49 wells listed in Table 2 were used in making the isothermal maps.

The geothermal regime of Neogene deposits in the Gulf Basin is primarily a function of water movement, as the thermal conductivity of water is only about one fifth that of the mineral grains, and its specific heat is about five times greater. Restriction of water movement from the

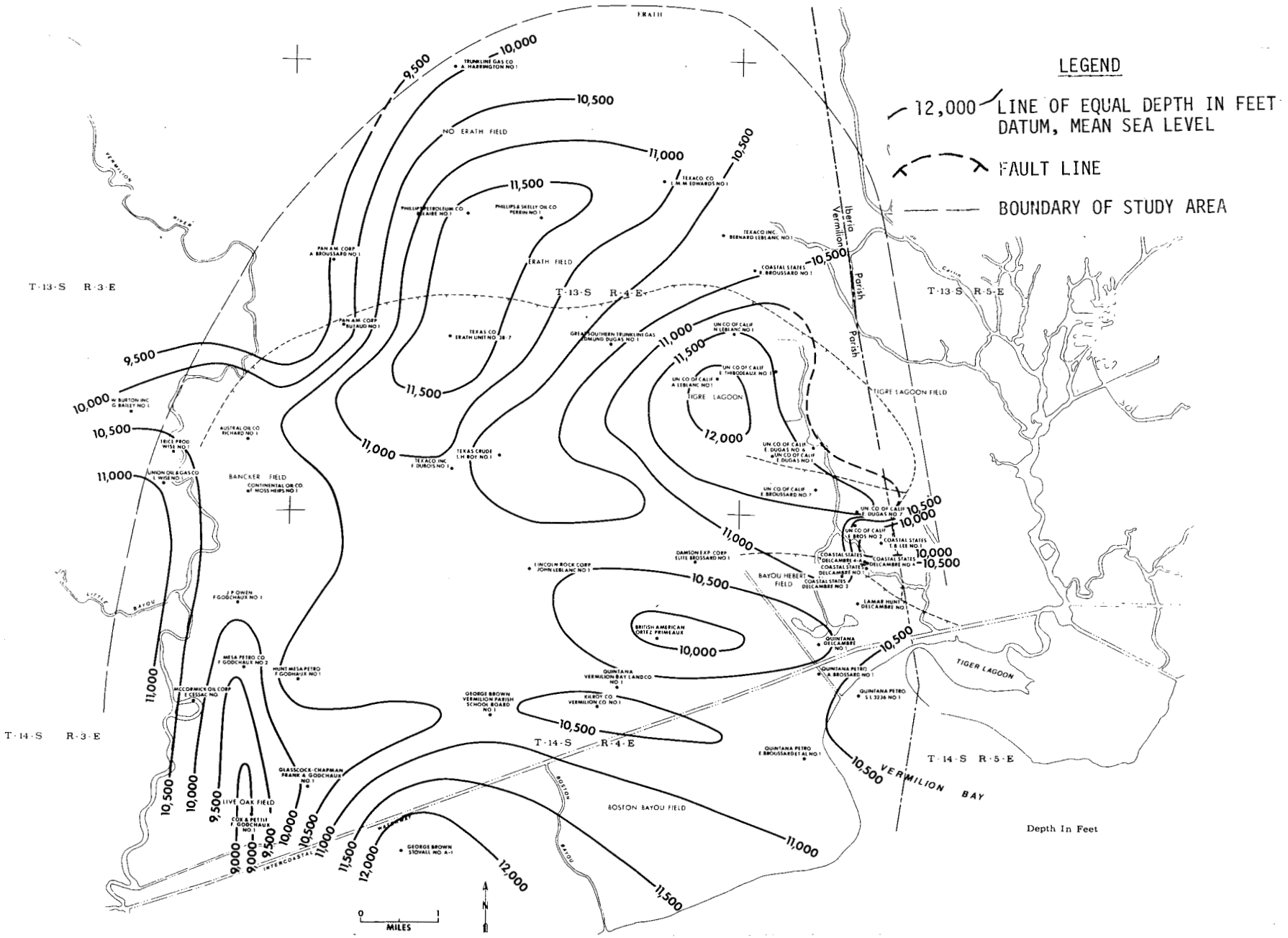

FIGURE 12. Depth of occurrence of the 200°F isothermal surface.

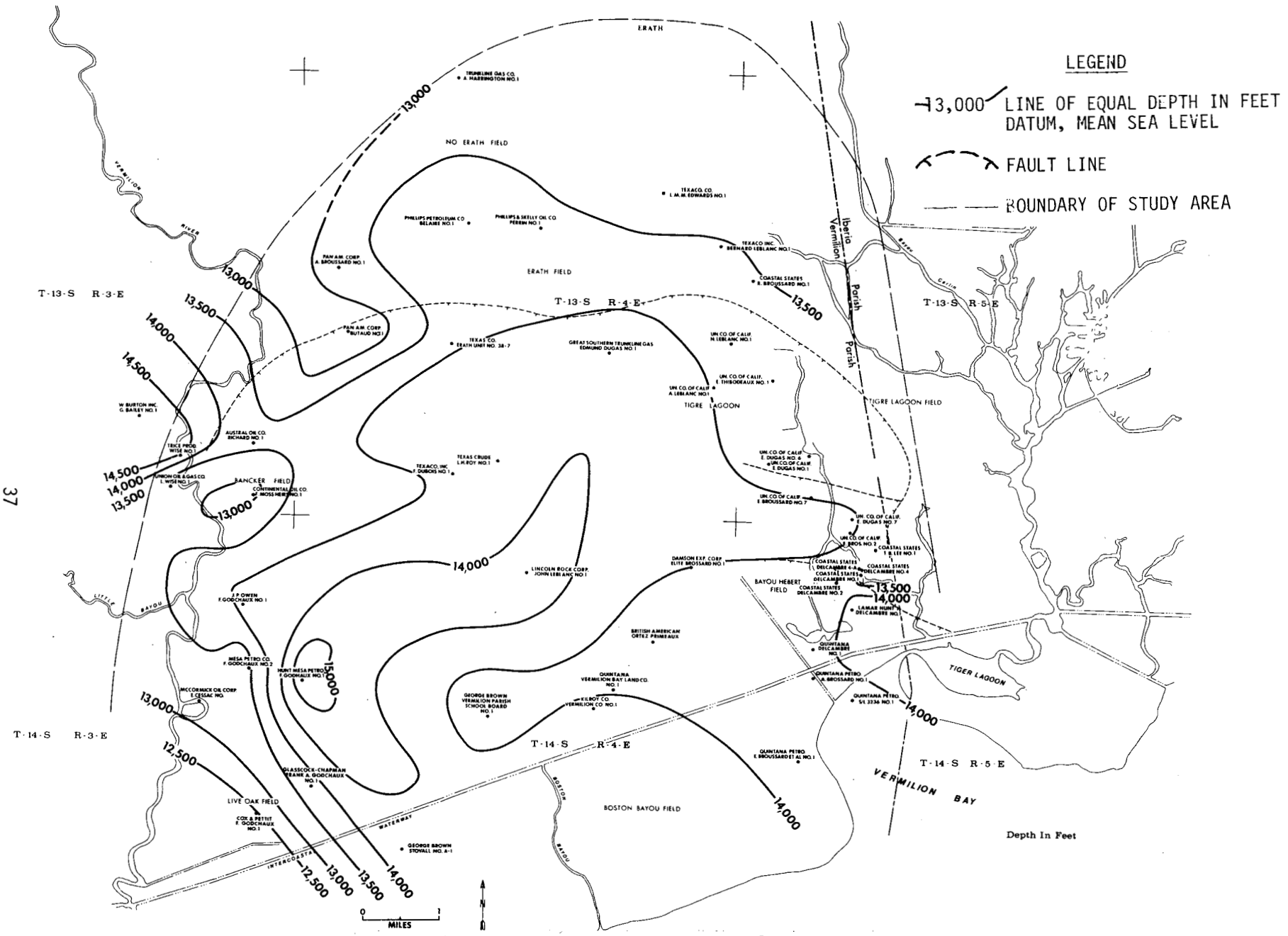

FIGURE 13. Depth of occurrence of the 250°F isothermal surface.

geopressure zone has resulted in retardation of geothermal heat flow from the underlying Upper Mantle. An increase in the geothermal gradient, appearing as a dogleg in the depth-temperature graphs (Figs. 14 and 15) is an excellent indicator of the top of the geopressure zone. And, because earth materials having high water content are excellent thermal insulators, any pulse of water movement upward from the geopressure zone into overlying deposits of the hydropressure zone produces a thermal plume, or halo which lasts for many years--long after the hydrodynamic forces that produced it have been dissipated. Thus, an isothermal map is an excellent indicator of the long-term mass-movement of water in the Neogene deposits of the Gulf Basin.

On the 200°F isothermal map (Fig. 12) there are four localities in which the isothermal surface occurs at depths less than 10,000 ft.: a narrow area trending north-south in the Live Oak Field (T 14S, R 3 E); the broad area bounding the northwest margin of the study area, possibly the result of water loss up the basin-margin fault in T 13 S, R 3 E; the small area immediately northeast of the Edna Delcambre Well No. 1 tested in this study; and an east-west trending area southwest of the Bayou Hebert Field (T 14 S, R 4 E) which may indicate local water movement upward through the southern boundary fault of the Planulina basin. The 200°F isothermal surface everywhere occurs within and near the base of the hydropressure zone, in the study area.

The 250°F isothermal surface (Fig. 13) everywhere occurs within the geopressure zone, in the study area; but it is upwarped beneath the "highs" shown on the 200°F isothermal surface to the southwest, northwest,

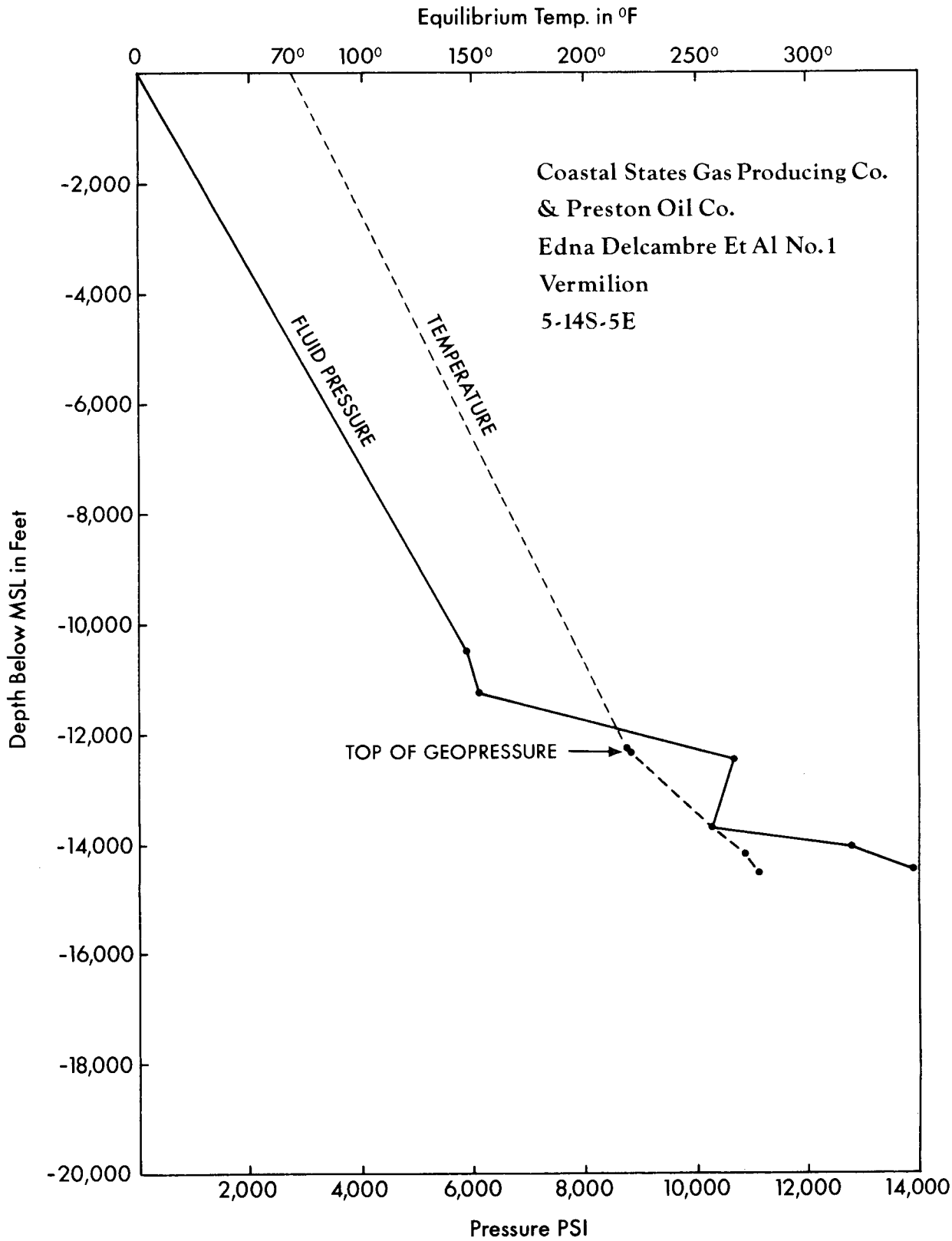

FIGURE 14. Graphs showing the changes in temperature and formation fluid pressure with depth in the Coastal States - Edna Delcambre Well No. 1.

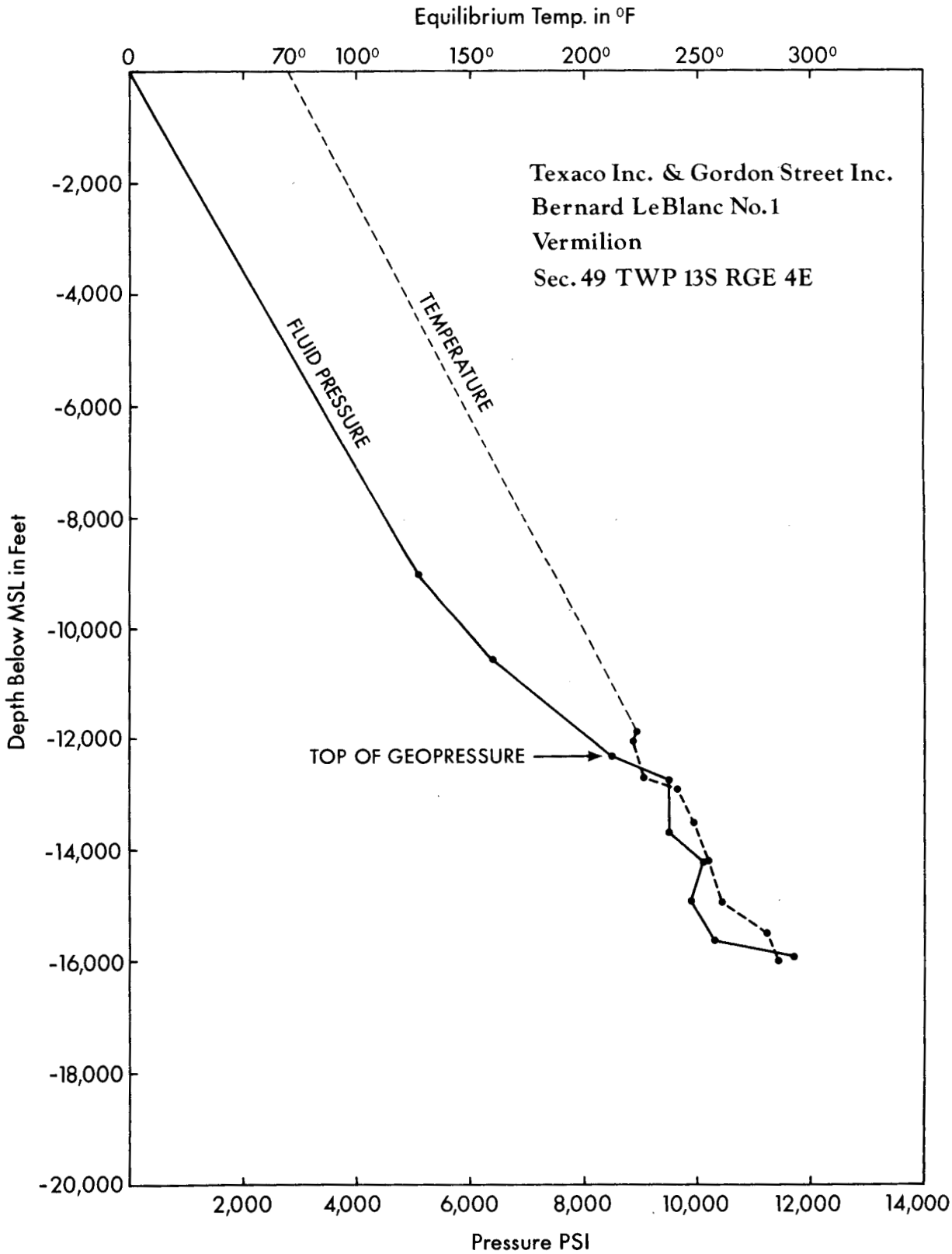

FIGURE 15. Graphs showing changes in temperature and formation fluid pressure in the Texaco-Bernard LeBlanc Well No. 1.

and eastward-- confirming an upflux of water from deeper in the geopressure zone in response to the leakage evidenced on the 200°F map.

Differences in the dissolved solids content (salinity) of water in an aquifer from place to place, and with depth in "stacked" aquifer systems can provide insight into the regional flow paths of the water, if the changes are related to geochemical or geophysical processes that can be identified in the sediments. The principal factors that change the salinity of formation waters in lower Miocene deposits of the study area are (1) the thermal diagenesis (chemical change) of the most abundant clay mineral species in the sediments, montmorillonite, which releases fresh water in an amount equal to about one half the volume of the mineral altered, (2) hyperfiltration (reverse osmosis), which separates dissolved solids from water forced through beds of clay or shale as a consequence of very large fluid pressure differentials (gradients in head) across them. A third factor, related to the hyperfiltration property of clay, is the change in the salinity of water expelled from marine clay beds as they are progressively compacted with deepening burial and increasing overburden load.

The release of fresh water by clay mineral change, described by Burst (1969) as dehydration, is temperature controlled. It begins at about 80°C (176°F) and is complete at about 120°C (248°F); up to 80 percent of the clay mineral present may be altered. The depth interval in which it occurs can be identified in any area by mapping these isothermal surfaces. The consequences of this process are dilution of formation waters (salinity decrease) in the aquifers affected. The converse effect,

concentration of dissolved solids (salinity increase) occurs where water escapes upward (or downward) across a clay bed that separates aquifers in which the fluid pressure differs greatly. The maximum pressure difference in the study area is across the clay-bed seal of the geopressure zone, and accordingly, the hyperfiltration effects are most apparent where leakage through the seal has occurred.

The isosalinity maps, Figures 16 and 17, show similar patterns of salinity distribution in both aquifers No. 1 and No. 3, in the southeastern part of the study area. Maximum salinity, more than 100,000 mg/l, occurs in the vicinity of the Edna Delcambre Well No. 1 in both aquifers in the area that is structurally high, suggesting this locality is a focus of flow, and of seepage through the geopressure "seal;" the clay bed at the top of the geopressure zone is generally less than 300 ft. thick in this area, and the pressure gradient is very steep--12.6 psi/ft. Minimum salinity, 20,000 to 40,000 mg/l, occurs to the south and southwest, in the areas that are structurally low.

All salinity values used in making the aquifer water salinity maps, Figures 16 and 17, were derived from electric log data, using the Schlumberger equation (Anonymous, 1972, p. 77-78). Numerical values are expressed in terms of equivalent sodium chloride concentrations, and are highly approximate. Salinity differences from place to place, as shown on the maps, are valid.

The solubility of natural gas (methane) in water varies with pressure and temperature as shown in Table 3 for indicated pressures and temperatures.

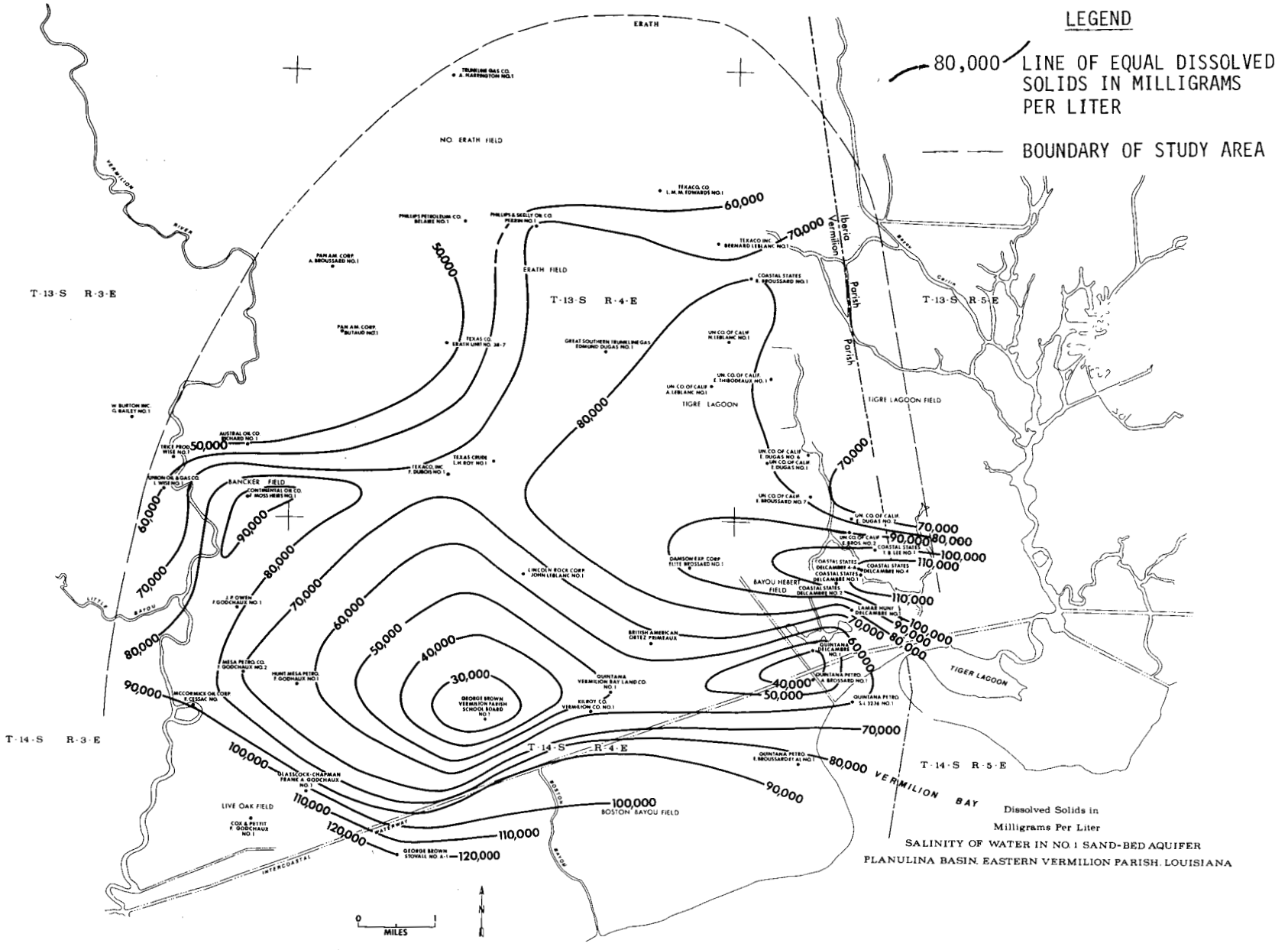

FIGURE 16. Salinity of water in the No. 1 sand-bed aquifer.

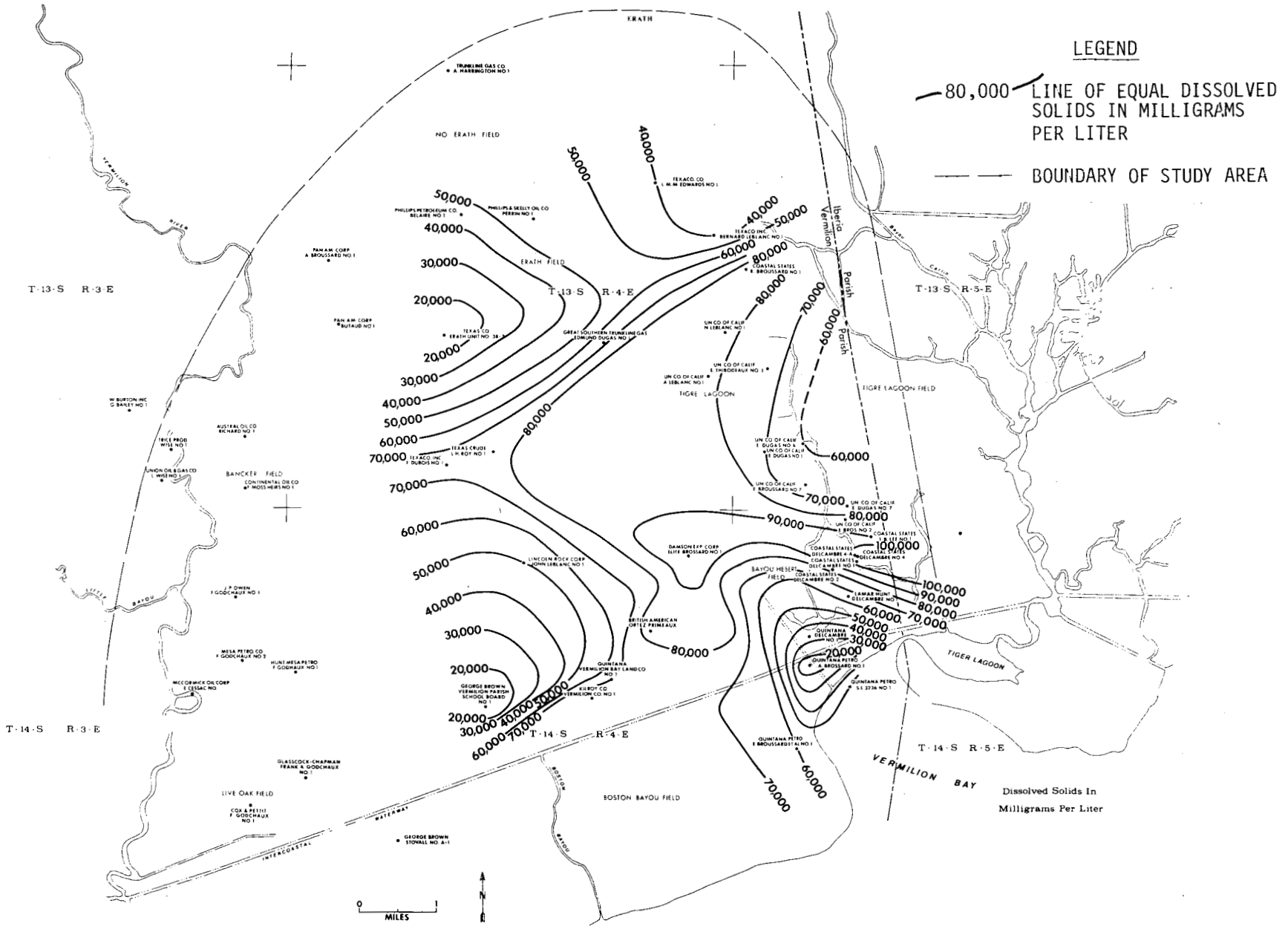

FIGURE 17. Salinity of water in the No. 3 sand-bed aquifer.

TABLE 3

SOLUBILITY OF METHANE IN FRESH WATER

(Sultanov, Skripka, and Namiot, 1972)

Pressure PSI	Temperature, °F 200	300	400	500	600	656
2,000	10	12	20	30	17	
3,000	13	17	30	52	80	
4,000	15	23	40	76	135	
6,000	20	29	52	105	230	380
8,000	24	35	64	130	285	440
10,000	28	41	77	149	340	620
12,000		47	86	168	400	800
14,000		53	95	186	440	900
16,000		58	104	200	480	1,000

Methane solubility is an inverse function of water salinity, and is appreciably reduced at dissolved solids contents greater than 100,000 mg/l (O'Sullivan and Smith, 1970). However, experimental data are not adequate to define methane solubility at in situ conditions of pressure, temperature, and water salinity under the full range of conditions known to occur in this study area.

Upward movement of formation waters saturated in methane is accompanied by decrease in temperature and pressure, as described by the graphs in Figures 14 and 15. According to the gradients shown in Figure 14 for conditions beneath the Coastal States Edna Delcambre Well No. 1, the decrease in pressure upward from a depth of 14,500 ft. is from almost

14,000 to about 10,000 psi in a depth interval less than 1,000 ft. The temperature decrease in this same depth interval is about 20°F, from about 275°F to about 255°F. According to methane solubility data, some 12 to 14 cubic ft. of natural gas is released from each barrel of water as it rises through this depth interval. Exsolved gas, in vapor phase, occurs as dispersed gas bubbles in the sand-bed aquifers until its increasing volume occupies some 4 to 6 percent of the sandstone pore volume. It is then able to flow in continuous gas phase to the top of the sand bed, migrate to the nearest structural high, and accumulate in the trap.

V. CONCLUSIONS

The geology and hydrology of the Tigre Lagoon Gas Field and the structural and depositional basin in which it occurs, as described in this report, define a hydrodynamic system which has been in operation for millions of years. Fluid entrapment and geopressuring of the deposits has resulted in steepened geothermal gradients, accelerated maturation and thermal degradation (cracking) of fluid hydrocarbons, thermal diagenesis of certain clay minerals with release of much bound and intracrystalline water as free pore water, and a systematic fluid migration history controlled by the sand-bed aquifers in the basin, and by upward leakage at growth faults wherever fluid pressures approached or exceeded rock pressures. Observed geotemperature, geopressure, water salinity, and natural gas occurrence in the study area conform nicely with the conceptual model developed in this study.

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