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Sandstone Distribution and Potential for Geopressured Geothermal Energy Production in the Vicksburg Formation Along the Texas Gulf Coast

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SANDSTONE DISTRIBUTION AND POTENTIAL FOR GEOPRESSURED GEOTHERMAL ENERGY PRODUCTION IN THE VICKSBURG FORMATION ALONG THE TEXAS GULF COAST[1]

R. G. Loucks[2]

ABSTRACT

Potential geopressured geothermal reservoirs in the Vicksburg Formation are limited to Hidalgo County along the Lower Texas Gulf Coast. In Hidalgo County, an area of approximately 385 square miles (designated the Vicksburg Fairway) contains up to 1,300 feet of geopressured sandstones with fluid temperatures greater than 300°F. Inplace effective permeability, however, averages less than 1 millidarcy in the Vicksburg sandstones because of fine grain size and extensive late carbonate cementation. Also, areal extent of indivdiual reservoirs is limited in a dip direction by growth faults and in a strike direction by the lenticular geometry of the sandstone bodies. Under present criteria for geothermal fairways, the Vicksburg has minimal potential because of inferred low reservoir deliverability, which is constrained by low permeability and limited reservoir continuity. If future tests indicate that lower permeabilities are acceptable, the Vicksburg Fairway should be reconsidered because of the presence of extremely thick sandstone bodies.

INTRODUCTION

General Statement

Geopressured geothermal prospects of the Oligocene Vicksburg Formation (Fig. 1) along the Texas Gulf Coast are minimal because of low permeability and restricted areal extent of reservoirs. This appraisal of the Vicksburg Formation results from a program being conducted by the Bureau of Economic Geology to evaluate the potential for producing geopressured geothermal energy from onshore Tertiary formations along the Texas Gulf Coast. Two other Tertiary units have been investigated: the Frio Formation (Bebout, Dorfman, and Agagu, 1975; Bebout, Agagu, and Dorfman, 1975; Bebout, Loucks, Bosch, and Dorfman, 1976; and Bebout, Loucks and Gregory, 1977), and the Wilcox Group (Bebout, Gavenda, and Gregory, 1978).

CENOZOIC – TEXAS GULF COAST

SYSTEM	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. Modified from Gregory (1966) and Bebout and others (1975).

An area of approximately 385 square miles (11 x 35 miles) was identified as the Vicksburg Fairway in Hidalgo County along the Lower Texas Gulf Coast (Fig. 2). A geopressured geothermal fairway is an area which meets a set of easily recognizable minimum requirements necessary for the production of geothermal energy, and which therfore warrants further investigation. These requirements demand a sandstone volume of 3 cubic miles (for example, 300 feet by 50 square miles) and subsurface fluid temperatures greater than 300°F. Further investigation of a fairway area involves evaluation of reservoir permeability and continuity, parameters which are more difficult to analyze.

An area with deep, thick sandstones in the Vicksburg Fairway was recognized by Bebout (1976) in a preliminary study of geopressured geothermal corridors in Texas (Fig. 3). Bebout also indicated that the Vicksburg Formation in an area of the Upper Texas Gulf Coast (Fig. 3) may have potential, but no prospective sandstones were identified during subsequent studies reported herein.

Method of Study

Stratigraphic and structural cross sections along the Lower Texas Gulf Coast were constructed on a grid downdip of the Vicksburg fault zone, where deep electrical-log data are available (Fig. 2). These cross sections are regional, and interpretive where data are sparse or absent. Cross sections were not prepared for the Middle and Upper Texas Gulf Coast because few deep wells are available downdip of the Vicksburg fault zone (Fig. 4), and the deep data which are available indicate that no sandstones of interest occur in the zone.

Published reservoir quality data by Ritch and Kozik (1971) and Swanson, Oetking, Osoba, and Hagens (1976) were integrated with data from this study to complete the preliminary analysis of the Vicksburg Fairway. Final detailed analysis of the fairway will come from a site-selection study now in progress at the Bureau of Economic Geology.

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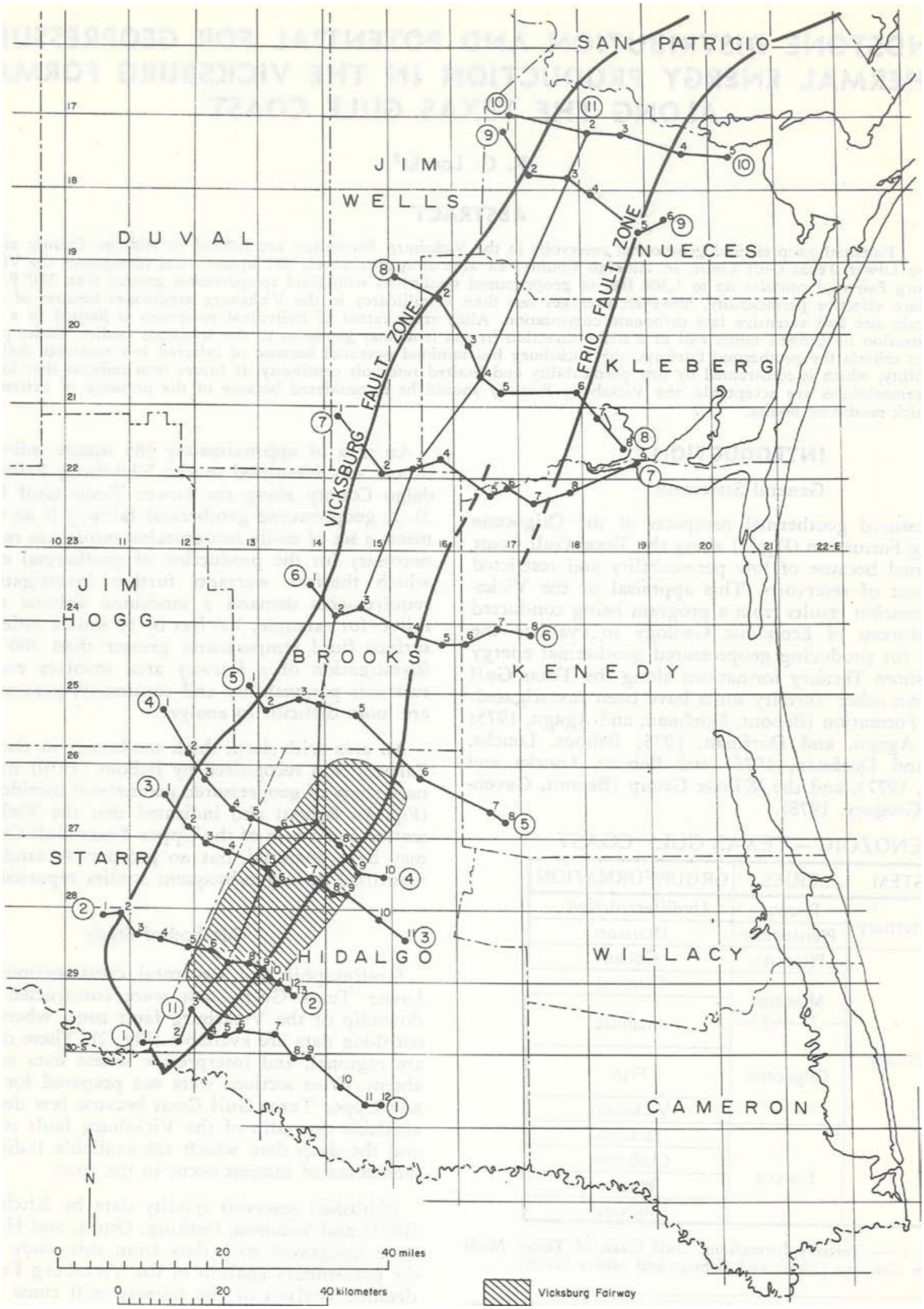


FIGURE 2 — Location of Vicksburg Fairway and lines of sections shown in Figures 9 to 29.

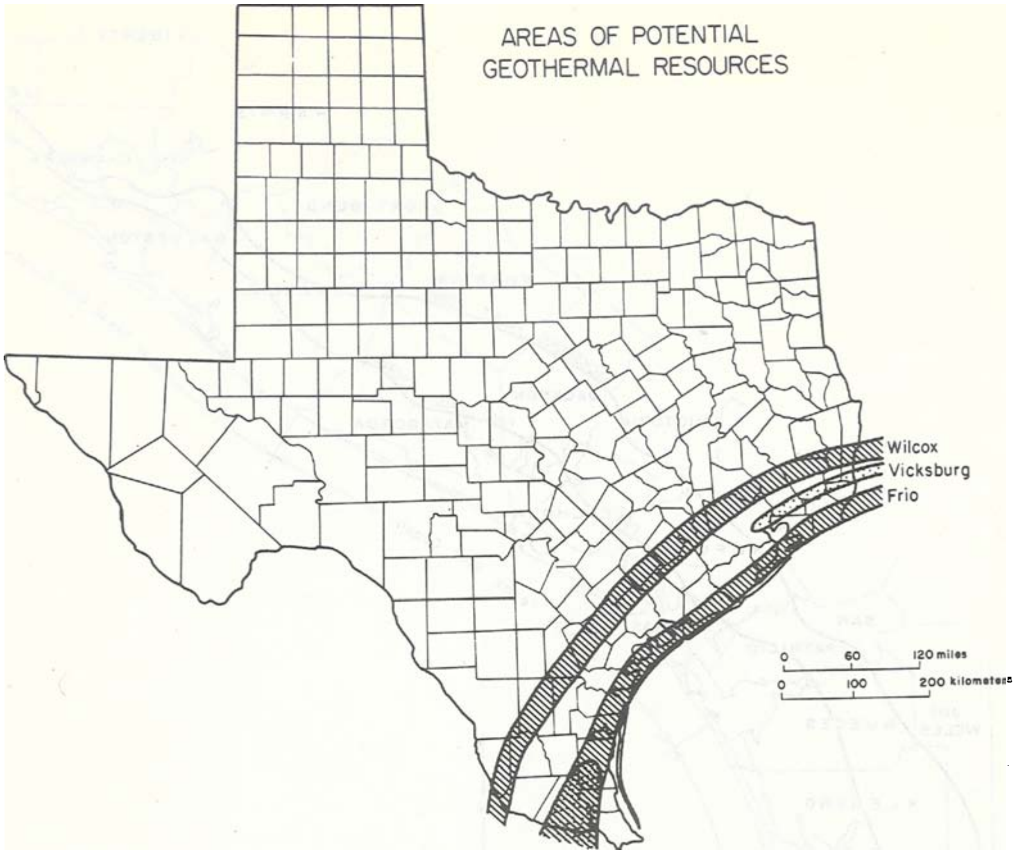


FIGURE 3 — Geothermal corridors of potential fairways. From Bebout (1976).

REGIONAL GEOLOGY

Growth Faults

Growth faults, common structural features in the Gulf Coast area (Bruce, 1973), were formed by contemporaneous subsidence during sediment loading (Fig. 5). Two major zones of growth faults affected the Vicksburg Formation: the Vicksburg and the Frio fault zones (Fig. 4).

More than 7,000 feet of Vicksburg sediment accumulated on the downthrown side of growth faults along the Vicksburg fault zone. Gulfward, on the downthrown side of the Frio fault zone, massive Frio sandstones are juxtaposed with older Vicksburg shales by movement along growth faults. Therefore, a basic understanding of the depositional and structural history of basal Frio sandstones is necessary in order to delineate the distribution of the Vicksburg sandstones, which are similar in appearance on electrical logs to the sandstones of the Frio Formation.

Index Foraminifera

Index Foraminifera are the basis for distinguishing formations in the otherwise similar sandstone-shale sequences of the Tertiary Gulf Coast basin. Contact between the Vicksburg and Frio Formations is traditionally picked at the last occurrence of *Textularia warreni* (Fig. 6). This study, however, indicates that in the Lower Texas Gulf Coast area the contact between the Vicksburg and the basal part of the Frio Formation occurs at the base of a thick progradational sequence of shale and sandstone which contains *T. warreni* (Fig. 7). *Textularia warreni,* therefore, is a basal Frio index foraminifer and does not occur in the Vicksburg Formation.

Updip of the Frio fault zone, the basal Frio Formation is predominantly fluvial in origin and contains only *T. warreni* in marine sandstones and shales which are restricted to the lower part of the section (Fig. 7). On the other hand, gulfward of the Frio fault zone, the entire, predominantly marine basal Frio strata contain a full suite of Frio index Foraminifera.

Vicksburg and Basal Frio Sandstone Distribution

General Statement

Downdip of the Vicksburg fault zone, the Vicksburg Formation changes from a very prominent sandstone section along the Lower Texas Gulf Coast to a sandstone-poor section along the Middle and Upper Texas Gulf Coast (Figs. 8 to 29). The major source of sand in the Vicksburg was the ancient Rio Grande as indicated by the abundance of sandstone only in the Hidalgo County area. In contrast, a sequence of basal Frio sandstones occurs along the entire Texas Gulf Coast (Figs. 8 to 29).

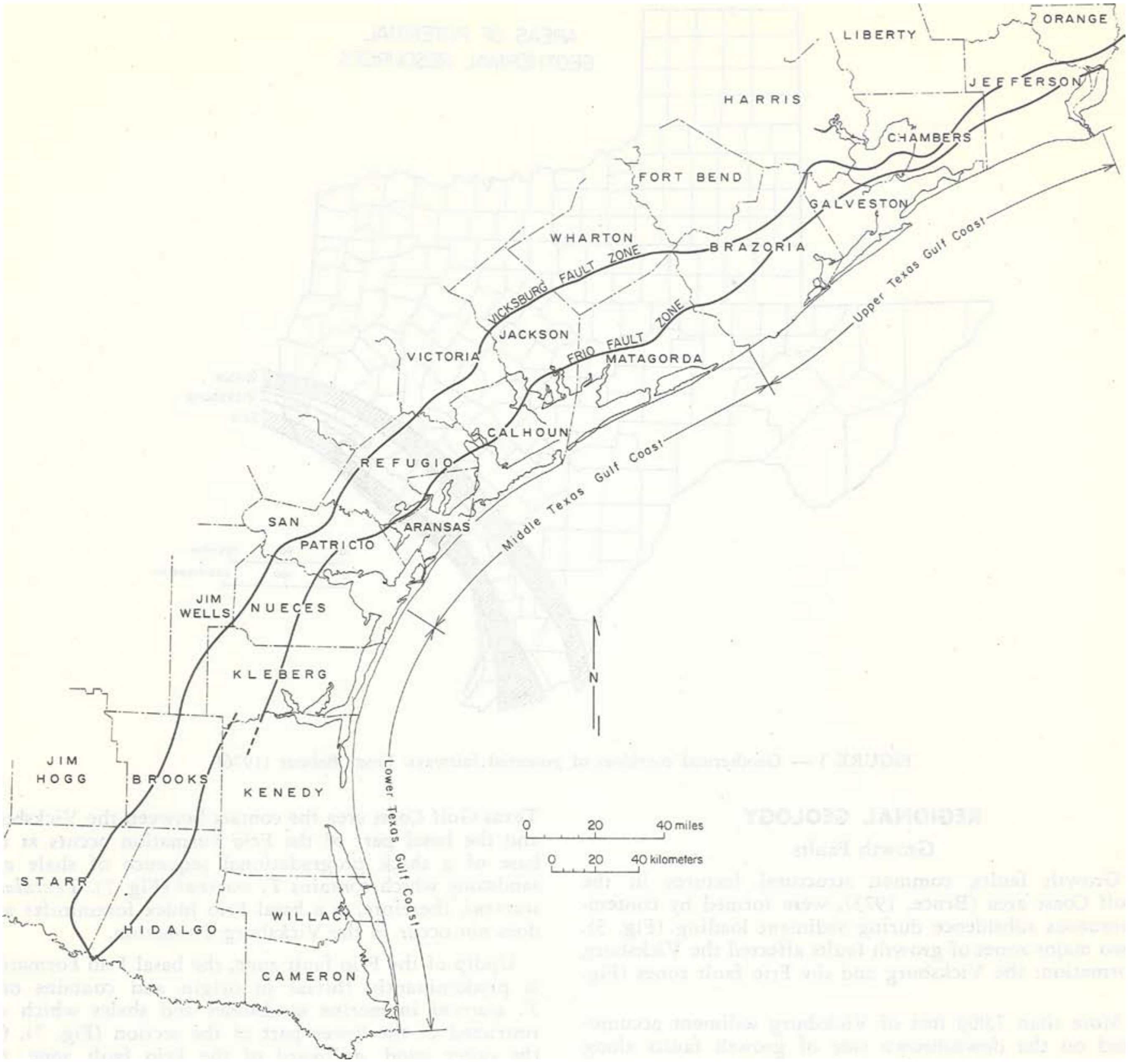


FIGURE 4 — Location of Vicksburg and Frio fault zones.

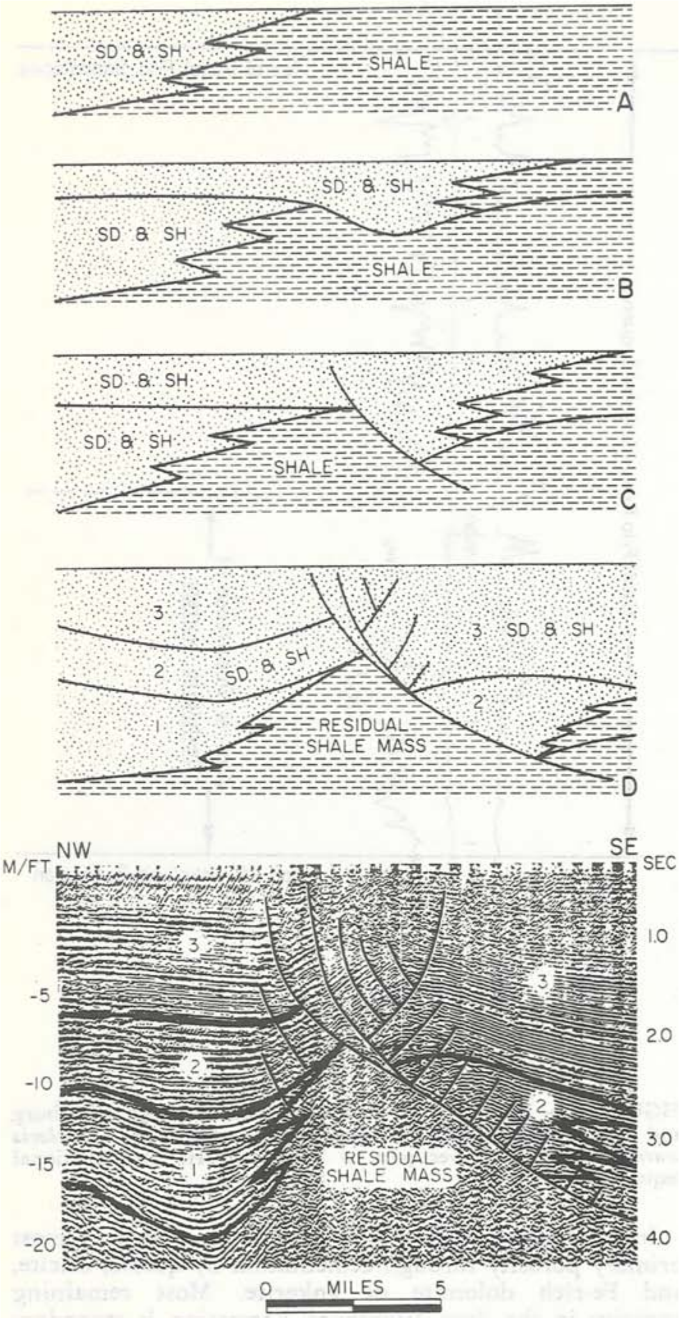


FIGURE 5 — Growth-fault development interpreted from a seismic section and shown sequentially by diagrams (Bruce, 1973).

Vicksburg Sandstone Distribution

Vicksburg Fairway Area. — In the Vicksburg Fairway area along the Lower Texas Gulf Coast, the Vicksburg section expands from a few hundred feet thick updip of the Vicksburg fault zones to more than 4,000 feet on the downthrown side of the fault (Figs. 8, 11 to 16). The lower part of the Vicksburg Formation contains more standstone than does the upper part of the formation. Massive sandstones in the lower part of the Vicksburg occur as far downdip as the Frio fault zone. These sandstones probably extend beyond the Frio fault zone but have not yet been penetrated. Also, the lower part of the Vicksburg Formation expands in thickness on the downthrown side of several growth faults gulfward of the Vicksburg fault zone, isolating sandstone bodies in separate fault blocks.

The upper part of the Vicksburg Formation contains massive sandstone beds immediately downdip of the Vicksburg fault zone, but toward the Frio fault zone (gulfward) these sandstones grade to shale. Sandstones in the upper part of the Vicksburg Formation are too shallow to have fluid temperatures greater than 300°F and are not prospective geothermal reservoirs. Only sandstones in the lower part of the formation are sufficiently hot to qualitfy the area as a geothermal fairway.

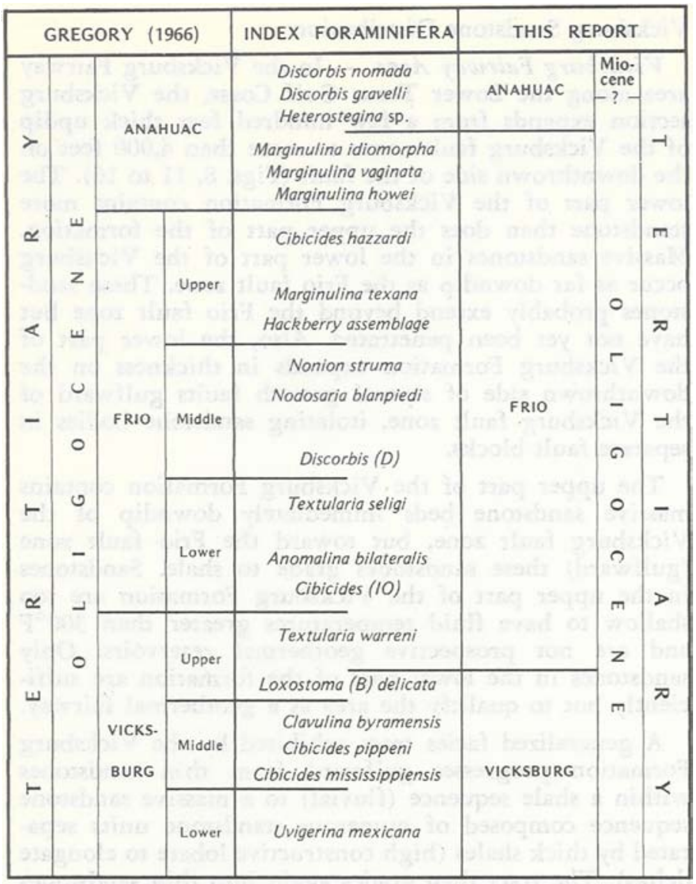
A generalized facies tract exhibited by the Vicksburg Formation progresses gulfward from thin sandstones within a shale sequence (fluvial) to a massive sandstone sequence composed of numerous standstone units separated by thick shales (high constructive lobate to elongate deltas). The tract then grades again into thin sandstones within a shale sequence (distal delta) and finally into a shale sequence (pro-delta to slope). Immediately updip of the Frio fault zones, a vertical sequence of the Vicksburg Formation grades from massive deltaic sandstones to slope shales, indicating a major marine transgression.

South of the Vicksburg Fairway Area. — The entire Vicksburg Formation south of the fairway and downdip of the Vicksburg fault zone is predominantly shale with a few thin siltstone lenses up to 4 feet thick (Fig. 9. These strata were deposited in distal delta to prodelta environments and are unfavorable for geothermal reservoirs.

North of the Vicksburg Fairway Area. — North of the fairway along the Lower Texas Gulf Coast, the lower part of the Vicksburg Formation grades laterally from sandstone to shale, followed by a similar change in the upper part of the formation (Figs. 17, 19, 21, 23, 25, 27, and 29). Along the Middle and Upper Texas Gulf Coast, most of the Vicksburg sequence is shale, as indicated by published cross sections (Gregory, 1966, fig. 30) and scattered deep wells. Some sandstones occur in the upper part of the Vicksburg section, but these sandstones are too shallow to have sufficiently high fluid temperatures for production of geothermal energy.

Basal Frio Sandstone Distribution

Along the Lower Texas Gulf Coast, basal Frio strata expand across the Frio fault zone which is located near the underlying Vicksburg shelf edge (Figs. 8 to 29).



GREGORY (1966)				INDEX FORAMINIFERA	THIS REPORT		
TERTIARY	OLIGOCENE	ANAHUAC		*Discorbis nomada*	ANAHUAC	Mio-cene ?	TERTIARY
				Discorbis gravelli			
				Heterostegina sp.			
				Marginulina idiomorpha	FRIO	OLIGOCENE	
				Marginulina vaginata			
				Marginulina howei			
		FRIO	Upper	*Cibicides hazzardi*			
				Marginulina texana			
				Hackberry assemblage			
			Middle	*Nonion struma*			
				Nodosaria blanpiedi			
				Discorbis (D)			
			Lower	*Textularia seligi*			
				Anomalina bilateralis			
				Cibicides (IO)			
		VICKS-BURG	Upper	*Textularia warreni*			
				Loxostoma (B) delicata	VICKSBURG		
			Middle	*Clavulina byramensis*			
				Cibicides pippeni			
				Cibicides mississippiensis			
			Lower	*Uvigerina mexicana*			

FIGURE 6 — Index Foraminifera. Data accumulated from Gregory (1966), Bebout and others (1975), and this investigation.

Updip of the Frio fault zone, basal Frio strata grade gulfward from a fluvial system containing scattred sandstone bodies within a shale sequence, to a delta system composed of massive sandstones.

The basal Frio delta system thickens across the Frio fault zone, juxtaposing downthrown, massive Frio deltaic sandstones against upthrown prodelta slope shale deposits of the Vicksburg Formation (Figs. 8 to 28). Swanson and others (1976) inferred that some massive Frio sandstones downdip of the Frio fault zone in Kenedy County were actually Vicksburg. However, according to Stratigraphic Dip Sections 6 and 7 (Figs. 19 and 21), these deep massive sandstones must occur within the Frio Formation because the facies tract updip of the sandstone is predominantly prodelta to slope shales of Vicksburg age. The sediment dispersal system for the deep sandstones in Kenedy County is composed of fluvial massive sandstone facies in the basal Frio section updip of the Frio fault zone.

Vicksburg Sandstone Composition, Diagenesis, and Porosity

Vicksburg fine-grained sandstones deposited in the zone of geothermal reservoirs were chemically unstable and, thus, have undergone intense diagenesis. Sandstone grains which are composed of quartz, feldspar, and carbonate and volcanic rock fragments are classified (Folk, 1974) as arkoses and volcanic lithic arkoses (Fig. 31).

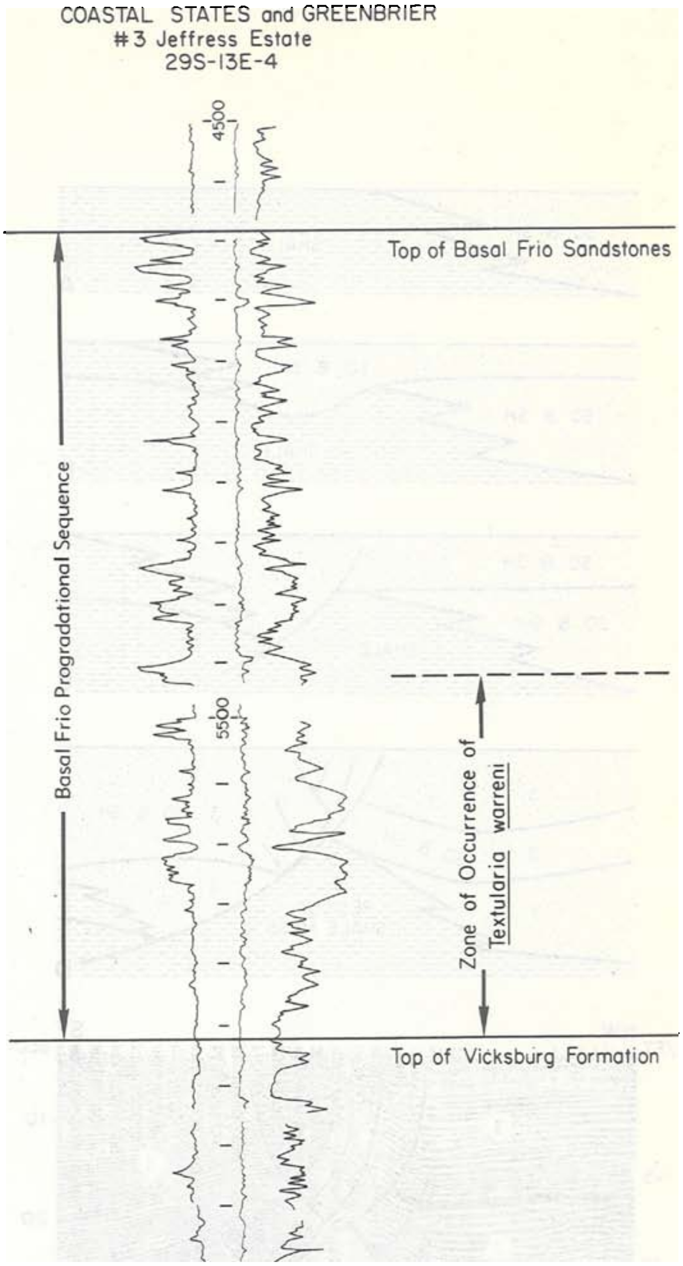


FIGURE 7 — Electrical log showing contact between Vicksburg and basal Frio sandstones. Zone of occurrence of *Textularia warreni* is in the lower part of the basal Frio progradational sequence.

Intense diagenesis of the sandstones has destroyed most primary porosity through cementation by quartz, calcite, and Fe-rich dolomite or ankerite. Most remaining porosity in the deep Vicksburg Formation is secondary in origin and results from the leaching of feldspar grains and carbonate cements. Similar leaching and late-stage cementation occurred in the Frio Formation in South Texas at depths of 8,000 to 11,000 feet (Lindquist, 1977; Loucks, Bebout, and Galloway, 1977).

Finding highly permeable sandstone reservoirs in the deep Vicksburg is unlikely because Vicksburg sandstones are fine grained, chemically immature, and highly altered. The Frio Formation in the South Texas Hidalgo Fairway (Bebout, 1976) exhibits similar properties and was judged to have no potential for the production of geothermal energy because of extremely low permeability.

VICKSBURG FAIRWAY

Pressure, Temperature, and Salinity

In the Vicksburg Fairway the top of the geopressured zone (pressure gradient greater than 0.7 psi per foot) ranges from a depth of 7,000 to 11,000 feet (Fig. 32); average depth is 8,700 feet (Swanson and others, 1976). The top of the geopressured zone is indicated on stratigraphic dip sections (Figs. 9, 11, 13, 15, 17, 19, 21, 23, 25, and 27). In the McAllen Ranch Field (Fig. 32) the top of geopressure ranges from 7,000 to 8,400 feet deep (Ritch and Kozik, 1971), and the transition zone from hydropressure into geopressure is 500 to 700 feet thick. In this field the pore-pressure gradient in the geopressured zone is from 0.86 to 0.92 psi per foot.

In the McAllen Ranch Field the 300°F isotherm is located approximately 2,700 feet below the top of geopressure at an average depth of 11,400 feet (Figs. 9, 11, 13, 15, 17, 19, 21, 23, 25, and 27) as indicated by data from Swanson and others (1971; Fig. 32). Fluid temperatures in the McAllen Ranch Field range from 240°F at 9,000 feet to 340°F at 14,000 feet (Ritch tnd Kozik, 1971); therefore the thermal gradient in this field is 2.0°F per 100 feet. This thermal gradient agrees with the 2.1°F per 100 feet plotted for the geopressured zone in the Vicksburg Fairway (Fig. 33). In addition, Swanson and others (1976) report a geothermal gradient of 1.8°F per 100 feet in the hydopressured zone in the McAllen Ranch Field; this is very closs to the 1.9°F per 100 feet for the Vicksburg Fairway (Fig. 33).

Available salinity data from two Vicksburg fields, Jefferies and McAllen Ranch (Fig. 32), indicate that the average salinity range in the geopressured Vicksburg Fairway is from 14,000 to 40,000 ppm (Ritch and Kozik, 1971; Swanson and others, 1976).

Porosity and Permeability

Low permeability is the factor precluding production of geopressured geothermal energy from the Vicksburg Fairway. Detailed investigations by Ritch and Kozik, (1971) and by Swanson and others (1976) concluded that porosity and permeability in the geopressured Vicksburg Formation are low.

Effective in-place permeability based on flow tests from six geopressured Vicksburg gas fields (Swanson and others, 1976) averages less than 1 millidarcy (Table 1). Swanson and others also note that permeability is a function of depth, decreasing by approximately one order of magnitude for every 2,000 feet of depth (Fig. 34) between 6,000 to 14,000 feet. By superimposing the depth range for the 300°F isotherm onto a depth-versus-effective permeability plot (Swanson and others, 1976), it can be readily observed that there are essentially no effective permeabilities greater than 1.0 millidarcy (Fig. 34).

Detailed porosity and permeability data for the geopressured Vicksburg Formation of the McAllen Ranch Field were summarized by Ritch and Kozik (1971) as follows:

> Based on the available data of 535 quality core samples, the majority (60.7%) had air permeabilities less than 1 md. with 78.3% and 87.8% having air permeabilities less than 2 and 5 md. respectively. Only 6.2% had air permeabilities greater than 10 md. Porosities for these 535 samples ranged from about 16 to 25%. The average porosity for all 535 samples was about 19%.

TABLE 1. Representative in-place effective permeability in geopressured gas fields along the Vicksburg Fault Zone in Hidalgo County. Data from Swanson and others (1976).

Field Name	Permeability (md)
South Kelsey	0.27
McMoran	0.69
McAllen Ranch	0.60
Arrowhead	0.65
McCook	0.21
Jeffress	0.20

These porosity and permeability values from the McAllen Ranch Field are surface readings to air at one atmosphere. Ritch and Kozik point out from isostatic compaction studies, using brine-filled core samples, that porosity readings taken at the surface should be reduced by 1.5 porosity percent. Also, air permeability readings should be reduced by one order of magnitude to allow for the effects of brines and differential pressure; for example 1.35 millidarcys air permeability reduces to 0.24 millidarcys in-place effective permeability.

Sandstone Thickness and Lateral Continuity

Sandstone reservoirs in the Vicksburg Fairway occur in units up to 1,100 feet thick separated by shale sequences up to 1,600 feet thick. Within the sandstone units, individual sandstone beds range in thickness from a few feet to 120 feet. Sandstones are separated by shale beds ranging in thickness from a few feet to 30 feet (Figs. 11, 13, and 15).

Lateral continuity of potential reservoirs is controlled by areal distribution of the sandstones which, in turn, depends on depositional environment. Ritch and Kozik (1971) show that Vicksburg sandstones in the Vicksburg

Fairway were deposited by a large delta system (Fig. 35). Deltaic deposition (Figs. 11, 13, 15, and 17) occurred in several progradational episodes, indicated by the numerous individual coarsening-upward sequences. Sandstone isopachous maps of the Jeffress Field area demonstrate that deltas in the lower part of the Vicksburg Formation were probably high-constructive systems with a strong dip orientation. Lateral continuity of individual sandstone beds in these deltaic sequences is expected to be poor and continuity probably will not extend more than a few miles in a strike direction. Lateral continuity of sandstones in a dip direction is interrupted by numerous growth faults in the lower part of the Vicksburg Formation. Poor lateral continuity of sandstone reservoirs is also further documented by Swanson and others (1976), who report that many geopressured fields in South Texas consist of one single well. They note that the complexity of faulting within the Vicksburg increases with depth. Faults are primarily growth faults spaced approximately 4 miles apart (Figs. 11, 12, and 15).

RECOMMENDATIONS

According to present criteria established for identifying geopressure geothermal fairways, the Vicksburg Formation is not a promising source of geothermal energy. Nevertheless, because of the presence of high fluid temperatures and thick sandstone bodies in the Vicksburg Fairway, it is recommended that takeover of a previously drilled well or a currently drilling well ("well-of-opportunity") that is uneconomical for hydrocarbon production be considered. An experimental test would provide data about deliverability of fluids from low-permeability reservoirs and about dissolved methane contained in deep geothermal fluids.

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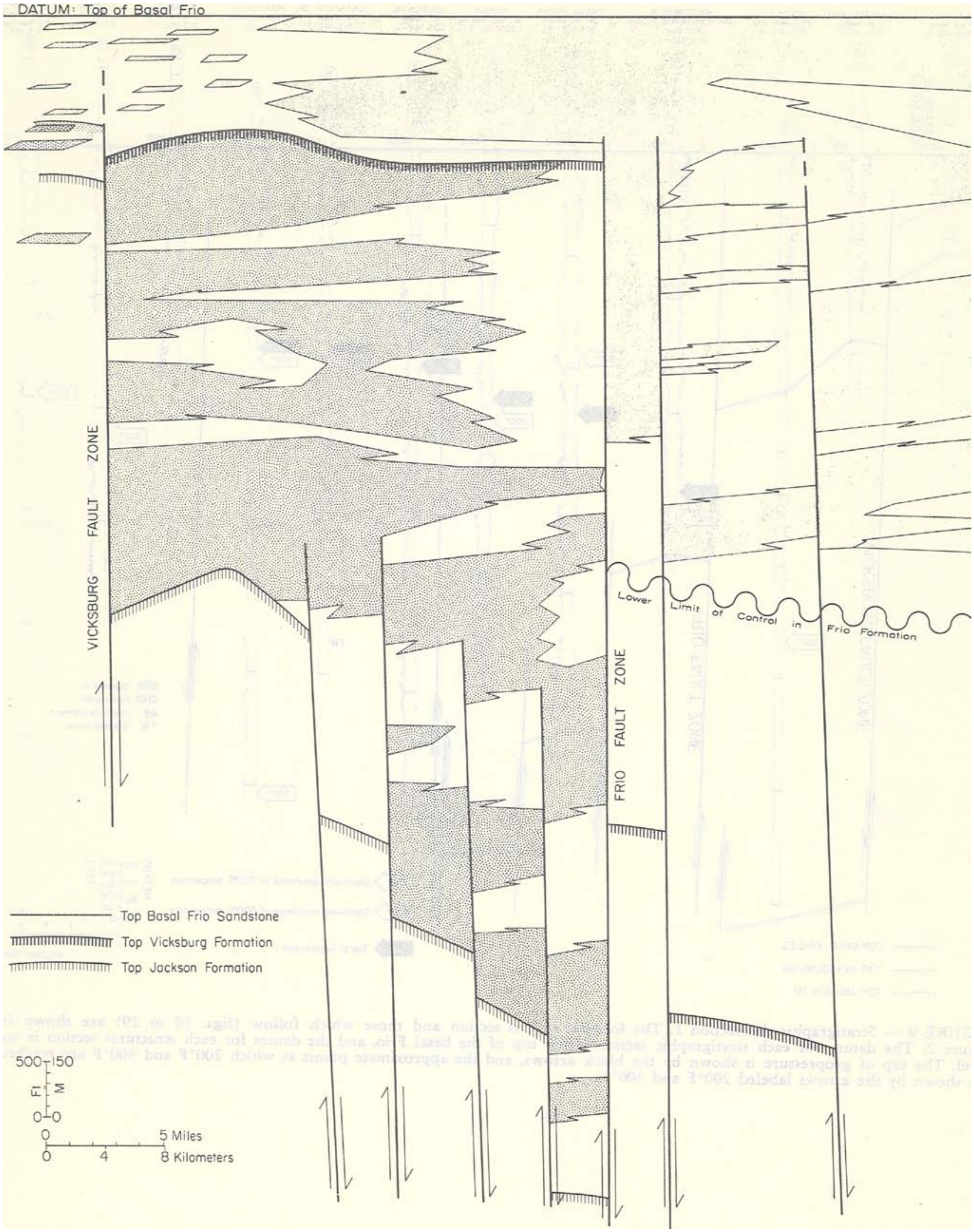

FIGURE 8 — Stratigraphic dip section showing Vicksburg and basal Frio sandstone distribution in the Vicksburg Fairway. Line of section is the same as in Figure 11.

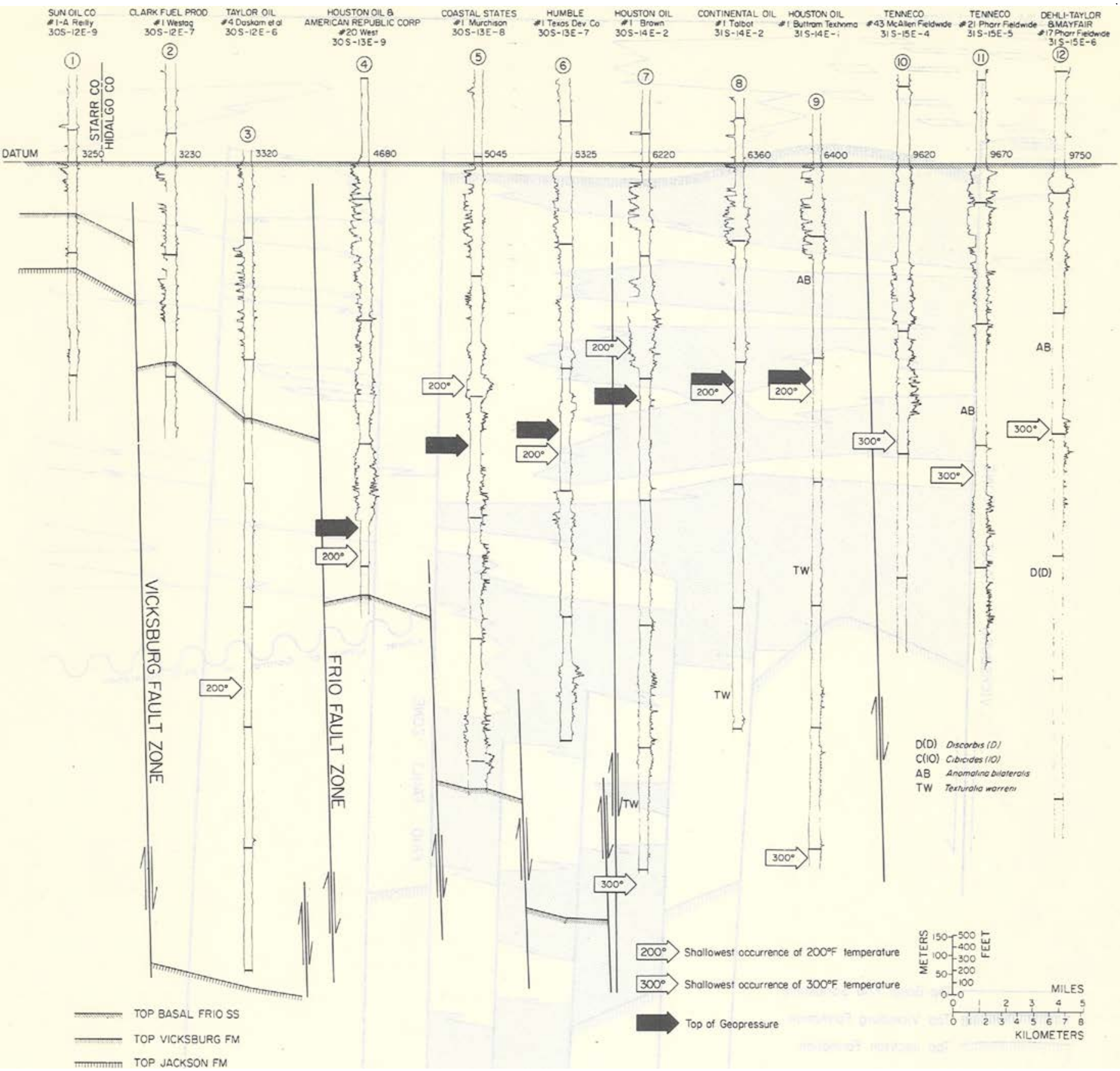

FIGURE 9 — Stratigraphic dip section 1. The location of this section and those which follow (figs. 10 to 29) are shown in Figure 2. The datum for each stratigraphic section is the top of the basal Frio, and the datum for each structural section is sea level. The top of geopressure is shown by the black arrows, and the approximate points at which 200°F and 300°F are reached are shown by the arrows labeled 200°F and 300°F.

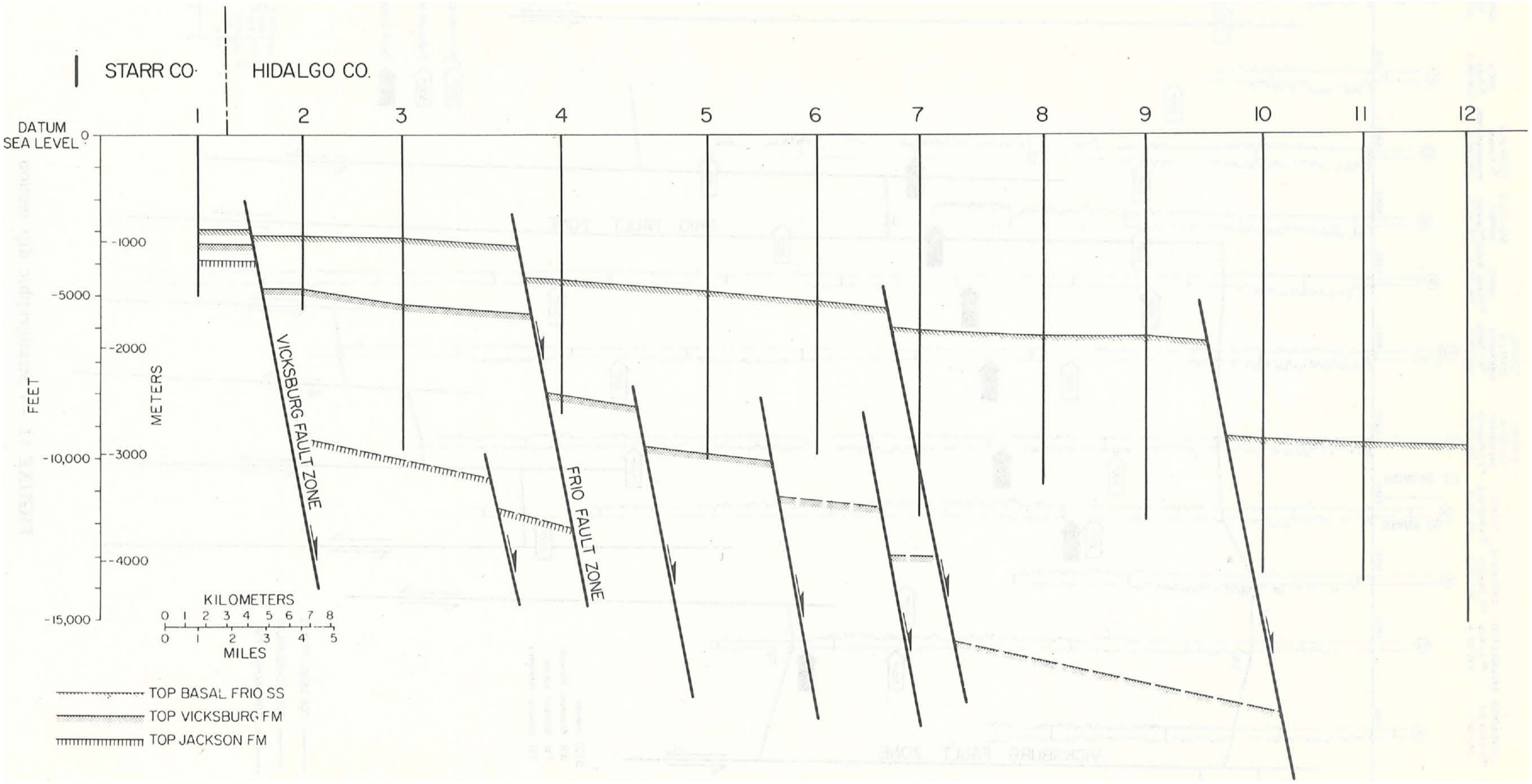

FIGURE 10 — Structure section 1.

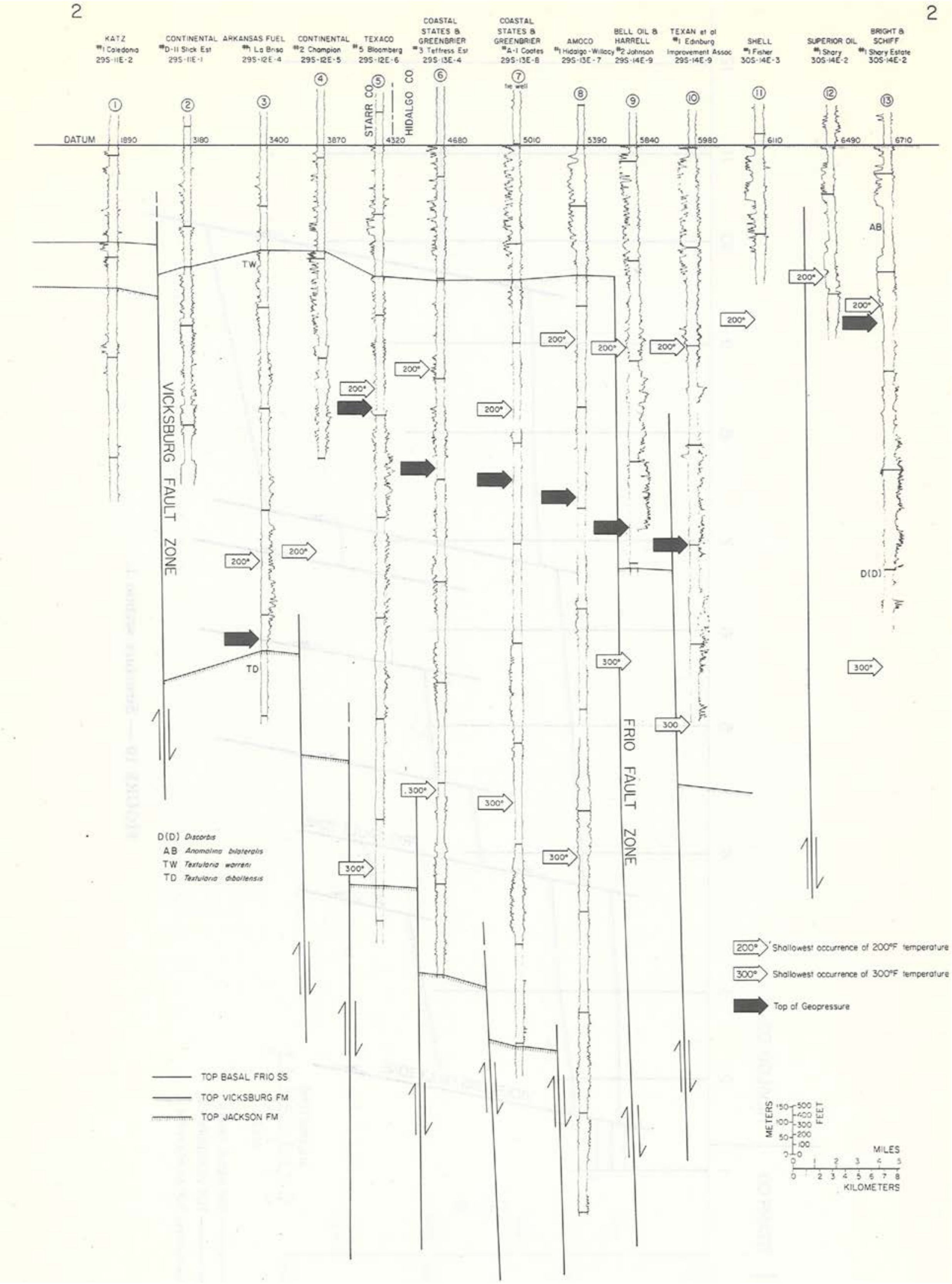

FIGURE 11 — Stratigraphic dip section 2.

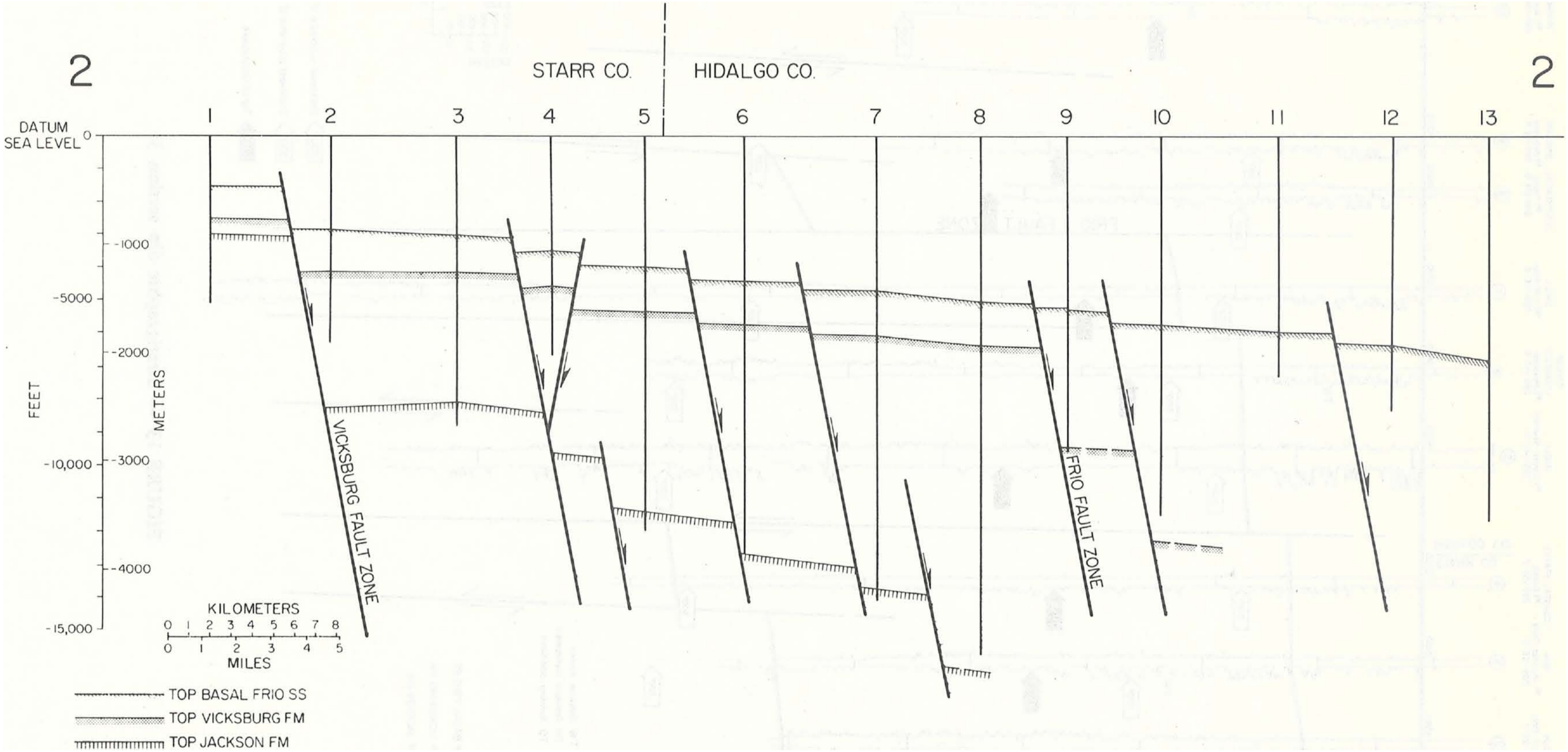

FIGURE 12 — Structure section 2.

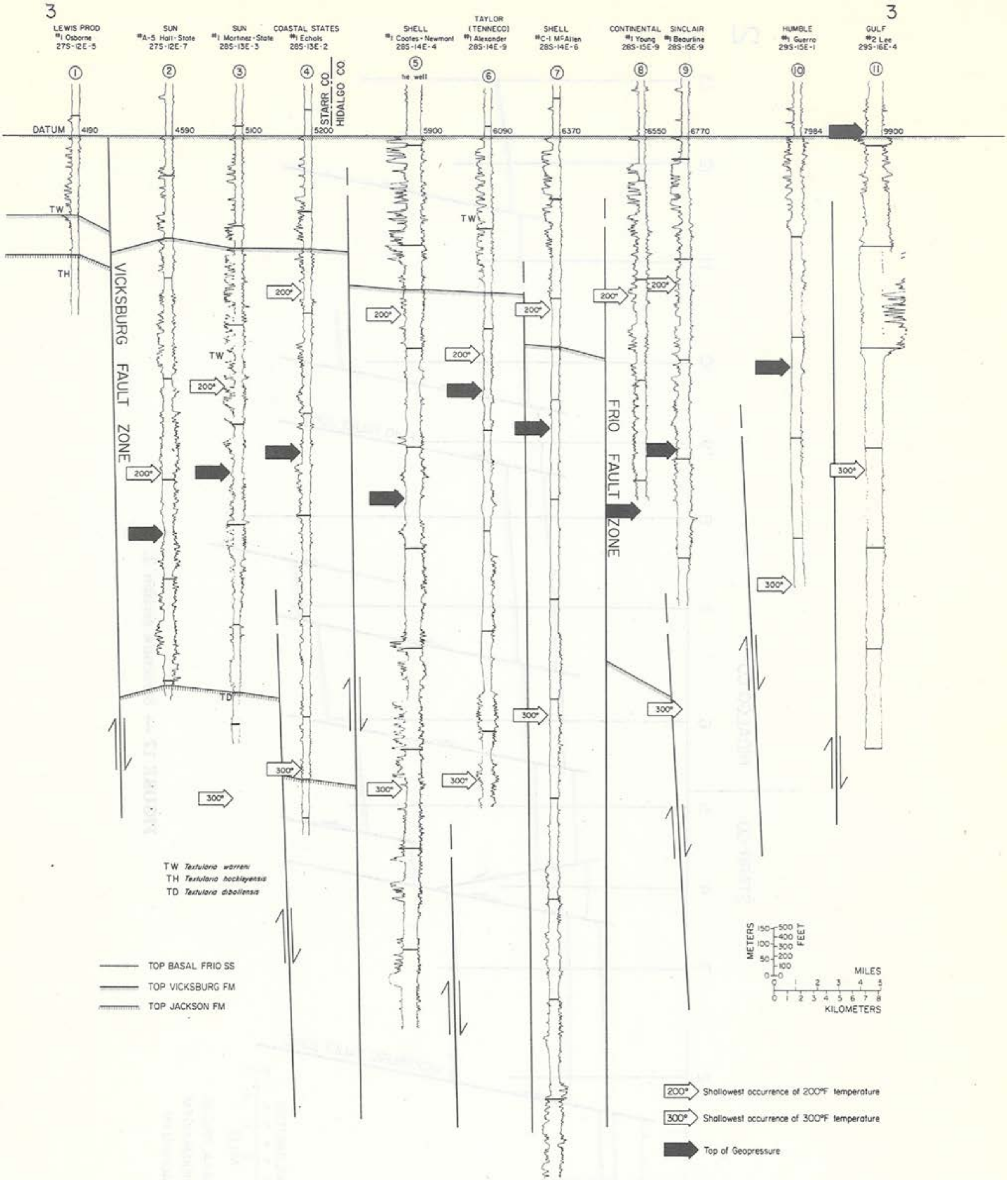

FIGURE 13 — Stratigraphic dip section 3.

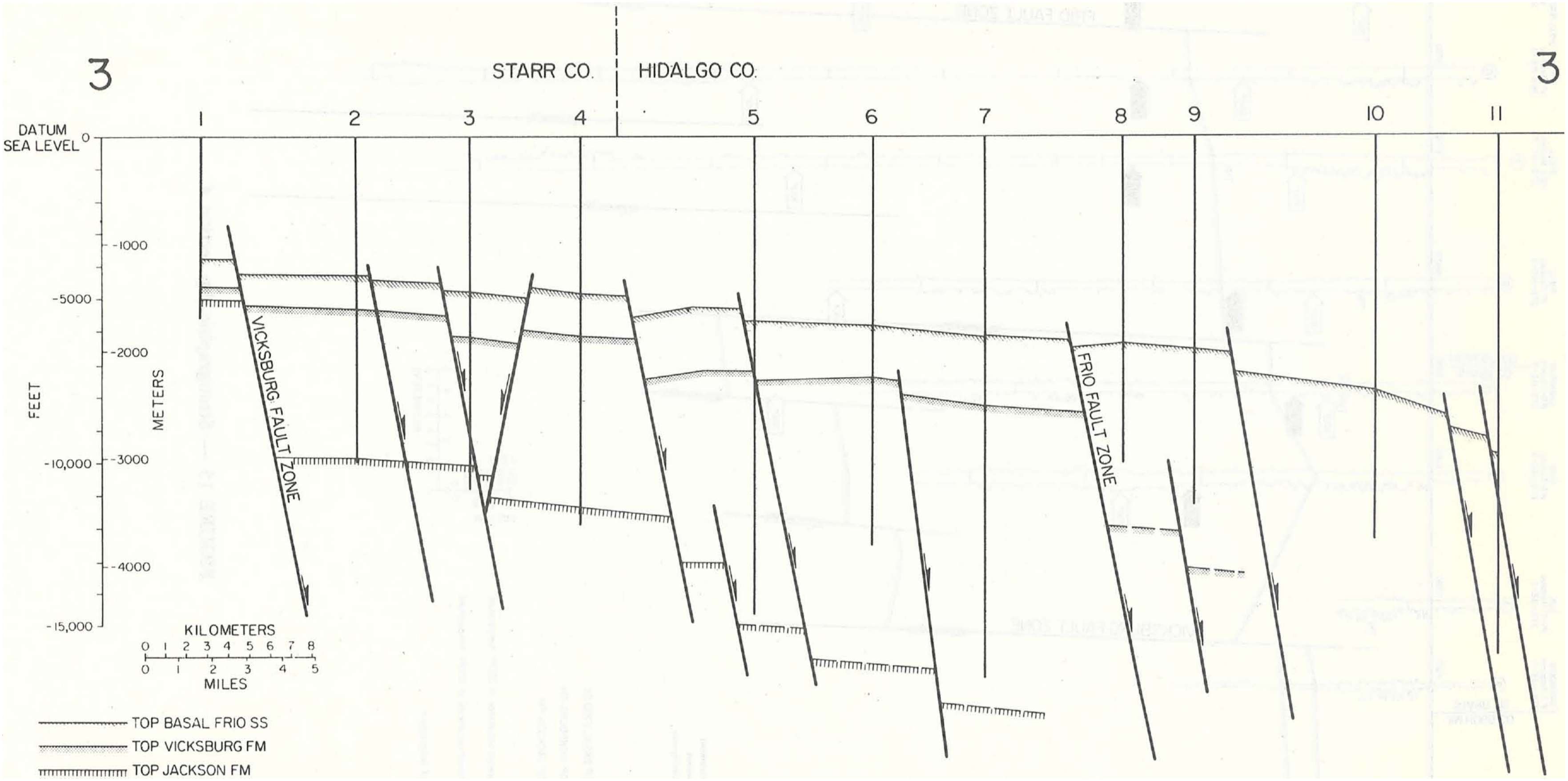

FIGURE 14 — Structure section 3.

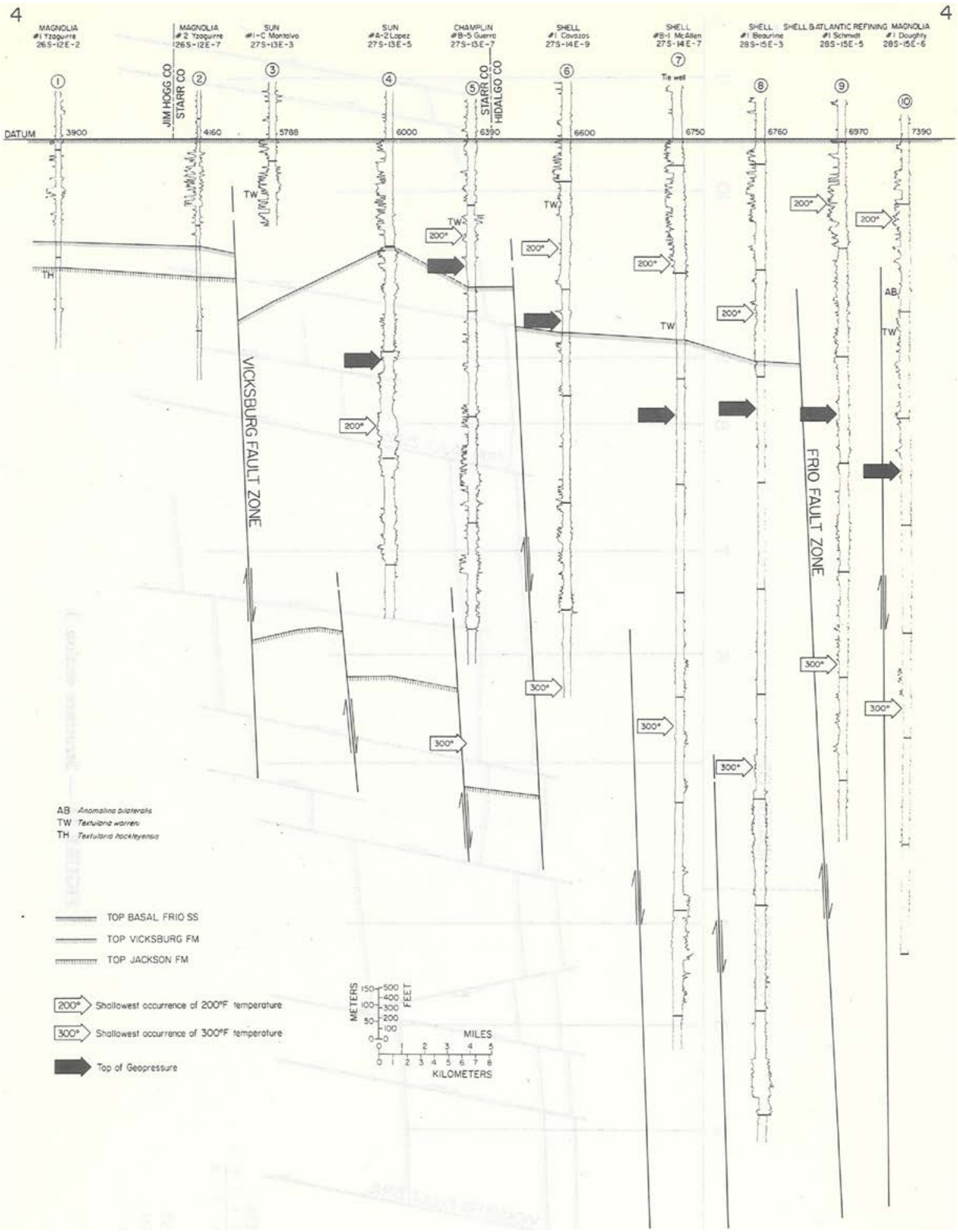

FIGURE 15 — Stratigraphic dip section 4.

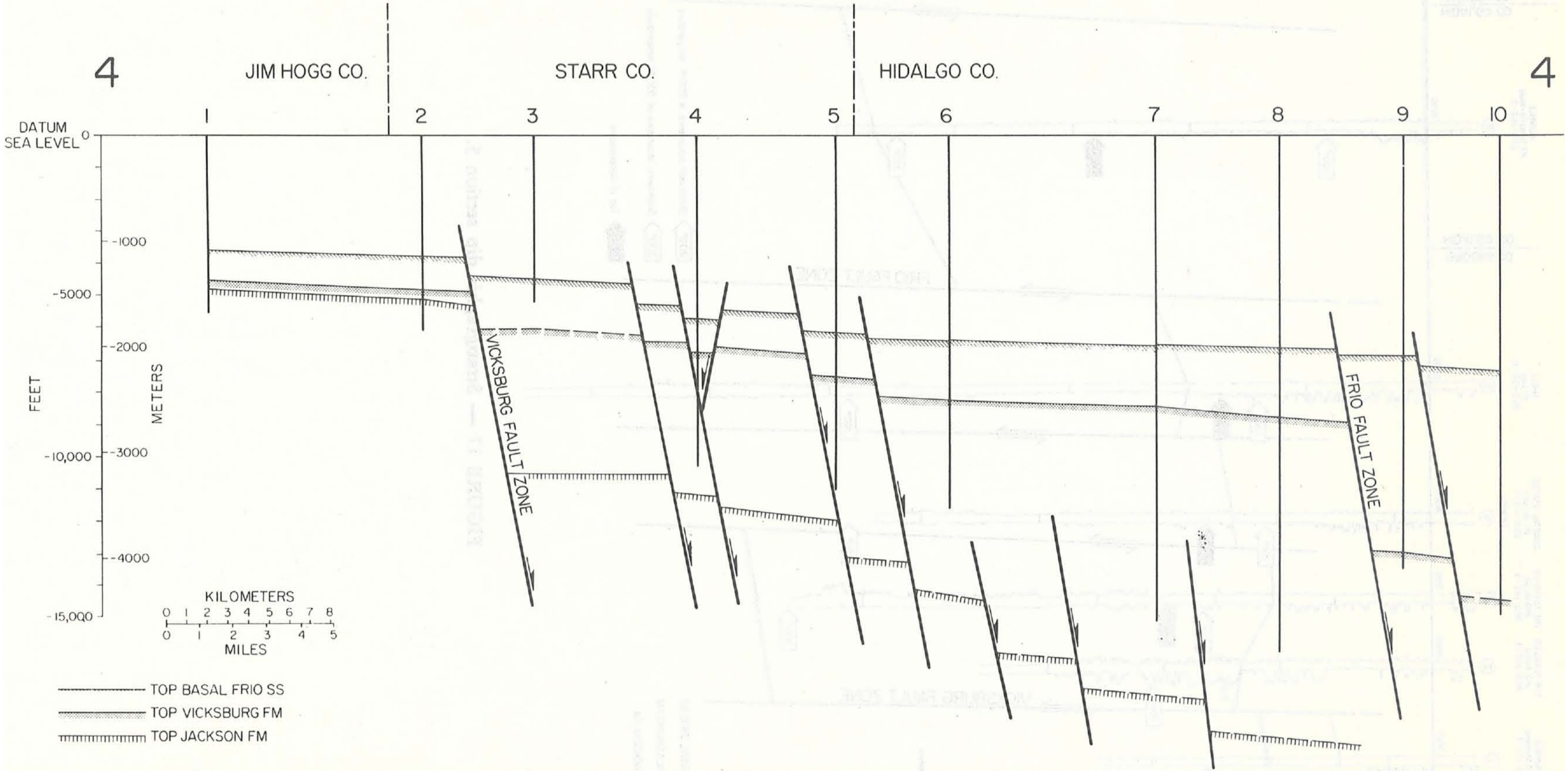

FIGURE 16 — Structure section 4.

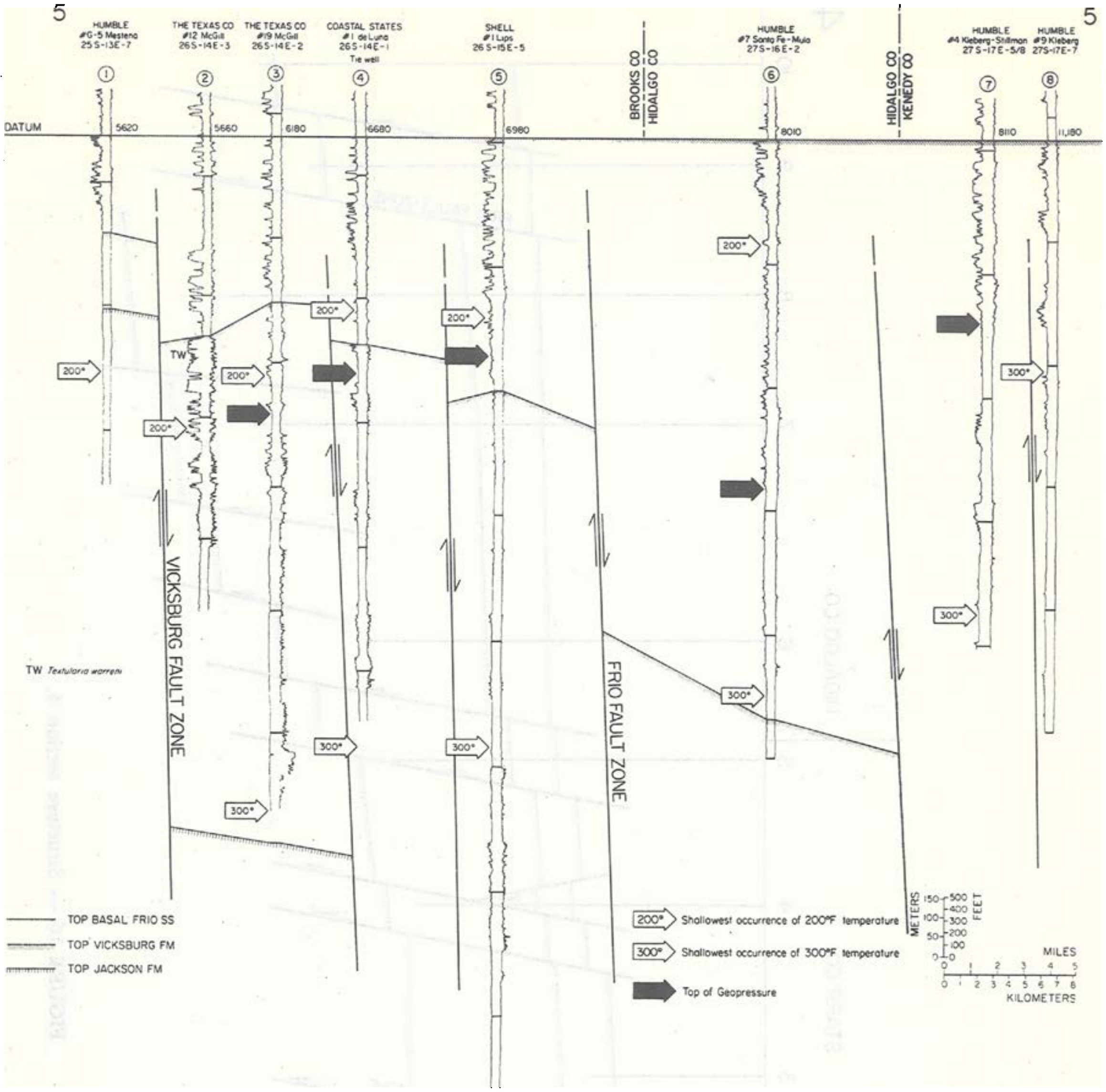

FIGURE 17 — Stratigraphic dip section 5.

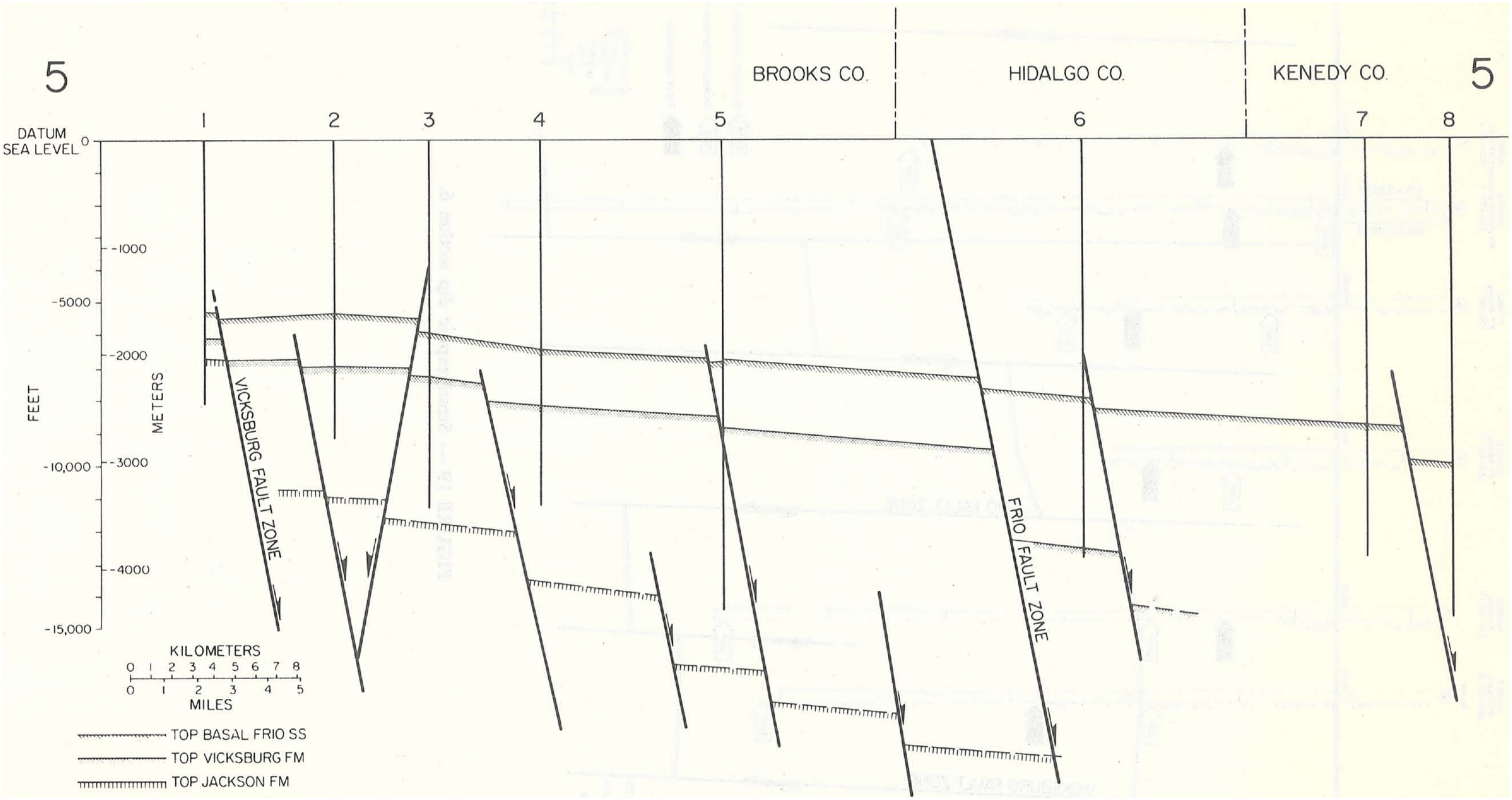

FIGURE 18 — Structure section 5.

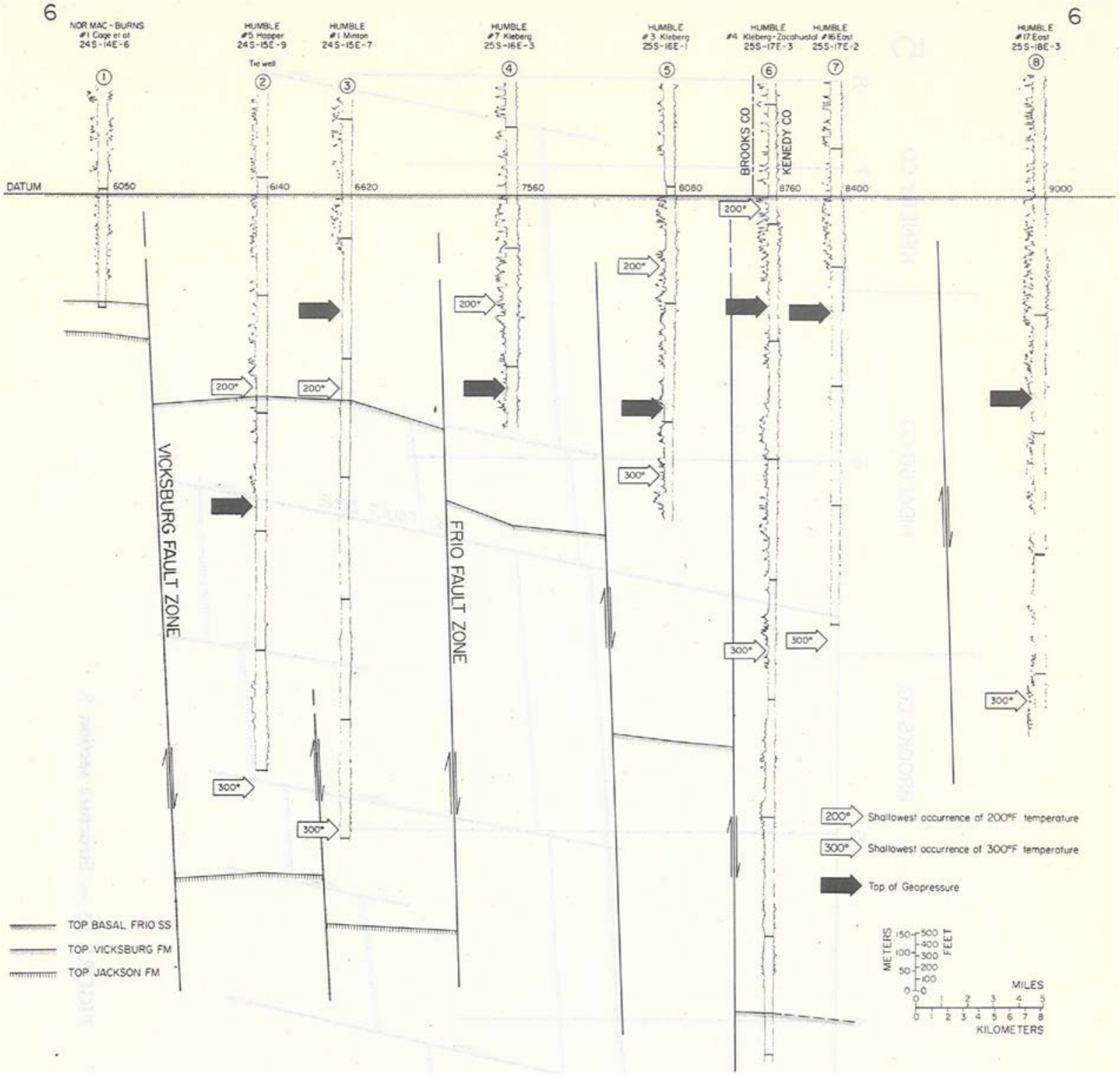

FIGURE 19 — Stratigraphic dip section 6.

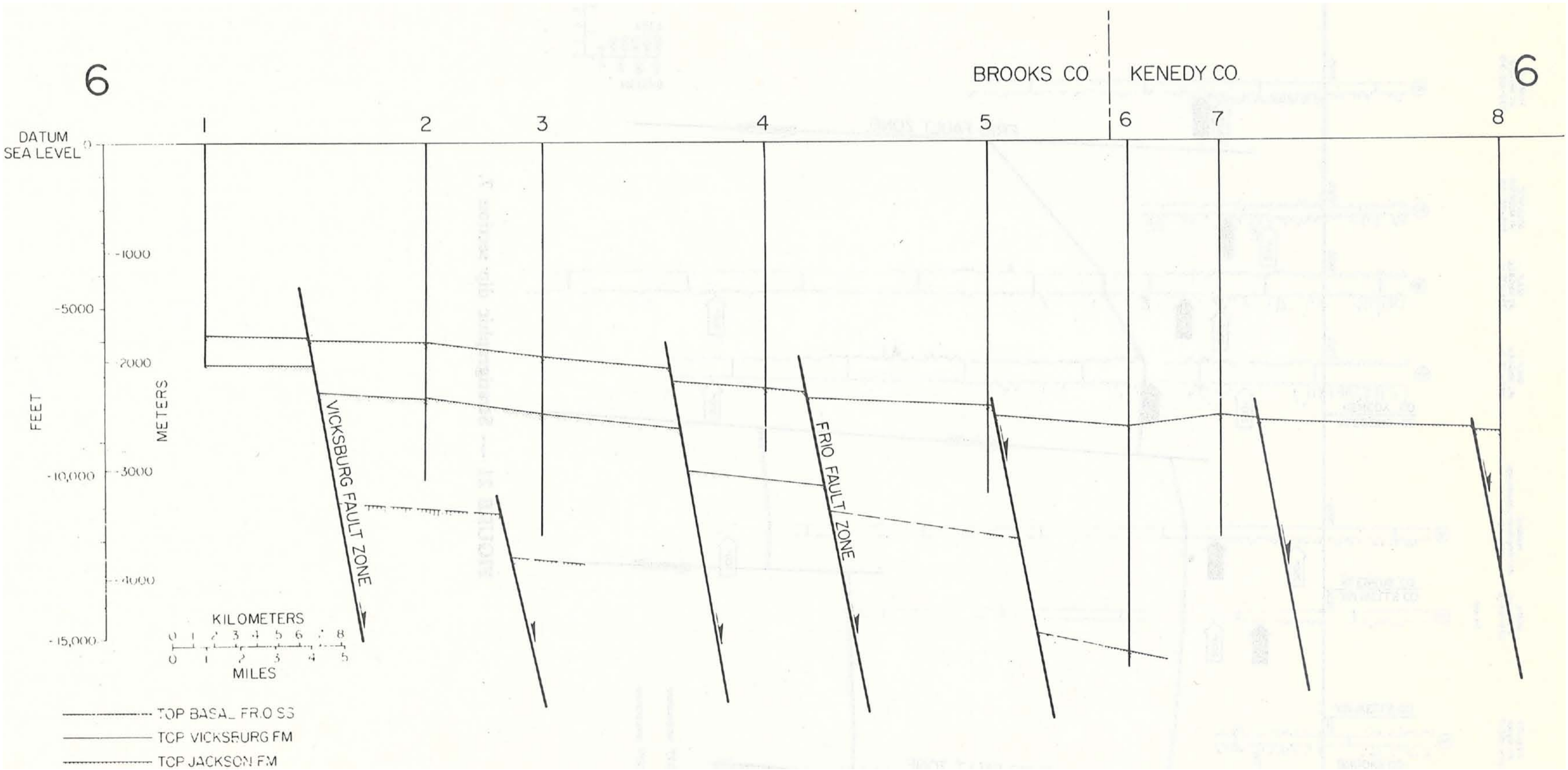

FIGURE 20 — Structure section 6.

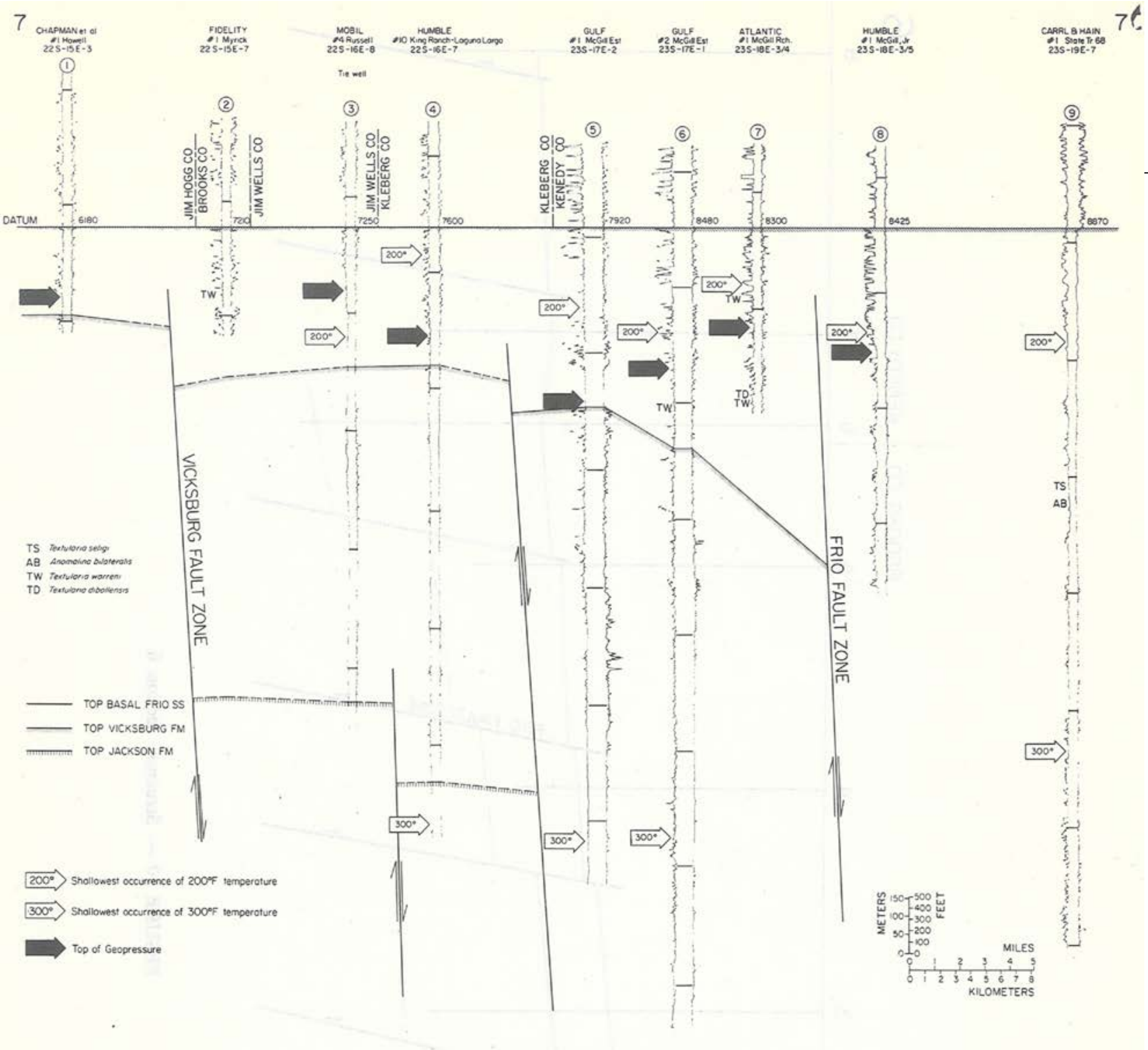

FIGURE 21 — Stratigraphic dip section 7.

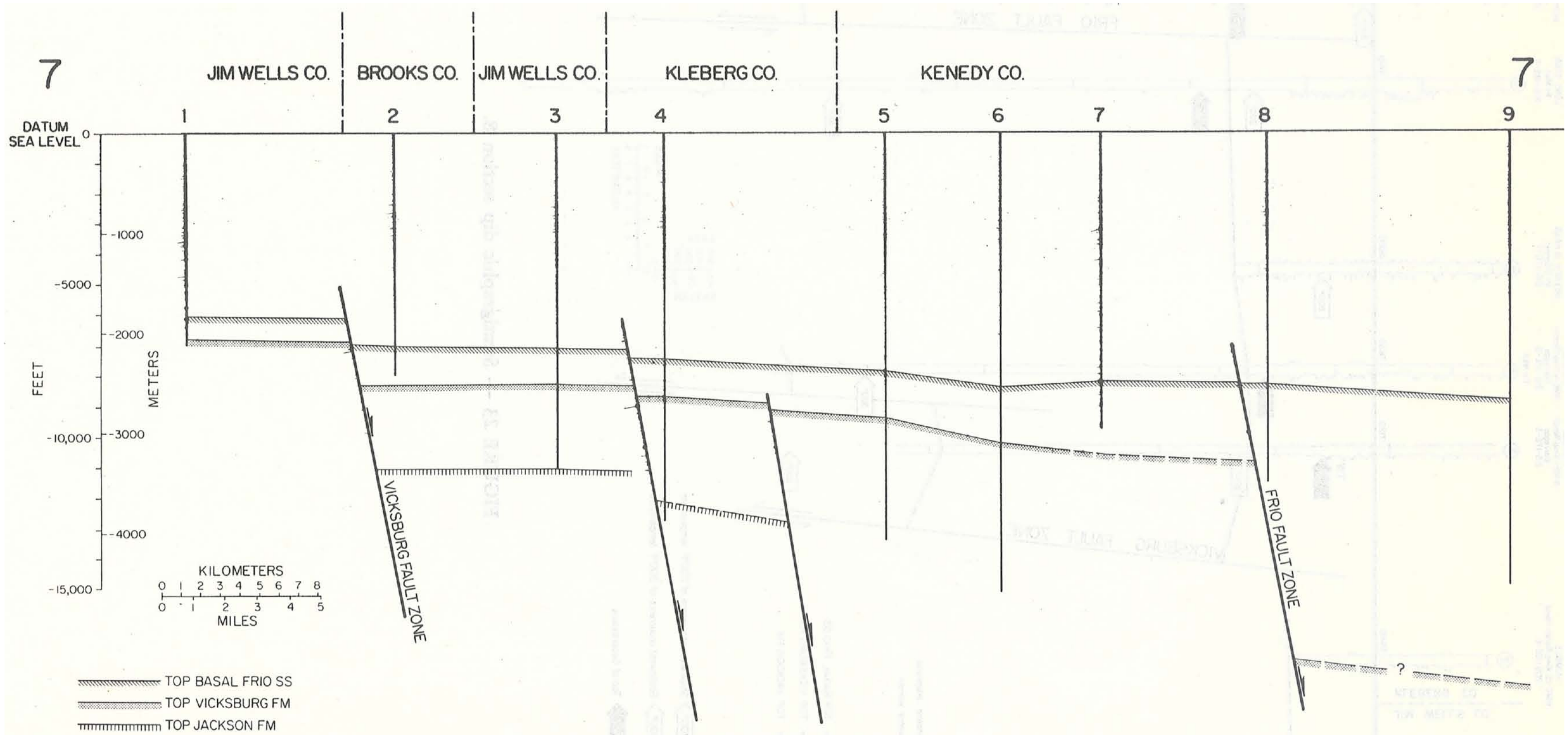

FIGURE 22 — Structure section 7.

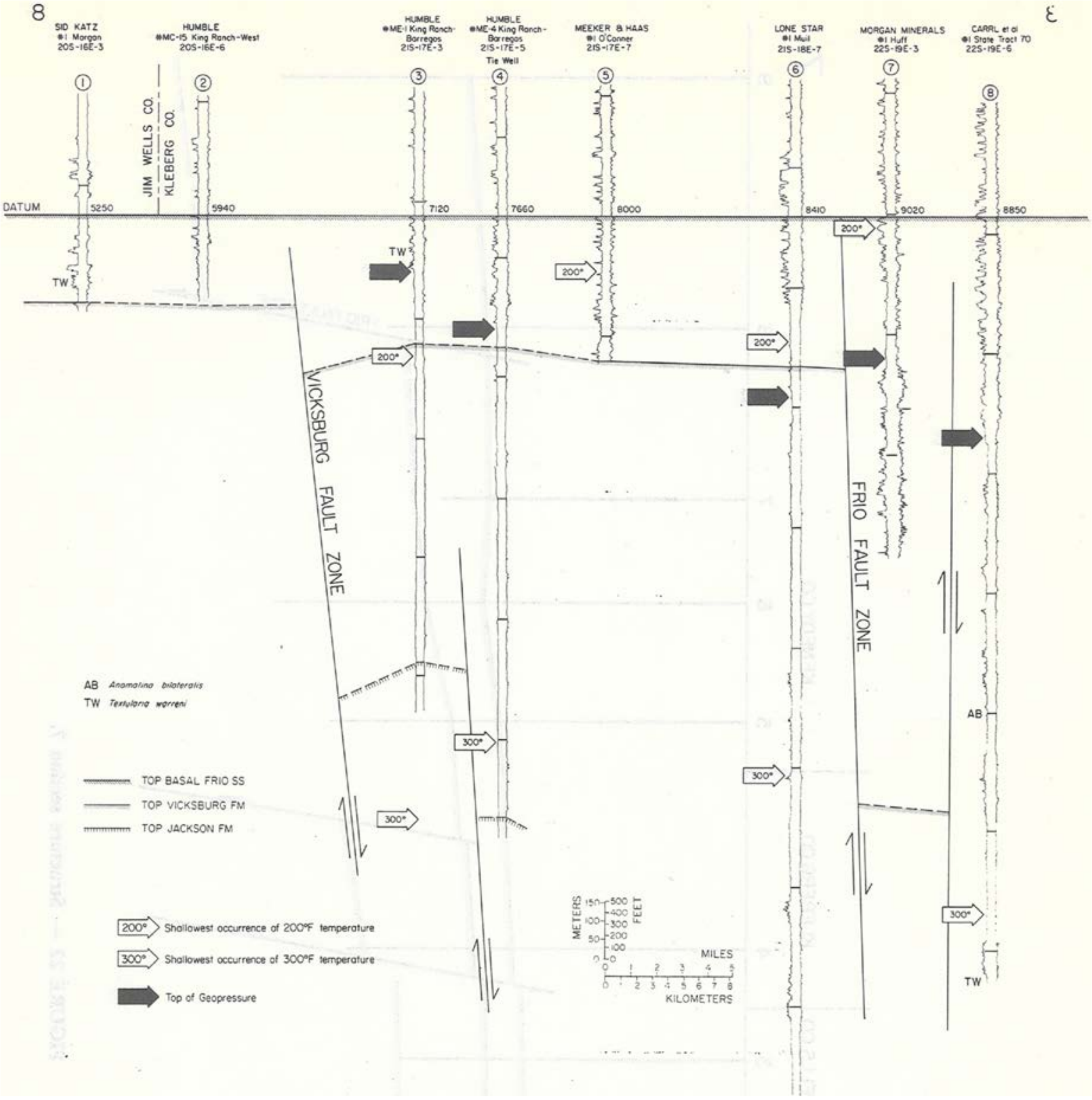

FIGURE 23 — Stratigraphic dip section 8.

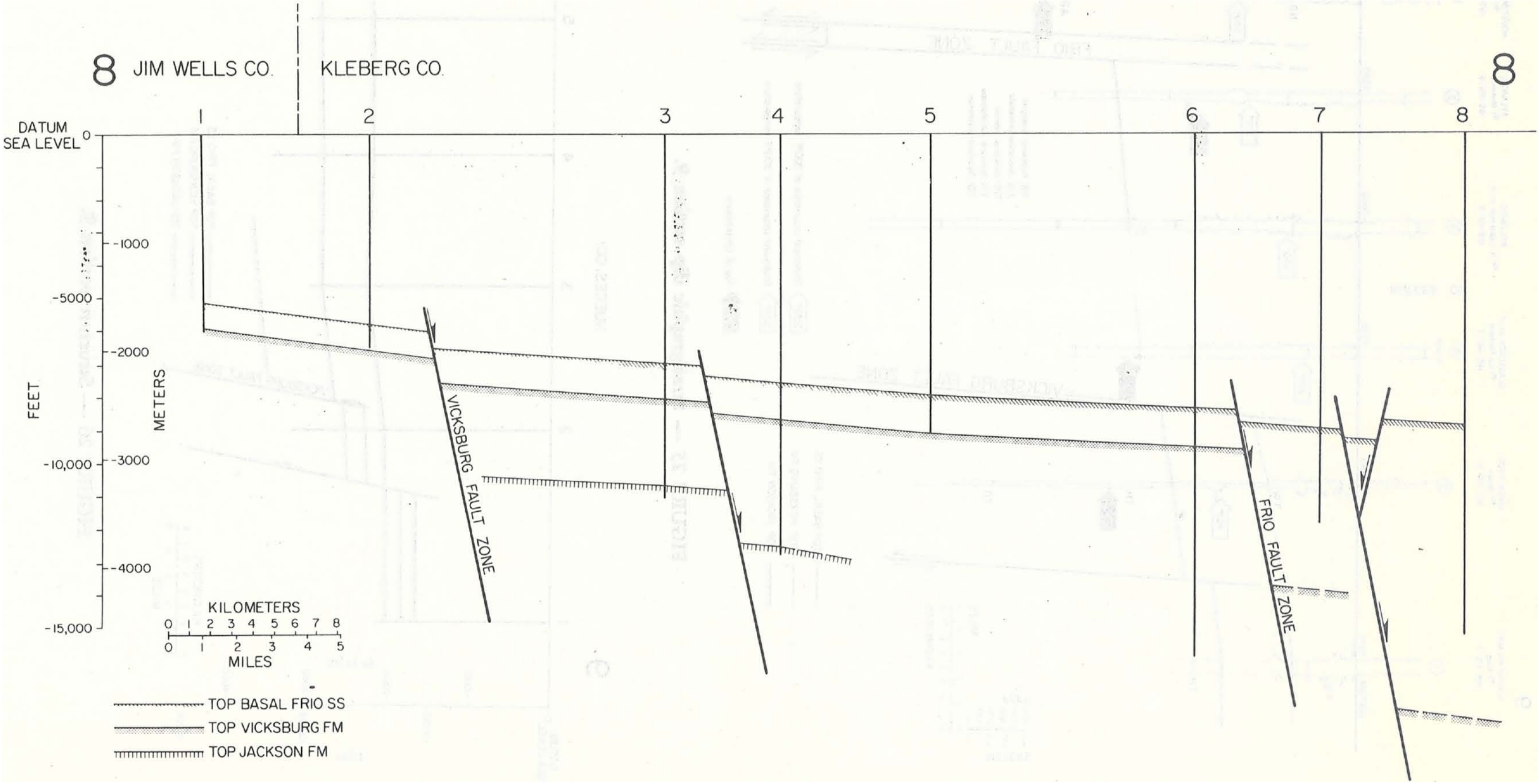

FIGURE 24 — Structure section 8.

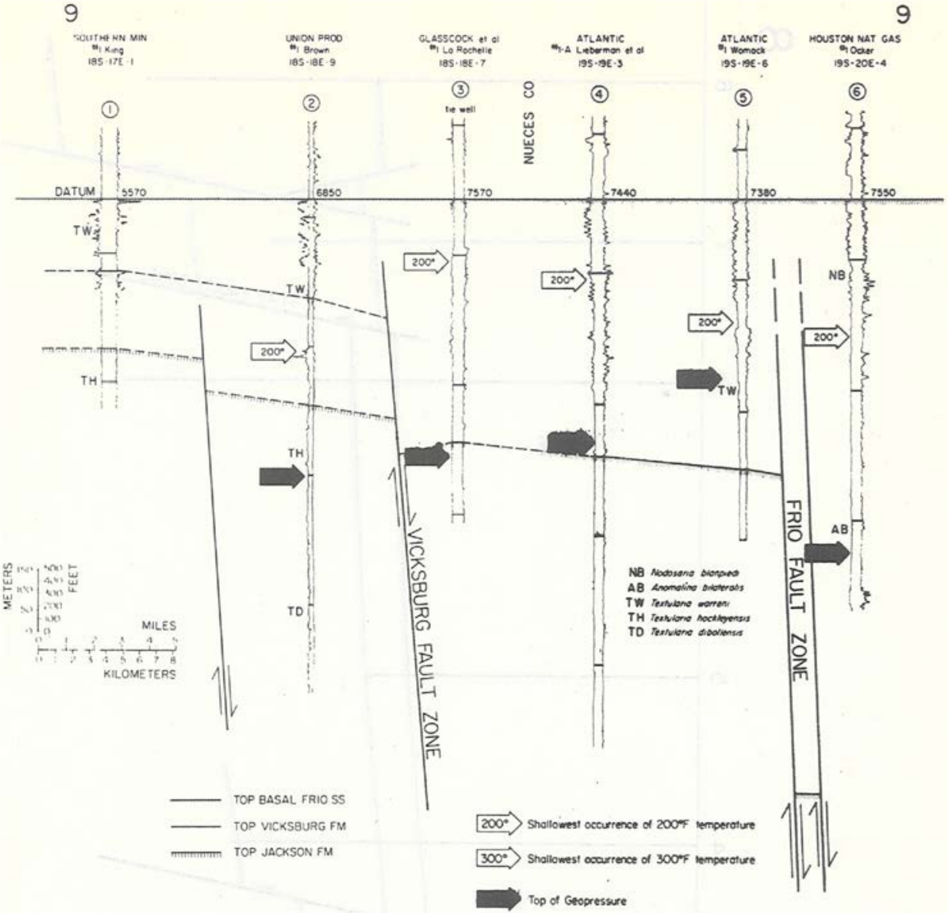

FIGURE 25 — Stratigraphic dip section 9.

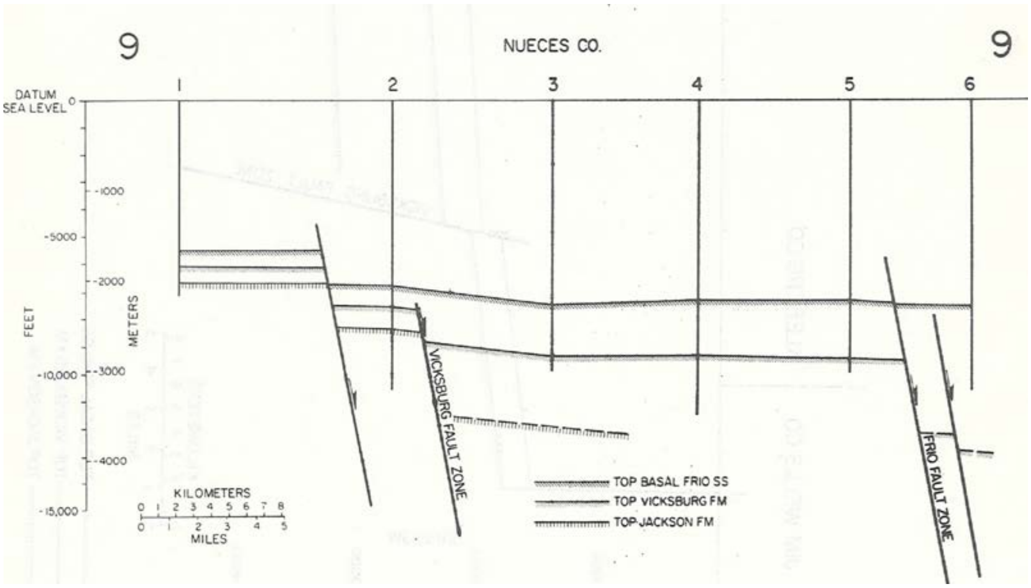

FIGURE 26 — Structure section 9.

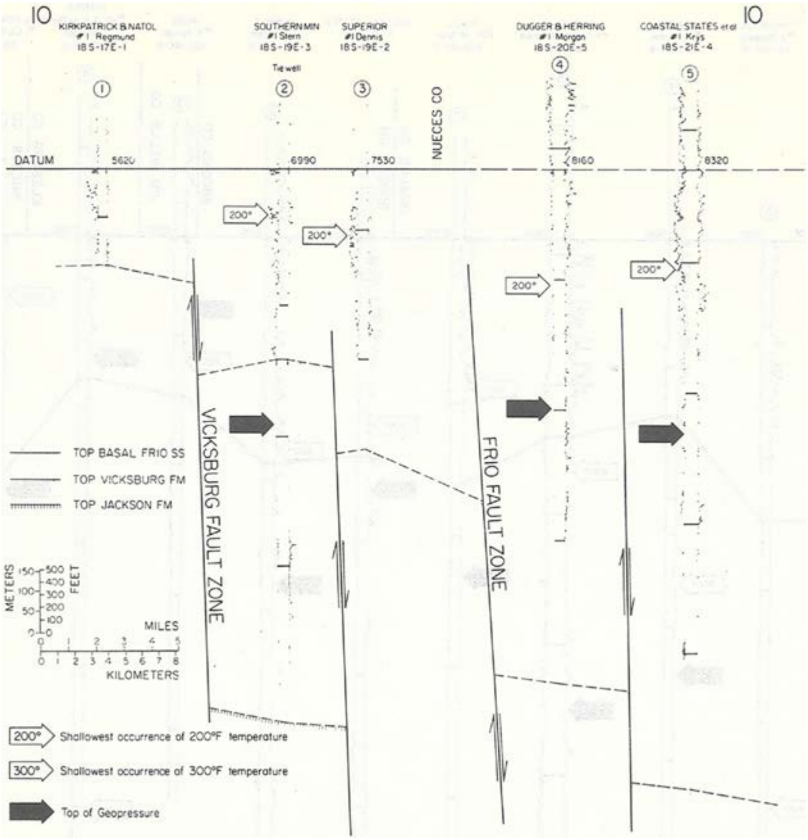

FIGURE 27 — Stratigraphic dip section 10.

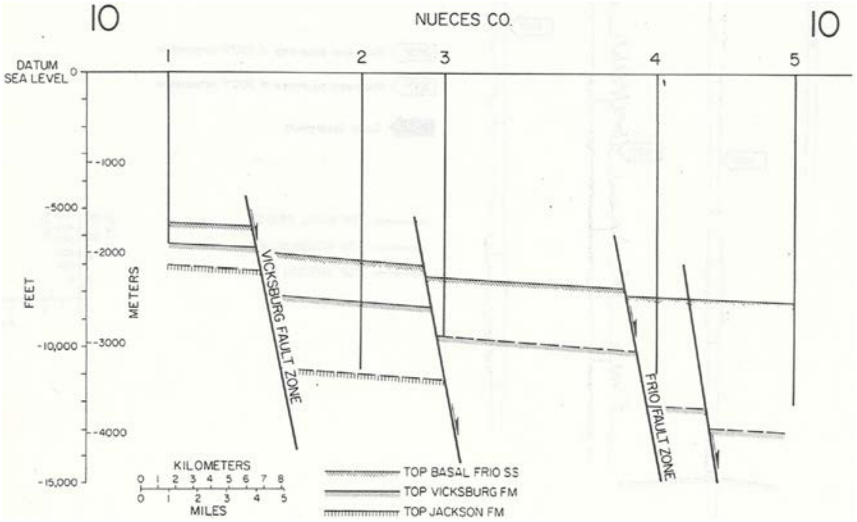

FIGURE 28 — Structure section 10.

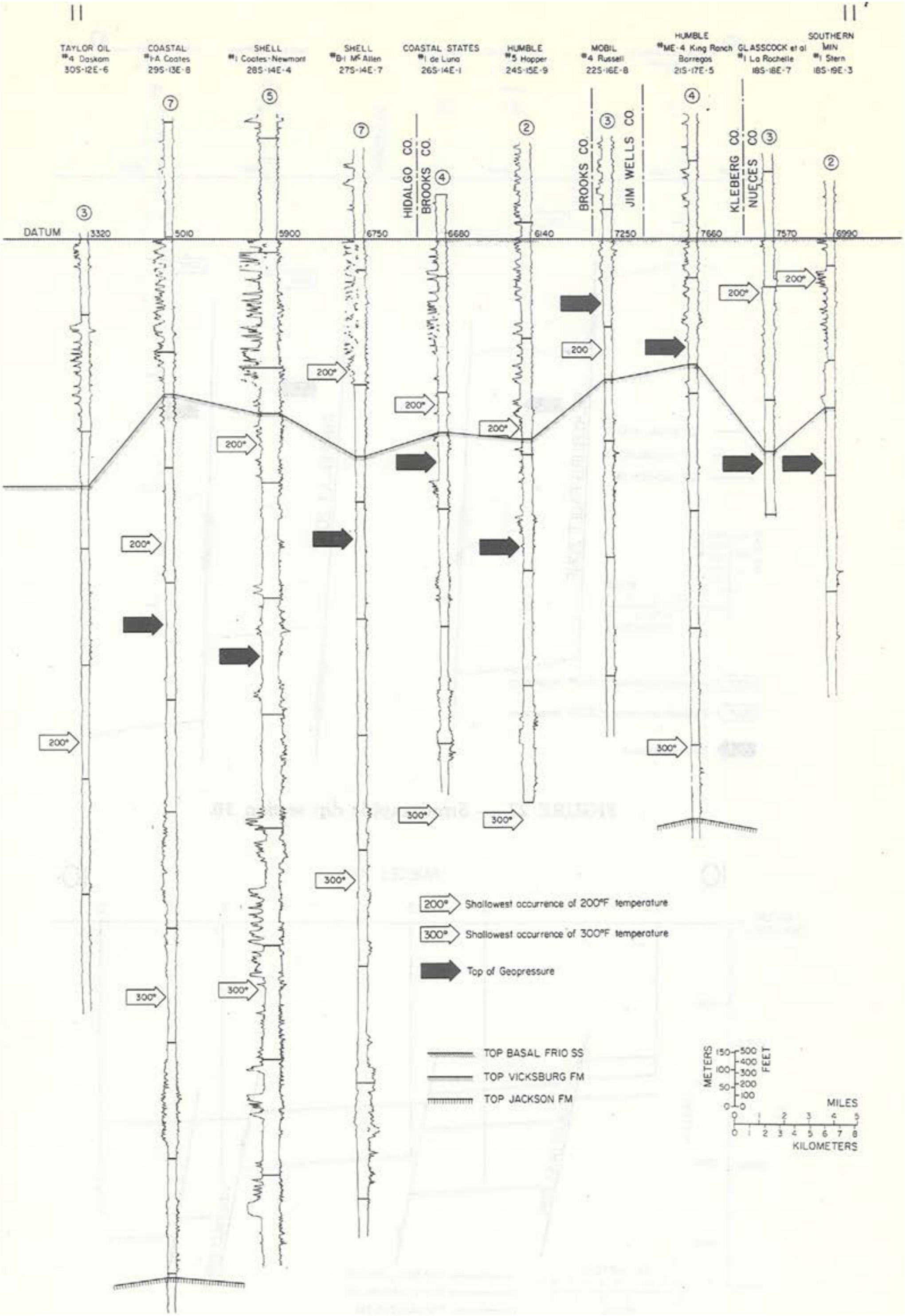

FIGURE 29 — Stratigraphic dip section 11.

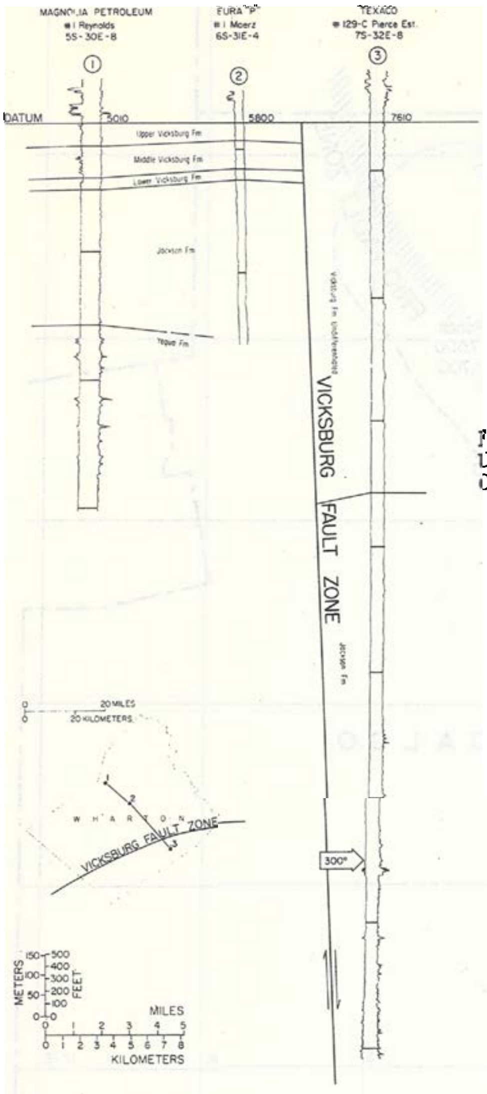

FIGURE 30 — Stratigraphic dip section in Wharton County, Upper Texas Gulf Coast. Section is modified from cross section C-C′ of Gregory (1966).

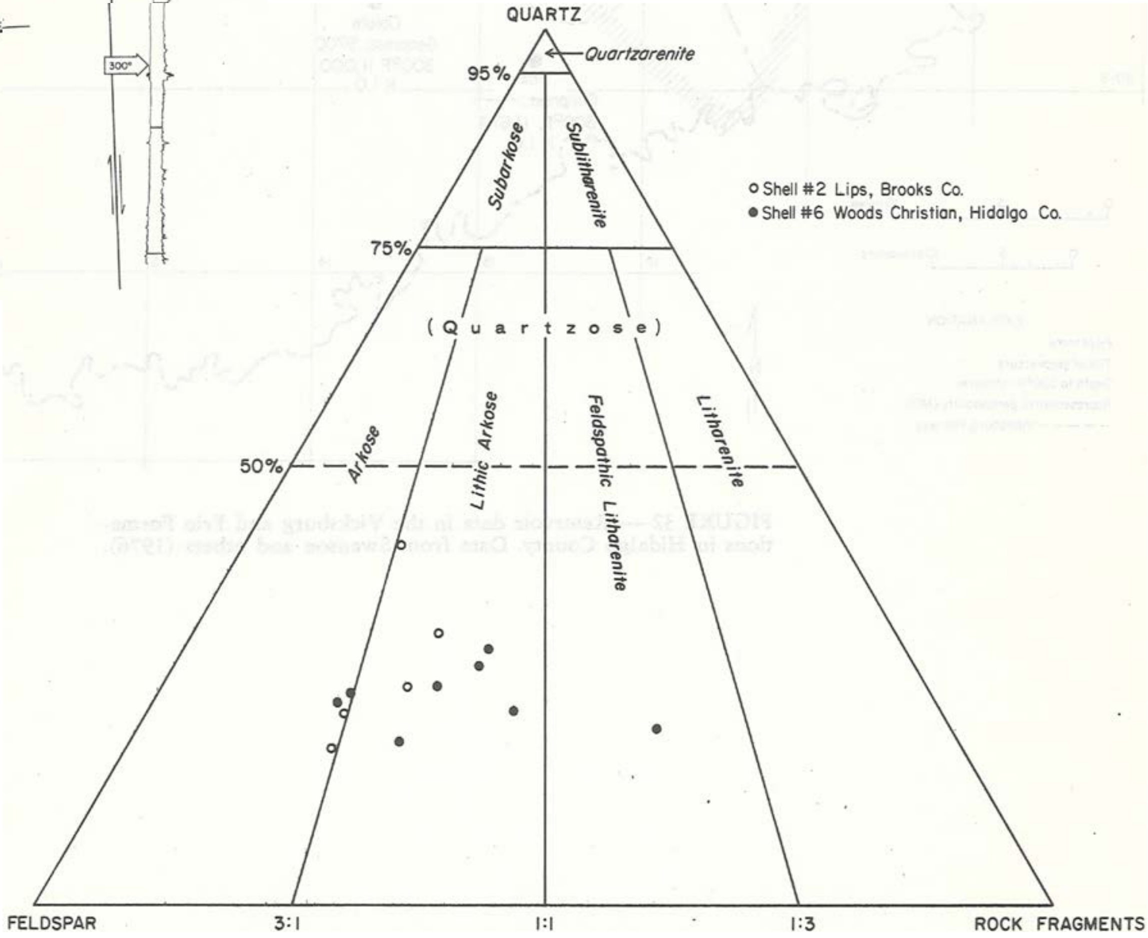

FIGURE 31 — Vicksburg sandstone composition. Sandstone classification after Folk (1968).

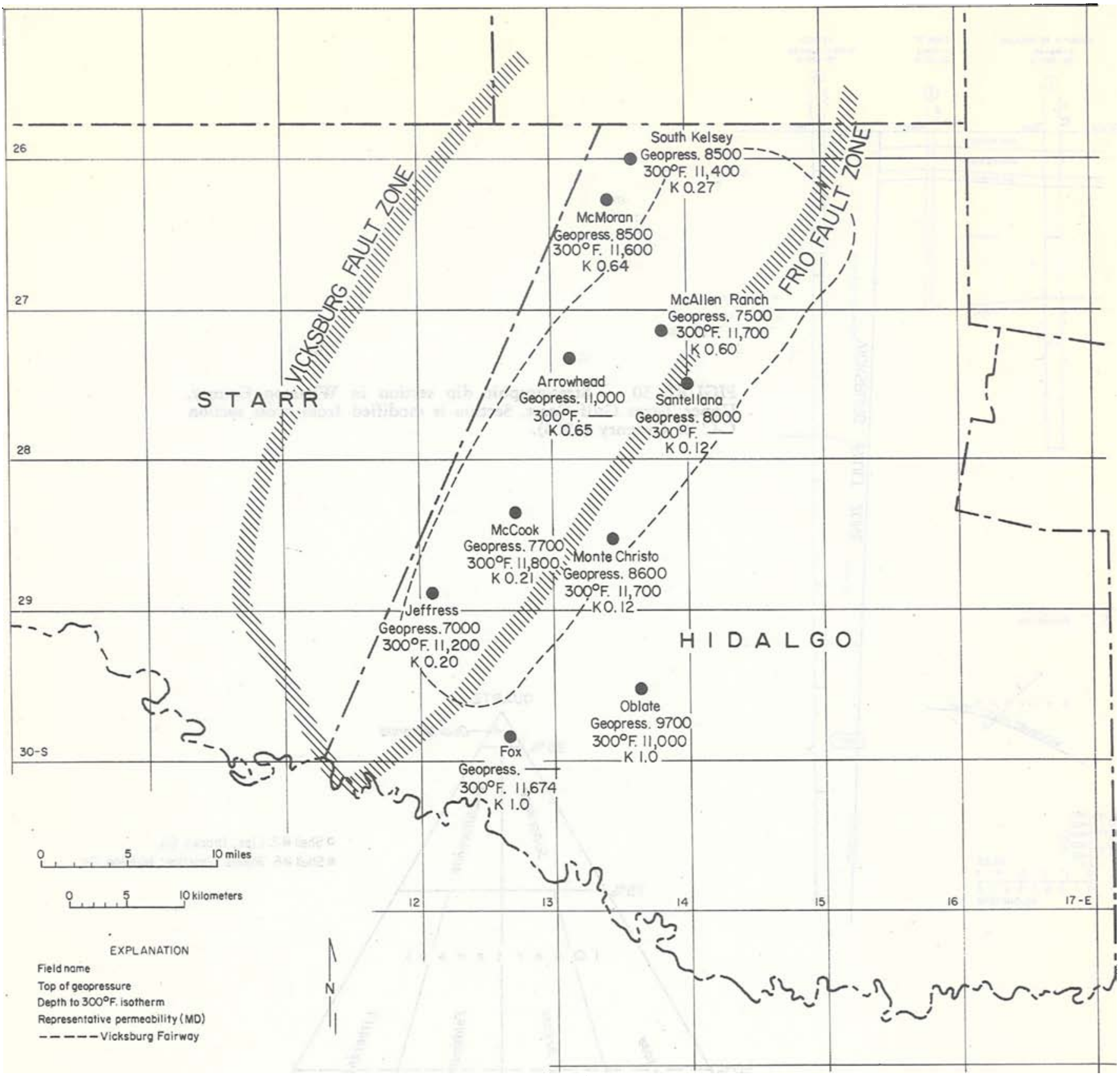

FIGURE 32 — Reservoir data in the Vicksburg and Frio Formations in Hidalgo County. Data from Swanson and others (1976).

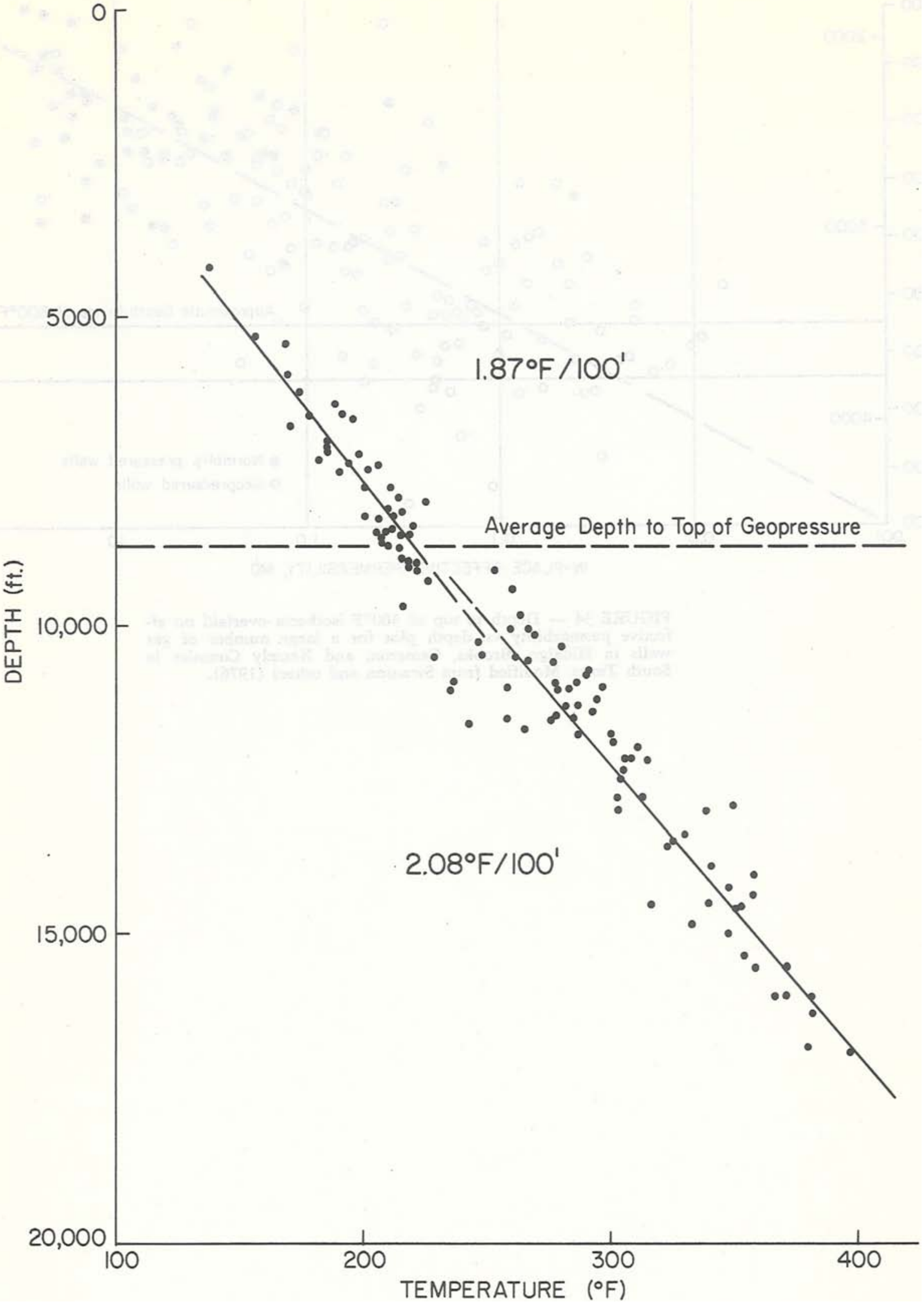

FIGURE 33 — Depth vs. temperature plot for wells from the Vicksburg Fairway.

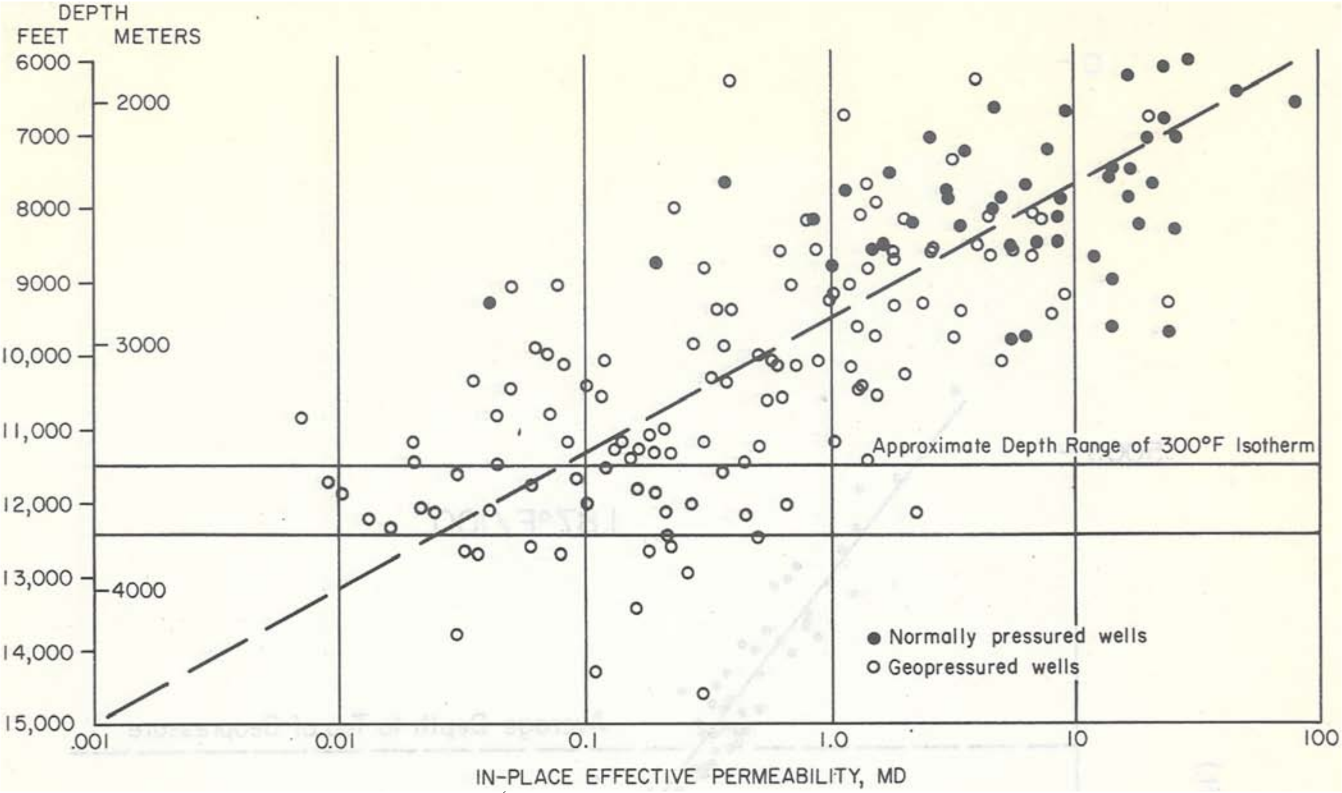

FIGURE 34 — Depth to top of 300°F isotherm overlaid on effective permeability vs. depth plot for a large number of gas wells in Hidalgo, Brooks, Cameron, and Kenedy Counties in South Texas. Modified from Swanson and others (1976).

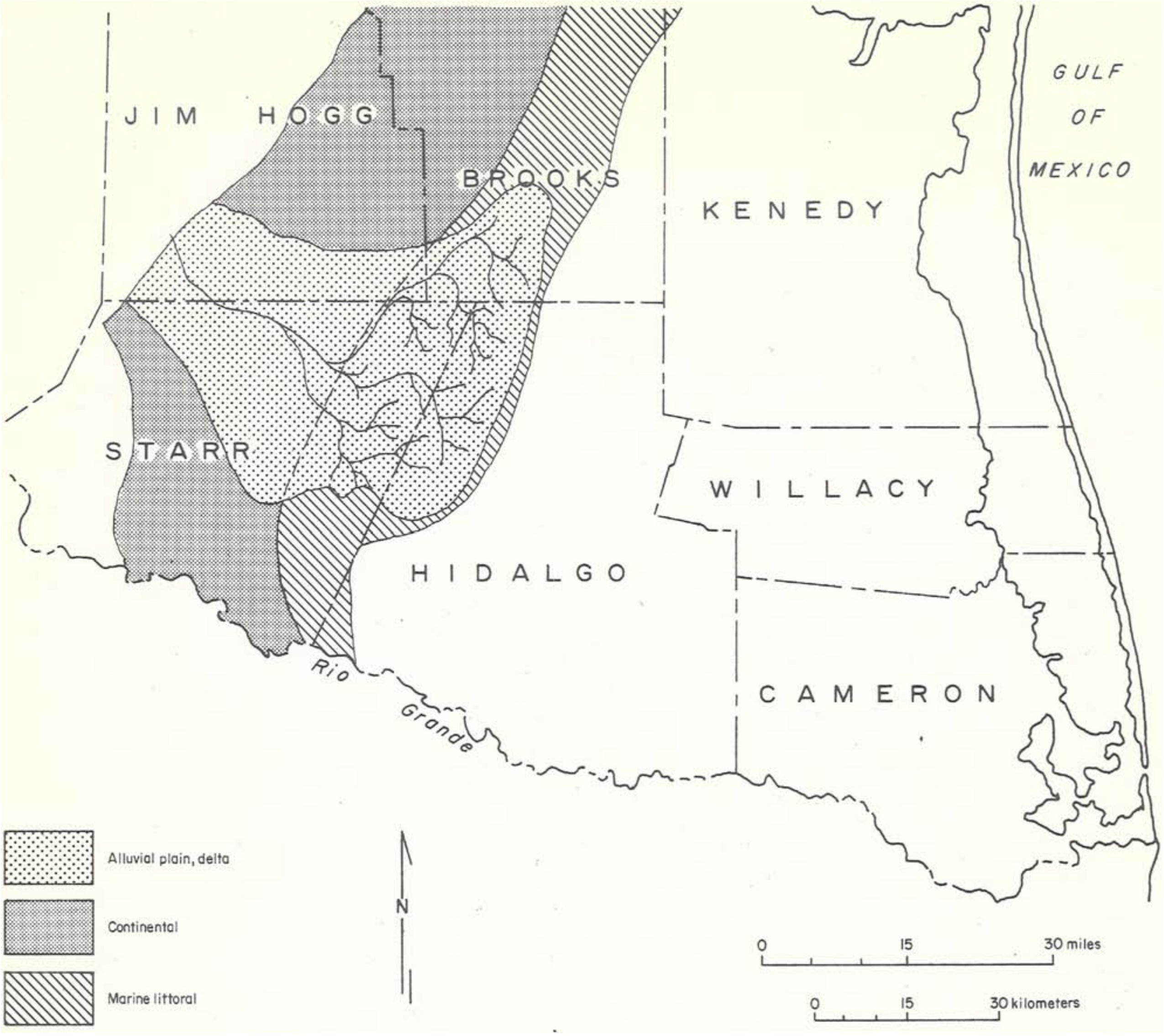

FIGURE 35 — Lower Vicksburg depositional environments. Modified from Ritch and Kozik (1971).