Report of Investigations No. 149

Controls on Porosity and Permeability of Hydrocarbon Reservoirs in Lower Tertiary Sandstones along the Texas Gulf Coast

Robert G. Loucks, Marianne M. Dodge,
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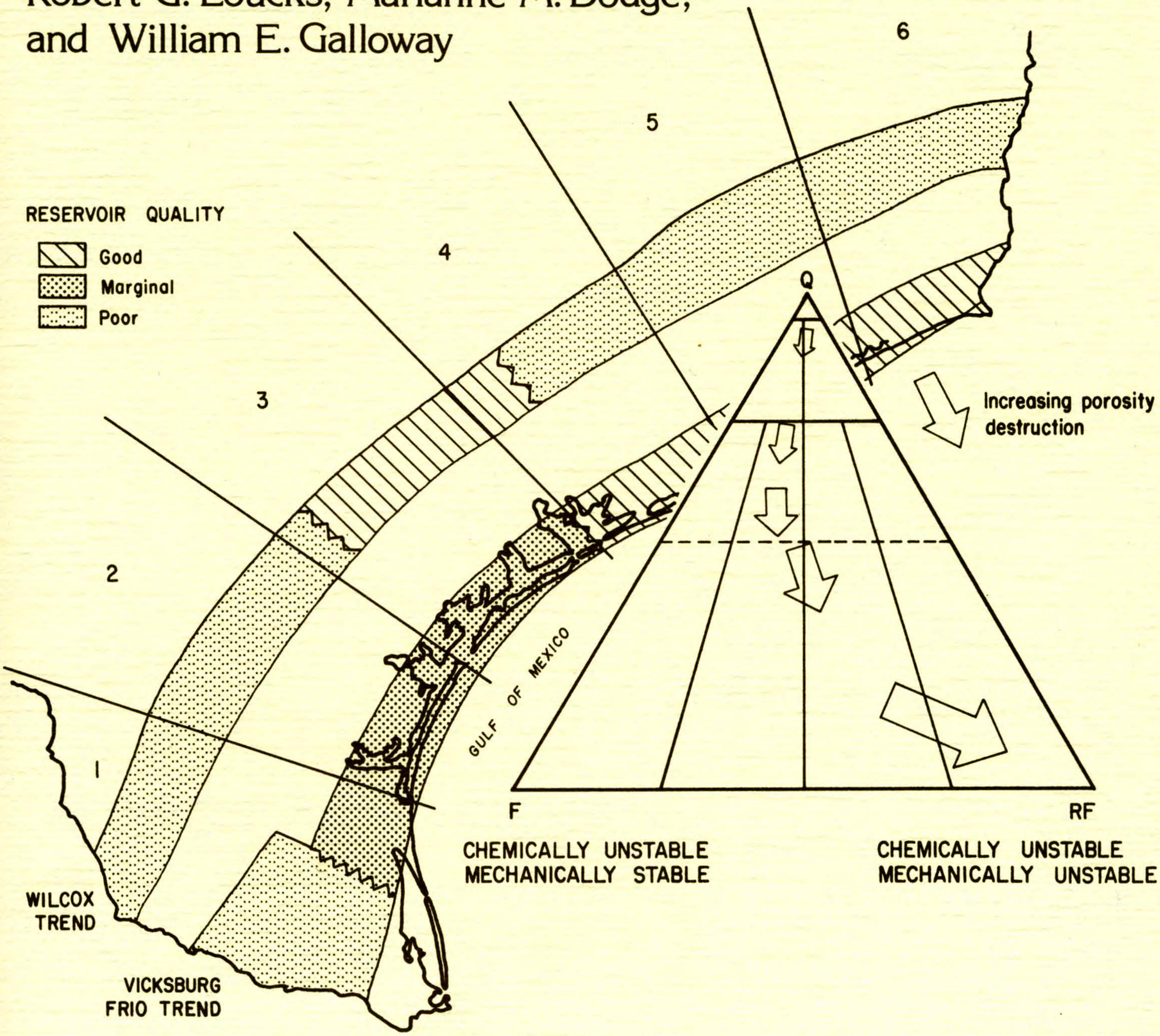

BUREAU OF ECONOMIC GEOLOGY
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ABSTRACT

Examination of porosity and permeability (reservoir quality) data, as determined by whole core, acoustic log, and petrographic analyses of lower Tertiary sandstones along the Texas Gulf Coast, made it possible to delineate areas most favorable for development of hydrocarbon reservoirs. Deep (about 3,350 m [11,000 ft] or greater) Wilcox sandstones exhibit no systematic regional reservoir-quality trends. Along the lower and parts of the middle and upper Texas Gulf Coast, deep Wilcox sandstones are tight, but in other parts of the middle and upper Texas Gulf Coast, porosity exists at depth. Yegua sandstone porosity is intermediate between that of the Vicksburg and Wilcox sandstones. Vicksburg sandstones have the poorest reservoir quality of all the deep sandstones. Frio sandstones improve systematically in reservoir quality from the lower to the upper Texas Gulf Coast owing to grain composition and geothermal gradient.

Wilcox sandstones are poorly to moderately sorted, fine-grained, quartzose lithic arkoses that become richer in quartz from the upper to the lower Texas Gulf Coast. Most rock fragments are metamorphic or volcanic. Yegua sandstones are moderately sorted, fine-grained, lithic arkoses to quartzose lithic arkoses. Volcanic and carbonate rock fragments are common along the lower Texas Gulf Coast, whereas volcanic and metamorphic rock fragments are common along the middle and the upper Texas Gulf Coast. Vicksburg sandstones are poorly sorted, fine-grained lithic arkoses. Rock fragments are mainly volcanic clasts containing lesser amounts of carbonate and minor amounts of metamorphic clasts. Frio sandstones range from poorly sorted, fine-grained, feldspathic litharenites to lithic arkoses along the lower Texas Gulf Coast to poorly sorted, fine-grained, quartzose lithic arkoses to subarkoses along the upper Texas Gulf Coast. Volcanic and carbonate rock fragments are common along the lower Texas Gulf Coast.

Although they vary in composition, lower Tertiary sandstones exhibit similar diagenetic sequences that may be idealized as follows:

Surface to shallow subsurface diagenesis (0 to 1,200 m± [0 to 4,000 ft±]) began with the formation of clay coats on framework grains, dissolution of feldspar, and replacement of feldspar by calcite. Minor amounts of kaolinite, feldspar overgrowths, and Fe-poor calcite were locally precipitated. Porosity was commonly reduced by compaction and cementation from an estimated original 40 percent to less than 30 percent.

Intermediate subsurface diagenesis (1,200 to 3,400 m± [4,000 to 11,000 ft±]) involved dissolution of early-formed carbonate cements and subsequent cementation first by quartz overgrowths and later by carbonate cement. Cementation may have reduced porosity to 10 percent or less, but this trend could have been reversed by later dissolution of feldspar grains, rock fragments, and possibly carbonate cements. Porosity was restored in some sandstones to more than 30 percent, but some porosity was later reduced by cementation by kaolinite, Fe-rich dolomite, and ankerite.

Deep subsurface diagenesis (>3,350 m± [>11,000 ft±]) was a continuation of late-stage Fe-rich and Fe-poor carbonate cement precipitation. Plagioclase was albitized during this stage.

Differences in intensity of diagenetic features that were related to changes in rock composition and geothermal gradient distinguish areas of high reservoir quality in the deep subsurface along the Texas Gulf Coast. Vicksburg and Frio reservoirs along the lower Texas Gulf Coast have extensive late-formed carbonate cements, whereas along the upper Texas Gulf Coast late-formed carbonate cements are minor. Wilcox reservoirs show no simple regional trend; quartz and carbonate are the dominant porosity-reducing cements, and their precipitation was governed by local chemical and physical conditions.

The deep Wilcox Group has good reservoir quality along the middle Texas Gulf Coast and possibly in adjacent areas, but reservoirs in other Wilcox areas are marginal. The deep Vicksburg Formation along the lower Texas Gulf Coast has low-quality reservoirs. Reservoir quality in the deep Frio Formation increases from very poor along the southernmost Texas Gulf Coast, to marginal along the middle Texas Gulf Coast, to good through the upper Texas Gulf Coast. The Frio Formation along the upper Texas Gulf Coast has the best deep-reservoir quality of units along the Texas Gulf Coast. Reservoir quality does not limit hydrocarbon production in shallow-buried Tertiary sandstones because porosity and permeability are generally adequate.

Keywords: diagenesis, geopressure, Gulf Coastal Plain, permeability, porosity, reservoir properties, reservoir rocks, sandstone, Tertiary, Texas

INTRODUCTION

General Statement

Porosity and permeability are major controls on reservoir quality and, hence, on production of hydrocarbons from sandstones. To be economically attractive, reservoirs must have porosity and permeability values that allow production of large volumes of fluids at a sufficiently rapid rate. Development, preservation, and distribution of porosity and permeability are controlled by physical and chemical processes that consolidate sand after burial. An understanding of these controls on reservoir quality delineates areas suitable for exploration and aids in the development of known fields.

The lower Tertiary section of the onshore Texas Gulf Coast is undergoing exploration for hydrocarbons. Abundant information is available on the structure, stratigraphy, and depositional systems of the area, but only in the last few years have data become available on diagenesis and reservoir quality (Lindquist, 1977; Loucks and others, 1977; Stanton, 1977; Boles, 1978; Loucks and others, 1979a, b; Richmann and others, 1980; Klass and others, 1981; Loucks and others, 1981; Franks and Forester, 1984; Kaiser, 1984; Land, 1984; Moncure and others, 1984). Loucks and others (1979b) were the first to investigate regional diagenesis and reservoir quality of lower Tertiary strata along the Texas Gulf Coast. The present report is a revision of that by Loucks and others (1979b). The previous study was initiated by the Bureau of Economic Geology and funded by the U.S. Department of Energy. Revision of this report was completed while the senior author was employed first by Cities Service Company and later by ARCO Oil and Gas Company.

Objectives and Scope of Study

The major objective of this regional investigation was to delineate the sandstone consolidation history of the onshore lower Tertiary stratigraphic section along the Texas Gulf Coast. We emphasized describing, quantifying, and interpreting the formation, preservation, and vertical and lateral distribution of sandstone porosity and permeability to develop a predictive capability for identifying favorable reservoir areas. The study addressed the Wilcox Group and the Yegua, Vicksburg, and Frio Formations (fig. 1), for which most onshore information was available.

Specific objectives were as follows:

1. To delineate the mineralogical composition of sandstones in each of the major lower Tertiary units of the onshore Texas Gulf Coast stratigraphic section and to establish regional compositional trends.

2. To synthesize a general sandstone diagenetic sequence for the entire lower Tertiary section.

3. To relate interval transit time from acoustic logs to sandstone diagenesis to broaden the interpretation of the diagenetic sequence and its effects on reservoir

SYSTEM		SERIES	GROUP/FORMATION
Quaternary		Holocene	Undifferentiated
		Pleistocene	Houston
Tertiary	Upper	Pliocene	Goliad
		Miocene	Fleming
		?—?	Anahuac
	Lower	Oligocene	Frio
			Vicksburg
		Eocene	Jackson
			Yegua
			Queen City
			Wilcox
			Midway

Figure 1. Stratigraphic chart of the Cenozoic Era, Texas Gulf Coast.

quality beyond those areas where core samples were available.

4. To generalize regional reservoir-quality trends.

Methodology

The onshore Texas Gulf Coast was divided into six geographic areas (fig. 2) to delineate regional trends. Areas 1 and 2 (lower Texas) include the Rio Grande Embayment; areas 3 and 4 (middle Texas) straddle the San Marcos Arch; and areas 5 and 6 (upper Texas) include the Houston Embayment.

The primary data base for the sandstone study consisted of whole cores and core plugs from 179 wells (figs. 2 and 3), core-plug porosity and permeability analyses from 253 wells (fig. 4), and acoustic logs from 86 wells (fig. 5). Lithology and primary structures of the cores were described, and environments of deposition were interpreted. From texturally mature, matrix-poor (<5 percent mud) sandstones, 1,961 thin sections were

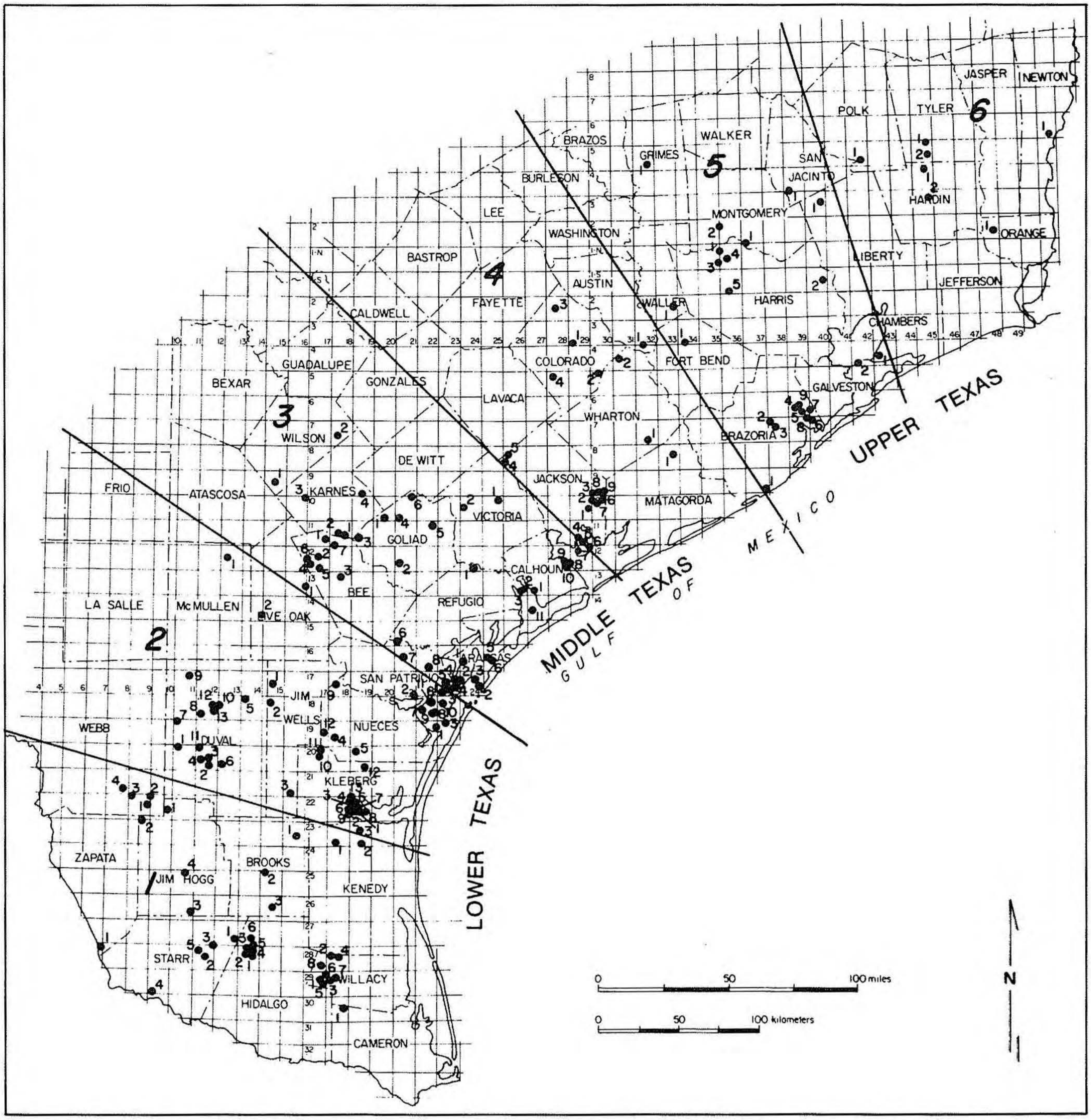


Figure 2. Area of investigation showing division of lower, middle, and upper Texas Gulf Coast areas and location of wells with whole core samples. Well names are listed in the appendix.

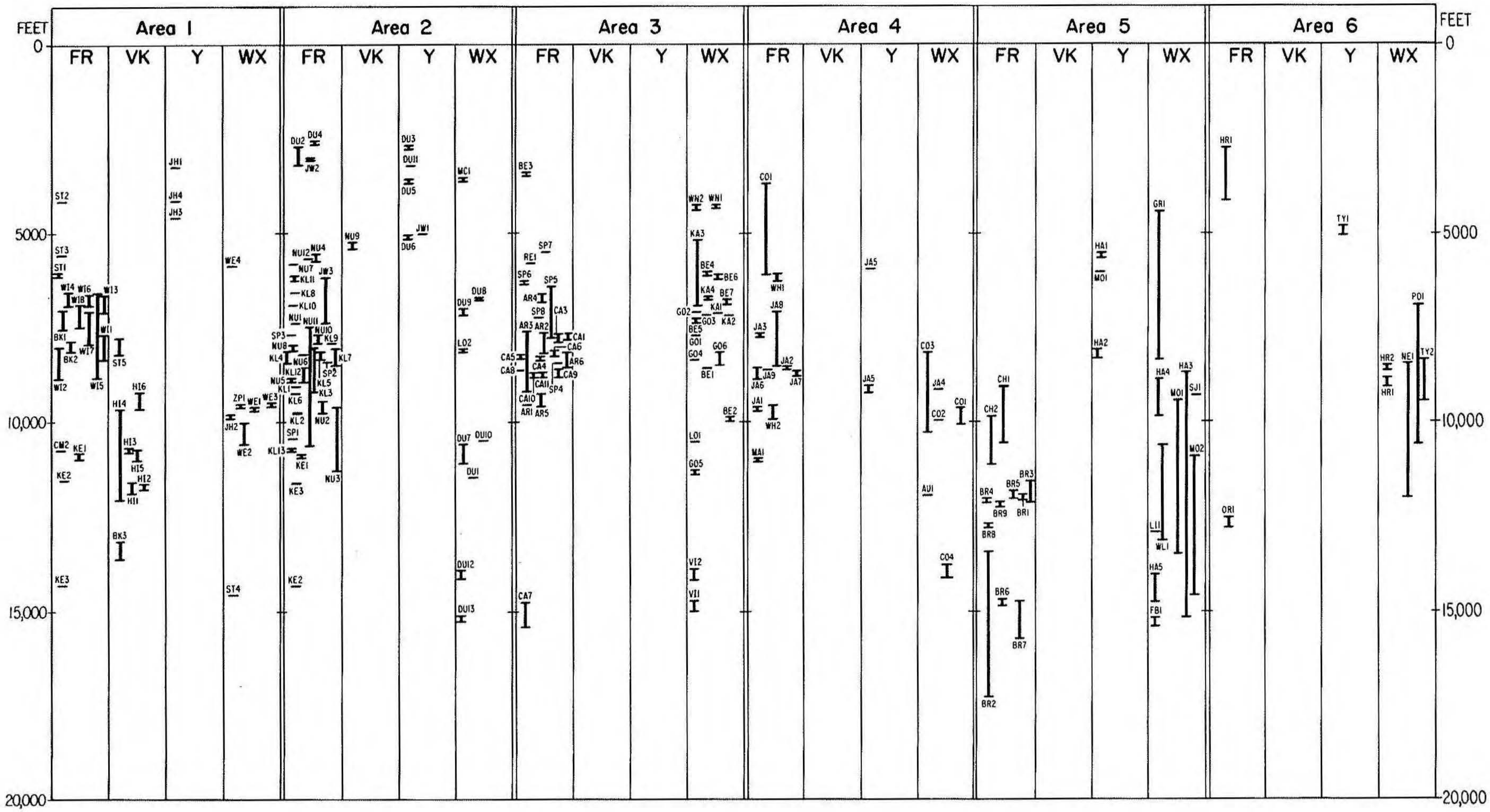


Figure 3. Distribution of whole core by area, unit, and depth. Units: FR-Frio, VK-Vicksburg, Y-Yegua, WX-Wilcox. Numbers refer to locations shown in figure 2. County names are abbreviated as follows:

AR-Aransas	DU-Duval	JH-Jim Hogg	MO-Montgomery	TY-Tyler
AU-Austin	FB-Fort Bend	JW-Jim Wells	NE-Newton	VI-Victoria
BE-Bee	FR-Frio	KA-Karnes	NU-Nueces	WL-Waller
BB-Brazoria	GO-Goliad	KE-Kenedy	OR-Orange	WE-Webb
BK-Brooks	GR-Grimes	KL-Kleberg	PO-Polk	WH-Wharton
CA-Calhoun	HR-Hardin	LI-Liberty	RE-Refugio	WI-Willacy
CM-Cameron	HA-Harris	LO-Live Oak	SJ-San Jacinto	WN-Wilson
CH-Chambers	HI-Hidalgo	MA-Matagorda	SP-San Patricio	ZP-Zapata
CO-Colorado	JA-Jackson	MC-McMullen	ST-Starr	

prepared at approximately 15-m (50-ft) intervals. Only matrix-poor sandstones were selected because the emphasis of the study was to delineate high-quality reservoirs. Of these thin sections, 540 were selected for detailed analysis, and 200 points per slide were counted for framework grain mineralogy, cement composition, and porosity type. Grain size, sorting, and packing proximity (a measurement of compaction as defined by Kahn, 1956) were also determined. All thin sections were treated with amaranth solution to stain calcium-bearing plagioclase pink and with sodium cobaltinitrite to stain potassium feldspar yellow, using a technique adapted from Laniz and others (1964). Selected thin sections containing carbonate cements were treated with alizarin red-S to stain nonferroan calcite red and with potassium ferricyanide to stain ankerite, ferroan calcite, and ferroan dolomite blue, using the method of Lindholm and Finkelman (1972). Selected samples were then analyzed with the electron microprobe for carbonate composition, with the scanning electron

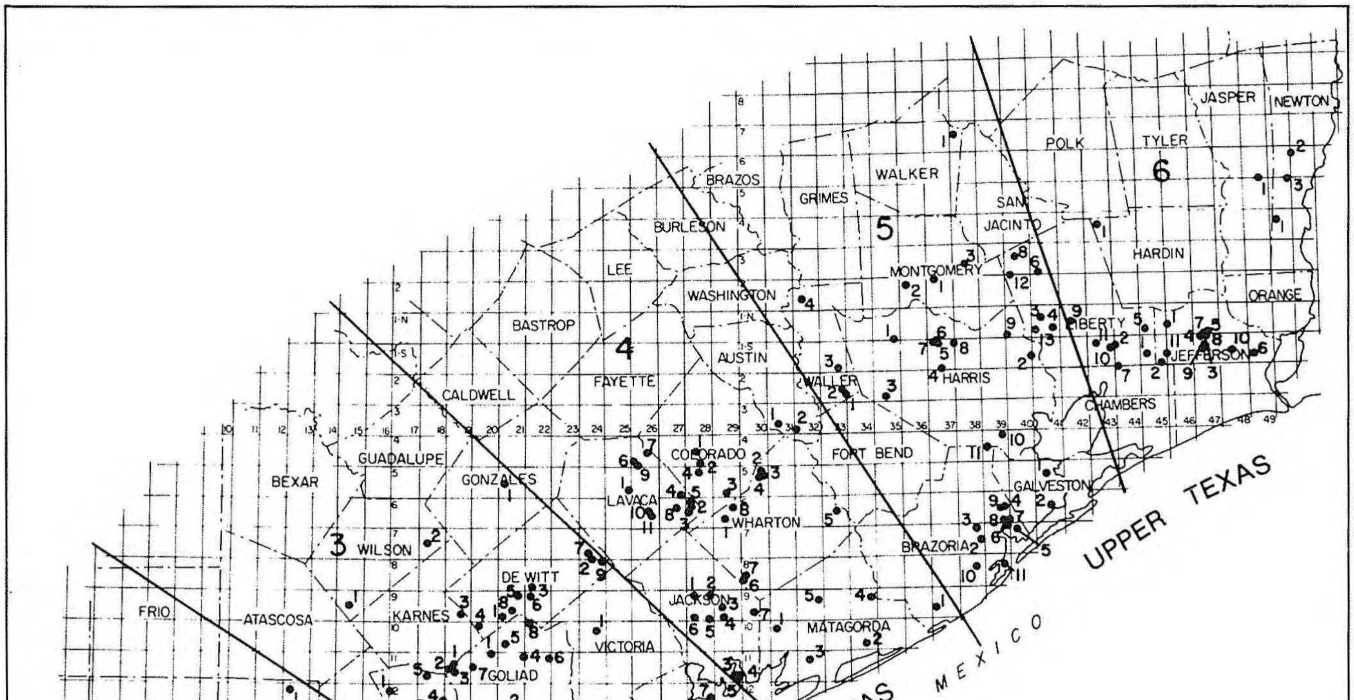


Figure 4. Location of wells with porosity and permeability data. Well names are listed in the appendix.

microscope for mineral composition, textural relationships, and diagenetic products, and with the X-ray diffractometer for mineral composition.

Porosity and permeability data were obtained from both whole core and sidewall core samples (fig. 4). The data base comprised 156 wells with whole cores (7,564 data points) and 97 wells with sidewall cores (3,559 data points). For each data point the corresponding in situ pore fluid pressure was calculated from mud weight and depth.

Interval transit time for sands and sandstones was calculated from acoustic logs at 33- to 66-m (100- to 200-ft) depth intervals (fig. 5). Graphs of interval transit time versus depth were prepared for each well. Interval transit times were also grouped by area and by trend (fig. 5). The updip trend is composed of wells aligned along a trend parallel to the coast that were drilled to the Wilcox Group; the downdip trend is composed of wells drilled to the Vicksburg and Frio Formations.

Figure 5. Location of wells with acoustic logs. Well names are listed in the appendix.

REGIONAL GEOLOGY

The onshore lower Tertiary section along the Gulf Coast is composed of terrigenous clastic wedges, which thicken downdip toward the Gulf of Mexico. Rapid loading of sand on water-saturated prodelta and continental slope muds resulted in contemporaneous growth faulting and subsequent vertical accumulation of large quantities of deltaic and strandplain sands and muds (fig. 6). Equivalent sediments updip remained in the relatively shallow subsurface, whereas sediments downdip were subjected to more rapid subsidence and deeper burial. Continual movement along growth faults isolated thick wedges of sand and mud, and trapped connate fluids created an overpressured zone (fluid pressure greater than hydrostatic pressure of 0.465 psi/ft). Flowage and diapirism of deeper Jurassic salt were caused by differential loading, which created linear trends of salt domes (fig. 7).

Several distinct clastic wedges have been identified along the Gulf Coast (fig. 6), of which only the Wilcox Group and the Vicksburg and Frio Formations contain deep sandstone reservoirs. The Wilcox Group was divided into three units by Bebout and others (1982) as a modification of the work of Fisher and McGowen (1969) and Fisher and others (1969). The lower Wilcox unit was deposited as a high-constructive deltaic system and was overlain by a transgressive, shaly middle Wilcox unit (Fisher and McGowen, 1969); the upper Wilcox unit was deposited as a high-destructive deltaic system. Sandstone content in the Wilcox Group is high everywhere except in the area farthest downdip, where growth faults are abundant and the proportion of shale increases markedly (Bebout and others, 1978a).

Yegua sandstones were deposited in two principal depositional systems (Fisher and others, 1969). Along the upper Texas Coastal Plain, an extensive fluvial-dominated delta system prograded from near present outcrop as far basinward as Houston, and locally beyond the underlying Wilcox shelf platform. Laterally, along the middle and lower Texas Coastal Plain, the Yegua Formation consists dominantly of strike-aligned barrier bar and strandplain sandstone facies of the wave-dominated shore-zone system. These coastal

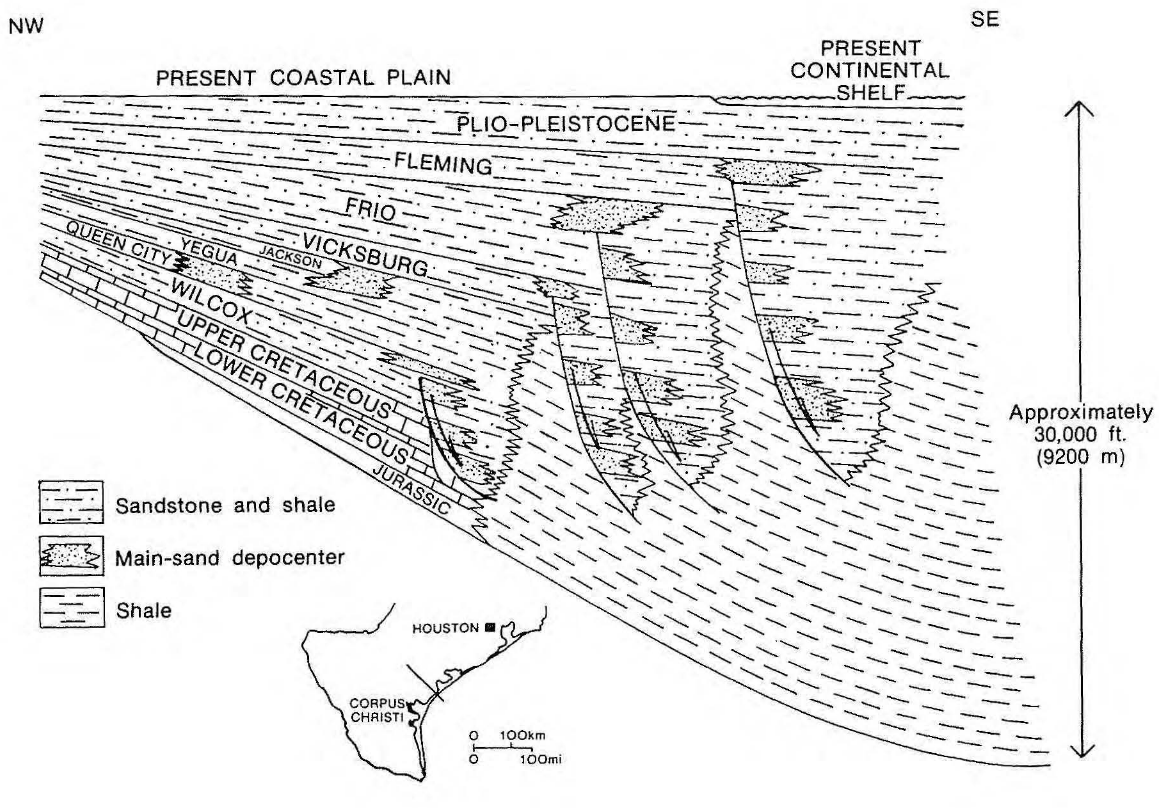


Figure 6. Depositional style of Cenozoic strata along the Texas Gulf Coast (Bebout and others, 1982).

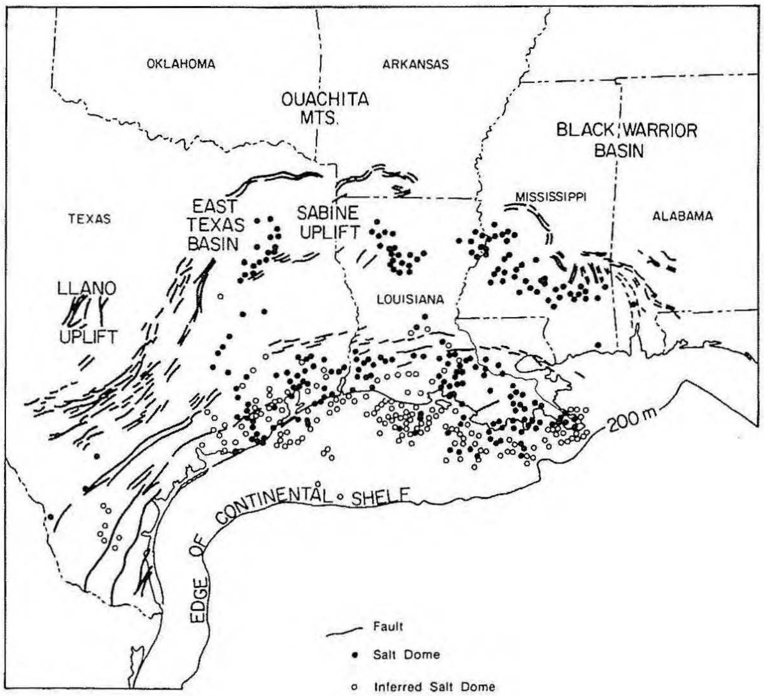


Figure 7. Salt domes and major faults of the Gulf of Mexico region (from Jones, 1975).

sands grade updip into lagoonal and coastal plain mudstones and downdip into shelf facies.

The Vicksburg Formation grades from a sandstone-rich section along the lower Texas Gulf Coast to a sandstone-poor section along the middle and upper Texas Gulf Coast (Loucks, 1978). Vicksburg sandstones along the lower Texas Gulf Coast were deposited in a large, high-constructive deltaic system having a strong dip orientation and poor lateral continuity (Ritch and Kozik, 1971; Loucks, 1978; Han, 1981).

Lobate sandstone bodies in the Frio Formation along the lower and upper Texas Gulf Coast are interpreted as high-constructive lobate deltaic deposits, and elongate, strike-aligned sandstones along the middle Texas Gulf Coast constitute a strandplain-barrier bar system (Boyd and Dyer, 1964; Galloway and others, 1982). Vertically, the Frio Formation has been divided into three parts. Thick sand units deposited in deltaic and barrier bar environments generally occur from 1,800 to 2,700 m (6,000 to 9,000 ft) below present sea level and shift gulfward in successively younger units. The section updip from the main sand depocenter is a fluvial sequence of thin, discontinuous sandstones interspersed with thick shales. The downdip section is dominantly shale deposited in prodelta and shelf environments (Bebout and others, 1978b).

RESERVOIR QUALITY

Sources of Data

Core analysis data from 253 wells were examined in this study (fig. 4). Short of production tests, analyzing cores from wells throughout the study area is the best way to determine reservoir quality. The principal drawback of core analysis is that porosity and permeability measurements are made at atmospheric pressures and temperatures and thus do not represent true in situ permeability to the original pore fluids. Values are commonly an order of magnitude too high. Of these 253 wells, only the 156 wells for which analyses

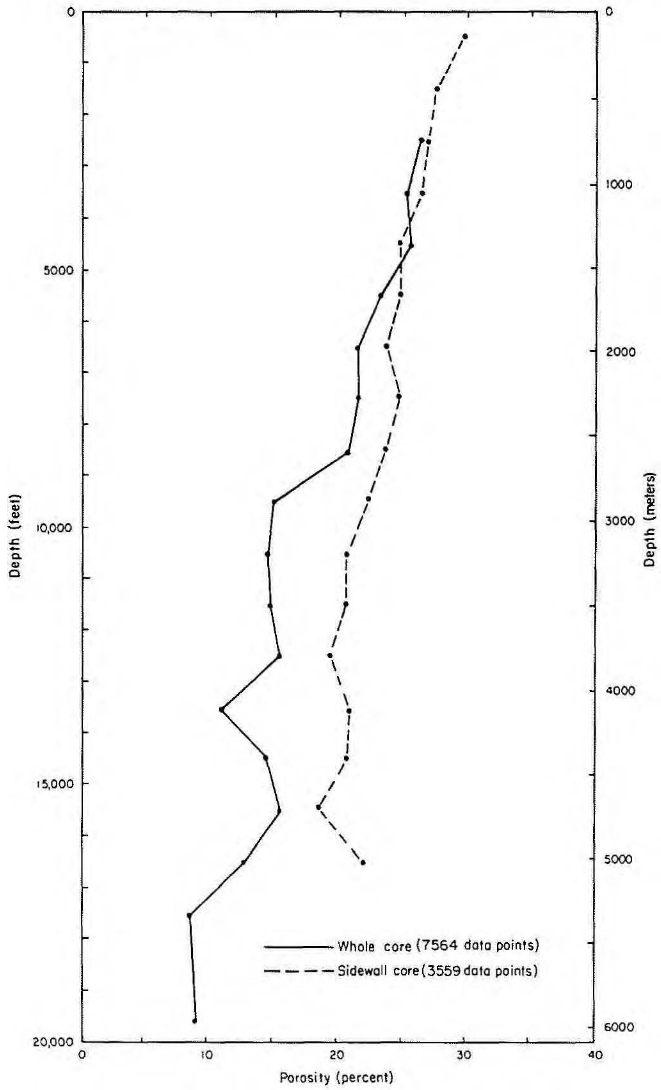


Figure 8. Mean porosity versus depth from both whole core and sidewall core for lower Tertiary sandstones along the Texas Gulf Coast. Data were averaged over 1,000-ft intervals and plotted at the midpoints of those intervals.

from whole cores were available were used to determine regional porosity and permeability trends along the Texas Gulf Coast. Core plugs, taken by drilling a cylinder into a whole core, do not disturb the fabric of consolidated sediments. In contrast, a sidewall core is taken by blasting a small hollow metal cylinder horizontally into the side of the borehole. The explosive impact of the cylinder into the rock often fractures the sample. Thin sections made from a sidewall core commonly have many fine fractures. A sidewall core, therefore, tends to give a much higher porosity value than a core plug. Below a depth of 1,500 m (5,000 ft), average porosity values from sidewall cores deviate significantly and systematically from those of whole cores because the sediments have begun to lithify and fracturing occurred when sidewall cores were taken. This error increases with depth (fig. 8), affecting both permeability and porosity readings. Therefore, only porosity and permeability values from whole core analyses were used in this investigation.

Porosity and Permeability Trends

A variety of graphical displays were used to show the patterns of reservoir quality along the Texas Gulf Coast.

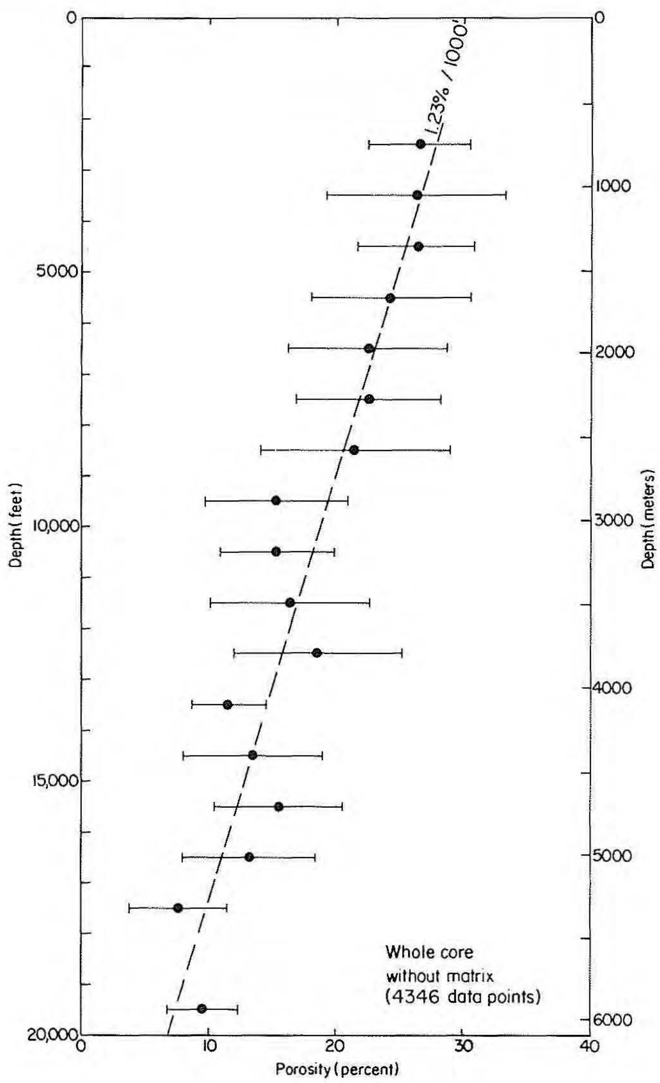


Figure 9. Mean sandstone porosity versus depth from whole core analyses for lower Tertiary units along the Texas Gulf Coast. Only values from sandstones without matrix were used. Data were averaged over 1,000-ft intervals and plotted at the midpoints of those intervals. Brackets indicate standard deviation.

Because of the large number of variables influencing these patterns, best-fit trend lines were drawn by visual inspection, and correlation coefficients were not calculated. Original data are on file at the Bureau of Economic Geology.

Sandstone porosity and permeability generally decrease with depth through compaction and cementation, although this trend may be reversed by dissolution of grains and cements (Schmidt and others, 1977). Porosity and permeability generally decrease with depth in the Texas Gulf Coast section (figs. 9, 10, and 11), but a wide range of values can be found at any given depth (figs. 10 and 11), indicating the complexities involved in understanding controls on reservoir quality. Mud matrix decreases reservoir quality at all depths (fig. 12). A comparison of permeability and porosity data for the Wilcox Group and the Vicksburg and Frio Formations showed a general relation between permeability and porosity (fig. 13): permeability increases as porosity increases.

Porosity by Formation and Area

By superimposing plots of porosity versus depth for each formation, differences in reservoir quality among

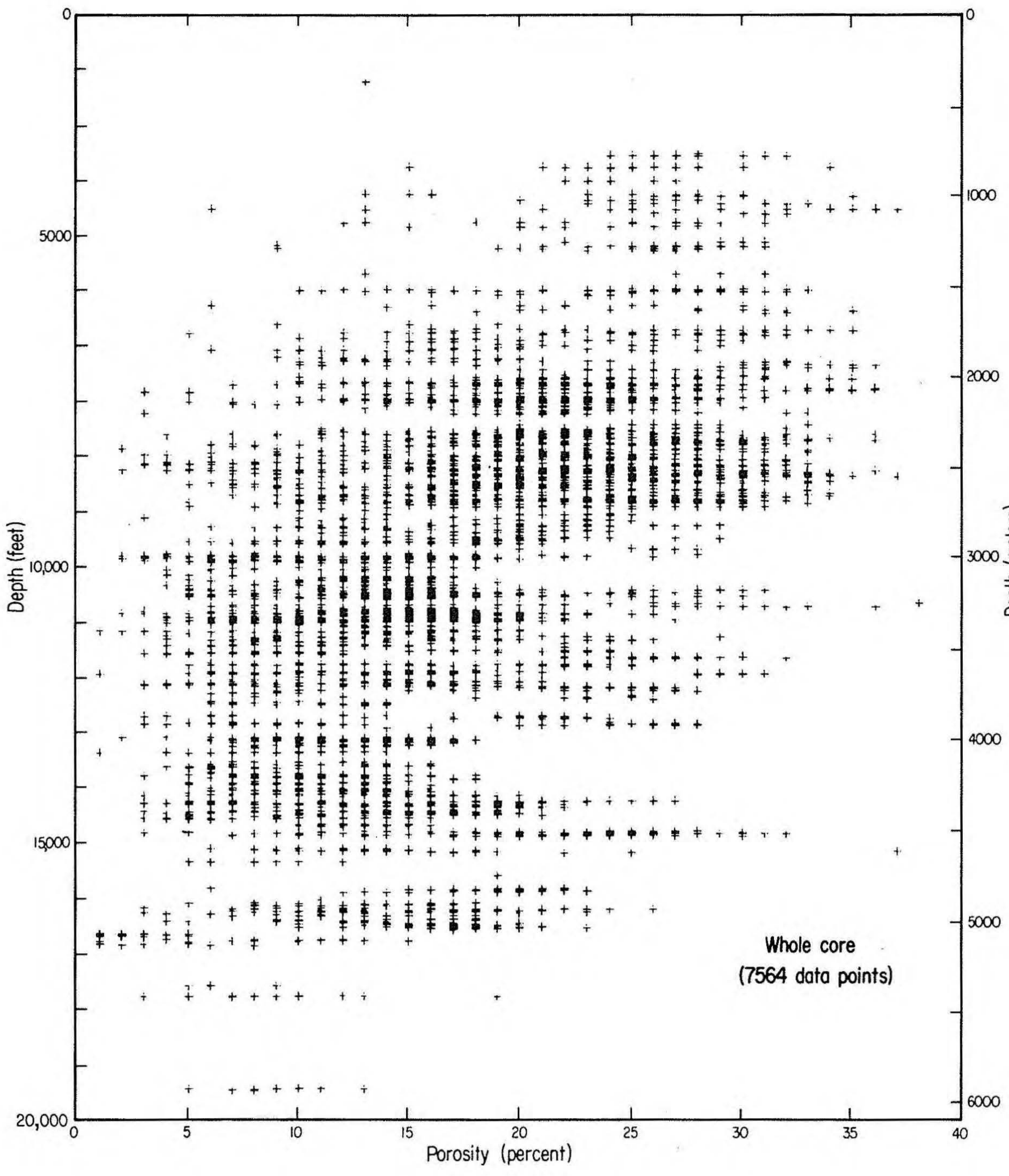


Figure 10. Sandstone porosity versus depth from whole core analyses for lower Tertiary units along the Texas Gulf Coast. Sandstones with and without matrix were included.

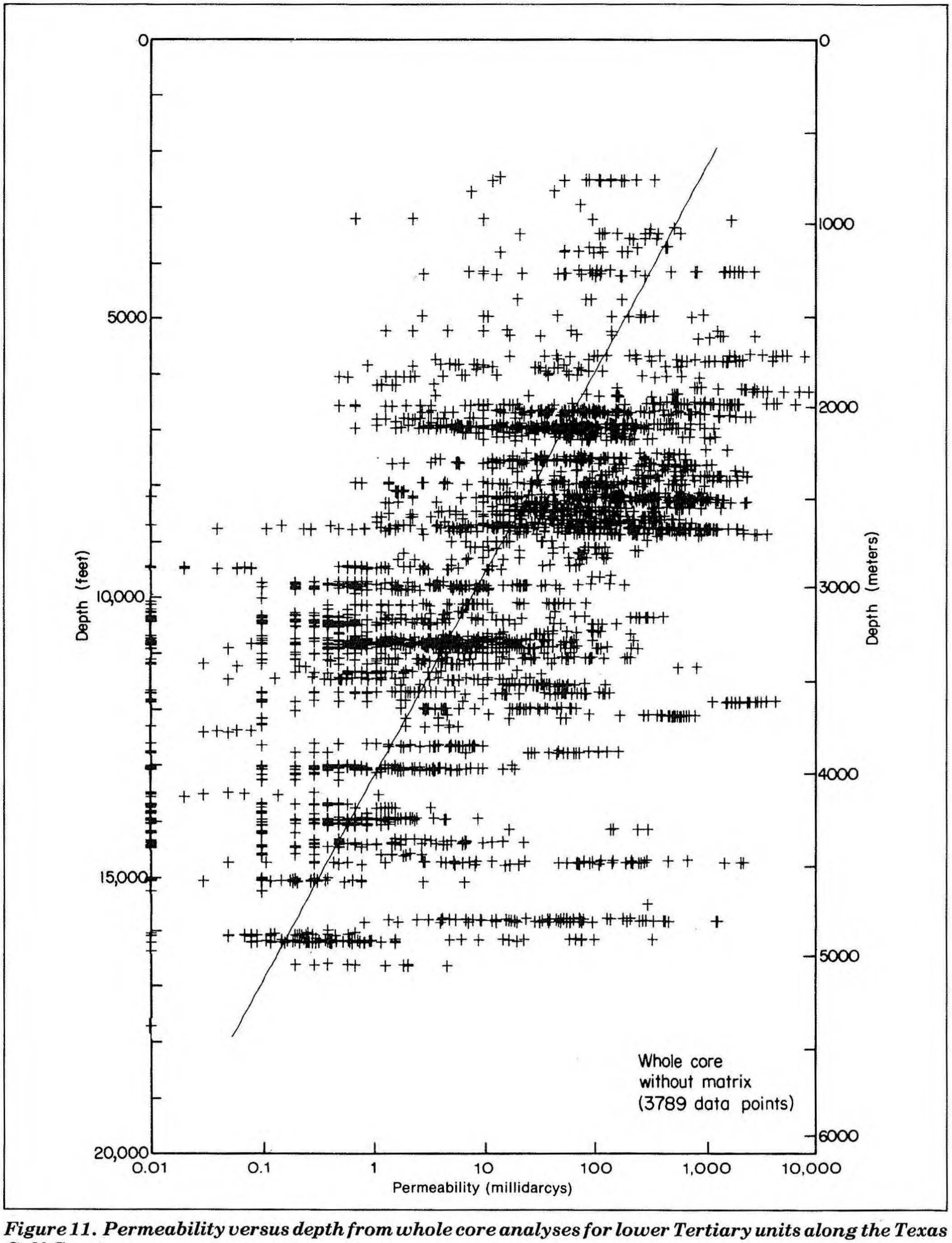


Figure 11. Permeability versus depth from whole core analyses for lower Tertiary units along the Texas Gulf Coast.

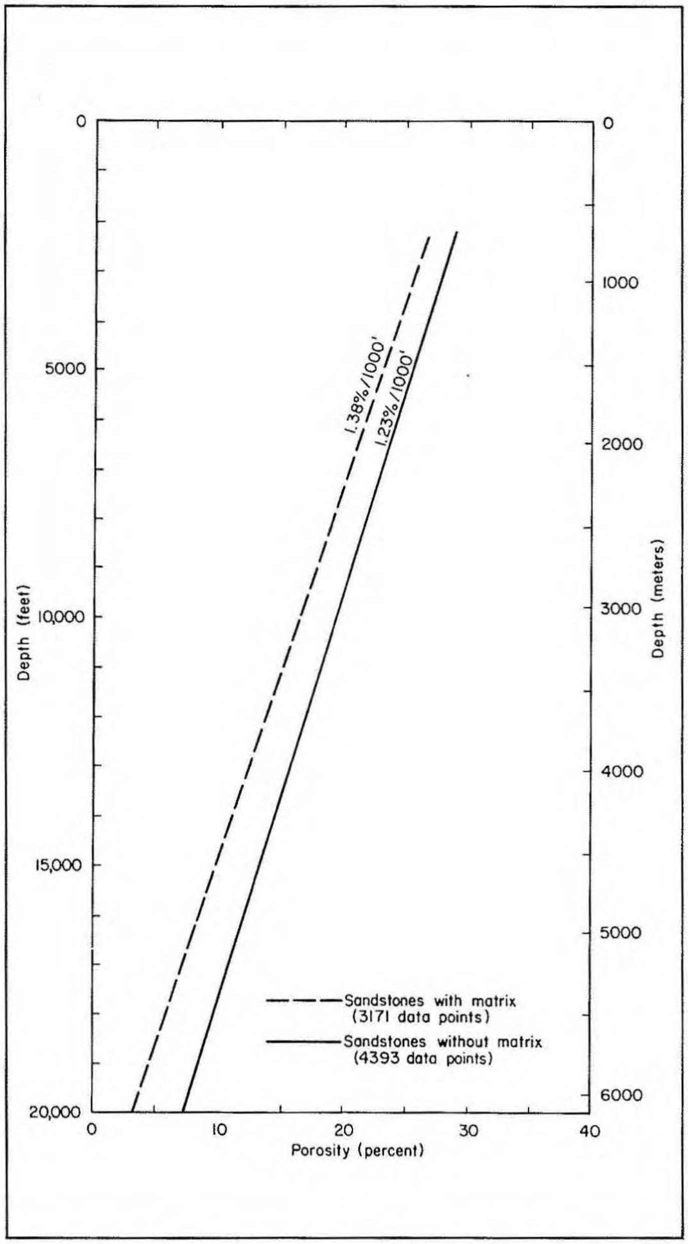


Figure 12. Mean porosity versus depth for lower Tertiary sandstones along the Texas Gulf Coast with and without clay matrix.

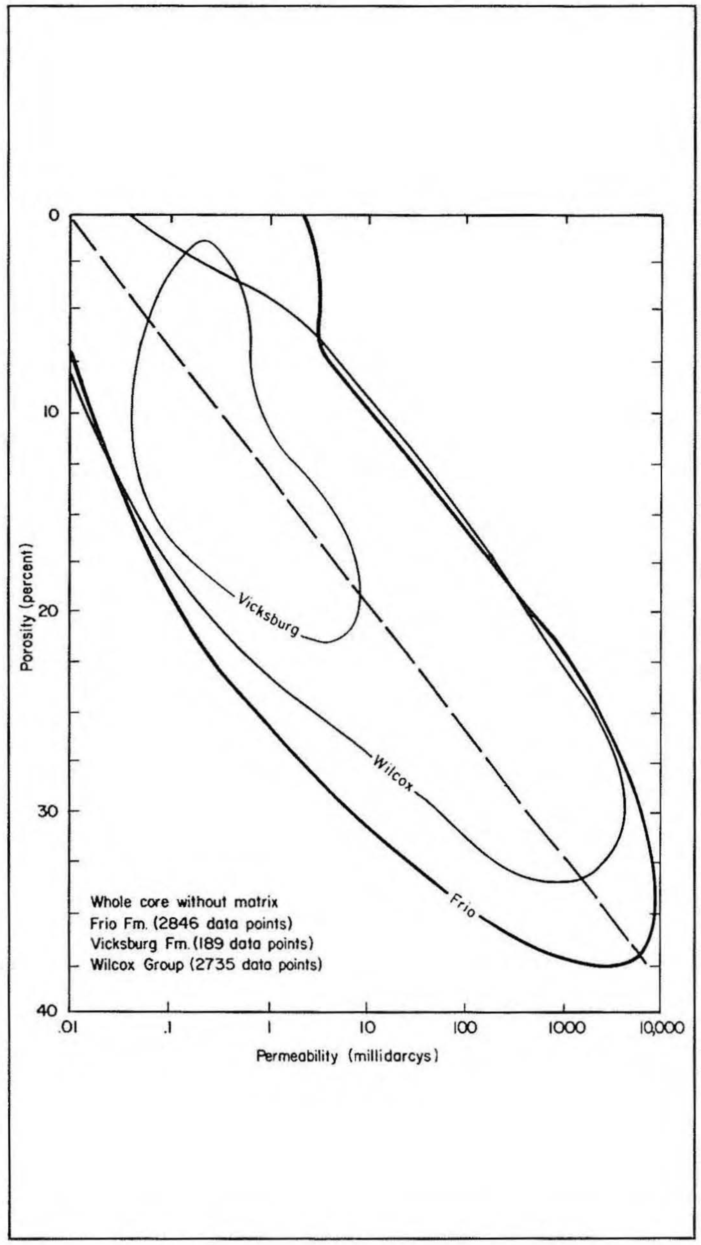


Figure 13. Relation of porosity to permeability for Wilcox Group and Vicksburg and Frio Formations.

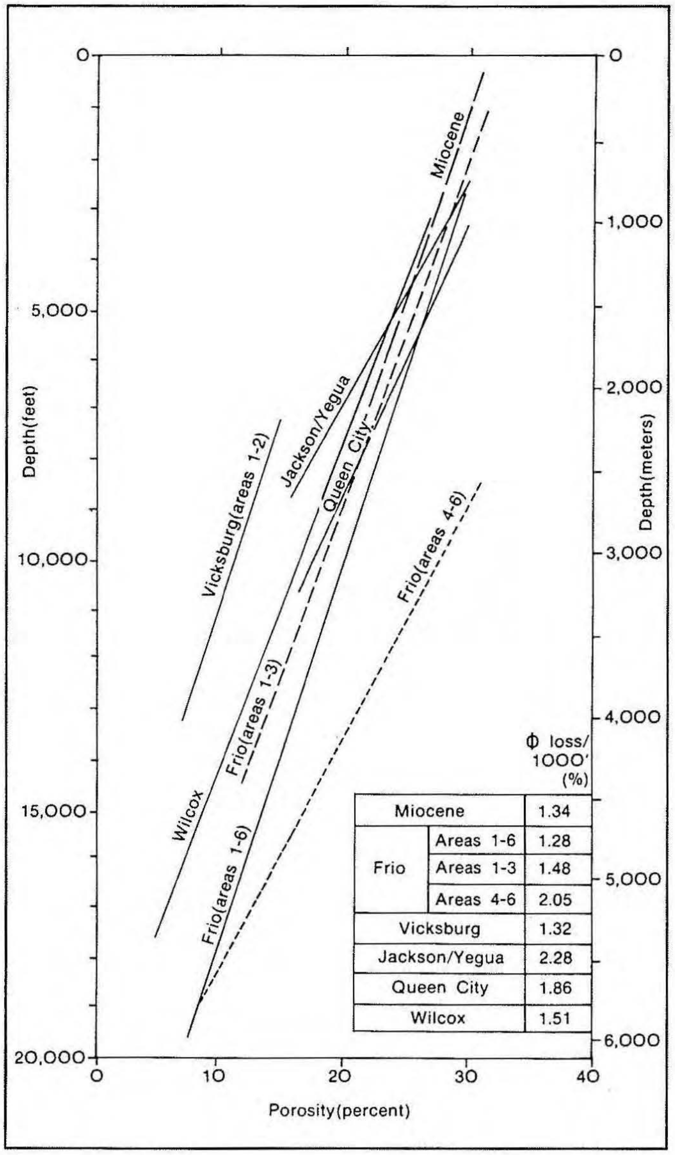


Figure 14. Mean sandstone porosity versus depth by formation for lower Tertiary units along the Texas Gulf Coast. Table in lower right-hand corner shows porosity loss per 1,000 ft for each formation.

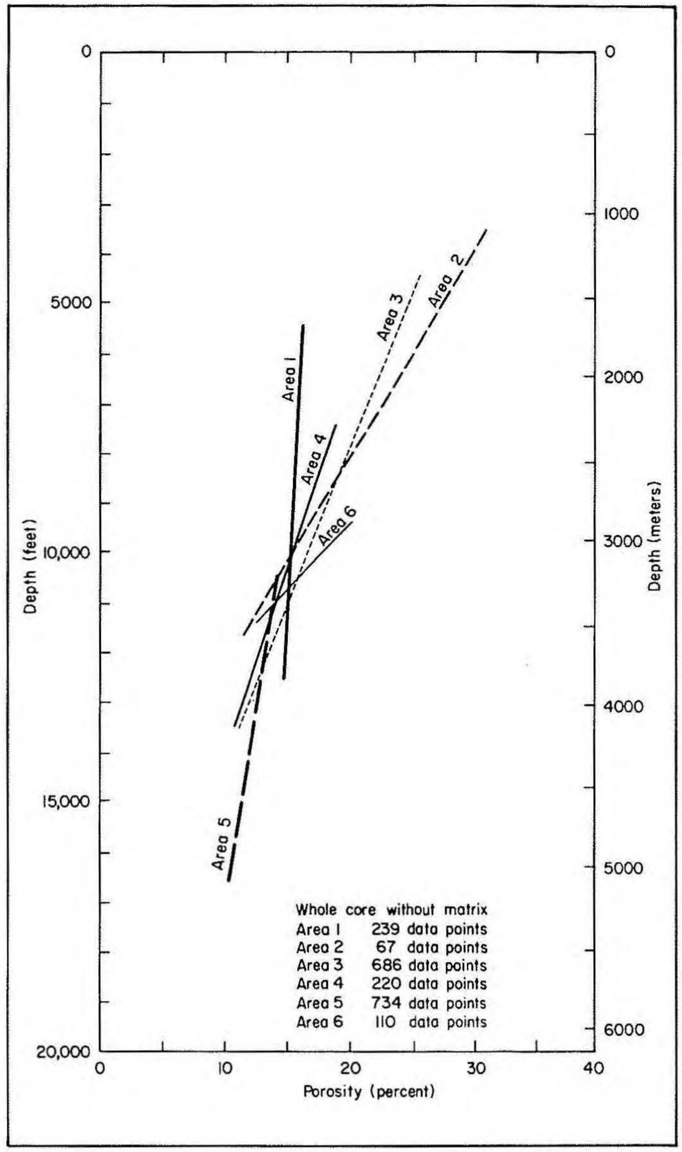


Figure 15. Mean Wilcox sandstone porosity by area.

formations can be compared (fig. 14). The Vicksburg Formation stands out as the unit with the poorest reservoir quality. Plots for Wilcox, Queen City, Yegua/Jackson, and Frio sandstones tend to coincide. However, if Frio values are grouped by areas 1 through 3 and areas 4 through 6 (figs. 2 and 14), Frio sandstones of the upper Texas Gulf Coast exhibit the best reservoir quality of the units.

Porosity-versus-depth plots of the Wilcox Group and the Frio Formation for the six areas indicate no strong systematic regional porosity trend in the Wilcox (fig. 15) and a strong regional porosity trend in the Frio (fig. 16). The Frio Formation displays a systematic increase in reservoir quality from area 1 northward to area 5. This increase in reservoir quality correlates with changes in rock composition, thermal gradient, and diagenesis.

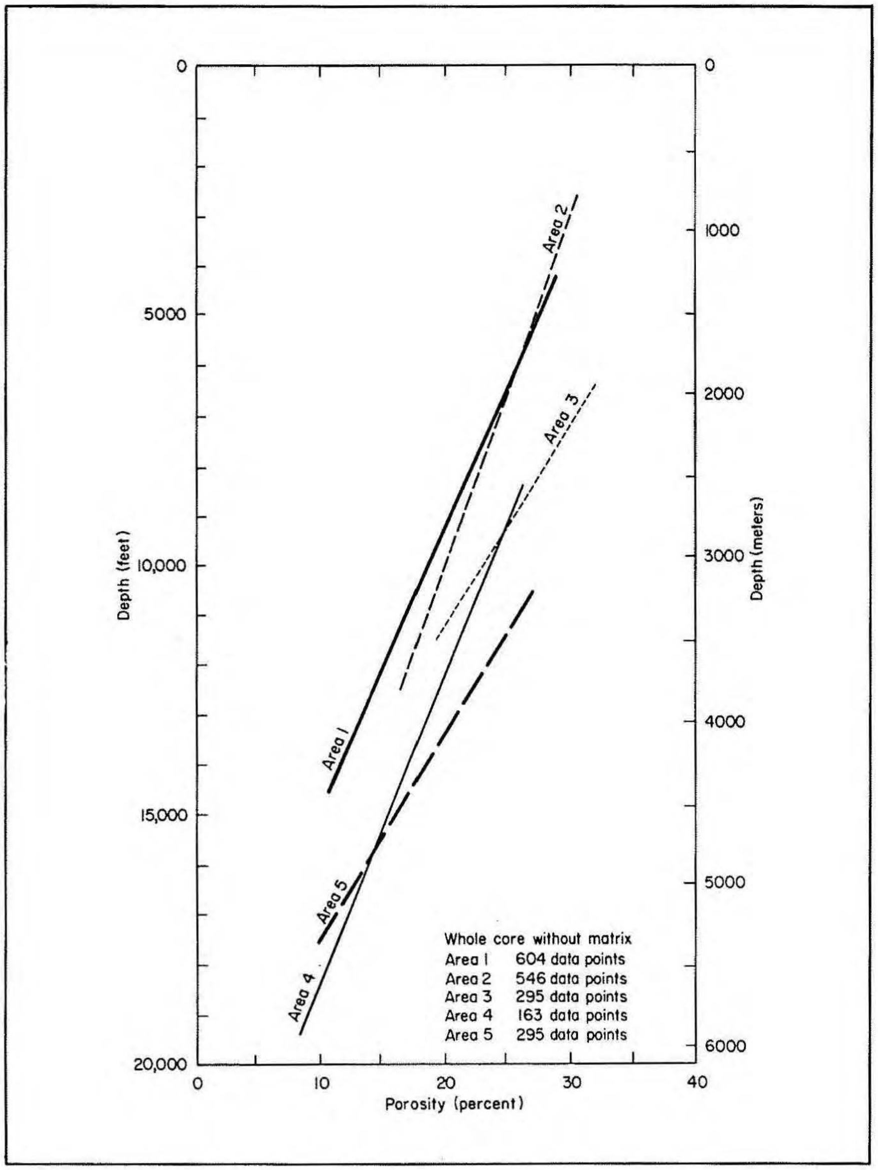


Figure 16. Mean Frio sandstone porosity by area.

REGIONAL CONTROLS ON RESERVOIR QUALITY

General Statement

Regional influences on reservoir quality include depositional environment, initial composition of the sand and associated muds, texture, time (geologic age), subsidence rate, pressure, thermal gradient, pore fluid composition, and diagenetic history. The influence of pore fluid composition was not studied in this investigation. Depositional environments do not correlate with reservoir quality on a regional scale but do on a local scale. Generally, sandstones with initial high porosities maintain high porosities during burial because of the development of secondary porosity. Framework mineralogy and diagenesis are important in

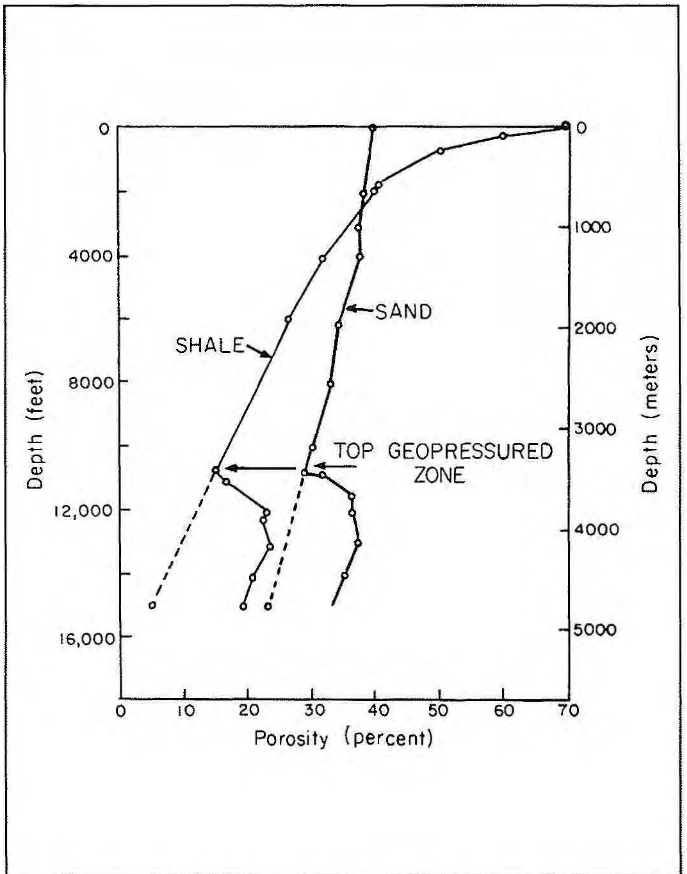


Figure 17. Relation of porosity to depth of burial in late Cenozoic sands and sandstones and Cenozoic shales in the hydropressured zone and in the geopressured zone in the Louisiana Gulf Coast basin (adapted from Stuart, 1970, by Jones, 1975).

determining reservoir quality along the Texas Gulf Coast, and they are discussed in this report. Time, subsidence, fluid pressure, and thermal gradient are also discussed in the following sections.

Effect of Time on Porosity

Loss of primary porosity and creation of secondary porosity are in part functions of time. Compaction increases with burial, and cementation increases with duration of burial. Both processes lead to loss of primary porosity. In theory, therefore, the Wilcox Group (50 to 55 m.y. B.P.), the oldest Tertiary unit studied, should have the least porosity, but in fact, the younger Vicksburg Formation (30 to 35 m.y. B.P.) has the least porosity. Compaction and cementation were counteracted by dissolution, a process that is also dependent on time. Thus, time alone is not a dominant control on reservoir quality along the Texas Gulf Coast.

Effect of Pressure on Porosity

Pore fluids in the Gulf Coast occur in two pressure regimes: hydropressure and geopressure. In the hydropressured zone, the fluid pressure gradient approximates the normal hydrostatic gradient of 0.465 psi/ft and rocks are under a lithostatic pressure gradient of about 1.0 psi/ft. In the geopressured zone, the fluid pressure gradient is greater than 0.465 psi/ft and pore fluids support some of the overburden load. The effective pressure on the rocks, therefore, is less than the lithostatic pressure.

The geopressured zone can be divided into two parts. The "soft" geopressured zone, in which the pressure gradient is greater than 0.465 psi/ft and less than 0.7 psi/ft, is transitional with the "hard" geopressured zone, in which the pressure gradient is greater than 0.7 psi/ft. In the soft geopressured zone, fluids move and can leak into the hydropressured zone. In the hard geopressured zone, fluid movement is largely retarded.

The partial support of the rock column by pore fluids results in undercompaction of shales in the geopressured zone (fig. 17). Jones (1975) postulated that sandstones in the geopressured zone are also undercompacted (fig. 17). This would be true if sands were uncemented; high pore pressures in the geopressured zone would have reduced physical compaction and allowed higher porosities to exist at greater depth. However, in rocks that were well cemented before subsiding into the geopressured zone, as were most pre-Miocene sediments along the Texas Gulf Coast, high pore pressure probably did not have a significant effect because cementation had already arrested compaction and produced a rigid framework. However, if abundant secondary porosity had been developed in the soft geopressured zone before the sediments subsided into the hard geopressured zone, higher pressures may have prevented large pores from collapsing under the weight of overburden. Therefore, a sandstone subsiding into the geopressured zone can retain high porosity because of the lack of compaction (fig. 17) if the sediment is largely uncemented or can increase in porosity as a result of the formation of secondary dissolution porosity if the sandstone is cemented.

Friedman (1977) concluded from working with the data of Atwater and Miller (1965) on uncemented Miocene sands in Louisiana that pore pressure affects the rate of porosity decline. He noted that the rate of porosity decline decreased with increasing pressure gradient (table 1). In effect, the potential for porosity preservation increases with an increase in pressure because of lack of compaction in the geopressured zone. A similar analysis of sandstones of the lower Tertiary section in Texas did not show a simple decrease in rate of porosity loss with depth (fig. 18). The data were sorted by unit to better define porosity/pressure relationships, but sufficient data for reliable results were available only for the Wilcox Group and the Frio Formation (table 2). Porosity is not related to pressure gradient in Wilcox sandstones, and porosity has an approximately

Table 1. Porosity loss relative to pressure gradient, calculated using Atwater and Miller's (1965) data from south Louisiana (Friedman, 1977).

LOUISIANA MIOCENE	
Pressure gradient (psi)	Porosity loss / 1000 ft (%)
0.5 to 0.6	1.12
0.6 to 0.7	0.80
0.7 to 0.8	0.57
0.8 to 0.9	0.40
>0.9	1.22

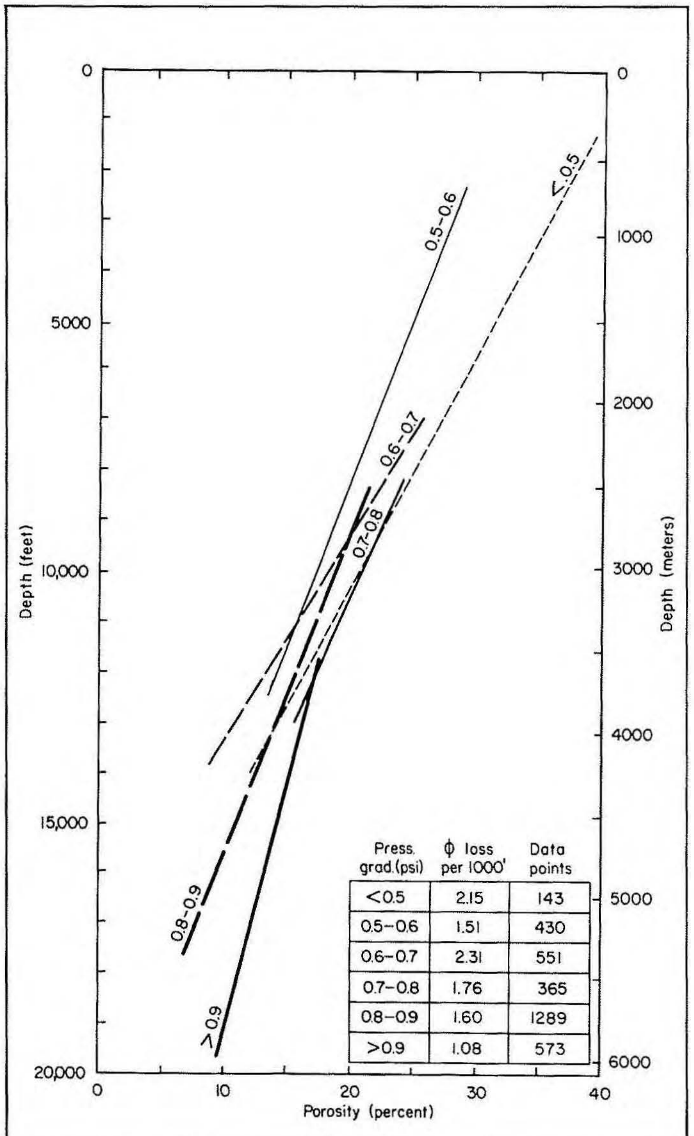


Figure 18. Porosity loss relative to pressure gradient for lower Tertiary sandstones along the onshore Texas Gulf Coast.

Table 2. Porosity loss relative to pressure gradient for Wilcox and Frio sandstones along the onshore Texas Gulf Coast.

WILCOX GROUP	
Pressure gradient (psi)	Porosity loss / 1000 ft (%)
<0.5	no data
0.5 to 0.6	2.33
0.6 to 0.7	0.85
0.7 to 0.8	3.66
0.8 to 0.9	0.75
>0.9	no data

FRIO FORMATION	
Pressure gradient (psi)	Porosity loss / 1000 ft (%)
<0.5	no data
0.5 to 0.6	1.14
0.6 to 0.7	2.79
0.7 to 0.8	2.58
0.8 to 0.9	3.92
>0.9	3.07

inverse relation to increase in pressure gradient in Frio sandstones. Fluid pressure may be important in porosity preservation in uncemented sediments, as indicated by Friedman's work, but it is of minimal importance in preserving porosity in cemented rocks along the Texas Gulf Coast.

Maps of bottom-hole pressure at depths of 3,048 to 3,810 m (10,000 to 12,500 ft) in the geopressured zone indicate a ridge of high fluid pressure that extends from Hidalgo County along the lower Texas Gulf Coast north to Bee County (figs. 19 and 20). From Bee County the ridge shifts gulfward and follows the present-day shoreline to the Texas-Louisiana border. The high-pressure area in Hidalgo and Brooks Counties along the lower Texas Gulf Coast corresponds to the deep, thick, low-porosity sandstone trend of the Vicksburg Formation. North of the Vicksburg sandstone trend, along the Gulf Coast, porosity distribution does not seem to be related to regional pressure differences.

The top of the geopressured zone in the Wilcox Group is deeper than in other units of the Texas Gulf Coast (Bebout and others, 1978a). The Wilcox Group is the oldest Tertiary sandstone unit (fig. 1), and fluids have had more time to leak, thus lowering the top of the geopressured zone.

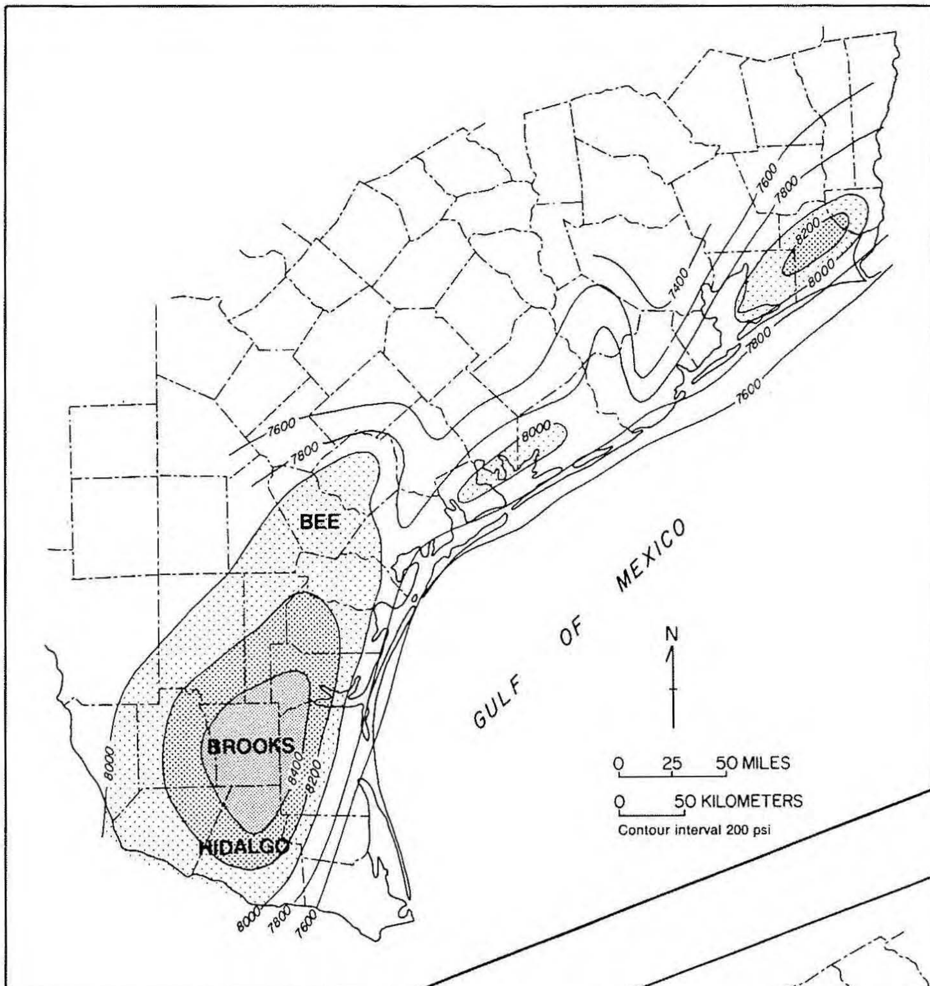


Figure 19. Pressure (psi) at 3,050 m (10,000 ft) in the geopressured zone. Pressures are calculated from drilling mud weights.

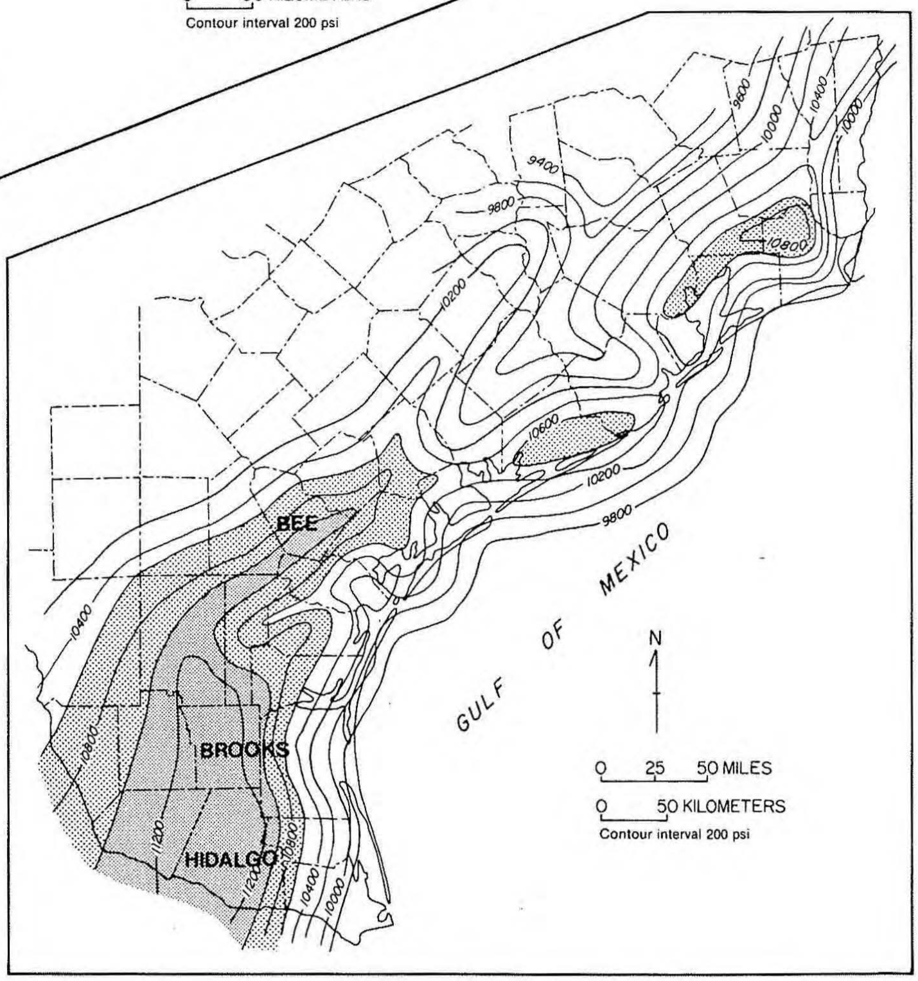


Figure 20. Pressure (psi) at 3,810 m (12,500 ft) in the geopressured zone. Pressures are calculated from drilling mud weights.

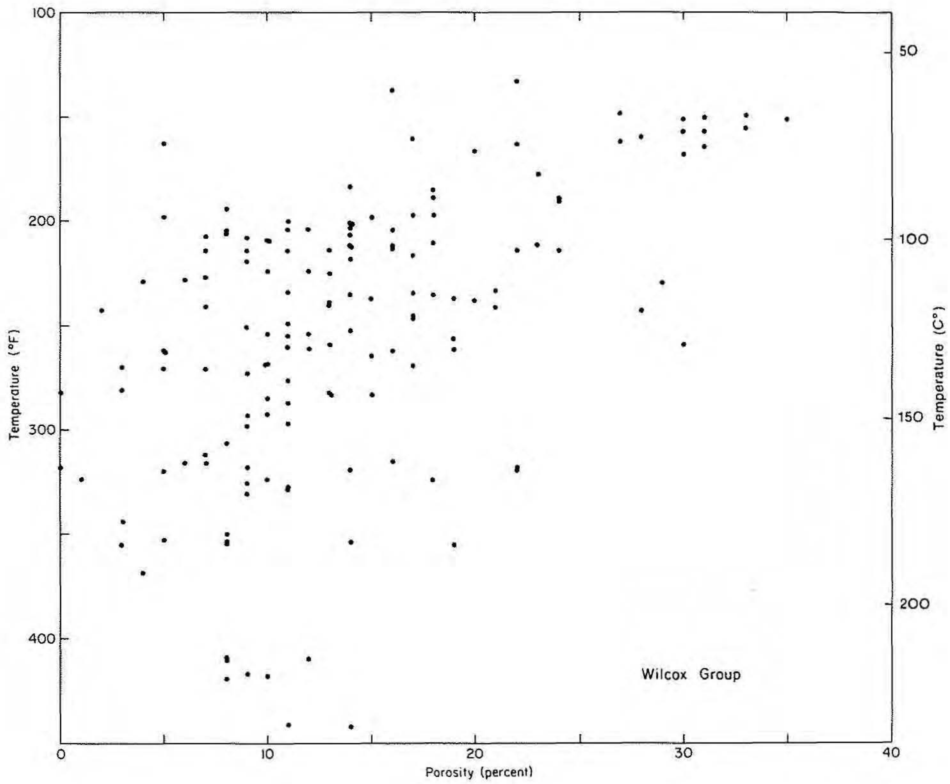


Figure 21. Porosity versus corrected bottom-hole temperature for Wilcox sandstones. Temperatures are corrected to equilibrium temperatures using the method of Kehle, 1971.

Effect of Temperature on Porosity

Temperature is a major control on diagenesis in some sandstone suites and, hence, on porosity preservation (Galloway, 1974, 1979; Loucks and others, 1981). Porosity in the Wilcox Group and Frio Formation generally decreases with increasing temperature (figs. 21 and 22). Because temperature increases with depth, this correlation is simply a restatement of the previously demonstrated trend of decreasing porosity with depth. Regional relations between porosity and temperature are better indicators of porosity trends. Temperature distribution along the Texas Gulf Coast shows two regional trends (figs. 23 and 24; table 3): a decrease in temperature from the lower to the upper Texas Gulf Coast and a decrease gulfward in temperature. These trends are seen in both hydropressured and geopressured strata. The trend toward cooler temperatures (figs. 23 and 24) and a lower geothermal gradient (table 3) along the upper Texas Gulf Coast area correlates with higher porosity values in the Frio sandstones (fig. 16). The higher geothermal gradient inland relative to that near the coast corresponds to lower porosity values in the inland Wilcox Group as compared with those of the Frio Formation along the coast (fig. 14).

Mineralogy and Diagenesis: Controls on Reservoir Quality

General Statement

Major controls on the evolution of reservoir quality are (1) original mineral composition of the rock and (2) sequential diagenetic changes, including cementation, replacement, and dissolution. During deposition and burial, sequential changes occur in the physical and chemical environments of sand grains. The sand and surrounding sediments alter to approach equilibrium with their environment, thereby increasing or decreasing reservoir quality. The degree of instability is determined by initial mineral composition relative to fluid chemistry, temperature, and pressure. Final

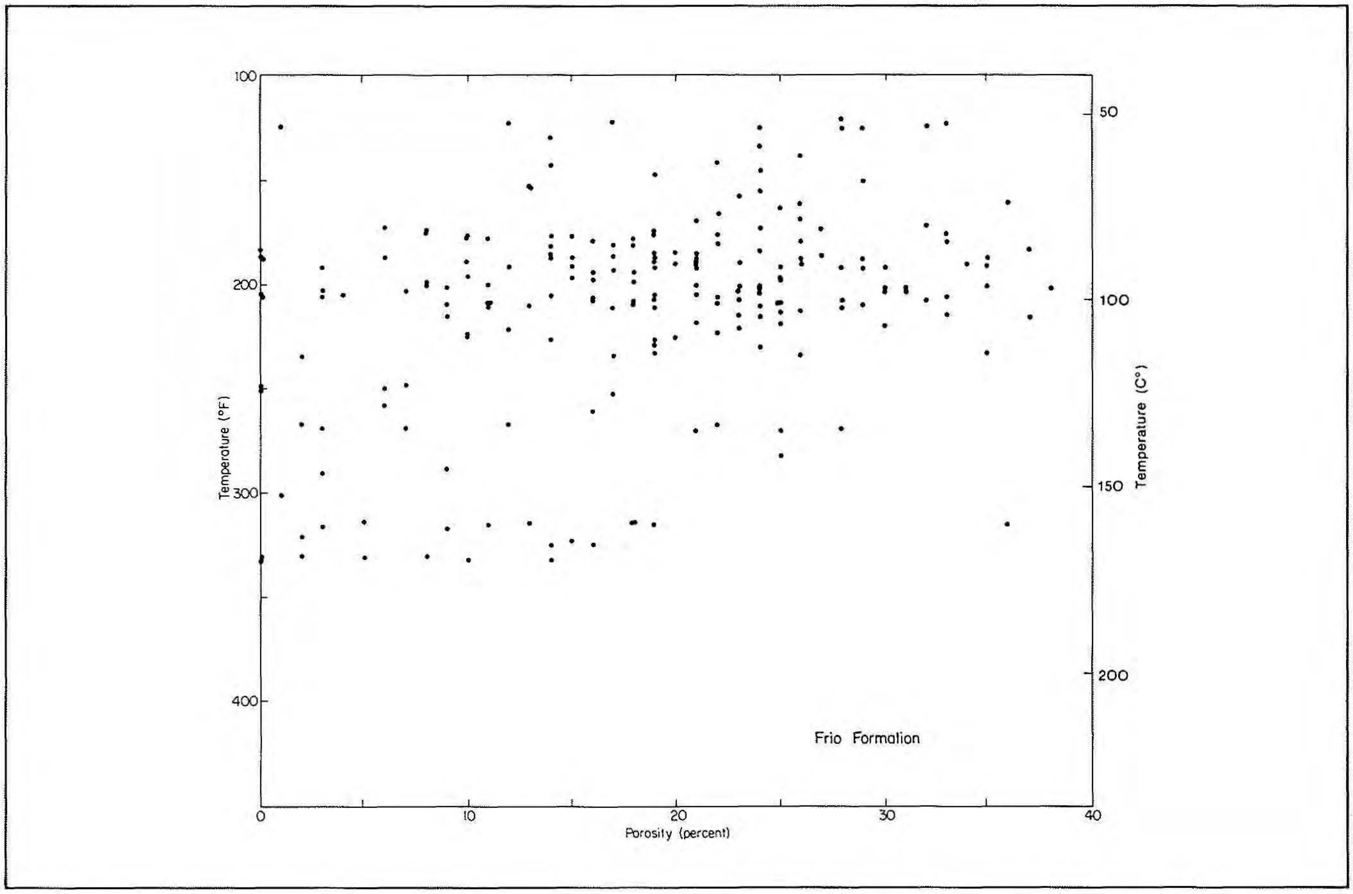


Figure 22. Porosity versus corrected bottom-hole temperature for Frio sandstones.

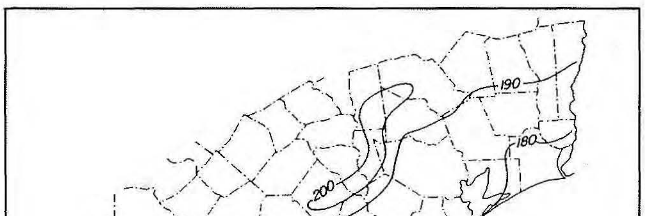


Figure 23. Corrected temperature (°F) at 2,290 m (7,500 ft) in the hydropressured zone.

reservoir quality is a complex result of initial mineralogical composition and the specific geochemical and physical history of reequilibration to changing conditions. The most important aspects of alteration or diagenesis that determine final reservoir quality (fig. 25) are the loss or preservation of primary porosity and the creation of secondary dissolution porosity. Primary porosity is the original porosity created by spaces left between grains when sediment accumulated. This type of porosity decreases through time and with burial by compaction and cementation. Secondary porosity is created by dissolution of cements, by dissolution of authigenic replacement products of grains, and by dissolution of detrital grains. Secondary porosity can develop and increase with depth (fig. 25); it is the dominant form of porosity in the intermediate and deep subsurface lower Tertiary section of the Texas Gulf Coast (fig. 26; Lindquist, 1977; Loucks and others, 1977; Stanton, 1977; and Loucks and others, 1979a). Criteria for recognition of secondary porosity were developed by Loucks and others (1977); McBride (1977); Schmidt and others (1977); and Loucks and others (1979a, b) and include the following:

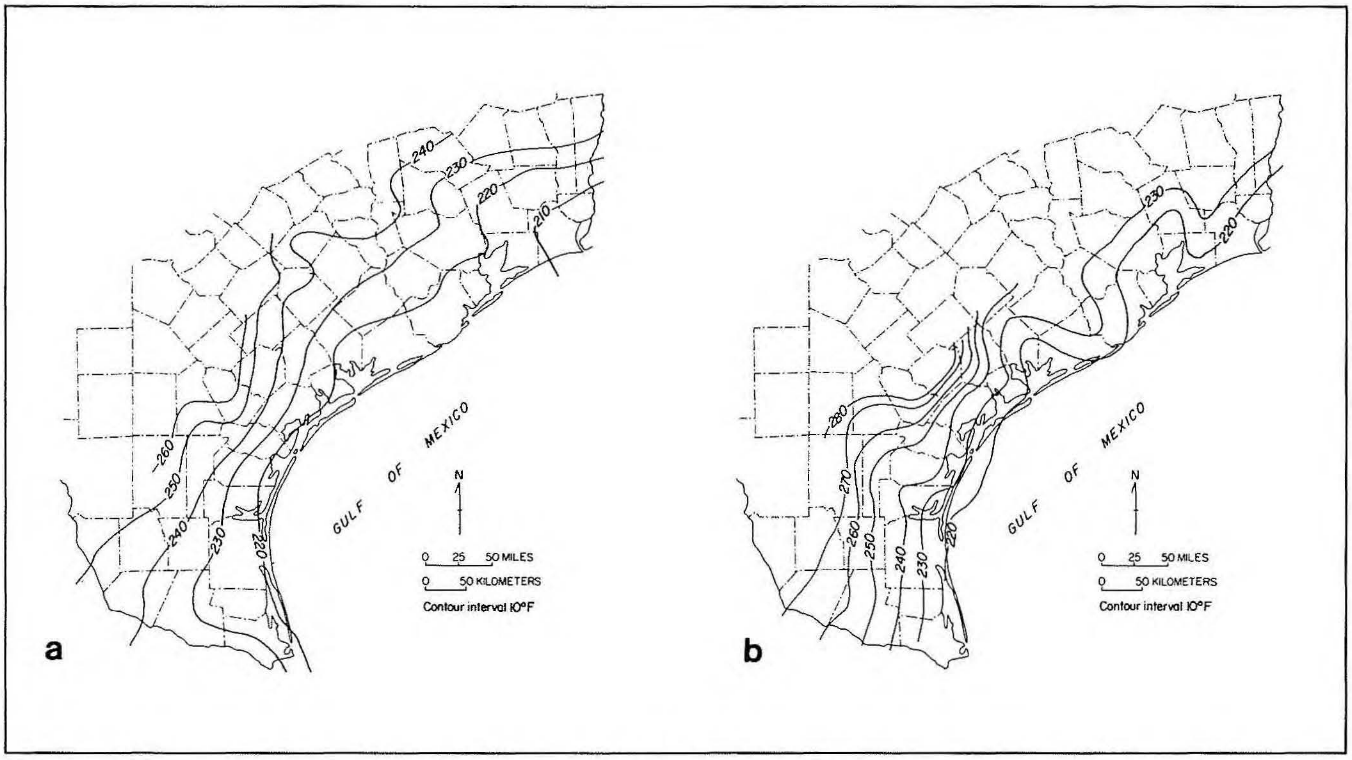


Figure 24. Corrected temperature (°F) at 3,050 m (10,000 ft) (a) in the hydropressured zone and (b) in the geopressured zone.

Table 3. Average geothermal gradients by area for the updip Wilcox and downdip Vicksburg/Frio trends, assuming a 70°F surface temperature. Geothermal gradients are taken from the Geothermal Survey of North America (American Association of Petroleum Geologists, 1976).

← GEOTHERMAL GRADIENT INCREASES

Trend \ Area	Lower Texas 1 & 2	Middle Texas 3 & 4	Upper Texas 5 & 6
Wilcox	1.9° F/100 ft	1.8° F/100 ft	1.6° F/100 ft
Vicksburg / Frio	1.7° F/100 ft	1.6° F/100 ft	1.5° F/100 ft

↑ GEOTHERMAL GRADIENT INCREASES

1. *Partial to complete dissolution of cements.* Calcite, dolomite, and ankerite cements are dissolved and leave patchy remnants with corroded boundaries (pl. 1a).

2. *Partial to complete dissolution of grains.* Most dissolved grains are feldspars (pl. 1b) and volcanic rock fragments (pl. 2a). Feldspars are commonly honeycombed (pls. 2b and 3a), and the original grain outline is preserved only by clay coats or rims (pls. 3a and 3b).

3. *Oversized pore spaces.* Oversized pore spaces result when a grain is completely dissolved, leaving a pore space larger than adjacent grains (pl. 4a). This process commonly creates the appearance of packing inhomogeneity (pl. 4a).

4. *Embayments in quartz overgrowths.* Embayments in quartz overgrowths result when dissolution affects grains around which the overgrowths previously precipitated (pl. 4b).

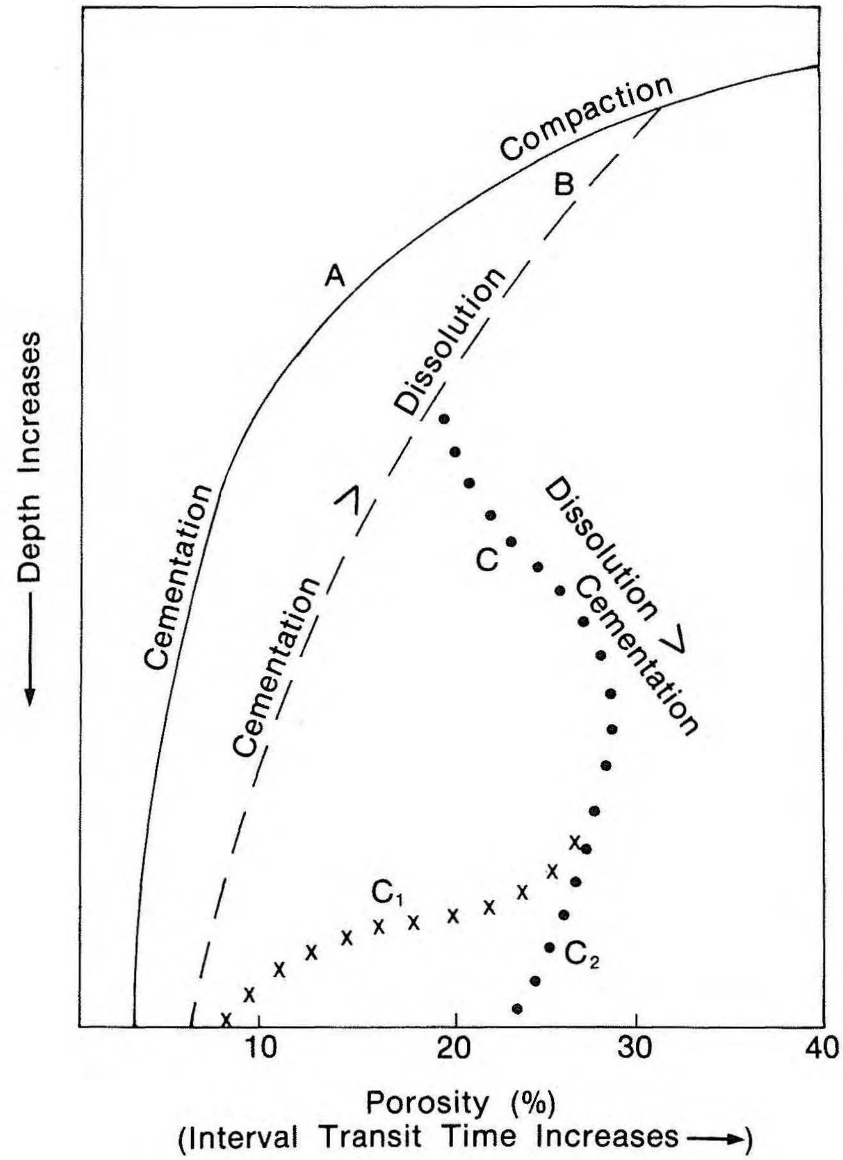


Figure 25. General pathways of porosity and interval transit time with depth. Curve A shows loss of primary porosity with depth by compaction and cementation; no secondary porosity was developed. Curve B represents porosity loss with depth where compaction and cementation rates are greater than the production of secondary porosity. Curve C shows porosity loss with depth by compaction and cementation followed by a major zone of secondary dissolution porosity development. Curve C_1 indicates a late stage of cementation destroying porosity, whereas curve C_2 indicates porosity preservation with further burial.

Secondary porosity in lower Tertiary Gulf Coast sandstones has been recognized in several diagenetic stages. These stages, which were determined by conventional petrographic techniques, are described in the following sections.

General Diagenetic Sequence

The general diagenetic sequence (fig. 27) defined by this study for the Wilcox, Yegua, Vicksburg, and Frio sandstones is based on a regional distribution of

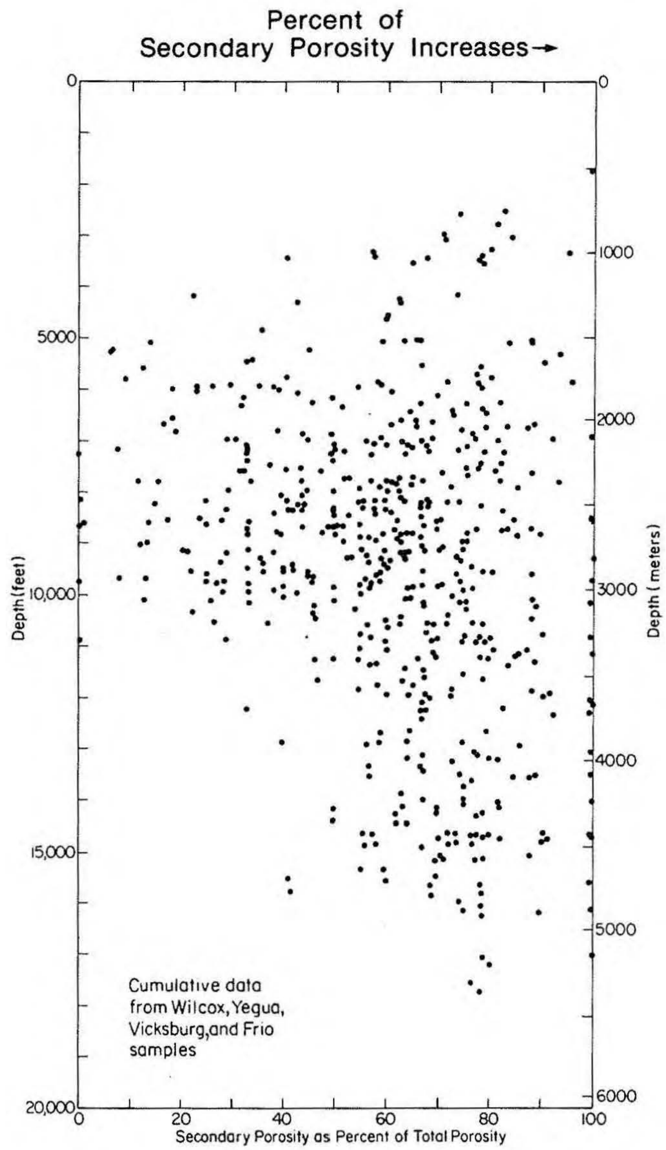


Figure 26. Secondary porosity as a percent of total porosity versus depth for lower Tertiary sandstones. Note that below 3,000 m (10,000 ft) most pore networks are predominantly secondary porosity. Each datum point represents an analysis of a thin section.

hundreds of samples (fig. 3). Depths at which diagenetic products first occurred differ among formations, and a few formations have unique features, but the general diagenetic sequence is consistent. The paragenetic sequence was delineated by noting the relative position of the various diagenetic products to each other. Not all features occur in each sample. The depth of first occurrence of each diagenetic feature helped determine maximum depth of burial at which a particular feature may have first appeared. Most diagenetic features are well developed above 3,000 m (10,000 ft) (fig. 27); this development indicates that most diagenesis occurred above the top of the hard geopressured zone. Porosity, however, continues to decrease downward in the geopressured zone, where some cementation must be taking place. Milliken and others (1981), using isotopic

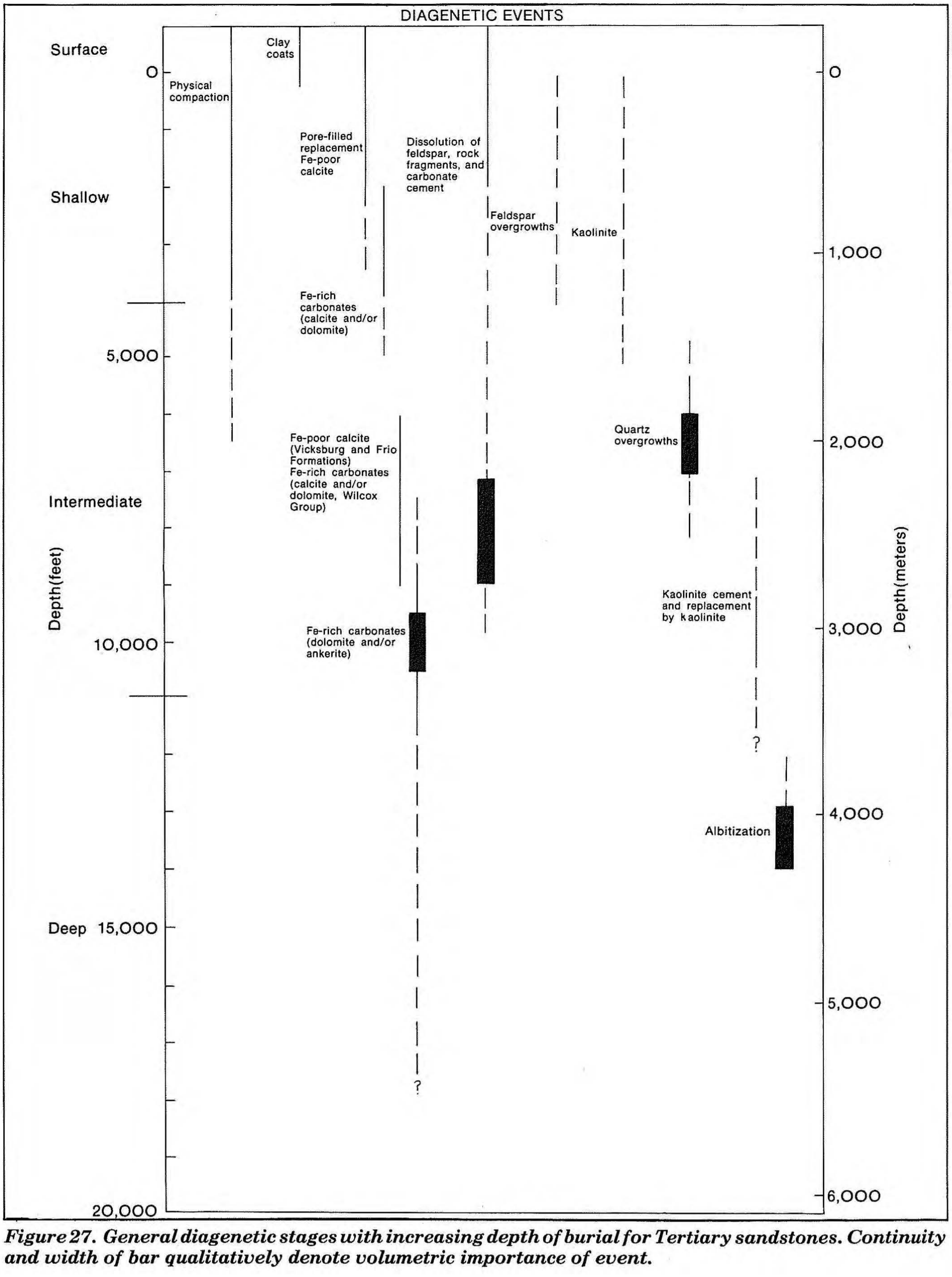


Figure 27. General diagenetic stages with increasing depth of burial for Tertiary sandstones. Continuity and width of bar qualitatively denote volumetric importance of event.

analysis of cements and pore fluids in the Frio Formation of the upper Texas Gulf Coast, confirmed the paragenetic sequence presented here.

Lower Tertiary formations display the following general diagenetic sequence:

Surface to shallow subsurface diagenesis (0 to 1,200 m± [0 to 4,000 ft±]) began with formation of clay coats (smectite?) by mechanical infiltration of colloidal clay-rich waters through the vadose zone (Burns and Ethridge, 1979; Galloway, 1974) or by the alteration of feldspars (see color centerfold, a, herein referred to as plate 5). Although clay coats occupy only a small volume of pore space, they can decrease permeability by reducing pore-throat diameter and causing resistance to fluid flow (Galloway, 1977).

Alteration of feldspars began in the source area and continued at the depositional surface and in the subsurface. Feldspars were either dissolved or replaced by Fe-poor calcite (pl. 5b, c). Fe-poor calcite is an abundant pore-filling cement in the Catahoula (updip equivalent of the Frio Formation; Galloway, 1977) and Frio Formations, and it is a common diagenetic element in paleosoil zones in Frio outcrop (McBride and others, 1968; Galloway, 1977). It is commonly poikilotopic (pl. 5d).

Carbonate cements continued to precipitate with depth at different intervals in the lower Tertiary section (fig. 27). They occur as a series of discrete events separated in the stratigraphic section by as little as a few inches or as much as thousands of feet. Several different phases of carbonate cement precipitated in each formation.

Dissolution occurred during the shallow and intermediate subsurface stages of diagenesis. Dissolution commonly alternated with carbonate cementation.

Feldspar overgrowths around detrital feldspars and, less commonly, around volcanic rock fragments were also a near-surface product. Overgrowths of plagioclase and orthoclase were precipitated on feldspars. In one example, as shown by staining, an orthoclase overgrowth was precipitated on a plagioclase overgrowth that had been precipitated on a volcanic rock fragment (pl. 5e). Overlap of early dissolution and feldspar cementation was observed in some samples. Volumetrically, feldspar cementation is insignificant.

Minor amounts of authigenic kaolinite were precipitated in the shallow diagenetic environment (pl. 5f, g). As described by Todd and Folk (1957), the kaolinite cement from Wilcox outcrop samples can range from poorly developed, scattered plates to well-developed booklets.

Fe-rich carbonate cement (calcite or dolomite or both) began to precipitate at about 600 m (2,000 ft) in pores and in molds of feldspar grains dissolved at a shallower depth (pl. 5h).

Throughout the shallow subsurface, sediments underwent relatively rapid compaction because of the lack of cementation. Early-formed Fe-poor calcite was the first major compaction-arresting cement. At depths of 1,200 m (4,000 ft) porosity was reduced from the original 40 percent to about 30 percent.

Intermediate subsurface diagenesis (1,200 to 3,400 m± [4,000 to 11,000 ft±]) comprised a complex stage of cementation and dissolution. Compaction was arrested during this stage by abundant cementation.

Fe-rich carbonate cement that precipitated in the shallow subsurface, detrital feldspar grains, and early-formed calcite that replaced feldspars all underwent dissolution in the intermediate subsurface, which created secondary dissolution porosity (pl. 5i, j). Secondary porosity reached a maximum value near the end of this stage.

Quartz overgrowths were common products that appear in the intermediate subsurface (pl. 5k). Overgrowths arrested compaction and occluded pore space, and they were resistant to later dissolution. In many areas of the Wilcox Group, quartz overgrowths occluded all or nearly all pore space, eliminating any potential for development of high-quality, deep reservoirs. Quartz overgrowths are less abundant in other lower Tertiary units, but locally they are still a common porosity-reducing cement.

Carbonate cements that precipitated after formation of quartz overgrowths exist in two modes. In the Vicksburg and Frio Formations, carbonate cement is Fe-poor (pl. 5l), and in the Wilcox Group, it is Fe-rich. Carbonate cementation was also a major porosity-reducing event.

After these last stages of quartz and carbonate cementation, porosity in some sandstones was reduced to 10 percent. This reduction in porosity could be reversed, however, by dissolution near the base of the intermediate subsurface zone. Components such as feldspars, volcanic rock fragments, and carbonate cements were dissolved. Evidence of this stage of dissolution is the dissolution of post-quartz overgrowth carbonate cement (pl. 5m) and the formation of embayments in quartz overgrowths where grains had been dissolved (pls. 4b and 5n). Continued dissolution may have resurrected porosities to more than 30 percent in some sandstones. This intermediate subsurface stage of dissolution is important in development of deep reservoirs.

After the dissolution stage, kaolinite was precipitated as a cement and as a replacement product of feldspars (pl. 5o, p). Commonly, replaced feldspars were nuclei for precipitation of the cement. Kaolinite, composed of booklets of stacked individual crystals several microns in diameter, formed a meshwork in the pore spaces that did not significantly reduce porosity but did reduce permeability. Kaolinite cement, however, is neither abundant nor widespread. Timing of this later stage of kaolinite cementation is evidenced by its growth on top of earlier formed quartz overgrowths.

The last cementation phase observed in the lower Tertiary section was precipitation of Fe-rich dolomite and ankerite (pl. 5q). The amount of this late-formed cement controlled preservation of deep reservoir quality in all lower Tertiary units except the Wilcox Group, where quartz overgrowths were more significant in reducing porosity.

Deep subsurface diagenesis (>3,400 m±[>11,000 ft±]) was a continuation of the precipitation of late-formed

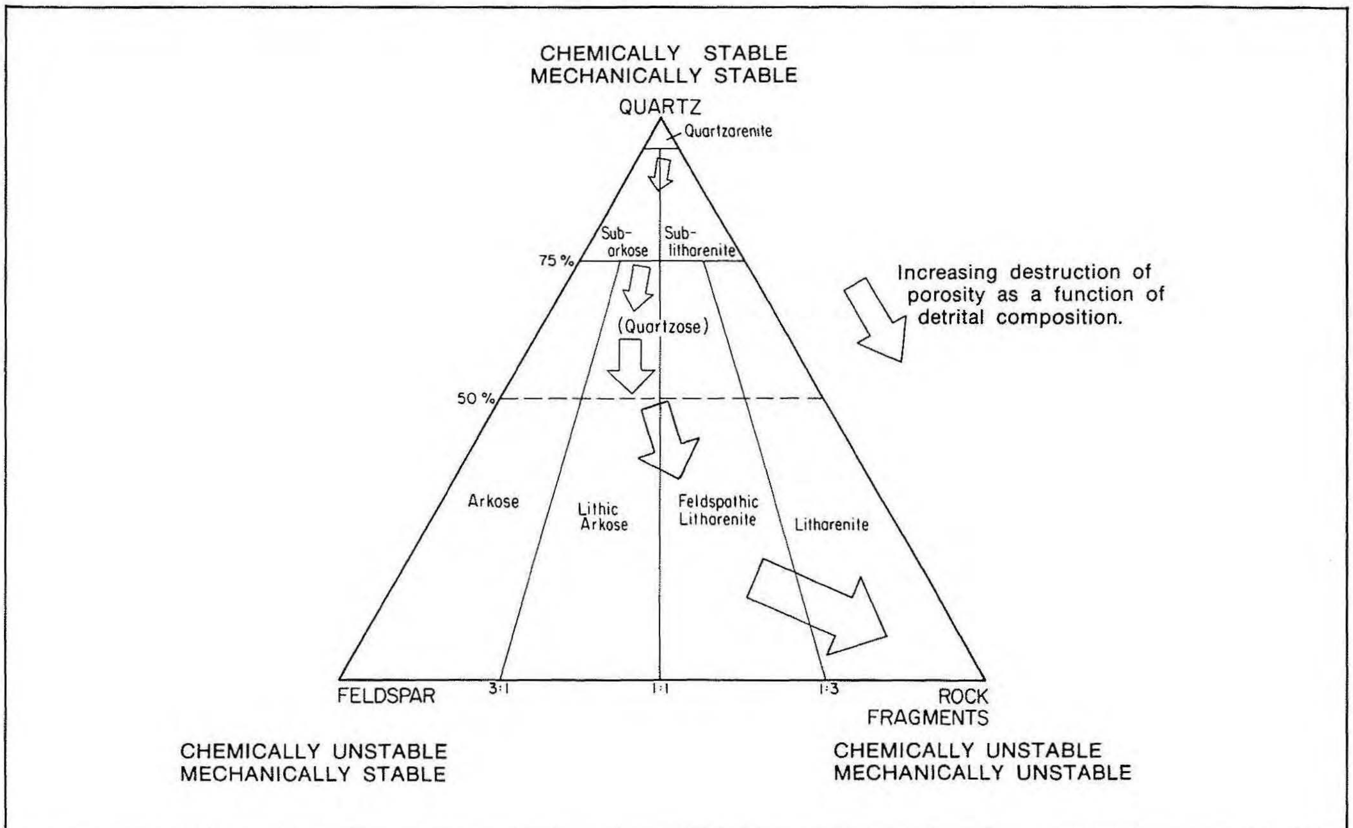


Figure 28. Sandstone classification from Folk (1968). "Quartzose" modifier added by these authors. Stability poles adapted from Hayes (1979).

Fe-rich carbonate cements. In some sections, such as in the Frio of the upper Texas Gulf Coast, late-formed carbonate cement is minor, and high-quality reservoirs exist at depth. In the deep subsurface, feldspars underwent albitization (Land and Milliken, 1981).

Reservoir development in the lower Tertiary sandstones along the Texas Gulf Coast was controlled by a series of porosity-reducing and porosity-enhancing events (fig. 25). In shallow reservoirs, porosity is both primary and secondary (fig. 26). Much early-formed porosity was lost through compaction and cementation. Dissolution events resurrected porosity and created reservoirs that were composed mainly of secondary porosity (fig. 26), but some of these reservoirs were destroyed by precipitation of significant amounts of late-formed Fe-rich carbonate cement.

Mineralogy and Diagenesis: Stratigraphic and Geographic Distribution of Reservoir Quality

Although most Tertiary strata along the Texas Gulf Coast have a similar diagenetic sequence (fig. 27), significant differences exist among units in mineral composition and in intensity of each diagenetic event; these differences affect porosity and permeability at depth.

Sandstone Classification

Folk's (1968) sandstone classification (fig. 28), based on three end members—quartz, feldspar, and rock fragments—is used in this report for two reasons. The compartmentalization of the classification triangle emphasizes feldspar and rock fragments, the more chemically unstable grains, making it useful in relating sandstones to their probable degree of reaction during diagenesis. It is also useful because chert is grouped with rock fragments instead of with quartz. Chert in the lower Tertiary strata of Texas is commonly difficult to distinguish from silicified volcanic rock fragments. The term "quartzose" has been added to Folk's classification to delineate sandstone types containing 50 to 75 percent quartz.

Wilcox Group

Texture and Mineralogy

Most samples used in this study are from the upper Wilcox Group as defined by Bebout and others (1982). These Wilcox sandstones are typically poorly to

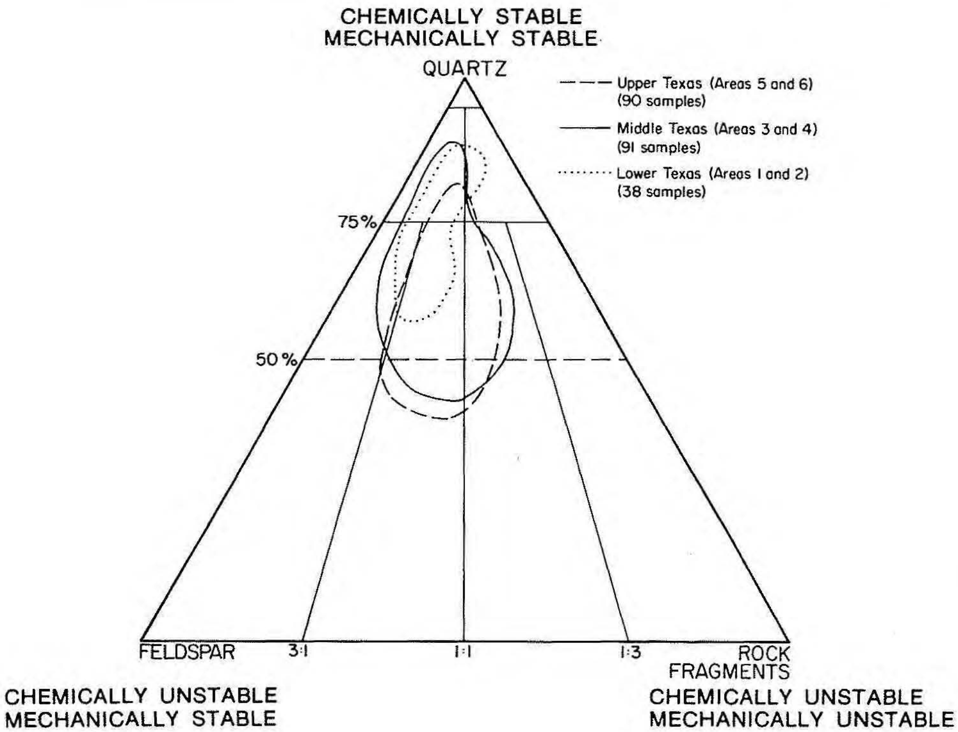


Figure 29. Wilcox sandstone composition. Envelopes highlight typical compositional range.

moderately well sorted, fine-grained quartzose lithic arkoses (figs. 29 through 32). Quartz content increases slightly from the upper to the lower Texas Gulf Coast; orthoclase increases in the opposite direction. Sorting also increases, and grain size decreases slightly (figs. 31 and 32) from north to south. These observations suggest transport from the upper to the lower Texas Gulf Coast, but sandstone distribution and rock fragment composition indicate a more complicated pattern of sediment transport.

The upper Wilcox Group was deposited in a series of deltaic systems along the Texas Gulf Coast. In the middle and upper Texas Gulf Coast areas, upper Wilcox deltas prograded over stable, sandy lower Wilcox deposits. In the lower Texas Gulf Coast, upper Wilcox deltas prograded over unstable, muddy sediments and were subject to extensive growth faulting. Sandstone depocenters were geographically restricted along strike, indicating that the upper Wilcox was essentially dip-fed, and significant transport of sediments along strike did not occur (Bebout and others, 1982).

The composition of Wilcox rock fragments suggests source areas to the north for middle and upper Texas Gulf Coast deltas and to the west for lower Texas Gulf Coast deltas. Metamorphic and volcanic rock fragments are the major lithic debris in the Wilcox sandstones (fig. 33). Metamorphic rock fragments are low to medium grade and range from slates to quartzites and muscovite schists. Muscovite is a common accessory mineral. Most volcanic rock fragments are highly altered and typically silicified. Many grains previously identified as detrital chert may actually be silicified volcanic rock fragments. Unaltered volcanic rock fragments are similar to those in the Frio Formation identified as predominantly rhyolitic (Lindquist, 1977). Wilcox sandstones along the lower Texas Gulf Coast have approximately equal amounts of volcanic and metamorphic rock fragments; along the middle and upper Texas Gulf Coast, metamorphic rock fragments predominate. The volcanic rock fragments probably came from West Texas, southern New Mexico, or northern Mexico (Cook and Bally, 1975). A source for the metamorphic rock fragments is still in dispute. Todd and Folk (1957) and Boggs (1978) proposed the southern Appalachian Uplift and the Ouachita Fold Belt as the metamorphic source, whereas Storm (1945) and Murray (1955) postulated that the Rocky Mountains and the Central Interior supplied metamorphic rock fragments. Carbonate rock fragments are a minor constituent in Tertiary strata of the upper Texas Gulf Coast and were probably locally derived from Cretaceous rocks from the Central Texas platform.

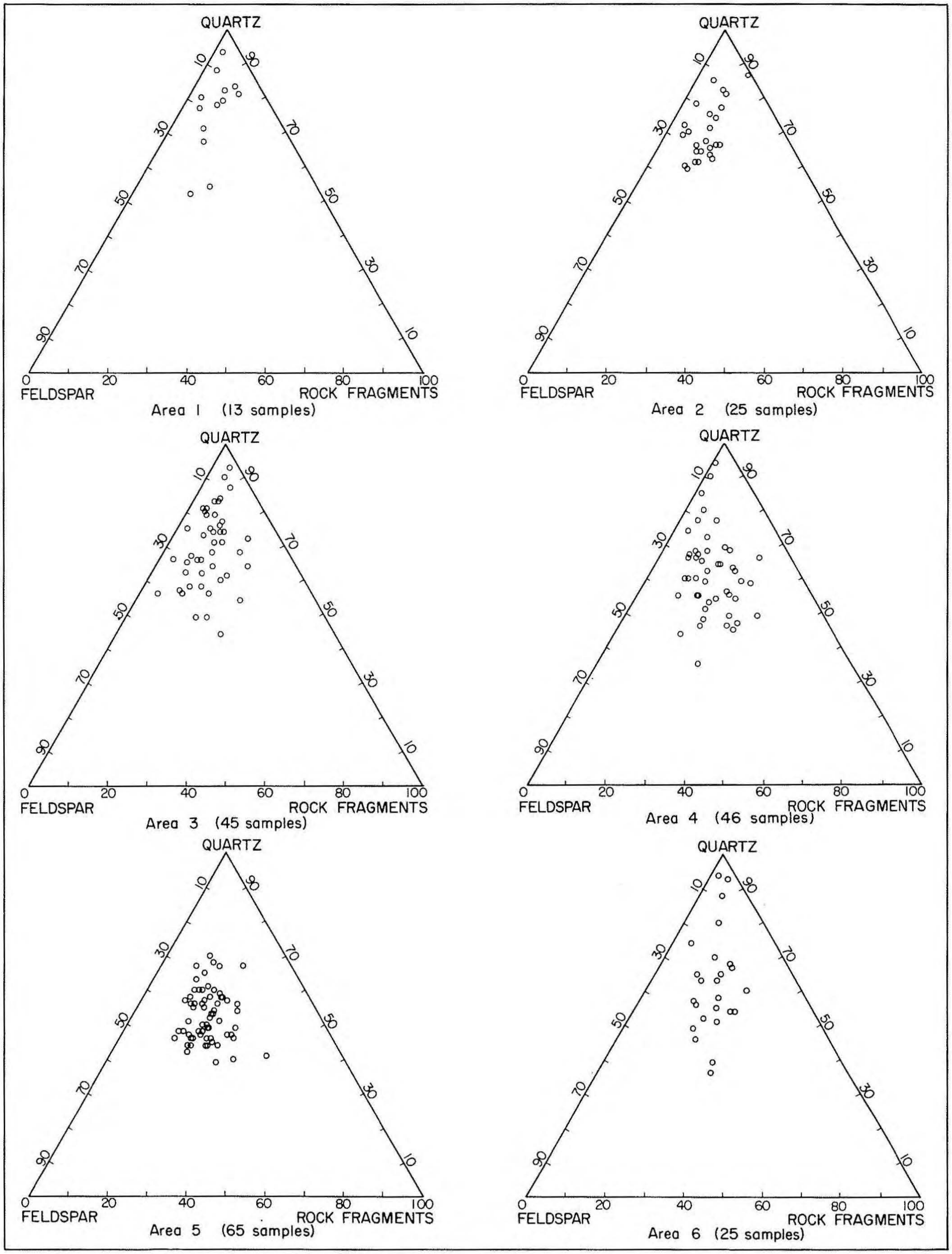


Figure 30. Basic data for Wilcox sandstone composition by area.

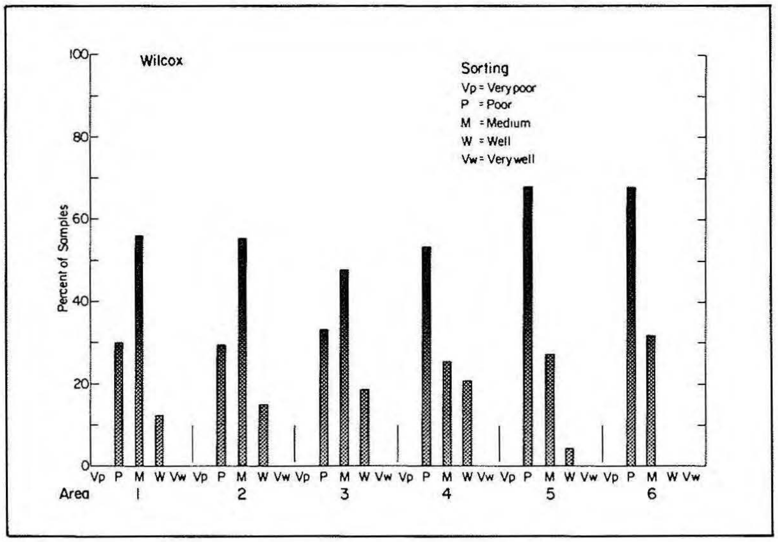


Figure 31. Distribution of sorting in Wilcox sandstones by area. Sorting was estimated visually using the criteria of Folk (1968).

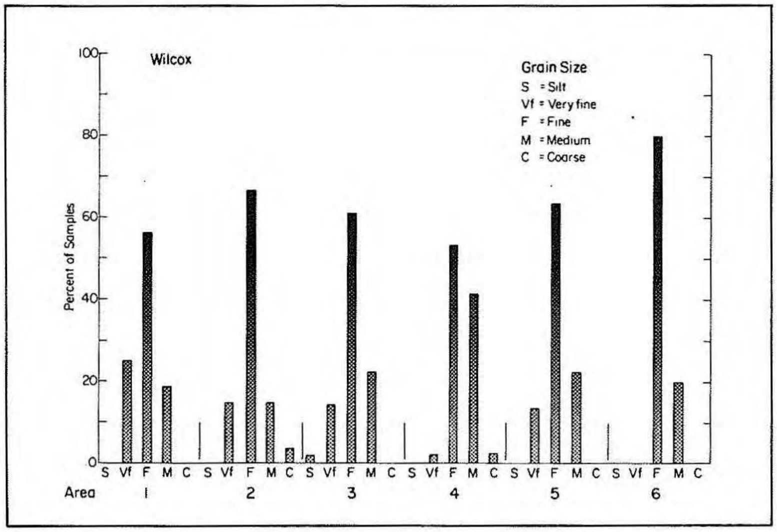


Figure 32. Distribution of grain size in Wilcox sandstones by area. Grain size was estimated visually using the Wentworth (1922) scale.

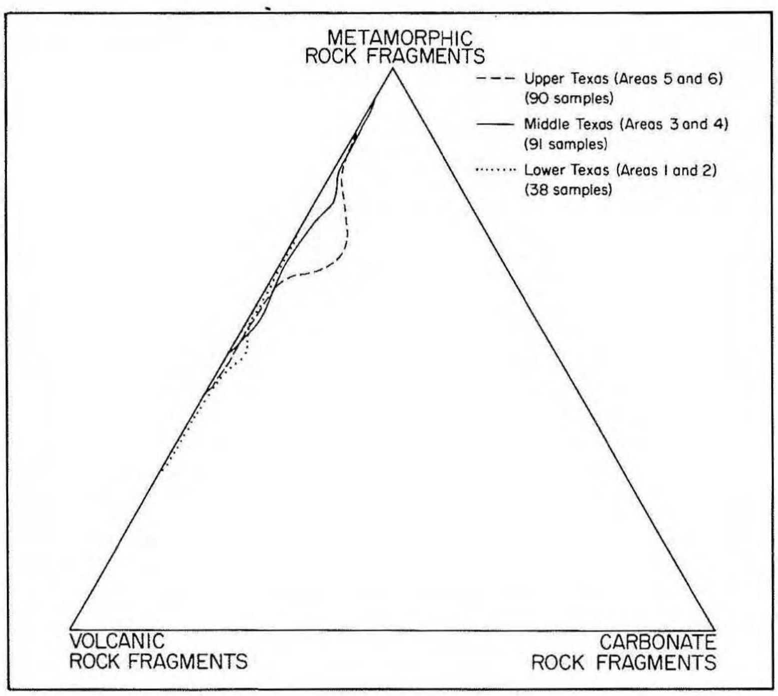


Figure 33. Wilcox sandstone rock fragment composition.

Trends in grain size, sorting, and quartz content must be considered separately for the upper and middle Texas Gulf Coast and for the lower Texas Gulf Coast. Wilcox sandstones may be slightly more mature in the middle than in the upper Texas Gulf Coast because of greater distance of transport and limited strike transport. The seemingly greater maturity of Wilcox sandstones in the lower Texas Gulf Coast is probably an artifact of a different source area.

Diagenesis

Diagenesis of Wilcox sandstones (fig. 34) progressed according to the general rock consolidation sequence outlined previously (fig. 27). Products in the intermediate subsurface, however, originated at shallower depths in the Wilcox sandstone than in other units, perhaps because of a higher thermal gradient in the Wilcox Group relative to other lower Tertiary units.

Todd and Folk (1957) described diagenesis in Wilcox outcrop samples from Bastrop County in Central Texas. They noted clay coats, abundant feldspar dissolution, feldspar overgrowths, and authigenic kaolinite booklets. Each of these alteration features commonly occurred during shallow subsurface diagenesis. No near-surface Fe-poor calcite replacement of feldspars, which is common in the shallow subsurface in other formations, was observed by Todd and Folk (1957) or during our study. Carbonate that has replaced feldspars or filled pores in dissolved feldspars in the Wilcox Group is Fe-rich and rarely occurs above a depth of about 2,440 m (8,000 ft). Feldspars may have been dissolved at the surface, but carbonate associated with them was precipitated in the intermediate subsurface.

Stanton (1977) studied a Wilcox core from the intermediate subsurface, 1,552 to 2,278 m (5,094 to 7,474 ft) deep, from Karnes County, Texas. He outlined a paragenetic sequence as follows: quartz overgrowths, kaolinite, Fe-poor calcite, dissolution, Fe-rich calcite, and dolomite. Stanton's observations are similar to those of this study for intermediate subsurface diagenetic features. However, we found no Fe-poor carbonate cement that precipitated after quartz overgrowths—only Fe-rich carbonate cements (fig. 34), and most kaolinite in our sequence formed after or during major dissolution, not before it.

Boles (1978), in a study of Wilcox sandstones of southwest Texas (Northeast Thompsonville field), recognized several stages of carbonate diagenesis. Calcite occurred to a depth of 2,300 m (7,600 ft), and ankerite (>20 mole percent iron) was present from 2,560 to at least 4,650 m (8,400 to 12,250 ft). Boles and Franks (1978) thought ankerite formed by addition of iron and magnesium to previously precipitated calcite. Our petrographic observations indicate ankerite is a pore-filling cement and not a replacement product.

Early-formed Fe-poor calcite is the first carbonate cement recognized by the general diagenetic sequence and has been observed by Fisher (1982) in the Wilcox sandstones. Of the Wilcox samples studied, 28 percent contain 5 percent or more carbonate cement relative to total rock volume. Samples from areas 1 and 3 have small amounts of carbonate cement, up to 15 percent, whereas samples from the northern areas, 5 and 6, have the largest amounts, up to 35 and 48 percent, respectively. Carbonate cement increases with depth, especially during the late Fe-rich carbonate stage that begins at about 2,600 m (8,500 ft) in depth. Above this depth, dissolution may have reduced the amount of carbonate cement. This late-formed carbonate cement helped destroy reservoir quality in the deep subsurface.

Twenty-six carbonate-cemented Wilcox sandstone samples from different depths were treated with potassium ferricyanide to detect iron and with alizarin red-S to differentiate calcite from dolomite and ankerite. Most carbonates took a dark-blue stain, indicating the presence of iron. Among examples of the last stage of Fe-rich cements, two types of blue stain were noted: a deep, true blue and a less intense, slightly greenish blue that stained carbonate cements that have highly undulose extinction and curved crystal faces. The greenish blue indicates the presence of ankerite, and the true blue, the presence of Fe-rich dolomite. Conclusions drawn from examining stains were verified by electron microprobe analysis.

Late-formed Fe-rich carbonate cements in four samples ranging in depths from 3,003 to 4,480 m (9,852 to 14,700 ft) were analyzed by electron microprobe for calcium, iron, and magnesium. These cements are predominantly Fe-rich dolomite $[Ca_{1.16-1.18}(Fe_{0.45-0.39}Mg_{0.55-0.61})_{0.84-0.82}(CO_3)_2]$ and less commonly ankerite $[Ca_{1.02}(Fe_{0.43}Mg_{0.57})_{0.98}(CO_3)_2]$.

As noted previously, kaolinite formed in two stages: first in the shallow subsurface and later in the intermediate subsurface. Most of the kaolinite precipitated during the intermediate subsurface stage of diagenesis. Petrographic evidence indicates that much of the kaolinite is associated with dissolved plagioclase and is probably an alteration product of the plagioclase. In general, kaolinite abundance and plagioclase abundance are inversely related on a regional scale. Replacement of kaolinite by chlorite was noted beginning at a depth of 2,960 m (9,700 ft).

Evidence of quartz overgrowths is first seen at depths of approximately 1,370 m (4,500 ft), but the overgrowths do not become common until depths of 1,830 m (6,000 ft). There is no direct relation between percentage of quartz grains and percentage of quartz overgrowths. A relation may exist, but the volume of quartz overgrowths may be inaccurate because of difficulty in recognizing them where they are not separated from quartz grains by clay coats.

Reservoir Quality

Vertical porosity distribution in the Wilcox Group (fig. 15) shows no regional trend. Plots of permeability values versus depth by geographic area indicate that area 3 has the highest maximum permeability values at all depths (fig. 35). Area 3 also has the best developed secondary dissolution porosity and the lowest percentage of quartz overgrowths.

Secondary dissolution porosity resulting from dissolution of feldspars and carbonate cements is the

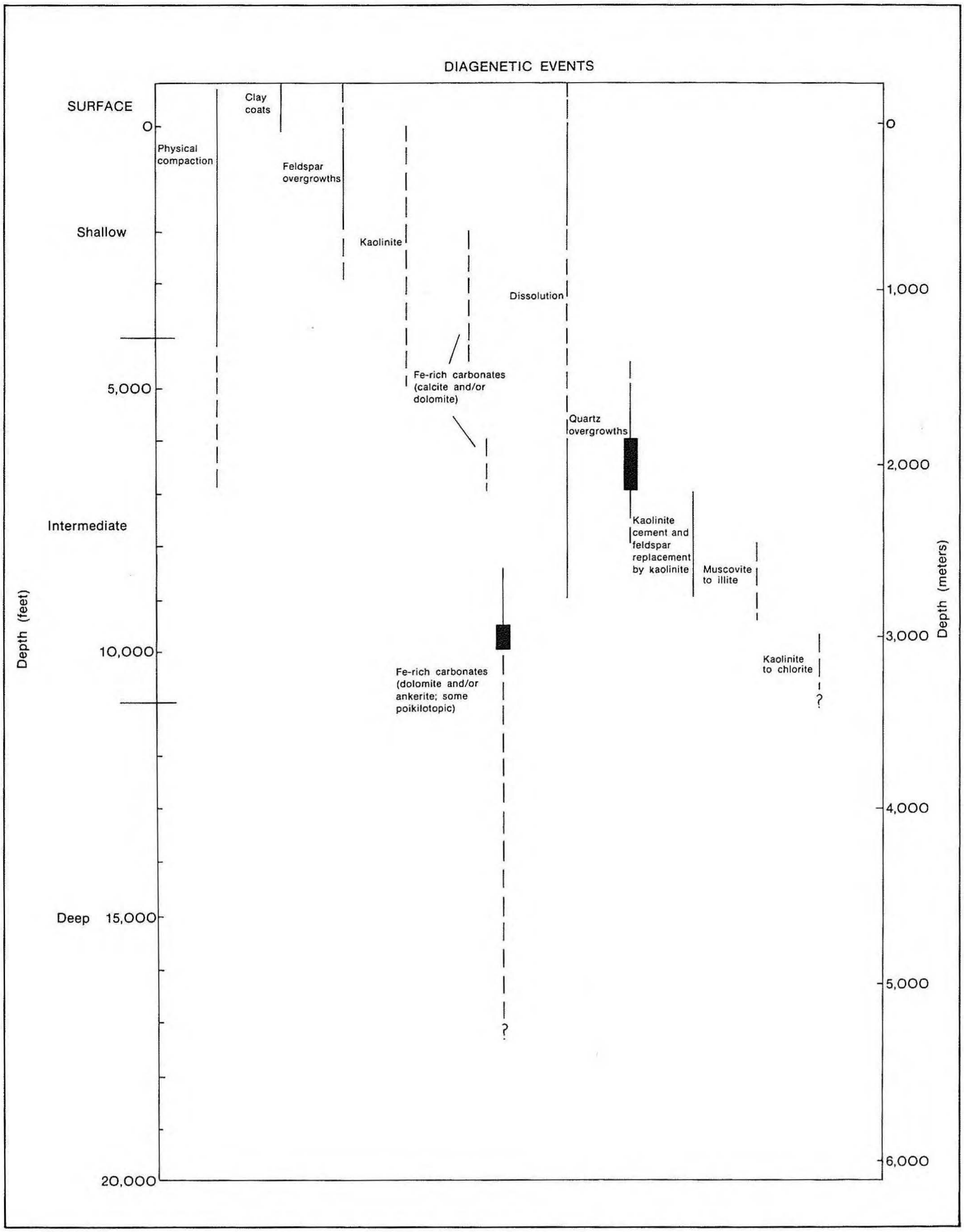


Figure 34. Diagenetic events versus depth for Wilcox sandstones.

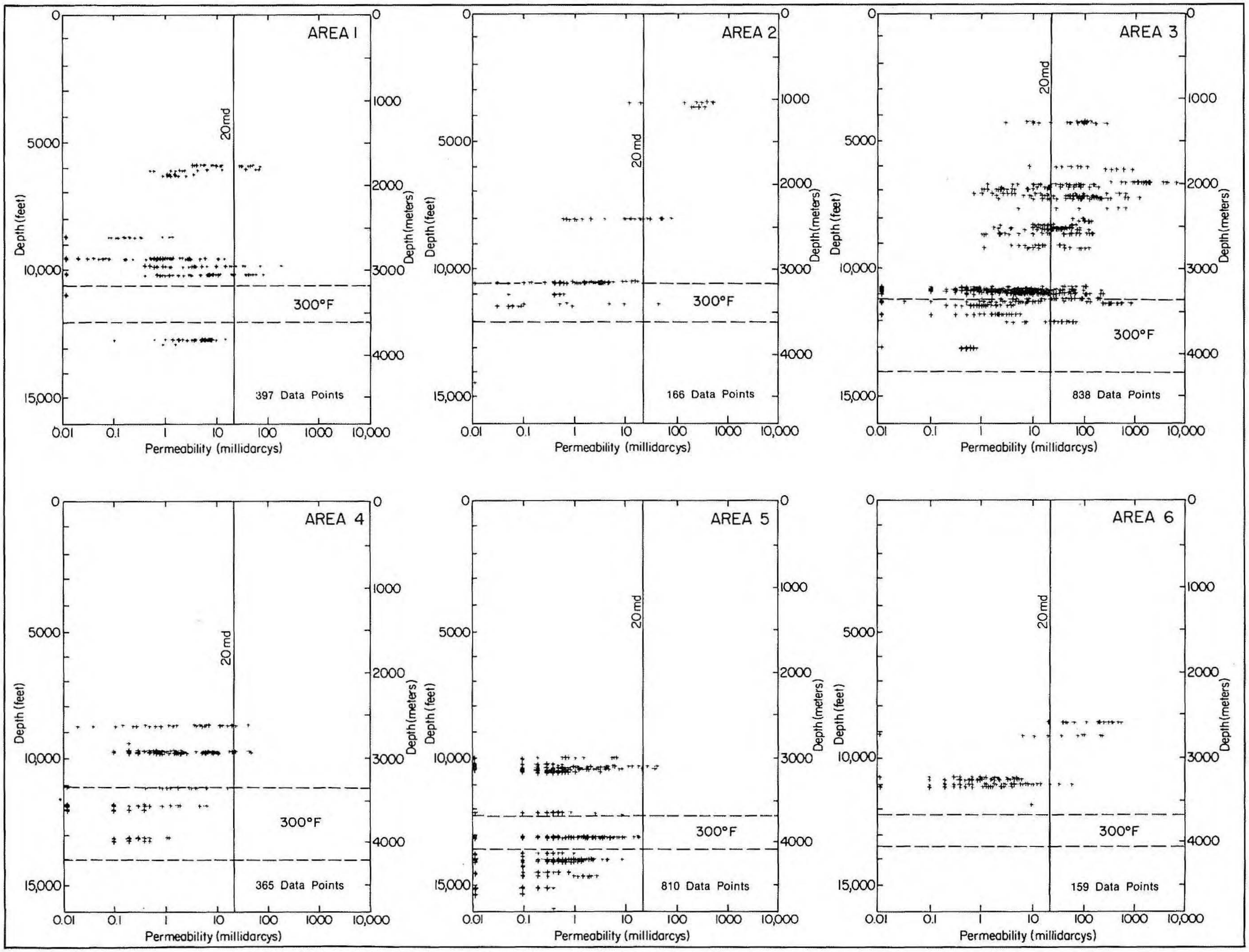


Figure 35. Permeability (core plugs from whole core) versus depth by area for Wilcox Group.

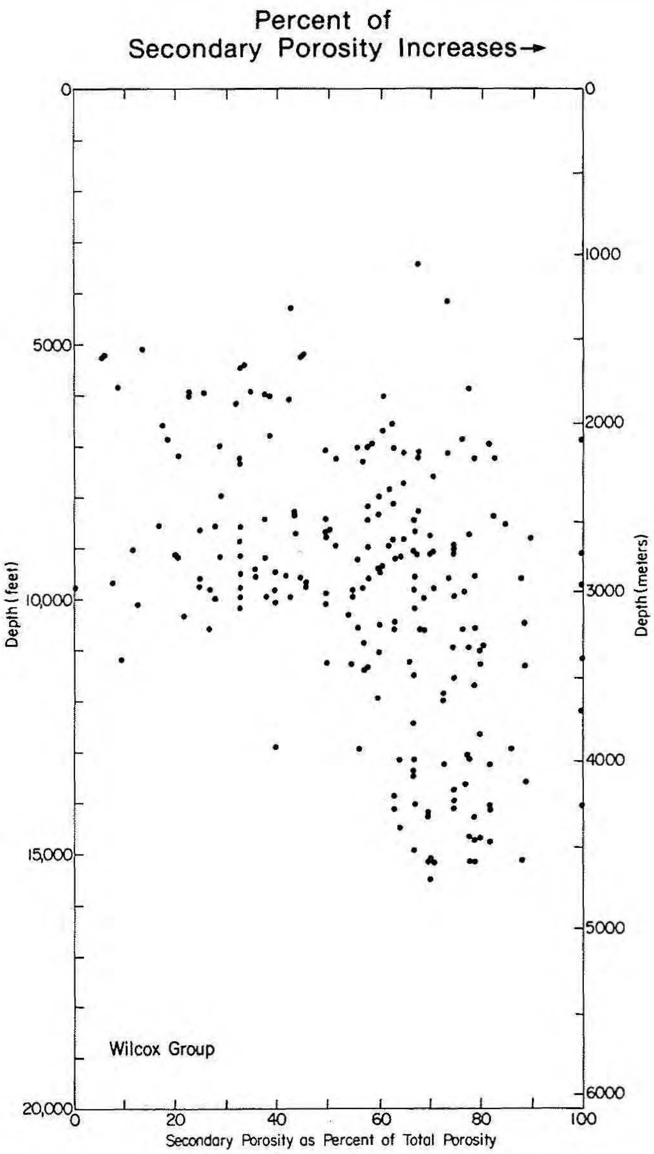


Figure 36. Secondary porosity as a percent of total porosity versus depth for Wilcox sandstones.

dominant porosity type in the Wilcox Group in the intermediate and deep subsurface (fig. 36). Analysis of primary and secondary porosity with depth shows that at 3,500 m (11,500 ft) primary porosity is less than 4 percent, whereas secondary porosity is as much as 10 percent.

Quartz cement is the major feature controlling reservoir quality in the Wilcox Group. It can be abundant enough to totally occlude pore spaces, and because it is less susceptible to dissolution than is carbonate cement, destruction of reservoir quality is virtually permanent. Carbonate cement, which does not necessarily permanently destroy a reservoir, does not cause as much porosity loss.

No strong regional trends in distribution of quartz and carbonate cements were observed in the Wilcox Group. This is probably because there is no significant regional variation in grain composition. Locally, porosity depends upon the extent of dissolution of feldspars and carbonate cement. More unstable

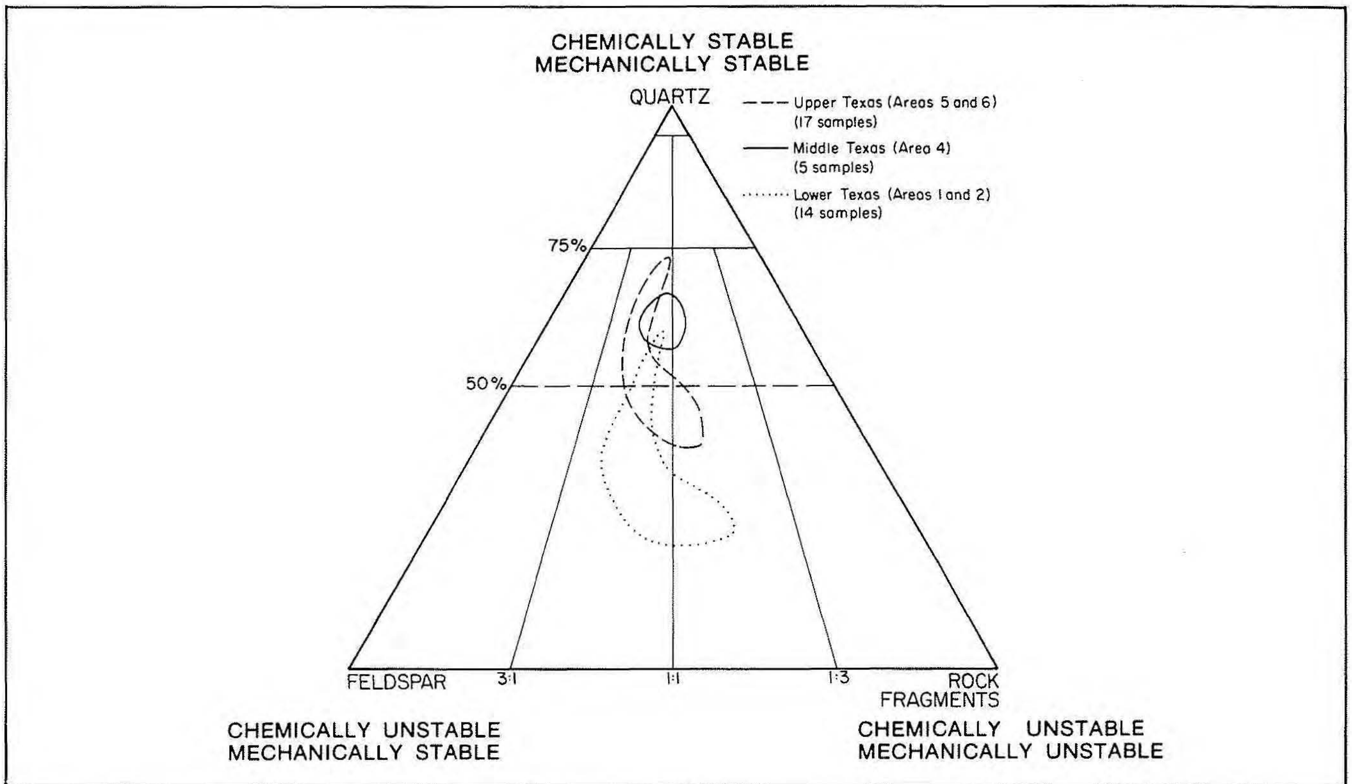


Figure 37. Yegua sandstone composition. Envelopes highlight typical compositional range.

components and less quartz result in development of more secondary porosity and, hence, greater total porosity.

Yegua Formation

Texture and Mineralogy

Sandstones of the Yegua Formation are moderately sorted, fine-grained lithic arkoses to quartzose lithic arkoses (figs. 37 through 40). They become richer in quartz from the lower to the upper Texas Gulf Coast. Along the lower Texas Gulf Coast, volcanic and carbonate rock fragments are the dominant rock fragment types (fig. 41). Volcanic rock fragments are similar in appearance to those in the Frio Formation and are probably rhyolitic. Along the middle and upper Texas Gulf Coast, rock fragments are composed of approximately equal amounts of metamorphic and volcanic rock fragments, whereas carbonate rock fragments are rare (fig. 41). Metamorphic rock fragments are similar to those in the Wilcox Group. Carbonate rock fragments are composed of micrite, which is probably eroded caliche fragments. The appearance of caliche clasts in the Yegua Formation might indicate a major change in climate from that during deposition of the Wilcox sediments. During Wilcox time the entire Texas coast area was probably subtropical; beginning in Yegua time the climate may have become increasingly like the present pattern—subarid along the lower Texas Gulf Coast to subhumid along the upper Texas Gulf Coast. Texturally, Yegua sandstones decrease slightly in grain size from the lower to the upper Texas Gulf Coast, but no sorting trends are apparent (figs. 39 and 40).

The source of metamorphic and volcanic rock fragments in the Yegua Formation was probably the same as that for the Wilcox Group. Caliche fragments had to have been locally derived because they would not have survived long transport distances.

Diagenesis

In the shallow subsurface, feldspars were dissolved and replaced with Fe-poor calcite (fig. 42). Much of this early-formed calcite associated with feldspars was dissolved in the intermediate subsurface, and only a few percent remain deeper than 1,830 m (6,000 ft). Also in the shallow subsurface, minor amounts of feldspar overgrowths, authigenic kaolinite, and pore-filling Fe-rich calcite or dolomite were precipitated.

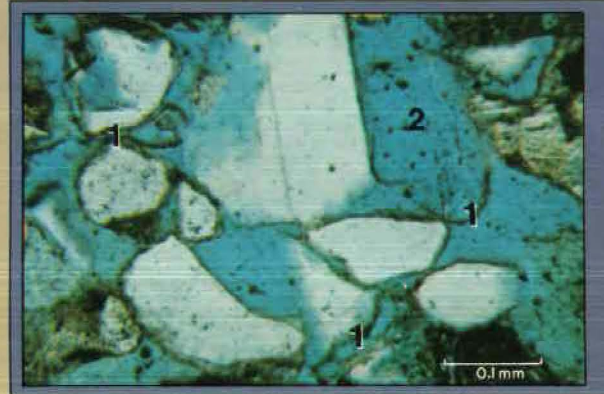
Precipitation of Fe-rich carbonate continued during subsidence into the intermediate subsurface. It also filled some dissolution pores within the early-formed calcite that replaced feldspar grains. Carbonate cement in the Yegua Formation is most abundant along the

Generalized rock consolidation sequence with increasing depth for Tertiary formations of the Texas Gulf Coast. Pore spaces are filled with blue-dyed epoxy.

Increasing Depth

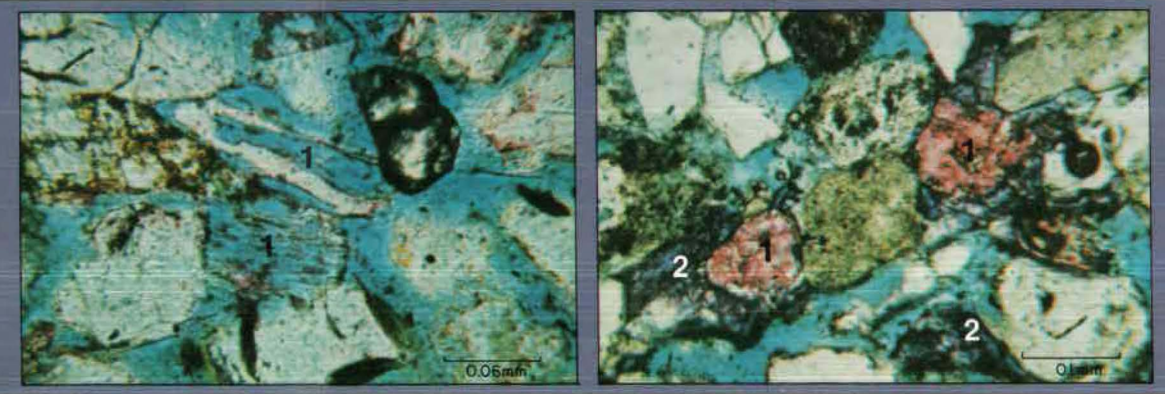
Sand Deposition

Clay Coats



a. Smectite coats (1) around grains. Note shallow subsurface secondary porosity (2). Frio Formation, Continental No. D-2 Clara Driscoll (781 m; 2,561 ft), Duval County, Texas.

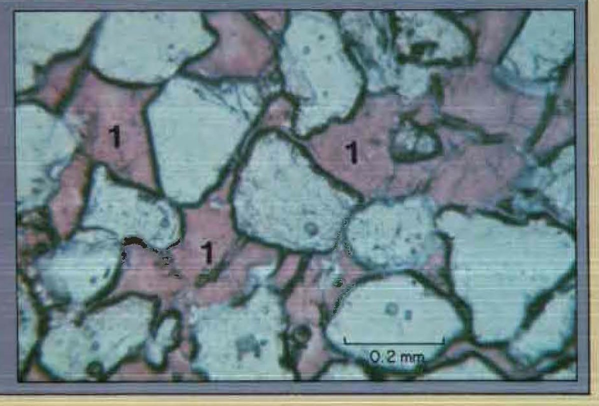
Shallow Feldspar Leaching and Replacement by Calcite



b. Shallow subsurface leaching of plagioclase grains (1). Wilcox Group, Abercrombie No. 1 Tyler (1,045 m; 3,429 ft), McMullen County, Texas.

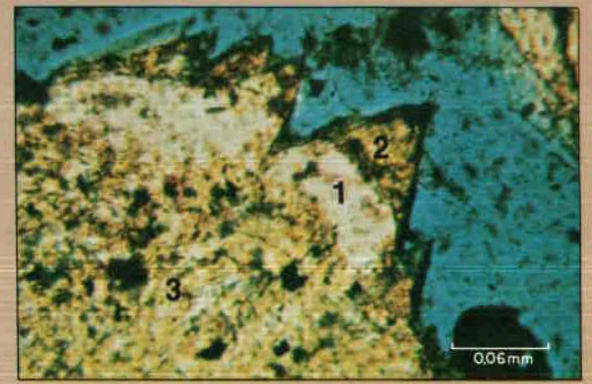
c. Replacement of feldspar grains by Fe-poor calcite (stained red; 1). Later calcite cement is Fe-rich (stained blue; 2). Frio Formation, Continental No. D-2 Clara Driscoll (781 m; 2,561 ft), Duval County, Texas.

Fe-poor Calcite Cement



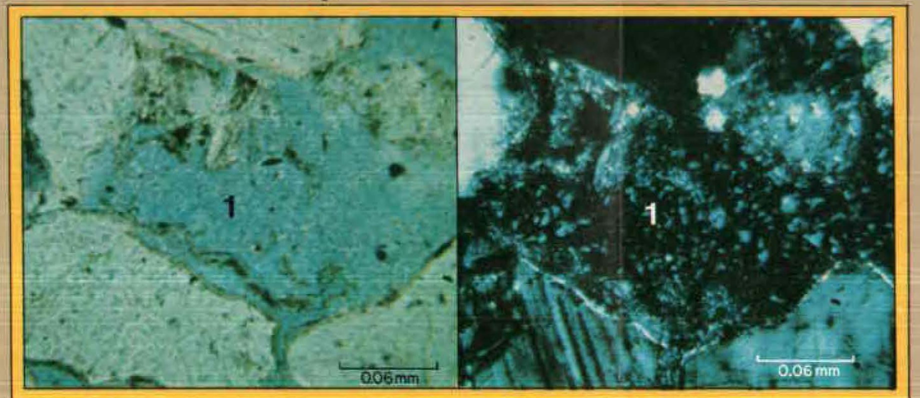
d. Poikilotopic Fe-poor calcite cement (1). Miocene, Sun No. 1 Winfree (681 m; 2,234 ft), Chambers County, Texas.

Feldspar Overgrowths



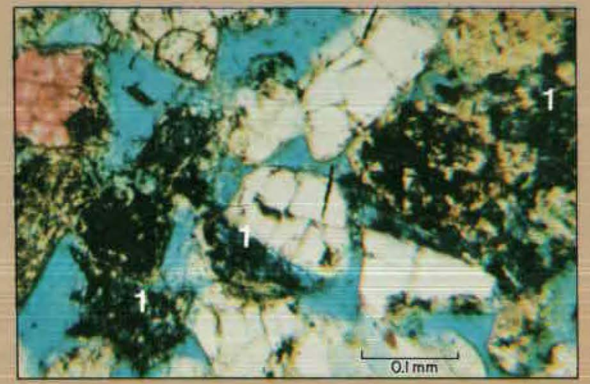
e. Plagioclase overgrowth (1) followed by orthoclase overgrowth (2) on a volcanic rock fragment (3). Frio Formation, Miller and Fox No. 6 Garcia (920 m; 3,017 ft), Jim Wells County, Texas.

Early Kaolinite Cement



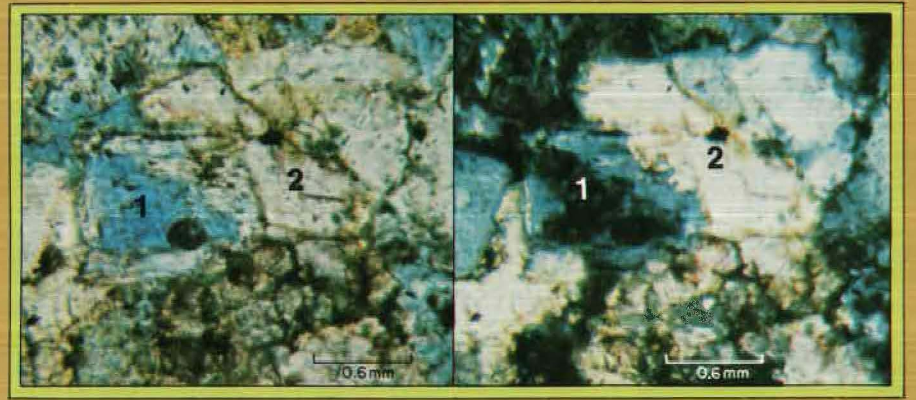
f. Plane light *and* **g.** Polarized light. Authigenic kaolinite (1) in leached pore. Frio Formation, Continental No. D-2 Clara Driscoll (781 m; 2,561 ft), Duval County, Texas.

Fe-rich Calcite or Dolomite Cement



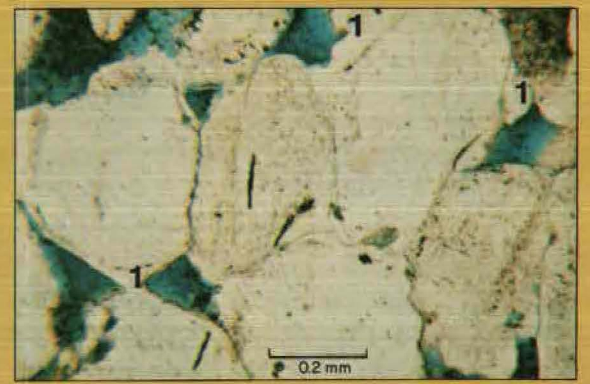
h. Fe-rich calcite cement (stained blue; 1). Yegua Formation, Continental No. 7 Ben Mew (1,074 m; 3,522 ft), Duval County, Texas.

Pre-Quartz Overgrowth Leaching



i. Plane light *and* **j.** Polarized light. Leaching of plagioclase (1) after calcite cement (2). Wilcox Group, Seaboard No. 1 Kulodjiejezyk (1,591 m; 5,220 ft), Karnes County, Texas.

Quartz Overgrowths

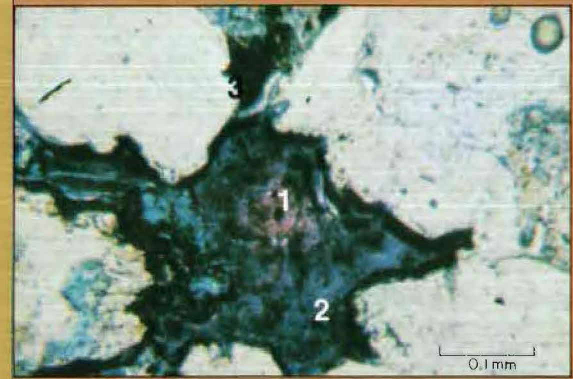


k. Quartz overgrowths (1). Wilcox Group, Pure No. 1 Frieda Vogelsang (3,032 m; 9,948 ft), Colorado County, Texas.

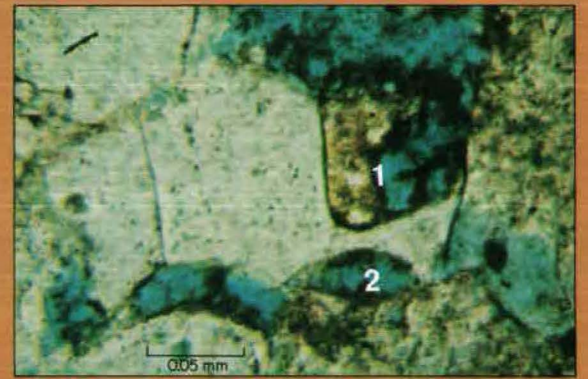
Fe-poor Calcite or Fe-rich Calcite or Dolomite Cement

l. Fe-poor calcite cement (stained red; 1) after quartz overgrowth (2). Vicksburg Formation, Shell No. 8 Woods Christian (2,930 m; 9,612 ft), Hidalgo County, Texas.

Post-Quartz Overgrowth Leaching

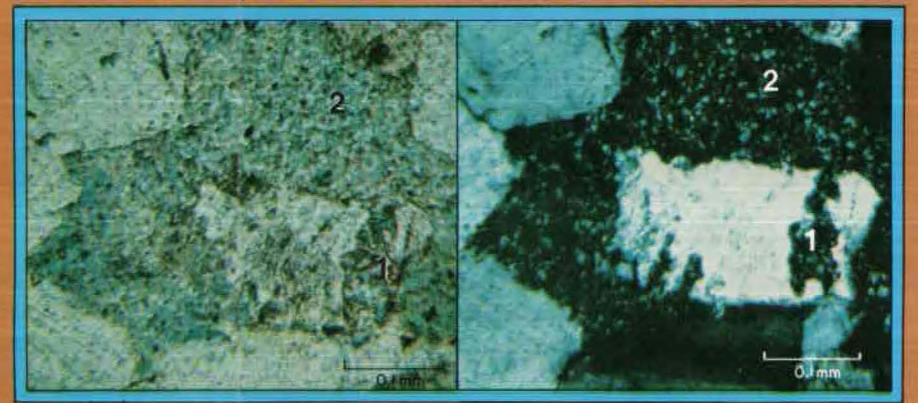


m. Partly leached Fe-poor calcite (stained red; 1) surrounded by Fe-rich dolomite or ankerite (stained blue; 2). Quartz overgrowths (3) preceded Fe-poor calcite. Frio Formation, Phillips No. 1 Houston "GG" (4,517 m; 14,821 ft), Brazoria County, Texas.



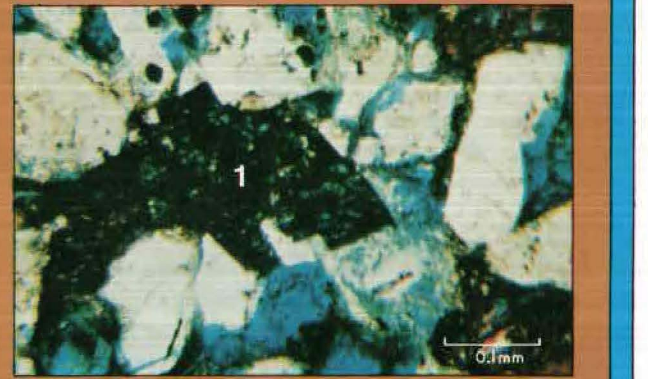
n. Leaching of orthoclase (stained yellow; 1) after quartz overgrowth leaving an embayment. Note other embayment in quartz overgrowth (2). Wilcox Group, Pure No. 1 Frieda Vogelsang (2,520 m; 8,268 ft), Colorado County, Texas.

Kaolinite Cement and Feldspar Replacement by Kaolinite



o. Plane light *and* **p.** Polarized light. Leached plagioclase (1) and primary porosity (2) filled in by authigenic kaolinite. Frio Formation, Phillips No. 1 Houston "GG" (4,539 m; 14,891 ft), Brazoria County, Texas.

Fe-rich Dolomite and Ankerite Cement



q. Euhedral Fe-rich dolomite or ankerite cement (1) with curved crystal faces. Vicksburg Formation, Shell No. 2 Lips (4,139 m; 13,578 ft), Brooks County, Texas.

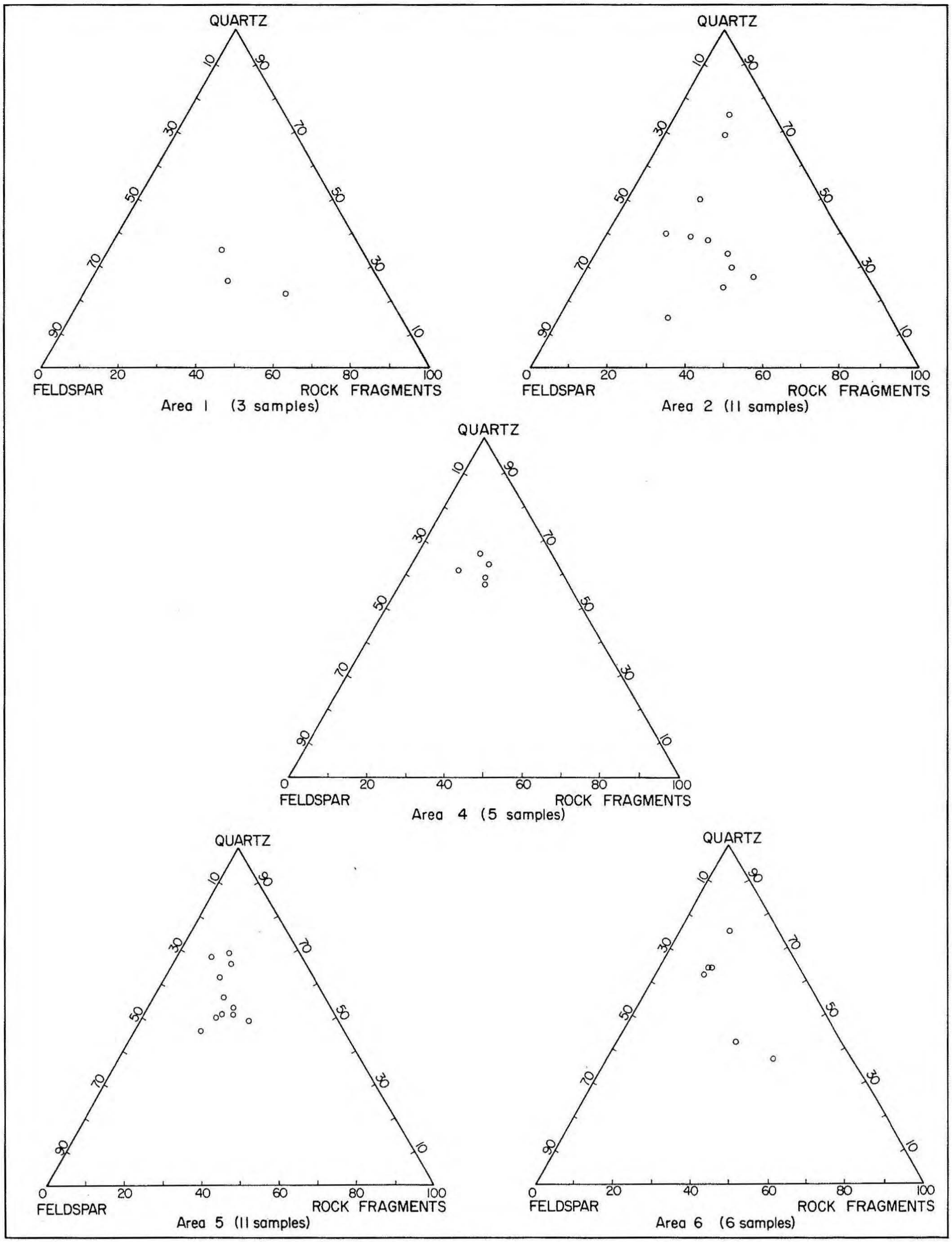


Figure 38. Basic data for Yegua sandstone composition by area.

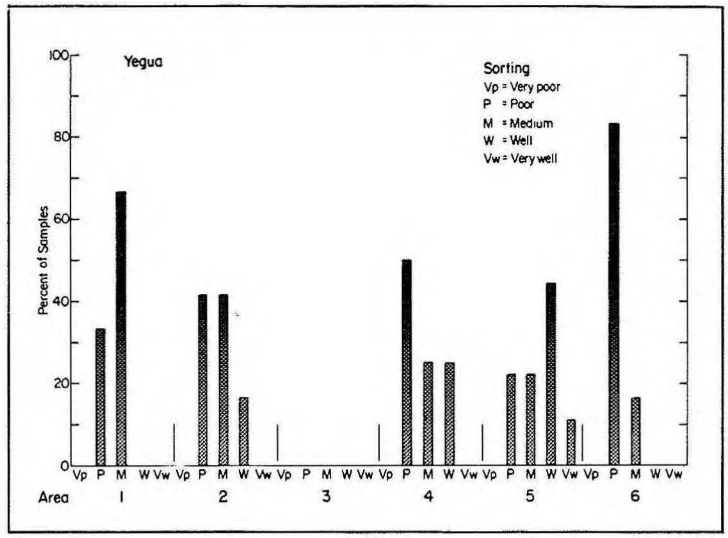


Figure 39. Distribution of sorting in Yegua sandstones by area. Sorting was estimated visually using the criteria of Folk (1968).

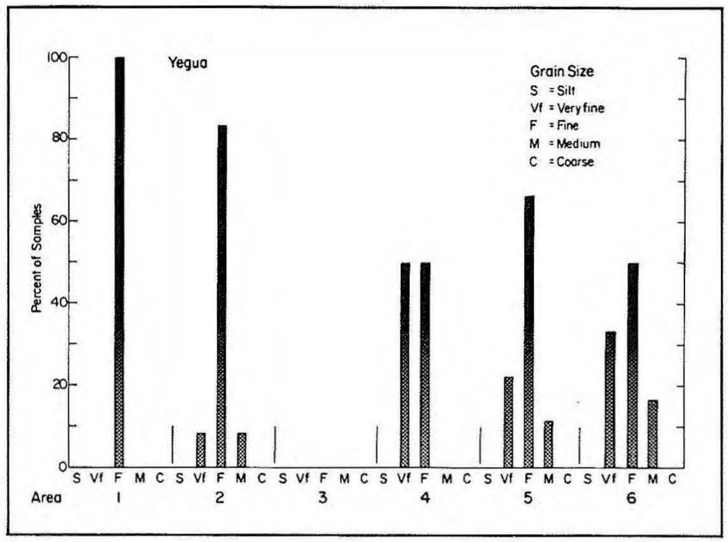


Figure 40. Distribution of grain size in Yegua sandstones by area. Grain size was estimated visually using the Wentworth (1922) scale.

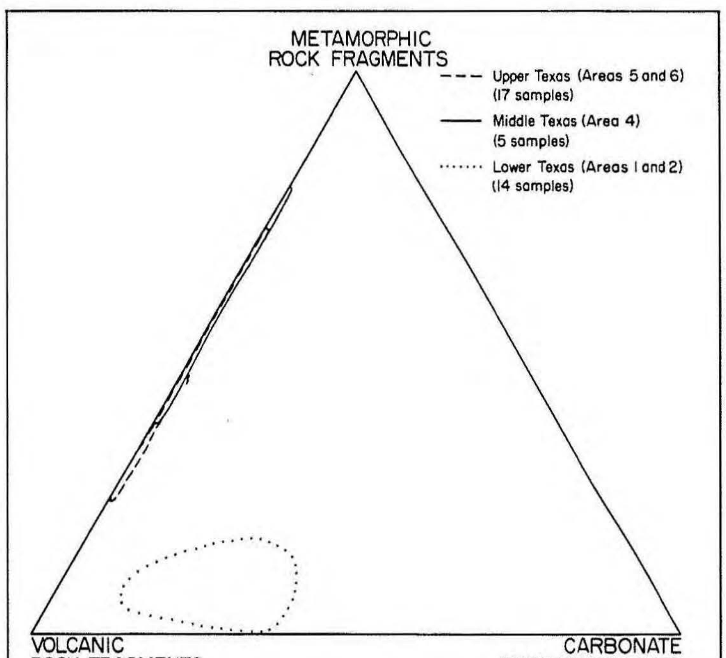


Figure 41. Yegua sandstone rock fragment composition.

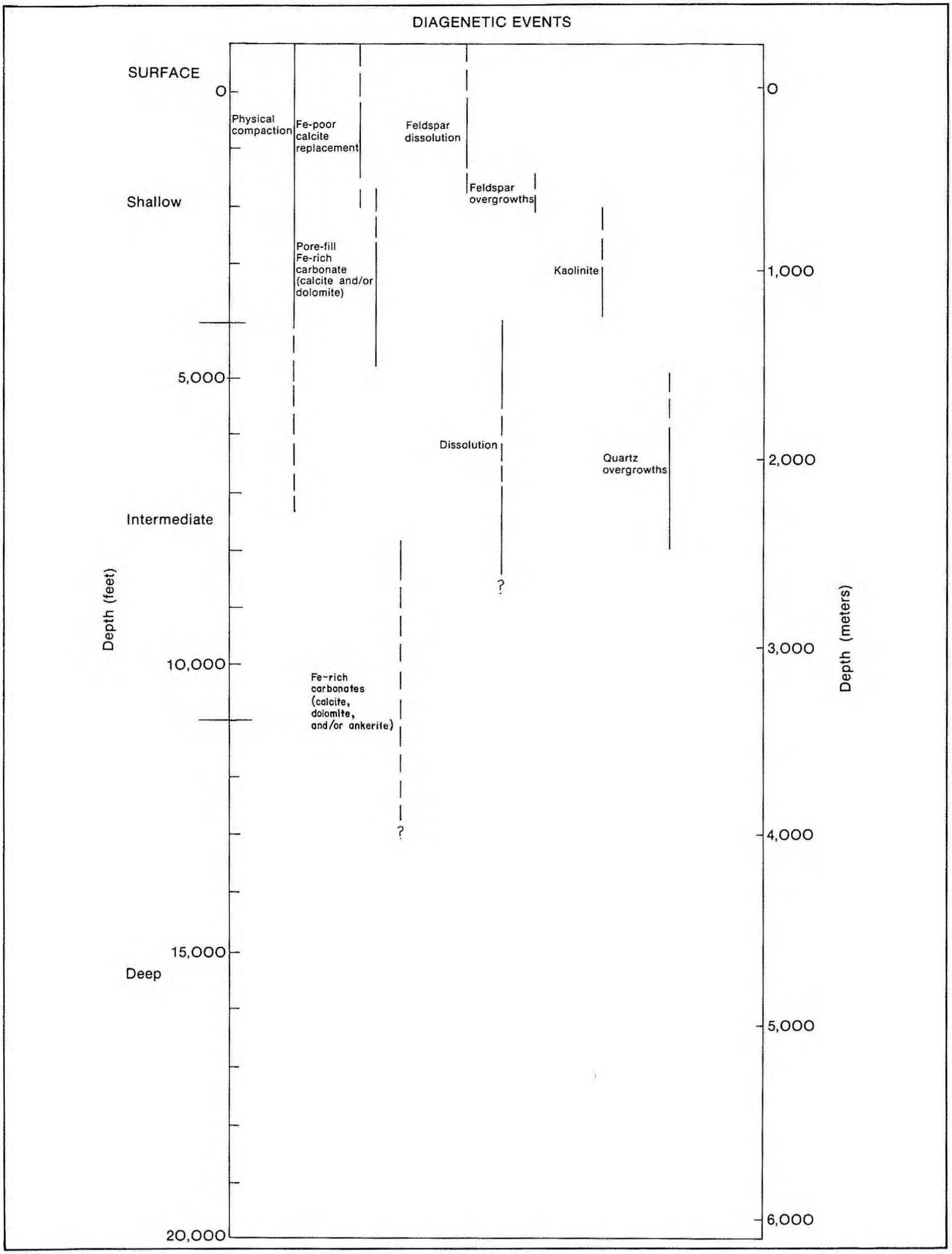


Figure 42. Diagenetic events versus depth for Yegua sandstones.

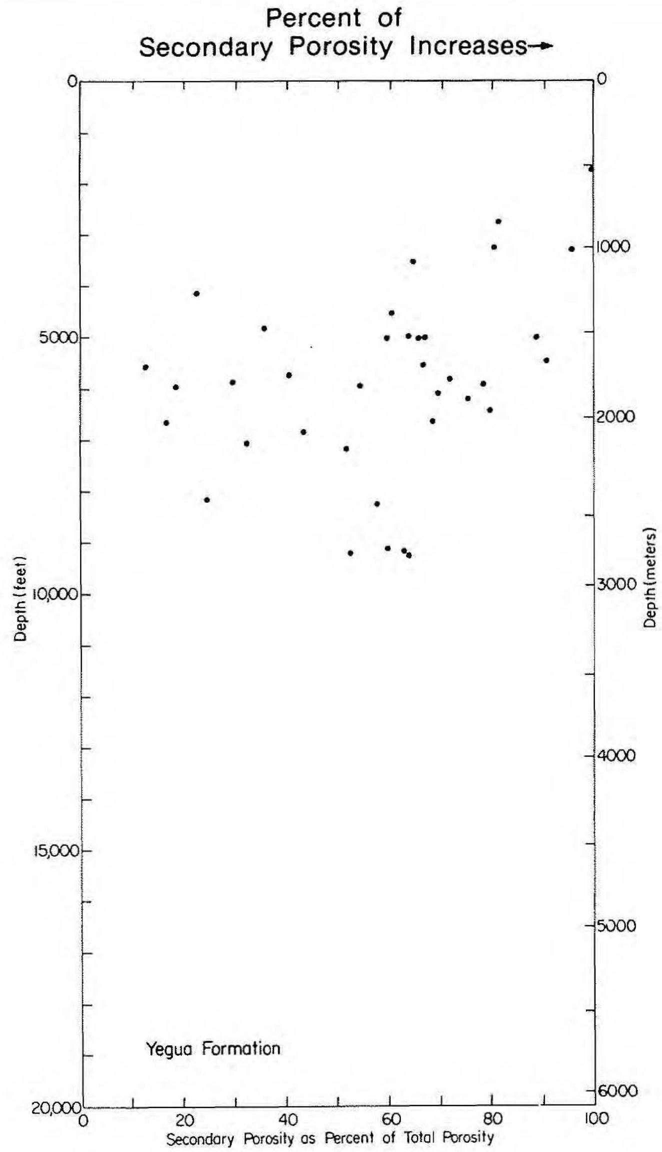


Figure 43. Secondary porosity as a percent of total porosity versus depth for Yegua sandstones.

lower Texas Gulf Coast and coincides with the occurrence of carbonate rock fragments. A similar relation occurs in the Vicksburg and Frio Formations.

Dissolution that preceded quartz overgrowths attacked feldspars and earlier-formed carbonate cements. Quartz overgrowths began to precipitate after dissolution at 1,370 m (4,500 ft) and are common by 1,980 m (6,500 ft). In the dissolution stage after quartz overgrowths, feldspars and calcite that replaced feldspars in the shallow subsurface decreased markedly in abundance.

The last stage of diagenesis in the intermediate subsurface was Fe-rich carbonate cementation. No samples from the deep subsurface Yegua were available because of lack of well control and because the Yegua sandstones grade into mudstone at depths greater than 3,350 m (11,000 ft).

Reservoir Quality

Porosity abundance in the Yegua Formation is intermediate between that of the Vicksburg Formation and the Wilcox Group. In the intermediate subsurface, primary porosity is as common as secondary porosity (fig. 43). Secondary porosity resulted from dissolution of feldspars and carbonate cements. Late-formed Fe-rich carbonate cement somewhat lessened porosity, but

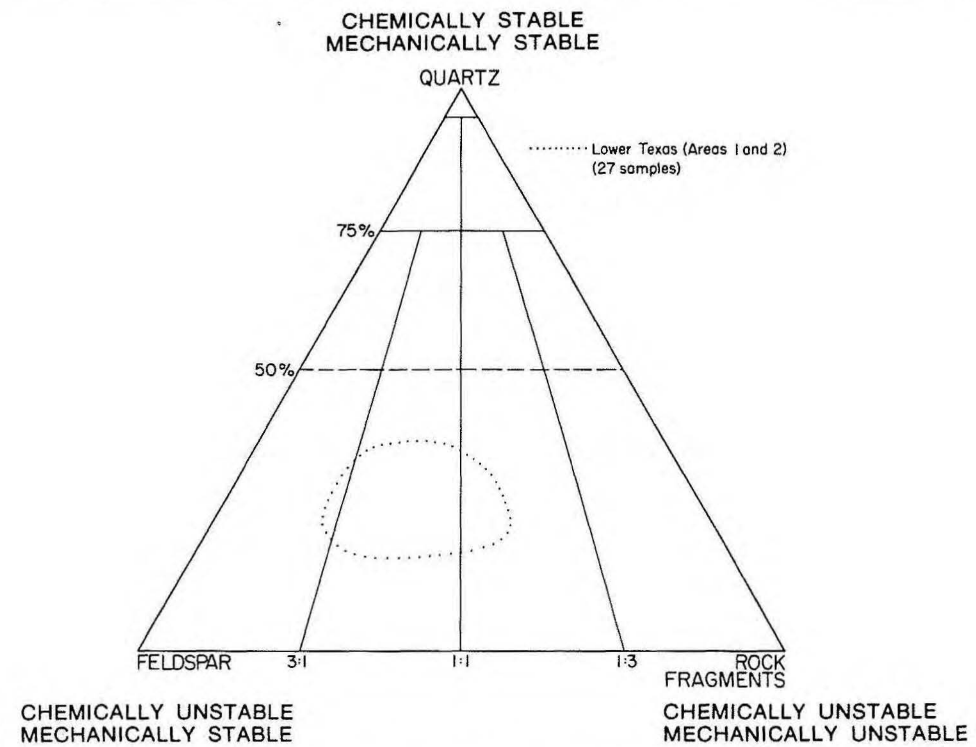


Figure 44. Vicksburg sandstone composition. Envelopes highlight typical compositional range.

quartz overgrowths were the major porosity-reducing factor at depth. With deeper burial, Fe-rich carbonate cement, which was probably still being precipitated, could have reduced porosity.

Vicksburg Formation

Texture and Mineralogy

Vicksburg sandstones were sampled from the lower Texas Gulf Coast region (areas 1 and 2) where the only deep, massive sandstones in this formation occur (Loucks, 1978). These sandstones are poorly sorted, fine-grained lithic arkoses (figs. 44 through 47). Rock fragments are mainly volcanic clasts, which resulted from more extensive volcanism in West Texas and in Mexico during Vicksburg time (fig. 48); lesser amounts of carbonate and metamorphic rock fragments are present (fig. 49). The ancient Rio Grande transported this volcanic sediment into the rapidly subsiding Rio Grande Embayment in the lower Texas Gulf Coast region (fig. 48). Carbonate rock fragments are eroded caliche clasts similar to those in the Yegua and Frio Formations and indicate continued arid conditions along the lower Texas Gulf Coast. The Rocky Mountain area may have been the source of the metamorphic rock fragments.

Diagenesis

Of the 27 samples from the Vicksburg Formation, 25 are from depths of 2,440 m (8,000 ft) or more (fig. 3); thus, direct information on diagenesis shallower than 2,440 m (8,000 ft) in this formation is unavailable. Rock composition and paragenetic sequences in the Vicksburg Formation are similar to those in the Frio Formation along the lower Texas Gulf Coast. Detailed diagenetic studies of the Vicksburg sandstones and shales were completed by Richmann and others (1980), Klass and others (1981), and Loucks and others (1981).

Diagenetic products in Vicksburg sandstones (fig. 50) record essentially the same events as does the general lower Tertiary diagenetic sequence (fig. 27), with the exception of a minor amount of laumontite cement (Loucks and others, 1981) that precipitated during shallow subsurface diagenesis and the relative rarity of kaolinite. Early-formed Fe-poor calcite replaced plagioclase, and a late stage of Fe-poor calcite formed after quartz overgrowths. Quartz overgrowths generally constitute less than 3 percent of rock volume because of the low volume of quartz grain nuclei. Dissolution following quartz precipitation was a major stage of reservoir development in the subsurface, but the secondary porosity resulting from dissolution of feldspars, volcanic rock fragments, and carbonate

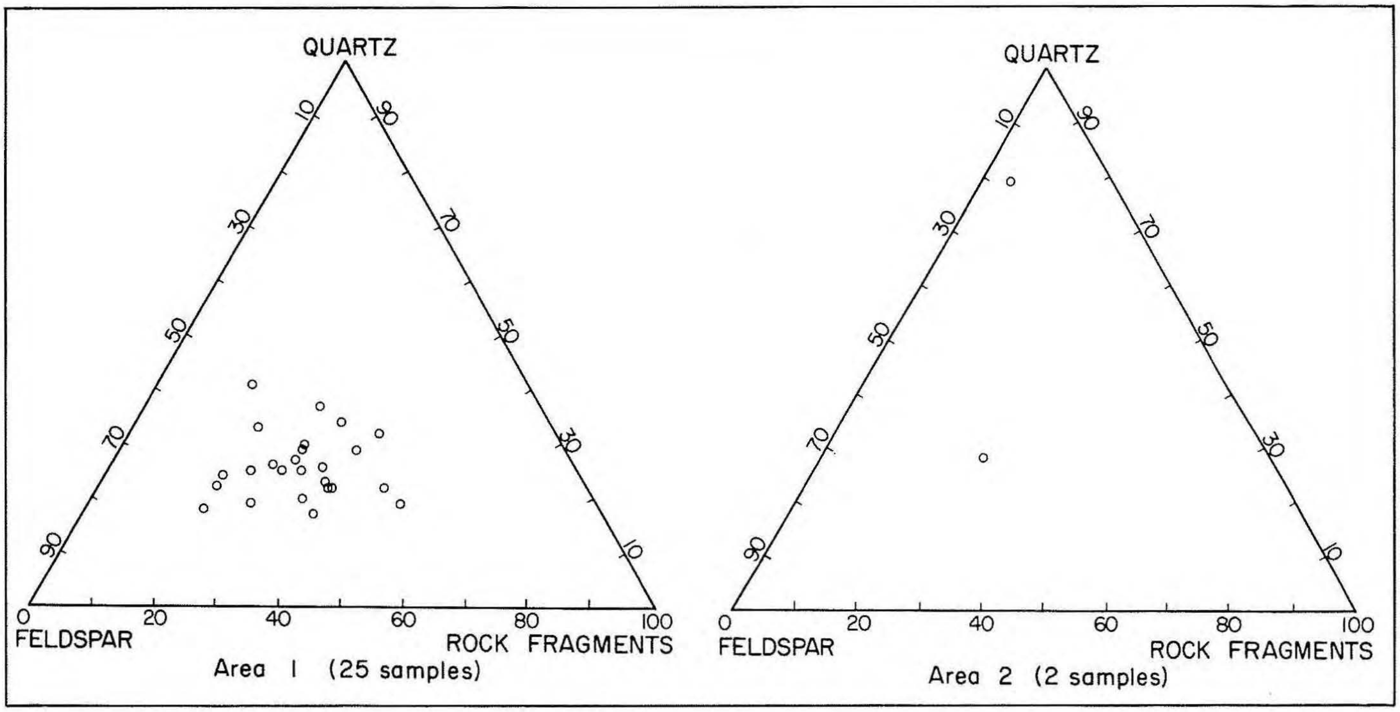


Figure 45. Basic data for Vicksburg sandstone composition by area.

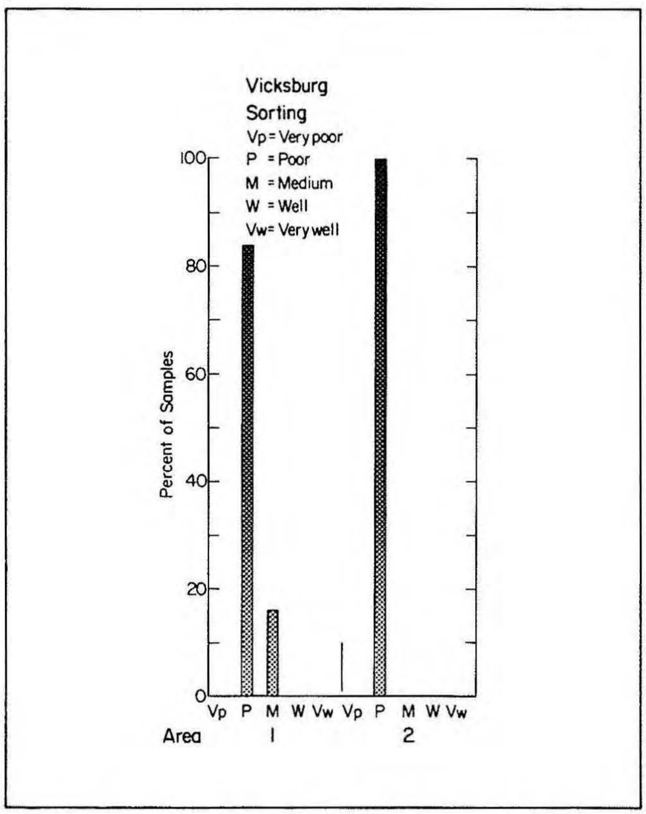


Figure 46. Distribution of sorting in Vicksburg sandstones by area. Sorting was estimated visually using the criteria of Folk (1968).

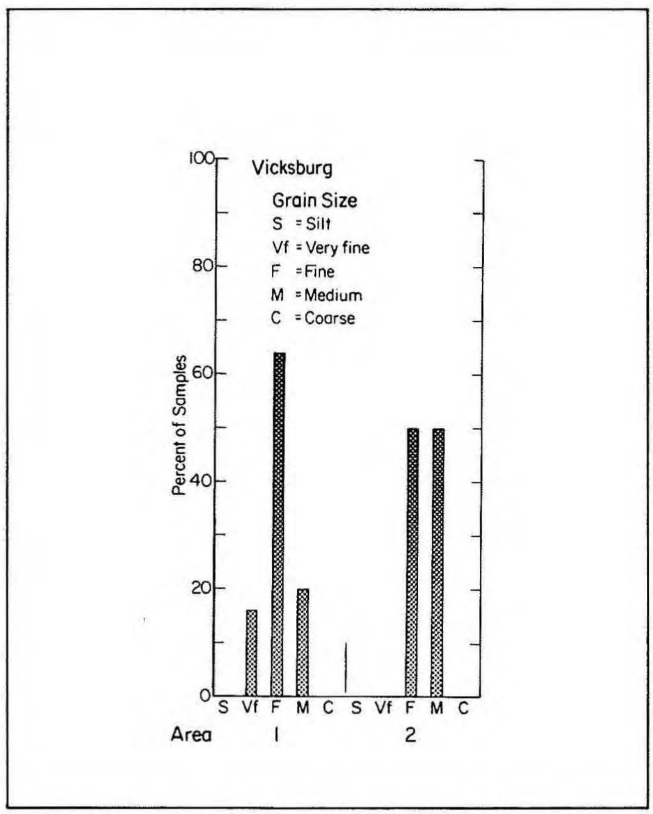


Figure 47. Distribution of grain size in Vicksburg sandstones by area. Grain size was estimated visually using the Wentworth (1922) scale.

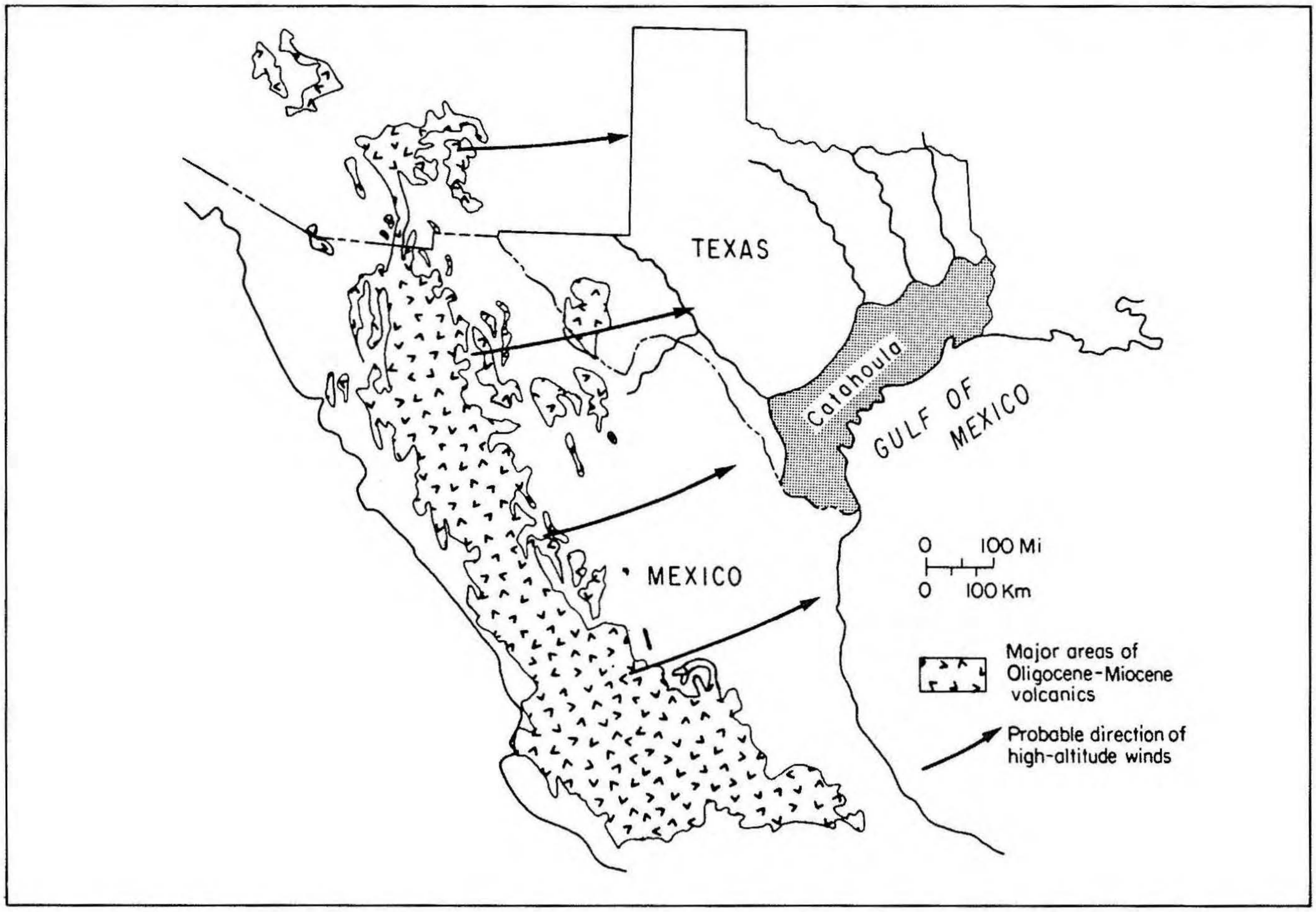


Figure 48. Source areas for sediments of the Vicksburg and Frio Formations. Adapted from Cook and Bally (1975) and Galloway (1977).

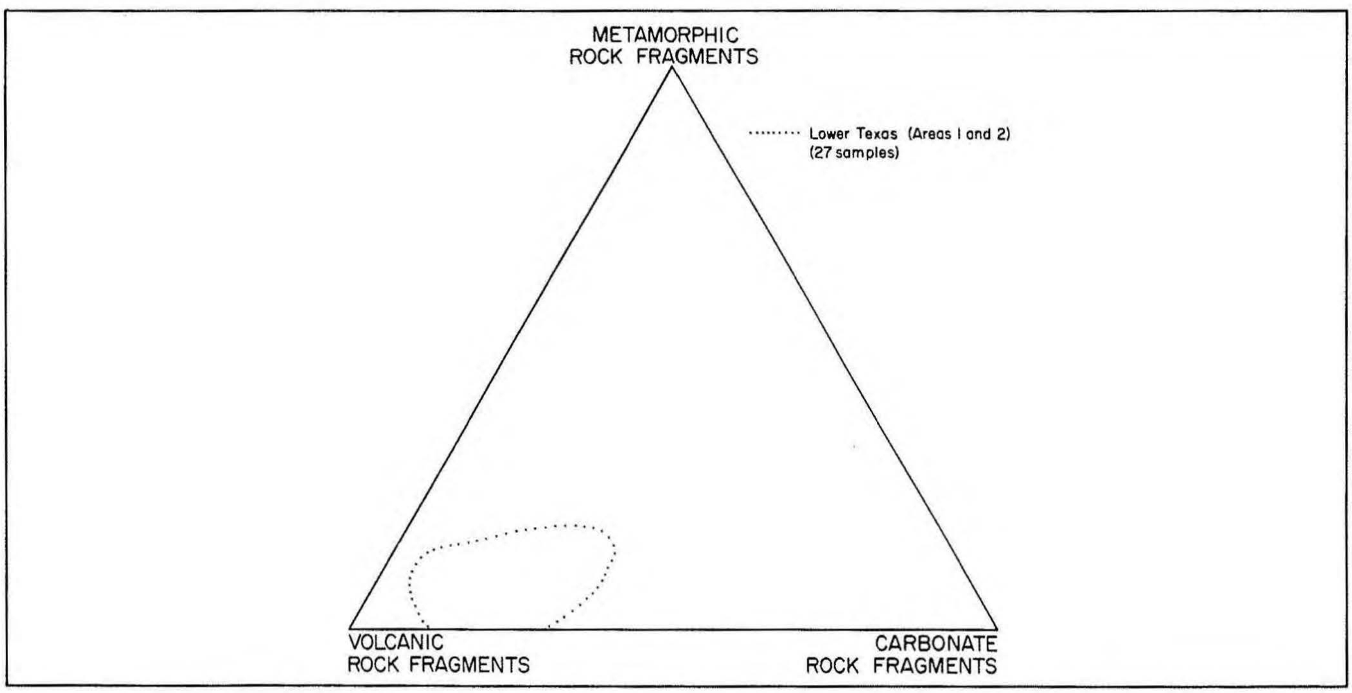


Figure 49. Vicksburg sandstone rock fragment composition.

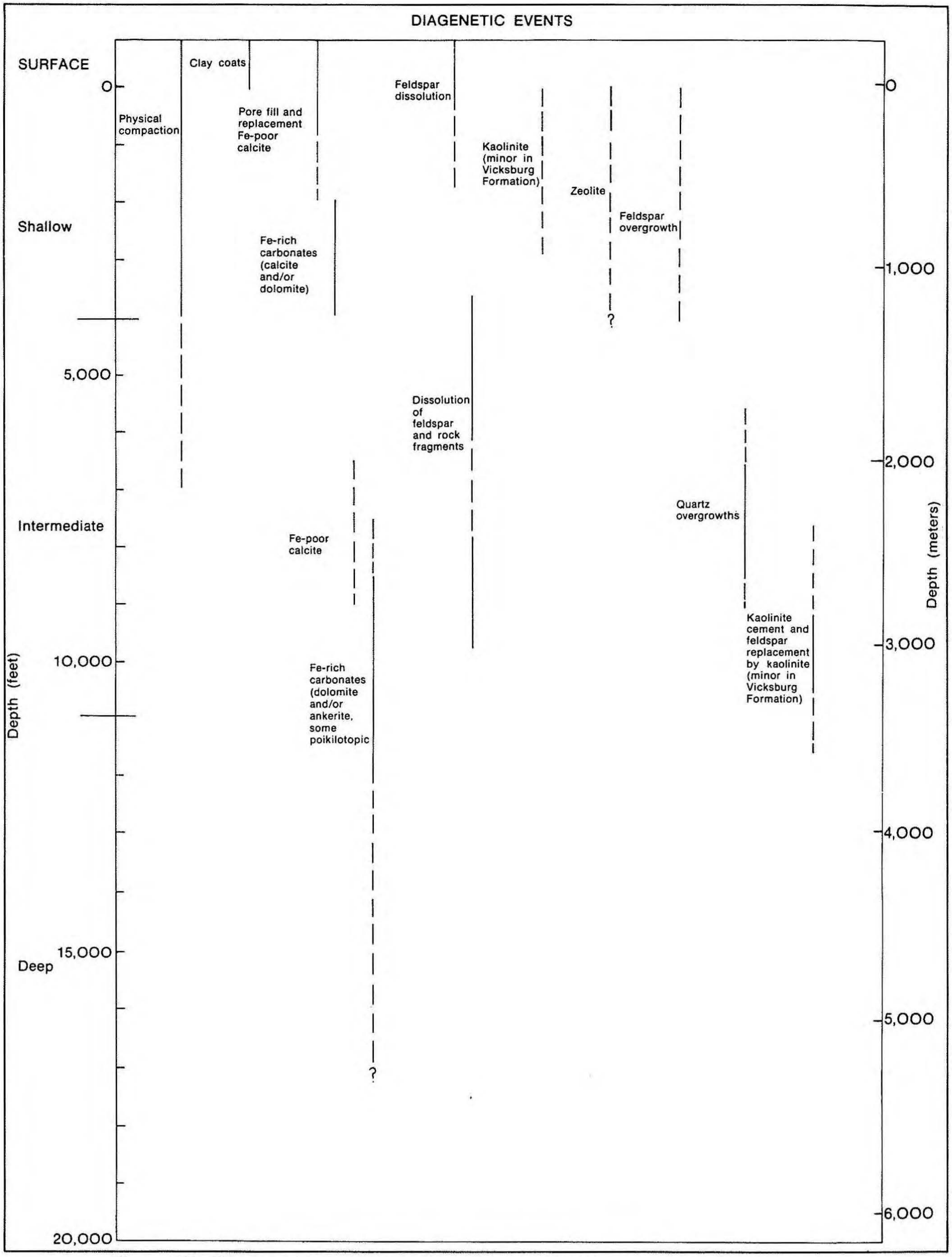


Figure 50. Diagenetic events versus depth for Vicksburg and Frio sandstones.

cements has been destroyed in most samples by late-formed, Fe-rich carbonate cement. Overall, a chemically and mechanically unstable mineralogy along with a high geothermal gradient in the Vicksburg Formation of the lower Texas Gulf Coast causes poor reservoir quality.

Reservoir Quality

The deep Vicksburg Formation exhibits the poorest reservoir quality of lower Tertiary units (figs. 14 and 51). The poor quality results from fine grain size, poor sorting, abundant unstable rock fragments, pervasive carbonate cement, high compaction from deep burial, and higher geothermal gradient along the lower Texas Gulf Coast.

Most porosity beneath 2,440 m (8,000 ft) in depth is secondary (fig. 52). Primary porosity is reduced to less than 5 percent, whereas secondary porosity may be as much as 15 percent.

Frio Formation

Texture and Mineralogy

Of the lower Tertiary units, the Frio Formation shows the greatest regional variation in mineral composition. Along the lower Texas Gulf Coast (areas 1 and 2), Frio sandstones are poorly sorted, fine-grained, feldspathic litharenites to lithic arkoses (figs. 53 through 56). Middle Texas Gulf Coast (areas 3 and 4) Frio sandstones are moderately to well sorted, fine-grained, quartzose lithic arkoses. The Frio sandstones of the upper Texas Gulf Coast (areas 5 and 6) are poorly sorted, fine-grained, quartzose lithic arkoses to subarkoses. This regional change in composition is independent of grain size (fig. 57).

Frio sandstones of the lower, middle, and upper Texas Gulf Coast areas contain distinct rock fragment populations (fig. 58). Along the lower Texas Gulf Coast the sandstones are extremely rich in volcanic rock fragments, and carbonate rock fragments are common. In the middle Texas Gulf Coast area volcanic rock fragments predominate, but some samples contain significant percentages of metamorphic rock fragments. In this area carbonate rock fragments are also present, but such fragments are much less common than along the lower Texas Gulf Coast. Rock fragments in sandstones of the upper Texas Gulf Coast are mainly volcanic rock fragments.

Sandstones of the lower Texas Gulf Coast contain the greatest abundance of rock fragments because of drainage from active volcanic areas in Mexico and West Texas into the ancient Rio Grande basin (fig. 48). These volcanic rock fragments are predominantly rhyolites and trachytes (Lindquist, 1977) and are normally silicified or altered to chlorite. Lesser amounts of these volcanics survived transport to the middle and upper Texas Gulf Coast areas. The abundant carbonate rock fragments along the lower Texas Gulf Coast are caliche clasts, locally derived from caliche soils that resulted from an arid climate (Lindquist, 1977). Caliche soils did not form in the more humid climate of the upper Texas Gulf Coast areas, and the abundance of carbonate rock fragments decreases in that direction. The source of abundant metamorphic rock fragments in Frio sandstones of the middle Texas Gulf Coast is debatable. If they were related to drainage from the Rocky Mountains, sandstones from the upper Texas Gulf Coast should contain more metamorphic rock fragments as well. Frio sandstones of the middle Texas Gulf Coast also contain more orthoclase, suggesting a western source of metamorphic rock fragments such as the Llano Uplift. Galloway (1977) reported a major late Oligocene-early Miocene river that crossed northern Karnes County and that may have drained the Llano Uplift area.

Diagenesis

The diagenetic sequence of the Frio Formation (fig. 50) was delineated in other studies by Lindquist (1977), Loucks and others (1977, 1981), Milliken and others (1981), Franks and Forester (1984), Kaiser (1984), and Land (1984).

Clay coats surrounding framework grains formed in the shallow subsurface in only about 20 percent of the samples and make up only a small percentage of the volume of the sample. The coats form thin, discontinuous layers. Also in the shallow subsurface, feldspar grains and feldspar in volcanic rock fragments were dissolved or replaced by Fe-poor calcite. Some plagioclase grains have been selectively dissolved along one twin orientation. Minor amounts of pore-filling cements are poorly formed booklets of kaolinite, feldspar overgrowths, and zeolite. About 15 percent of the samples have feldspar overgrowths, and overgrowths generally form less than 3 volume percent of a sample. Zeolite cement, possibly laumontite, is most common along the lower Texas Gulf Coast (up to 13 percent volume of individual samples). The amount of zeolite cement is directly related to the abundance of volcanic rock fragments.

At a depth of about 600 m (2,000 ft), an Fe-rich carbonate cement begins to appear. It was the first major subsurface cement in the Frio, but it is probably localized because most Frio sediments are not well cemented above a depth of 1,830 m (6,000 ft) or more.

The intermediate subsurface stage of diagenesis began with the dissolution of early-formed carbonate cements and feldspar grains. This dissolution is followed by quartz cementation that began between depths of 1,520 to 1,830 m (5,000 to 6,000 ft). Quartz overgrowths are more abundant in samples having more quartz grains, and the overgrowths are more common along the upper Texas Gulf Coast, where Frio sandstones are quartz-rich.

After the formation of quartz overgrowths, an Fe-poor calcite cement was precipitated. This calcite, with earlier carbonate cements and feldspar grains, was subjected to the most extensive dissolution event in the diagenetic history of the Frio Formation. Porosity may have been resurrected to more than 30 percent.

After post-quartz dissolution, cementation again became the dominant diagenetic process. Some of the remaining feldspars were replaced by well-developed booklets of kaolinite. Commonly kaolinite grew out from

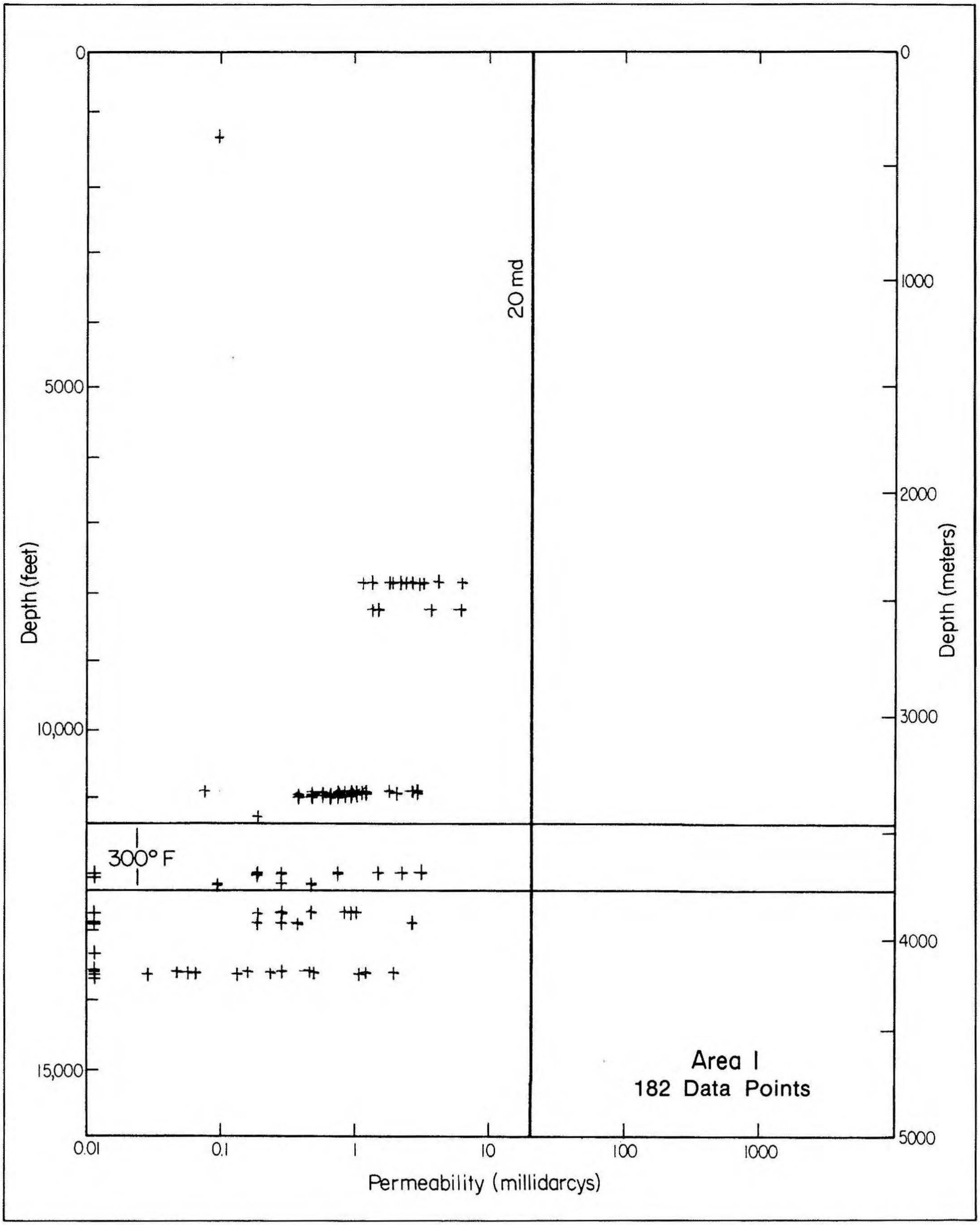


Figure 51. Permeability (core plugs from whole core) versus depth by area for Vicksburg Formation.

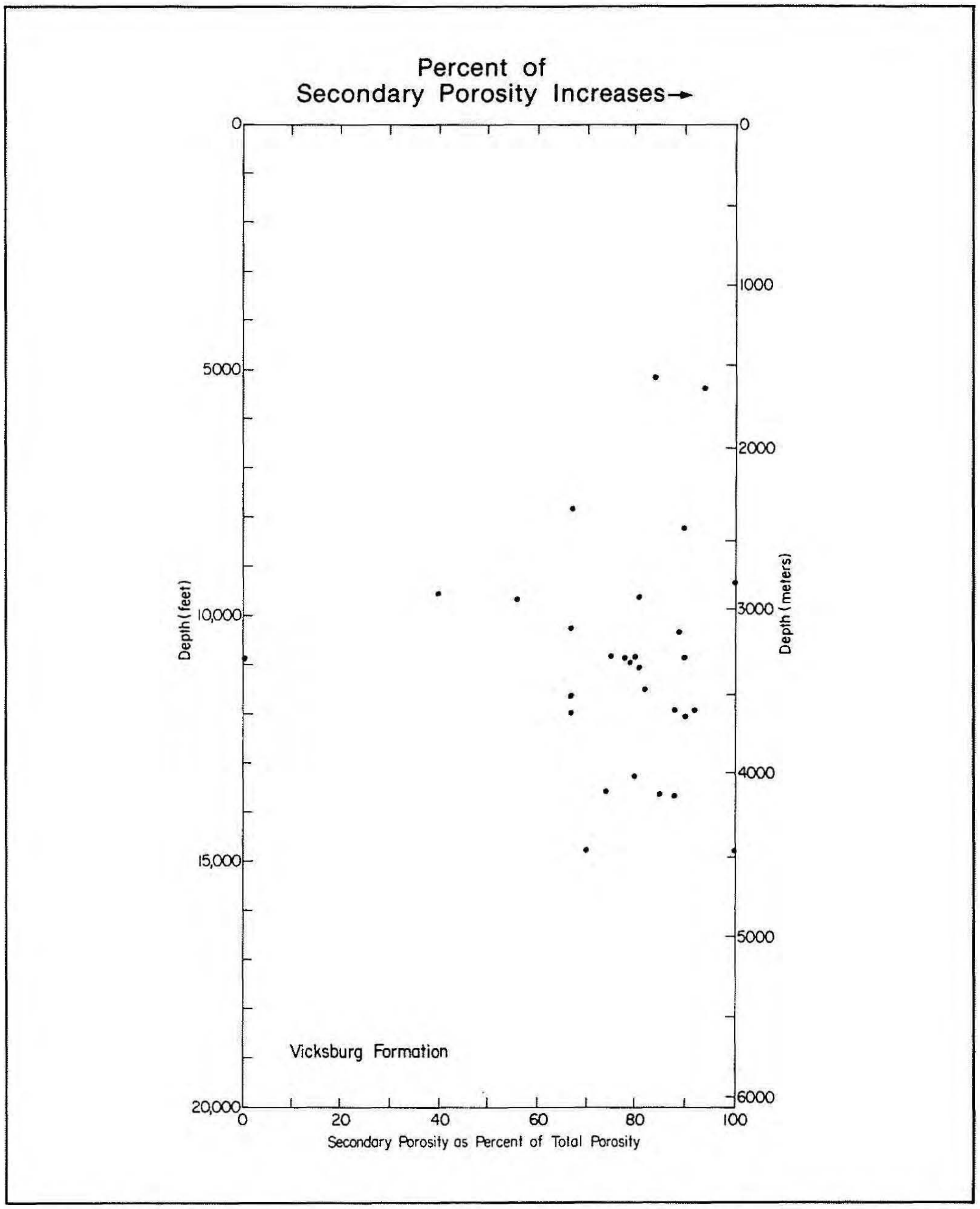


Figure 52. Secondary porosity as a percent of total porosity versus depth for Vicksburg sandstones.

replaced feldspars to fill surrounding pore space. In samples with higher percentages of kaolinite, the percentage of feldspar generally decreases. This correlation may be due to replacement of feldspar by kaolinite. Kaolinite cement forms up to 5 percent of some samples.

The last cements to be precipitated were carbonates in the form of Fe-rich dolomite $[Ca_{1.08-1.16}(Fe_{0.43-0.39}Mg_{0.57-0.61})_{0.92-0.84}(CO_3)_2]$ and ankerite. These cements are especially common along the lower Texas Gulf Coast. Dissolution was not observed to attack Fe-rich dolomite.

Reservoir Quality

The Frio Formation displays the best deep-reservoir quality in the lower Tertiary section. Porosity-versus-depth plots, however, indicate that this high reservoir quality, especially at depth, is restricted to area 4 of the middle Texas Gulf Coast and areas 5 and 6 of the upper Texas Gulf Coast (figs. 14, 16, and 59). Samples from areas 4 and 5 from depths greater than 4,500 m (15,000 ft) may have permeability values greater than 1,000 millidarcys. In the northern part of area 1 some

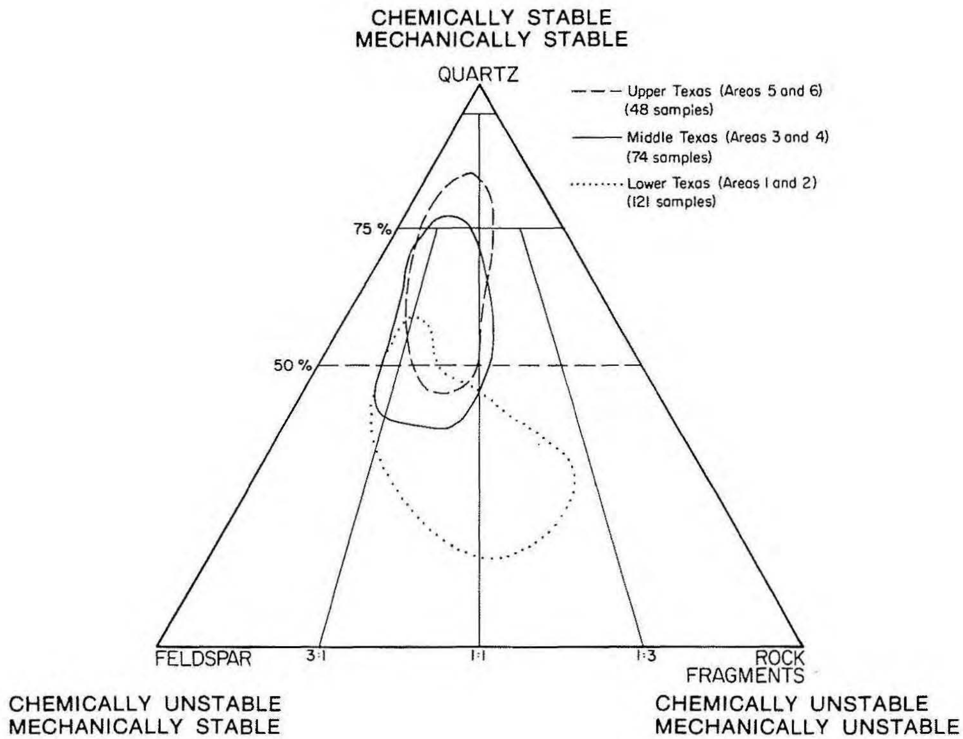


Figure 53. Frio sandstone composition. Envelopes highlight typical compositional range.

permeability readings near 10 millidarcys were recorded at depths of about 4,500 m (15,000 ft), but most permeability values are less than a few millidarcys. Frio porosity in the deep subsurface is predominantly of secondary dissolution origin (fig. 60).

The increase in reservoir quality from the lower to the upper Texas Gulf Coast (fig. 16) corresponds to trends in rock composition, climate, and geothermal gradient. The change in rock composition is probably the most important of these. Along the lower Texas Gulf Coast, where reservoir quality is poor, Frio sandstones are low in quartz and rich in volcanic and carbonate rock fragments. Along the upper Texas Gulf Coast, where reservoir quality is good, Frio sandstones are rich in quartz, low in volcanic rock fragments, and lacking in carbonate rock fragments. The abundance of chemically and mechanically unstable volcanic and carbonate rock fragments along the lower Texas Gulf Coast favored diagenetic processes that destroyed porosity. Laumontite cement, present along the lower Texas Gulf Coast, is associated with high volumes of volcanic rock fragments. Ductile chloritized volcanic rock fragments are commonly deformed in a way that blocks pore throats.

The geothermal gradient decreases from the lower to the upper Texas Gulf Coast (figs. 23 and 24; table 3). The high geothermal gradient (1.7°F/100 ft) typical of the lower Texas Gulf Coast resulted in a shallower onset of thermally controlled diagenetic events. This trend was further accentuated by the unstable mineral assemblages in this area. The Rio Grande Embayment also underwent more rapid subsidence relative to the Houston Embayment, leading to greater compaction of sediments. A plot of packing proximity (a measure of number of grain contacts; Kahn, 1956) versus depth showed greater compaction for area 1 than for area 5 (fig. 61). Frio sand grains in areas 5 and 6 have fewer grain contacts than area 1 even though sandstones in areas 5 and 6 are more deeply buried.

Variations in the post-Eocene climate along the Texas Gulf Coast, from arid conditions in the south to subhumid and humid conditions in the north, indirectly influenced reservoir quality by preserving and creating unstable rock fragments. The arid Tertiary climate in the south produced caliche soils that were a source of carbonate rock fragments. Caliches did not form along the more humid upper Texas Gulf Coast, and carbonate rock fragments are rare there. The more arid climate in

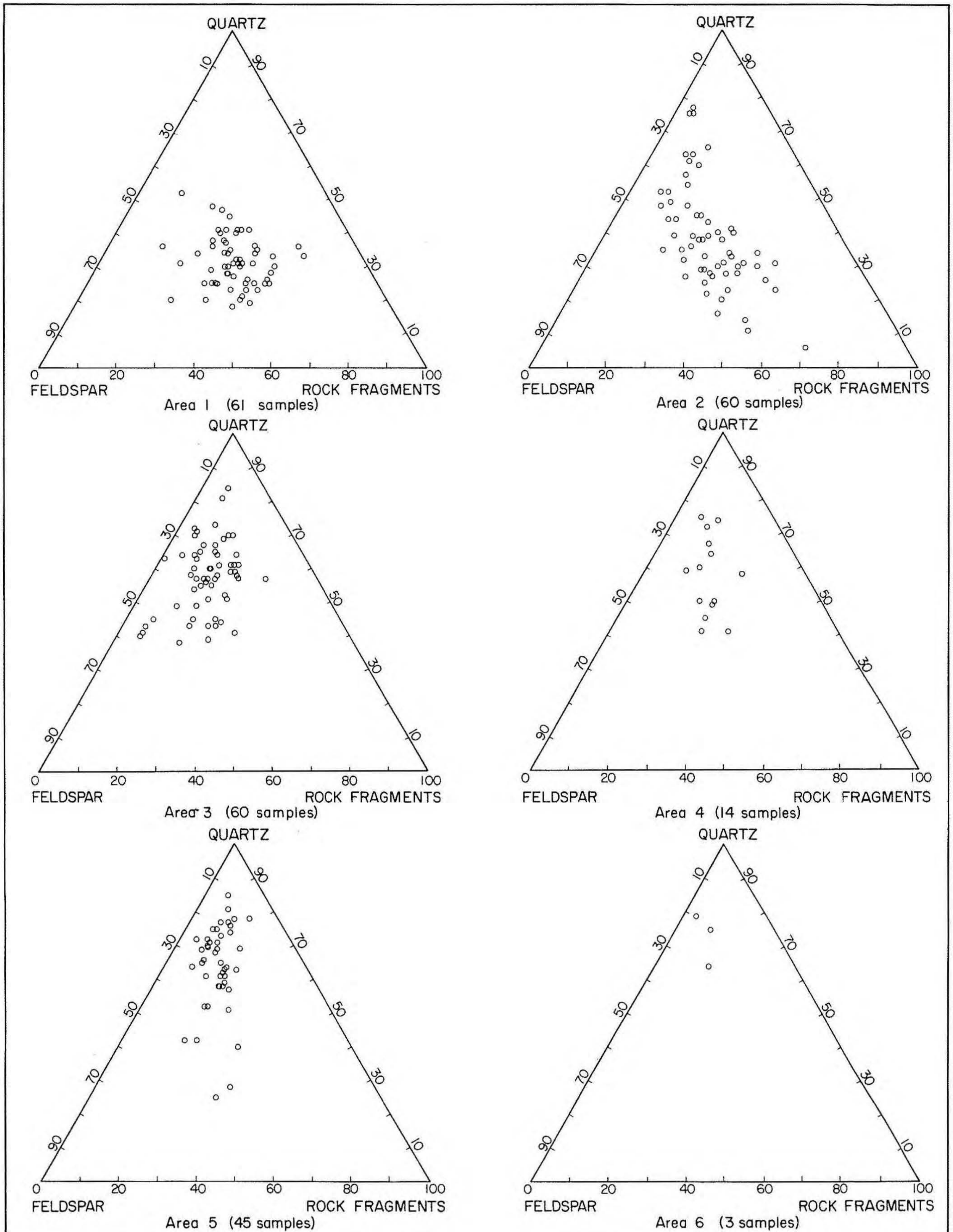


Figure 54. Basic data for Frio sandstone composition by area.

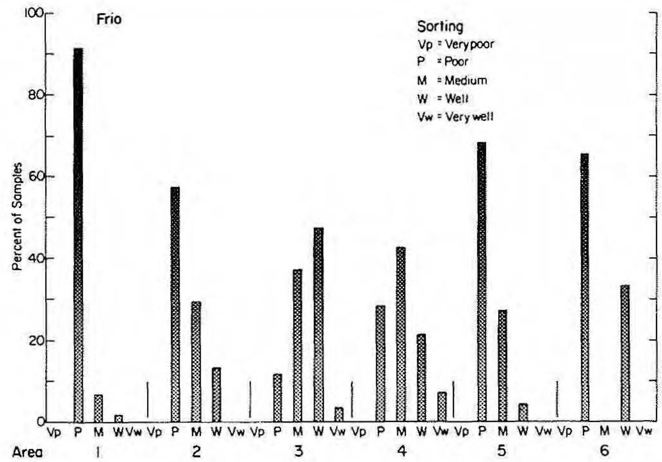


Figure 55. Distribution of sorting in Frio sandstones by area. Sorting was estimated visually using the criteria of Folk (1968).

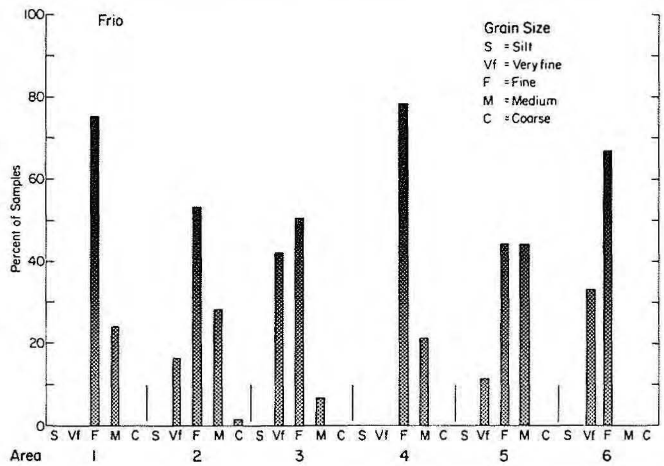


Figure 56. Distribution of grain size in Frio sandstones by area. Grain size was estimated visually using the Wentworth (1922) scale.

the lower Texas Gulf Coast region preserved volcanic rock fragments and allowed them to be incorporated into the sandstones.

Summary of Reservoir Quality in Lower Tertiary Gulf Coast Sandstones

Diagenetic processes, which determined reservoir quality in the Vicksburg and Frio Formations, were a function of rock composition, geothermal gradient, paleoclimate, and subsidence rate. Sandstone composition and geothermal gradient were probably the most important of these factors. As the geothermal gradient and amount of unstable components decreased northward along the Gulf Coast, less cementation occurred and reservoir quality remained high. The Wilcox Group, however, does not show such a trend. Rock composition varied little in the Wilcox Group along the Gulf Coast, and reservoir quality appears to be improved by local rather than regional conditions. However, the best reservoirs in the Wilcox Group were found in area 3, where the lowest percentage of quartz overgrowths exist. In the Frio Formation a higher percentage of quartz typically correlates with a lower percentage of unstable rock fragments and, therefore, less carbonate and laumontite cements. Locally in the Wilcox Group, more quartz generally correlates with less feldspar, and, therefore, less secondary porosity. These local differences in reservoir quality can be predicted by detailed regional investigations.

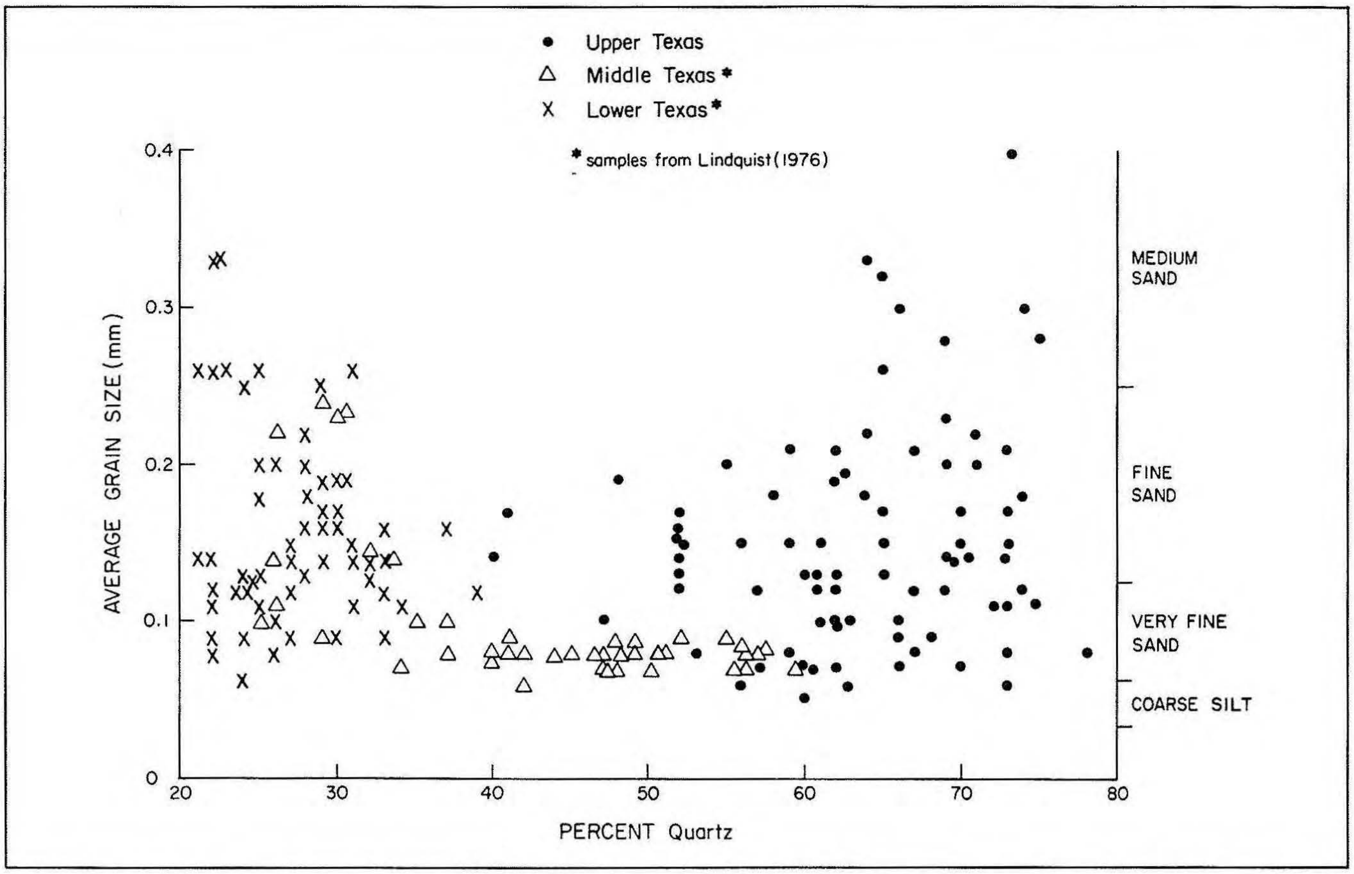


Figure 57. Relation of percent quartz to average grain size for Frio sandstones along the Texas Gulf Coast. Note that percent quartz is not dependent on grain size.

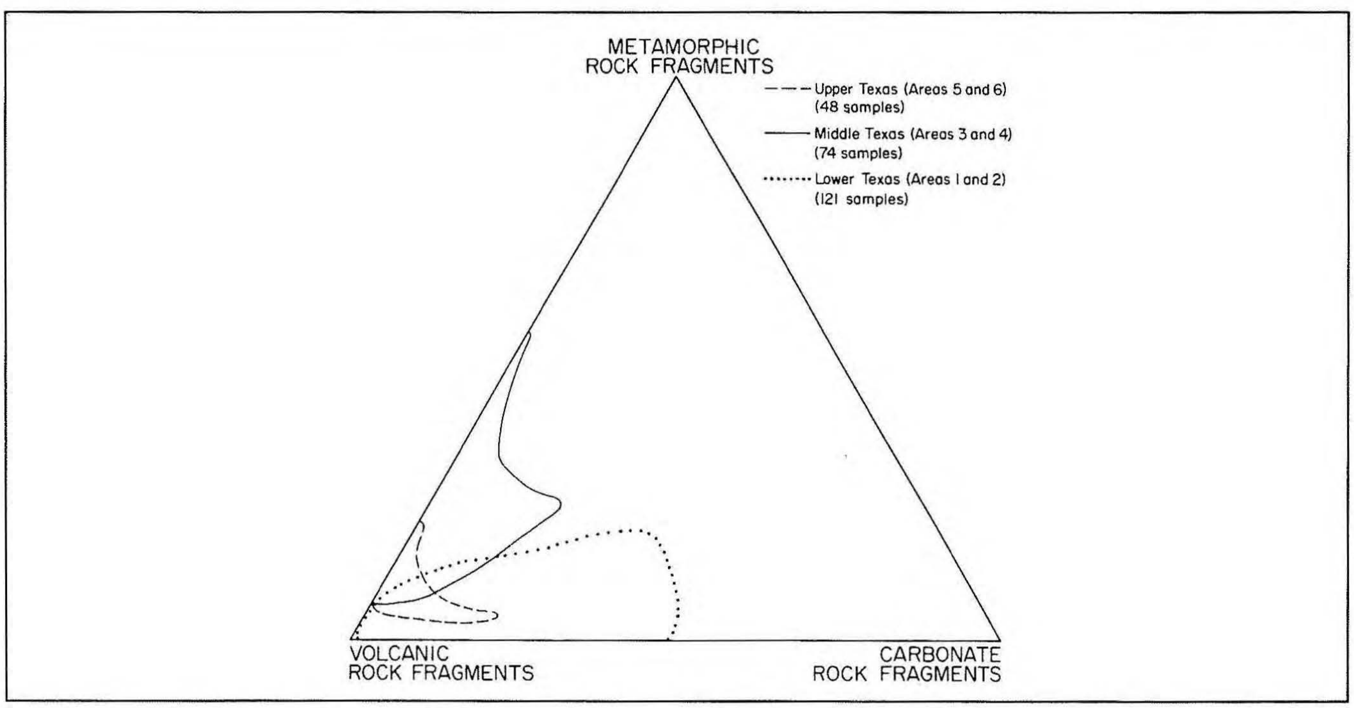


Figure 58. Frio sandstone rock fragment composition.

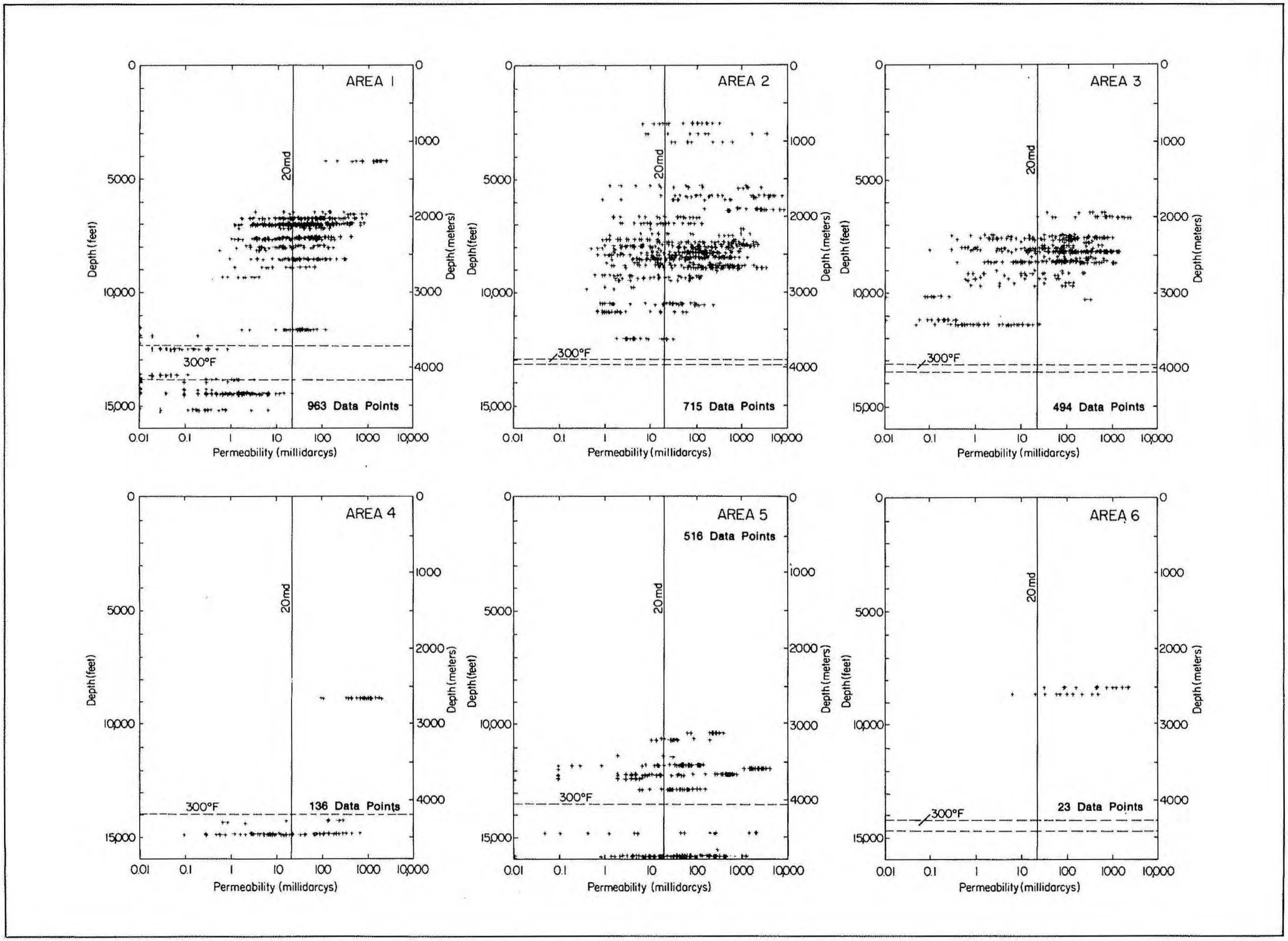


Figure 59. Permeability (core plugs from whole core) versus depth by area for Frio Formation.

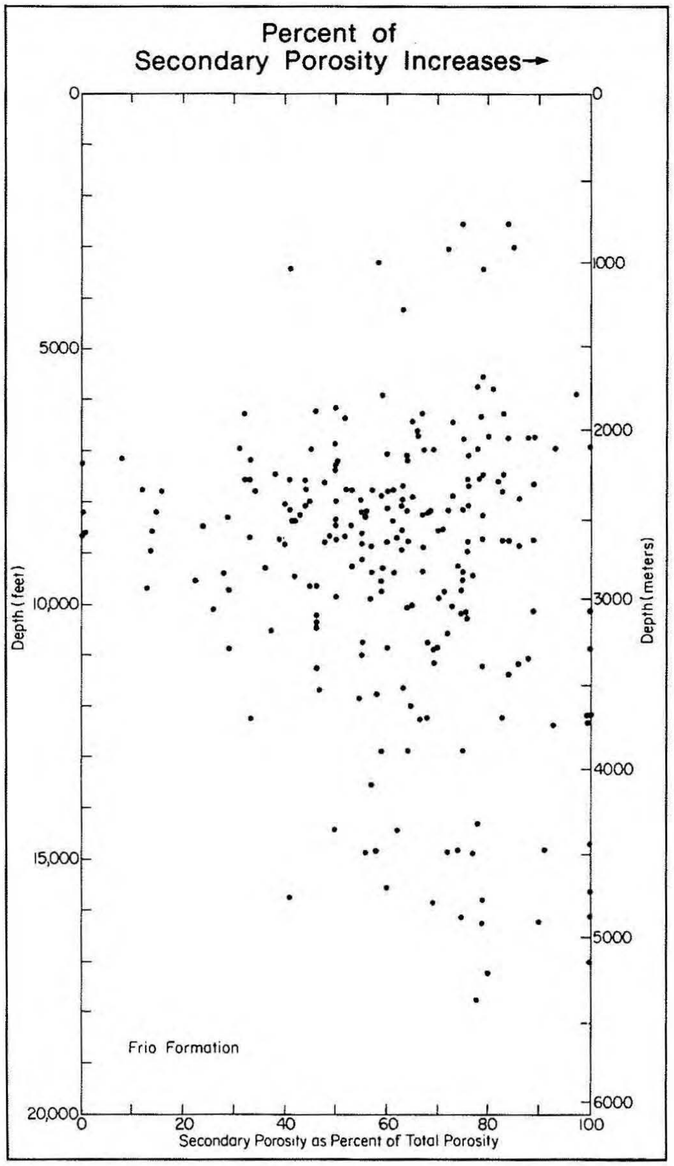


Figure 60. Secondary porosity as a percent of total porosity versus depth for Frio sandstones.

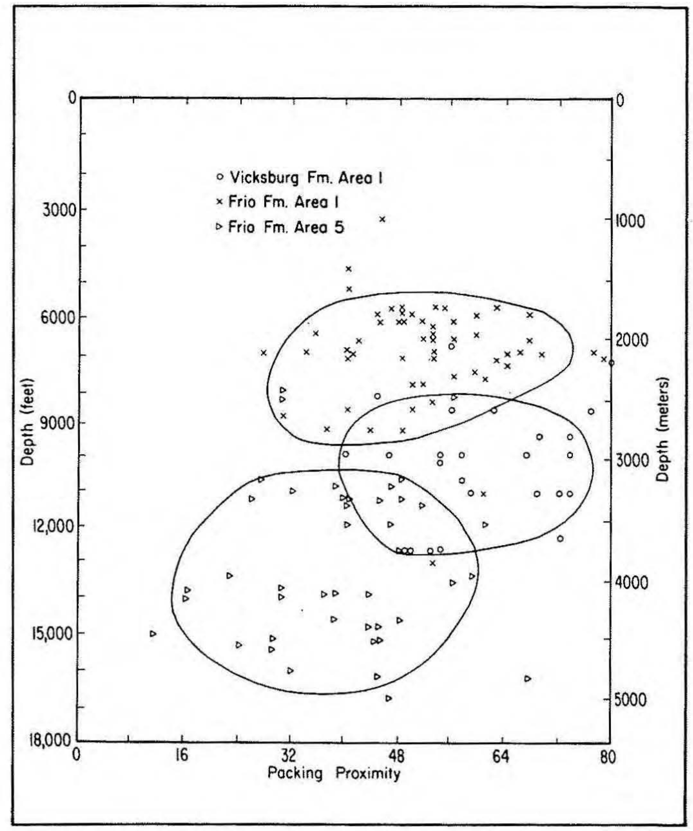


Figure 61. Packing proximity (a measure of the number of grain contacts) versus depth for Vicksburg sandstones from area 1 and Frio sandstones from areas 1 and 5.

PETROPHYSICAL PARAMETERS AND DIAGENESIS

Rock Consolidation Gradient from Interval-Transit-Time Plots

Interval transit time is the reciprocal of velocity of the compressional sound wave traveling through a rock. With increasing depth, velocity increases as a function of effective pressure ($P_{overburden}$-P_{fluid}) and cementation at grain contacts. The rapid increase in velocity continues until a depth is reached at which the rock is well consolidated. At this depth, the increase in velocity begins to level off and becomes asymptotic to the time-average velocity (Gregory, 1977). According to Gregory (1977), at shallow depths interval transit time in sandstones depends on porosity, rock composition, grain sorting, clay content, and overburden pressure; at high overburden pressures, corresponding to deeper burial, only porosity and rock composition affect interval transit time.

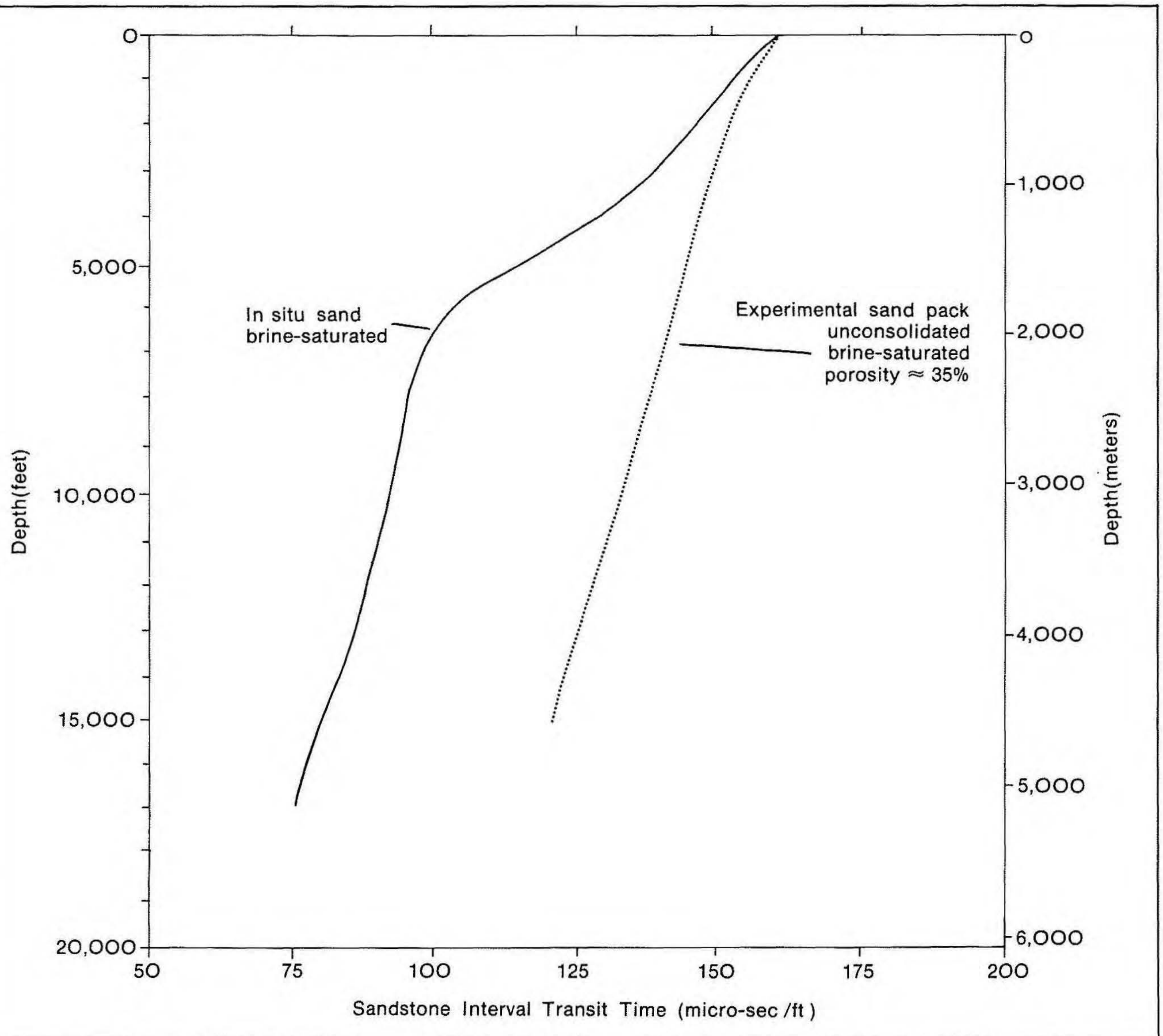


Figure 62. Interval transit time as a function of depth showing consolidation effect for Louisiana Tertiary sandstones. Modified from Gardner and others (1974).

A plot of interval transit time versus depth modified from Gardner and others (1974) for a normally pressured Louisiana Miocene sandstone sequence is presented in figure 62. The plot reflects high interval transit time characteristic of unconsolidated sediments in the shallowest strata. At about 2,130 m (7,000 ft) the rocks are relatively well consolidated, and interval transit time is directly related to porosity. In this plot, divergence of true interval transit time (solid line) from interval transit time related to pressure (dotted line) is attributed to consolidation (fig. 62).

Interval transit times for sand and sandstones from acoustic logs (fig. 5) were plotted against depth to show the relation between consolidation history and interval transit time along the Texas Gulf Coast. The data align along two trends parallel to the coast (fig. 5): an updip trend that corresponds to wells drilled into the Wilcox Group and a downdip trend that corresponds to wells drilled into the Vicksburg and Frio Formations. Plots of interval transit time versus depth exhibit the same compaction/consolidation curve as those of Gardner and others (1974), except that some wells show an

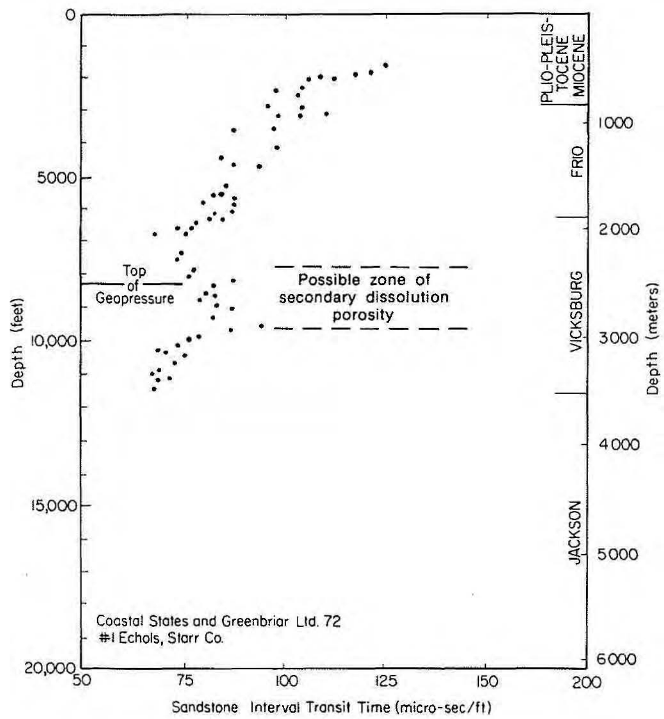


Figure 63. Sandstone interval transit time versus depth for the Coastal States and Greenbriar Ltd. 72 No. 1 Echols in Starr County. Zone of possible secondary dissolution porosity is marked.

increase in interval transit time at the top of the geopressured zone (fig. 63). In abnormally high pressured (geopressured) sandstones, fluid pressure supports some of the rock column, making the effective pressure on the rocks less than that for hydropressured sandstones. Thus, interval transit time increases at the top of the geopressured zone because of reduced effective pressure on the rocks. The relation between consolidation history and interval transit time along the Texas Gulf Coast is more complicated, however, because the top of the geopressured zone commonly coincides with a zone of well-developed secondary dissolution porosity, causing an additional increase in interval transit time. The effect of one zone on interval transit time may be inseparable from the effect of the other.

An idealized plot of porosity and interval transit time of sandstone versus depth (fig. 25) for Tertiary sandstones of the Gulf Coast shows an initial rapid decrease in interval transit time owing to compaction of unconsolidated sediments. As cementation begins, compaction decreases and eventually stops, and the rate of porosity loss decreases. This porosity loss corresponds to an increase in slope on the interval-transit-time plot. Minor dissolution porosity may also occur. Figure 64 is a plot of interval transit time versus depth that shows a curve similar to curve B in the idealized plot (fig. 25). With major post-quartz overgrowth dissolution, a reversal in the interval-transit-time slope may occur (fig. 25; curve C). The interval-transit-time curve will decrease again (fig. 25; curve C_1), however, if late-stage Fe-rich carbonate cements are abundant.

Only a few plots of interval transit time from acoustic logs from wells along the Texas Gulf Coast display a curve similar to the idealized plot of compaction and cementation followed by dissolution (fig. 25; curve C). A possible zone of secondary dissolution porosity in the Greenbriar Ltd. 72 No. 1 Echols well (fig. 63) occurs at the top of the geopressured zone. This increase in interval transit time may be the result of both dissolution porosity (see Vicksburg diagenetic sequence in fig. 50) and high fluid pressures. There are also slight breaks in slope in this plot (fig. 63) at about 760 m (2,500 ft) and 1,520 m (5,000 ft). These breaks correspond to the top of the Frio Formation and to the top of the "basal" Frio sandstones, respectively. Formational changes commonly affect interval transit time (fig. 65), reflecting slight changes in rock composition or porosity and, consequently, velocity.

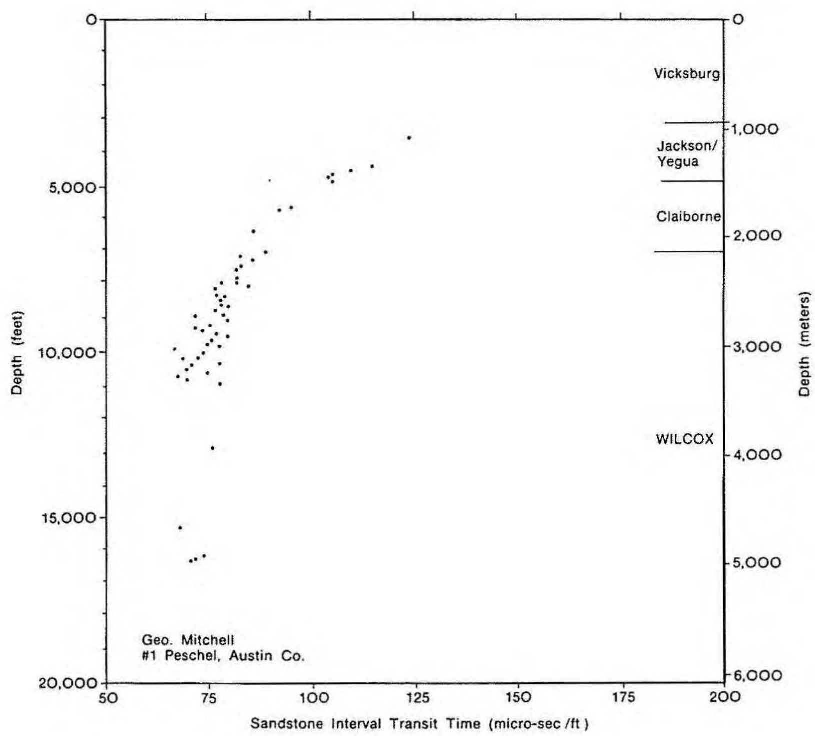


Figure 64. Sandstone interval transit time versus depth for the George Mitchell No. 1 Peschel in Austin County. The curve shows no zone of secondary porosity development. Compaction and cementation occurred at a greater rate than the development of secondary porosity.

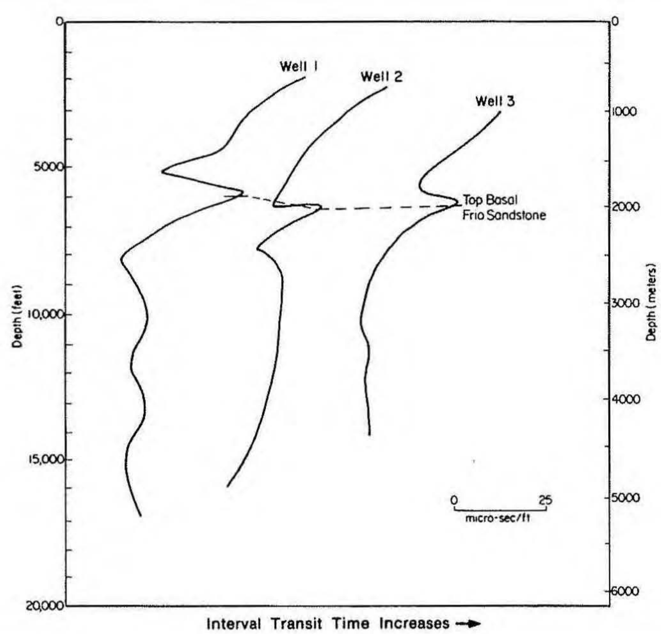


Figure 65. Sandstone interval transit time versus depth for three wells in area 1 of the Vicksburg/Frio trend showing effect of formation changes.

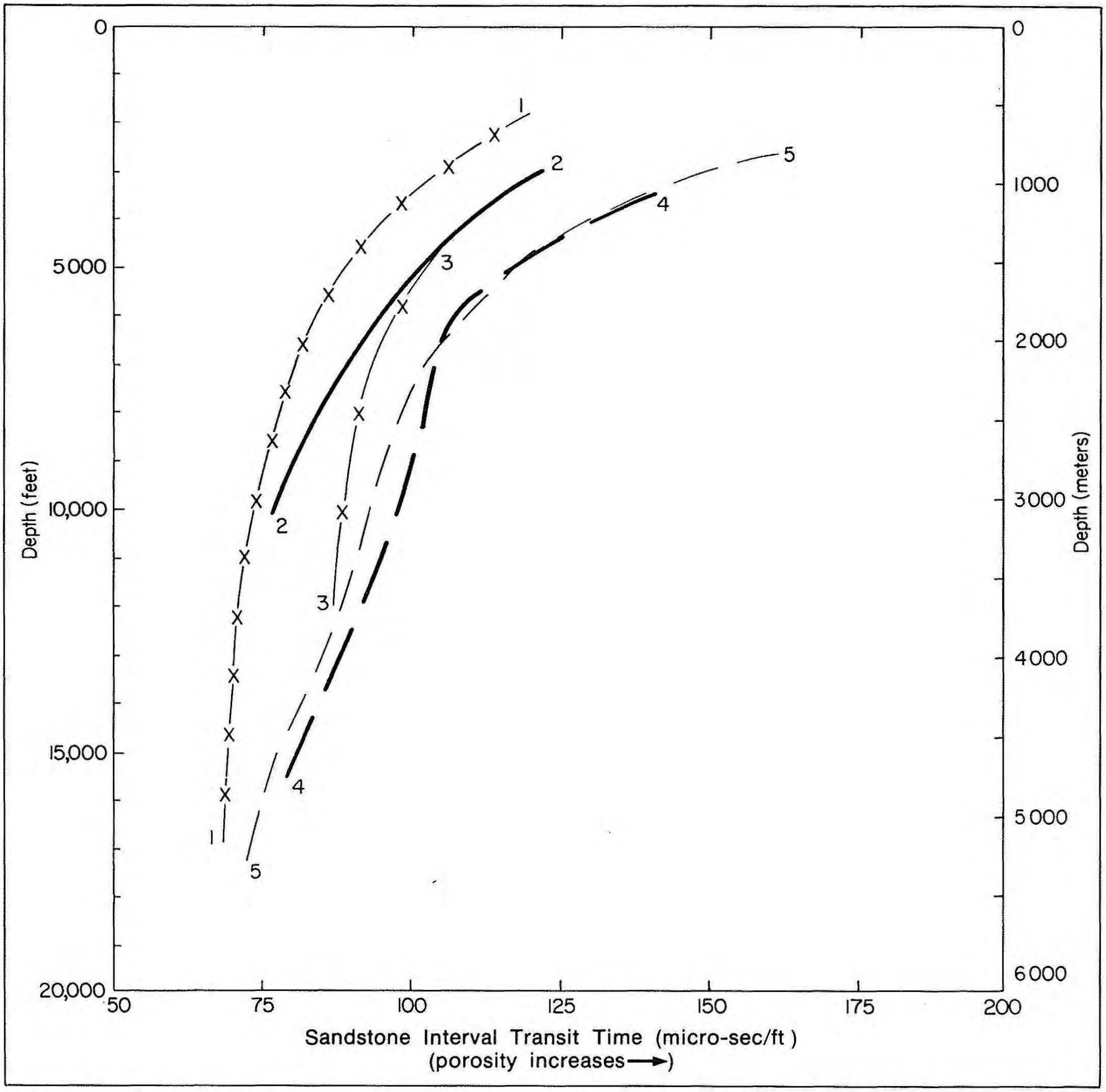


Figure 66. Sandstone interval transit time versus depth by area for the Vicksburg/Frio trend. Each curve represents a visual best-fit line drawn through data in that area.

Regional Variation in Rock Consolidation Gradient

The acoustic logs used in this investigation were grouped by areas 1 through 6 and further divided into an updip Wilcox trend and a downdip Vicksburg/Frio trend (fig. 5). In each trend all data in each area were combined to produce an average, or representative, plot of sandstone interval transit time versus depth (figs. 66 through 69).

Sandstones from the Vicksburg/Frio trend show progressively greater consolidation gradients from the upper to the lower Texas Gulf Coast (figs. 66 and 67), further substantiating conclusions based on core analyses and petrographic descriptions. Integration of reservoir data from acoustic logs greatly expanded the

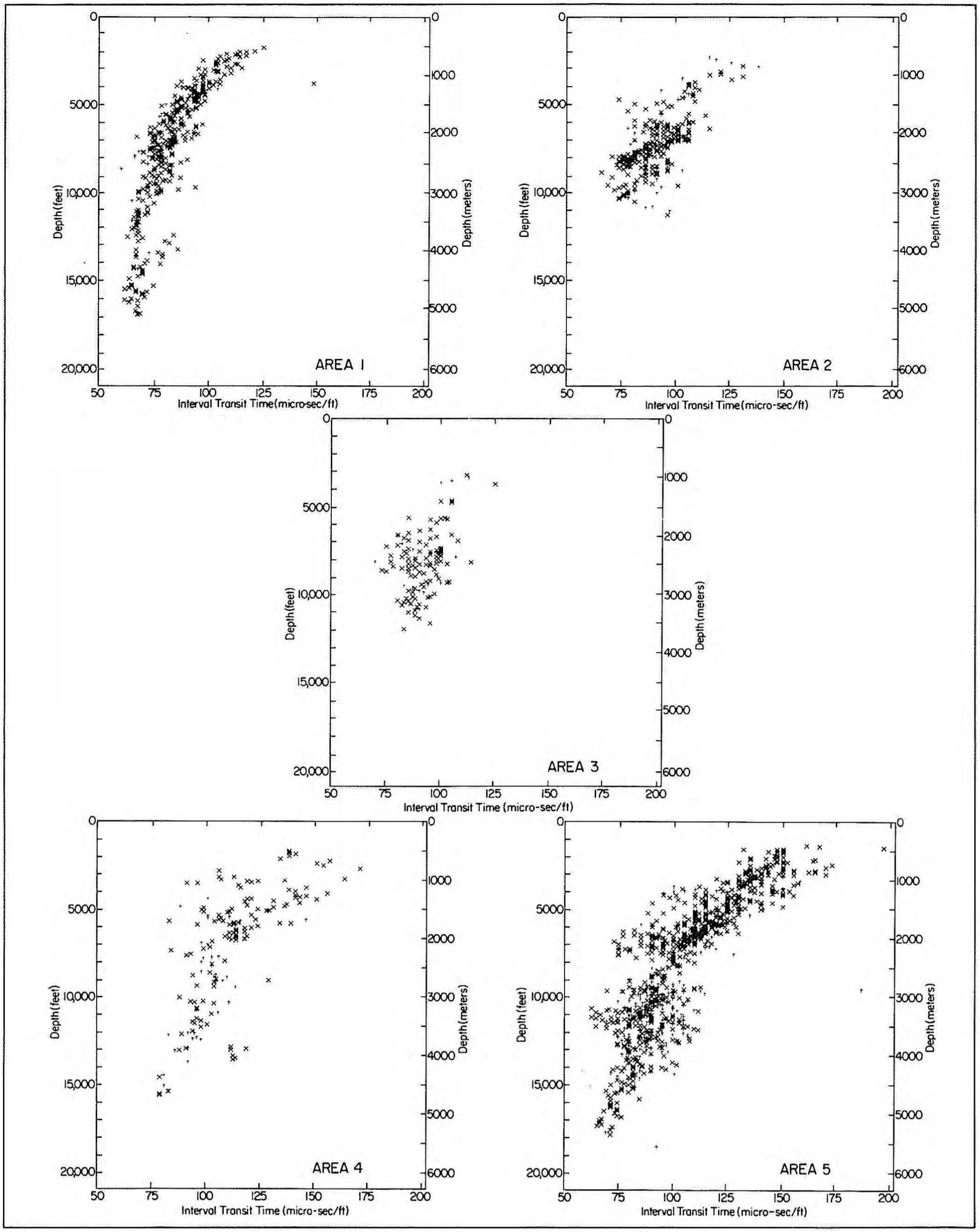


Figure 67. Basic data for plot of interval transit time versus depth for the Vicksburg/Frio trend sandstone.

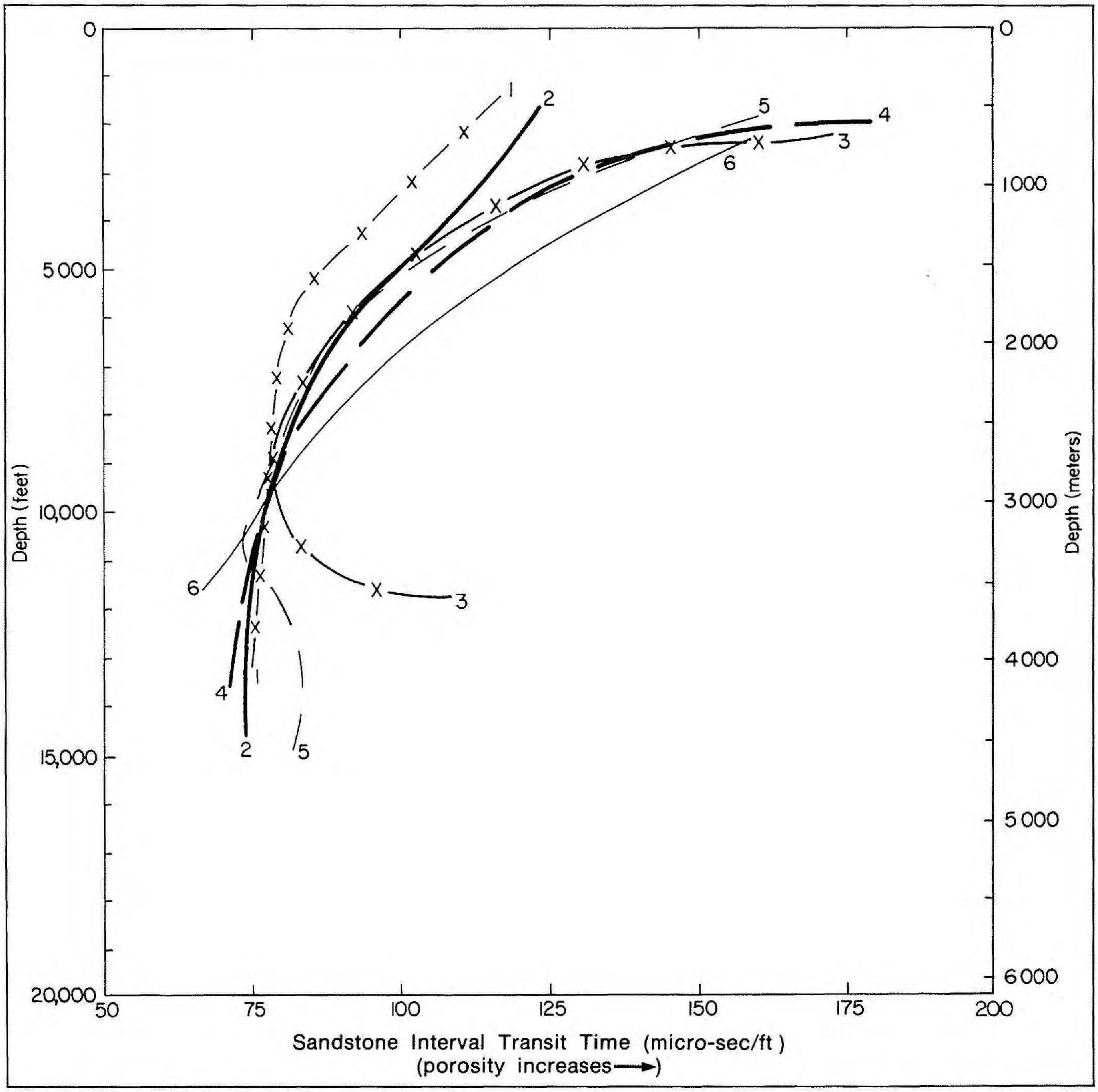


Figure 68. Sandstone interval transit time versus depth by area for the Wilcox trend. Each curve represents a visual best-fit line drawn through data in that area.

base on which generalizations were made. These changes correspond to high reservoir quality along the upper Texas Gulf Coast and poor reservoir quality along the lower Texas Gulf Coast. Reservoir quality improves northward at all depths.

Many of the sandstones in the updip Wilcox trend shallower than 3,050 m (10,000 ft) are younger than the Wilcox Group, and they include strata equivalent to the Vicksburg and Frio Formations. They exhibit a higher consolidation gradient along the lower Texas Gulf Coast relative to the upper Texas Gulf Coast. This trend is the same for similar rocks in the downdip Vicksburg/Frio trend.

At a depth greater than 3,350 m (11,000 ft), plots of interval transit time versus depth for the Wilcox Group in areas 1, 2, 4, and 6 indicate relatively well

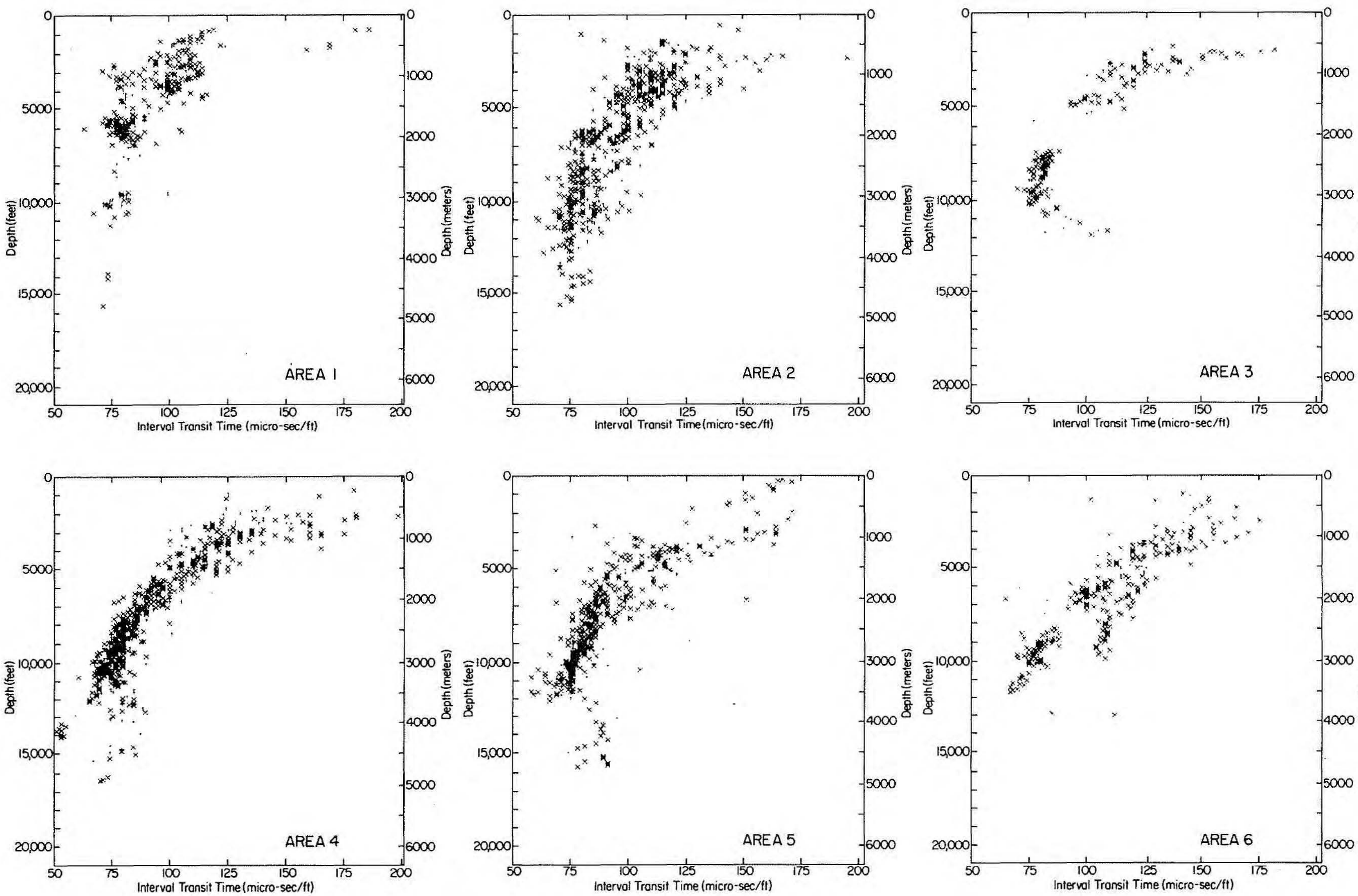


Figure 69. Basic data for plot of interval transit time versus depth for the Wilcox trend sandstone.

consolidated sandstones, but similar plots for area 3 and possibly area 5 show a reversal toward an apparent increase in porosity at depth (figs. 68 and 69). Core analyses in area 3 (fig. 35) indicate high permeability values from samples deeper than 3,350 m (11,000 ft).

At depths shallower than 2,130 m (7,000 ft), both the Wilcox and the Vicksburg/Frio interval-transit-time trends are similar (figs. 66 and 68). At depths greater than 2,130 m (7,000 ft), areas 1 and 2 of the Vicksburg/Frio trend exhibit interval-transit-time curves similar to those in the Wilcox trend; all these curves correspond to low reservoir quality in the deep subsurface. Sandstones from areas 3, 4, and 5 have higher Vicksburg/Frio interval transit times beneath 2,130 m (7,000 ft) than those in the Wilcox trend except for those in area 3 of the Wilcox trend. Areas 4 and 5 of the Vicksburg/Frio trend, which have higher interval transit times, correspond to areas having highest quality deep reservoirs on the basis of core analysis. However, data for the Vicksburg/Frio trend in area 3 are available only to a depth of 3,350 m (11,000 ft); beneath this depth, reservoir quality may be marginal.

CONCLUSIONS

Trends in reservoir quality in the lower Tertiary section along the Texas Gulf Coast were defined by whole core analyses, grain composition of the sandstones, intensity of diagenetic features, and interval transit times for sandstones. Porosity and permeability in sandstone sections shallower than 3,050 to 3,350 m (10,000 to 11,000 ft) are generally adequate for hydrocarbon production. However, reservoir quality in deep subsurface sandstones in the lower Tertiary section of the onshore Texas Gulf Coast is highly variable. Most of these deep sandstone reservoirs have permeability values of less than 1 millidarcy, but in a few areas permeabilities are higher than 1,000 millidarcys. The potential for high-quality reservoirs to occur in the deep subsurface (approximately below 3,350 m [11,000 ft] of burial) is summarized in figure 70.

Porosity and permeability were controlled by a complex series of diagenetic events that consisted of compaction, cementation, and dissolution. Many physical and chemical parameters influenced these diagenetic events. Each formation along the onshore Texas Gulf Coast exhibits a similar general diagenetic history. Most diagenesis occurred in the hydropressured and soft geopressured zone (fluid pressure gradient less than 0.7 psi/ft), but some carbonate cementation continues into the hard geopressured zone (fluid pressure gradient greater than 0.7 psi/ft), as indicated by continued loss of porosity.

Primary porosity predominates in the shallow subsurface, but secondary dissolution porosity is dominant in the deeper subsurface. Loucks and others (1977; 1979a) pointed out that the zone of well-developed secondary porosity occurs at depths and at ambient temperatures that place it well within the liquid window of hydrocarbon generation and preservation (fig. 71) as defined by Pusey (1973). The liquid window encompasses the temperature/depth range within which major oil fields occur, unless there was significant vertical or lateral migration or post-accumulation changes in the thermal regime. The liquid window characteristically brackets oil production in Tertiary basins such as the Gulf Coast. The window, which extends from 66°C to 149°C (150°F to 300°F), includes the minimal temperature 66°C (150°F) for generation of petroleum from source kerogen and the maximum temperature 149°C (300°F) of liquid preservation (LaPlante, 1972; Pusey, 1973). At temperatures above 149°C (300°F), only dry gas or gas with minor amounts of liquids is typically found (Klemme, 1972). The high porosity produced by dissolution within a similar depth range of the liquid window suggests that most oil and all deep gas and gas-plus-condensate production from the lower Tertiary is from secondary-porosity-dominated pore networks (fig. 71). Enhancement of deep sandstones by dissolution porosity, however, seems to have affected only 20 to 30 percent of the sandstone section. The sandstones that were enhanced are generally those that had high initial primary porosity.

The Wilcox Group has good deep subsurface porosity and permeability in area 3 and possibly in the adjacent part of area 4. Other areas in the Wilcox Group have marginal potential for development of high-quality reservoirs at depth. A few high-quality sandstone reservoirs possibly formed in marginal areas, but these sandstones would be rare and would not accumulate to any appreciable thickness.

The Vicksburg Formation in area 1 has very poor porosity and permeability at depth. Predictions of reservoir quality in other areas of the Vicksburg Formation were not made because of the lack of deeply buried sandstones.

Reservoir quality in the deep Frio Formation increases from very poor in the southern two-thirds of area 1 to marginal through area 3 to good in areas 4, 5, and 6. The Frio Formation in area 5 has the best deep-reservoir quality of any onshore formation in any area.

An understanding of the variables that control porosity and permeability along the Texas Gulf Coast permits more insight into exploring for deep hydrocarbon reservoirs. Conclusions concerning controls on reservoir quality can be applied to other similar sandstone sequences.

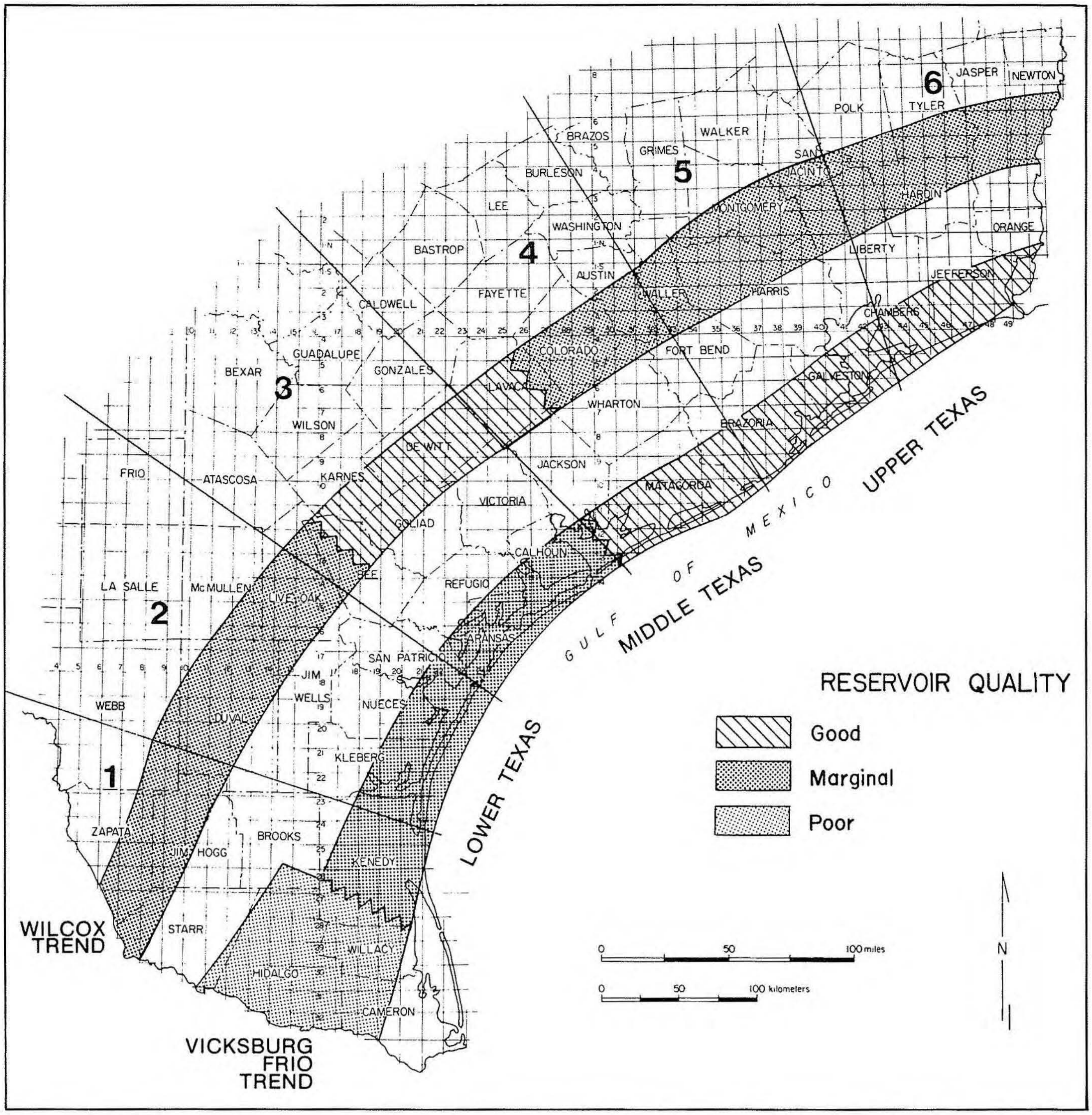


Figure 70. Potential for high-quality, deep reservoirs (3,350 m [11,000 ft]) in lower Tertiary strata along the Texas Gulf Coast. Good *indicates permeability values commonly greater than 20 md;* marginal *indicates most permeability values less than a few millidarcys, but some as high as 20 md;* poor *indicates permeability values generally less than a few millidarcys.*

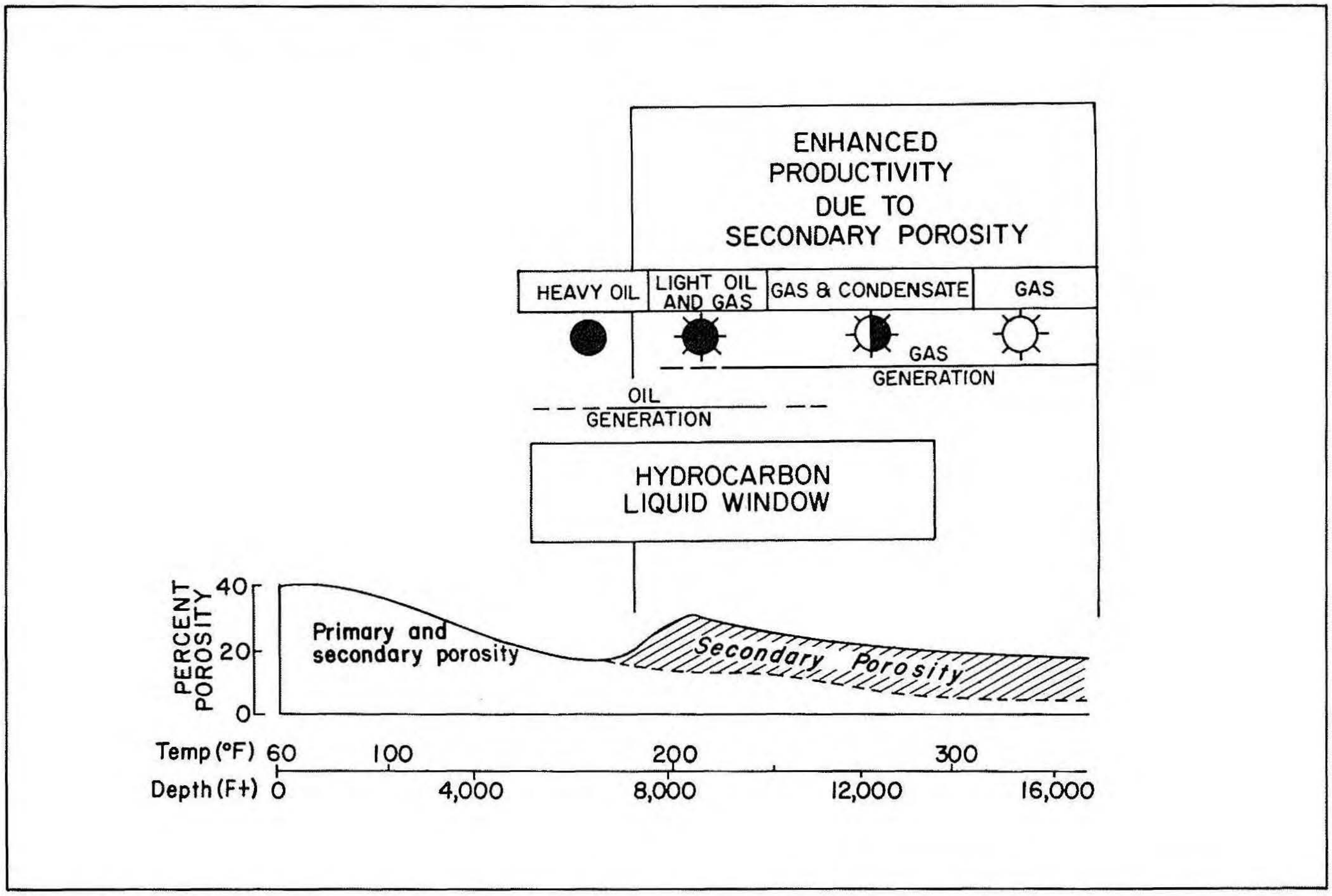


Figure 71. Schematic porosity versus depth/temperature curve for lower Tertiary sandstones showing relative significance of primary versus secondary porosity. The lower three-quarters of the hydrocarbon liquid window, which is characterized by the production of light liquids and distillate, as well as all of the deep gas productive section, lies within the zone of secondary porosity and permeability. From Loucks and others (1979a).

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Dow Chemical Company
Enserch Exploration, Incorporated
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Fitzpatrick Drilling Company
Forest Oil Company
Frankfort Oil Company
Gas Producing Enterprises, Incorporated
General Crude Oil Company
Getty Oil Company
Gulf Oil Company
Michel T. Halbouty
Jake L. Hamon
Houston Natural Gas Company
Hassie Hunt, Incorporated
Kerr-McGee Corporation
Killam & Hurd
Lone Star Producing Company
Maguire Oil Company
Miller & Fox Drilling Corporation
Mitchell Energy Corporation
Mobil Oil Corporation
Mokeen Oil Company
Monsanto Company
Robert Mosbacher
Northern Pump Company
Oleum, Incorporated
Oxy Petroleum, Incorporated
Phillips Petroleum Company
Quintana Petroleum Corporation
Shell Oil Company
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Tenneco Oil Company
Texaco, Incorporated
Texas Eastern Transmission Corporation
Texas Oil & Gas Corporation
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REFERENCES

American Association of Petroleum Geologists, 1976, Geothermal survey of North America: sponsored by the American Association of Petroleum Geologists Research Committee, 28 maps.

Atwater, G. I., and Miller, E. E., 1965, The effect of decrease in porosity with depth on future development of oil and gas reserves in South Louisiana (abs.): American Association of Petroleum Geologists Bulletin, v. 49, no. 3, p. 334.

Bebout, D. G., Gavenda, V. J., and Gregory, A. R., 1978a, Geothermal resources, Wilcox Group, Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, Report to U.S. Department of Energy, Division of Geothermal Energy, Contract No. AT-E(40-1)-4891, 82 p.

Bebout, D. G., Loucks, R. G., and Gregory, A. R., 1978b, Frio sandstone reservoirs in the deep subsurface along the Texas Gulf Coast, their potential for the production of geopressured geothermal energy: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 91, 92 p.

Bebout, D. G., Weise, B. R., Gregory, A. R., and Edwards, M. B., 1982, Wilcox sandstone reservoirs in the deep subsurface along the Texas Gulf Coast, their potential for production of geopressured geothermal energy: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 117, 125 p.

Boggs, A. S., 1978, Petrology of the lower Eocene sandstones in south central Colorado compared to their time equivalents in Texas: The University of Texas at Austin, unpublished Master's thesis, 166 p.

Boles, J. R., 1978, Origin of late-stage iron-rich carbonate cements in sandstones—active ankerite cementation in Wilcox of southwest Texas (abs.): American Association of Petroleum Geologists Bulletin, v. 62, no. 3, p. 498.

Boles, J. R., and Franks, S. G., 1978, Clay diagenesis in Wilcox sandstones of southwest Texas—implications of smectite-illite reaction for sandstone cementation (abs.): American Association of Petroleum Geologists Bulletin, v. 62, no. 3, p. 497.

Boyd, D. R., and Dyer, B. F., 1964, Frio barrier bar system of South Texas: Gulf Coast Association of Geological Societies Transactions, v. 14, p. 309-322.

Burns, L. K., and Ethridge, F. G., 1979, Petrology and diagenetic effects of lithic sandstones: Paleocene and Eocene Umpqua Formation, southwest Oregon, *in* Scholle, P. A., and Schluger, P. R., eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication No. 26, p. 307-317.

Cook, T. D., and Bally, A. W., 1975, Stratigraphic atlas of North and Central America: Princeton, N. J., Princeton University Press, 272 p.

Fisher, R. S., 1982, Diagenetic history of Eocene Wilcox sandstones and associated formation waters, south-central Texas: The University of Texas at Austin, Ph.D. dissertation, 185 p.

Fisher, W. L., Brown, L. F., Jr., Scott, A. J., and McGowen, J. H., 1969, Delta systems in the exploration for oil and gas: A research colloquium: The University of Texas at Austin, Bureau of Economic Geology, 212 p.

Fisher, W. L., and McGowen, J. H., 1969, Depositional systems in the Wilcox Group (Eocene) of Texas and their relation to occurrence of oil and gas: American Association of Petroleum Geologists Bulletin, v. 53, no. 1, p. 30-54.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill Publishing Company, 182 p.

Franks, S. G., and Forester, R. W., 1984, Relationships among secondary porosity, pore-fluid chemistry and carbon dioxide, Texas Gulf Coast, *in* McDonald, D. A., and Surdam, R. C., eds., Clastic diagenesis: American Association of Petroleum Geologists Memoir No. 37, p. 63-79.

Friedman, Mel, 1977, Rock mechanics and structural geology seminar: Midland, Texas, Permian Basin Graduate Center, course notes, 60 p.

Galloway, W. E., 1974, Deposition and diagenetic alteration of sandstone in Northeast Pacific arc-related basins: implications for graywacke genesis: Geological Society of America Bulletin, v. 85, no. 3, p. 379-390.

Galloway, W. E., 1977, Catahoula Formation of the Texas Coastal Plain: depositional systems, composition, structural development, ground-water flow history, and uranium distribution: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 87, 59 p.

Galloway, W. E., 1979, Diagenetic control of reservoir quality in arc-derived sandstones: implications for petroleum exploration, *in* Scholle, P. A., and Schluger, P. R., eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication No. 26, p. 251-262.

Galloway, W. E., Hobday, D. K., and Magara, Kinji, 1982, Frio Formation of Texas Gulf Coastal Plain: depositional systems, structural framework, and hydrocarbon distribution: American Association of Petroleum Geologists Bulletin, v. 66, no. 6, p. 649-688.

Gardner, G. H. F., Gardner, L. W., and Gregory, A. R., 1974, Formation velocity and density—the diagnostic basics of stratigraphic traps: Geophysics, v. 39, p. 770-780.

Gregory, A. R., 1977, Aspects of rock physics from laboratory and log data that are important to seismic interpretation, *in* Payton, C. E., ed., Seismic stratigraphy—applications to hydrocarbon exploration: American Association of Petroleum Geologists Memoir 26, p. 15-46.

Han, J. H., 1981, Genetic stratigraphy and associated growth structures of the Vicksburg Formation, South Texas: The University of Texas at Austin, Ph.D. dissertation, 162 p.

Hayes, J. B., 1979, Sandstone diagenesis—the hole truth, *in* Scholle, P. A., and Schluger, P. R., eds., Aspects of diagenesis: Society of Economic Paleontologists and Mineralogists Special Publication No. 26, p. 127-139.

Jones, P. J., 1975, Geothermal and hydrocarbon regimes, northern Gulf of Mexico Basin, *in* Dorfman, M. H., and Delles, R. W., eds., First Geopressured Geothermal Energy Conference: The University of Texas at Austin, Center for Energy Studies, Proceedings, p. 15-97.

Kahn, J. S., 1956, The analysis and distribution of the properties of packing in sand-size sediments, Part 1. On the measurement of packing in sandstones: Journal of Geology, v. 64, p. 384-395.

Kaiser, W. R., 1984, Predicting reservoir quality and diagenetic history in the Frio Formation (Oligocene) of Texas, *in* McDonald, D. A., and Surdam, R. C., eds., Clastic diagenesis: American Association of Petroleum Geologists Memoir No. 37, p. 195-215.

Kehle, R. O., 1971, Geothermal survey of North America, 1971 annual progress report: Research Committee, American Association of Petroleum Geologists, unpublished, 31 p.

Klass, M. J., Kersey, D. G., Berg, R. R., and Tieh, T. T., 1981, Diagenesis and secondary porosity in Vicksburg sandstones, McAllen Ranch field, Hidalgo County, Texas: Gulf Coast Association of Geological Societies Transactions, v. 31, p. 115-123.

Klemme, H. D., 1972, Geothermal gradients, Part 1: Oil Journal, v. 69, p. 136, 141-144.

Land, L. S., 1984, Frio sandstone diagenesis, Texas Gulf Coast: a regional isotopic study, *in* McDonald, D. A., and Surdam, R. C., eds., Clastic diagenesis: American Association of Petroleum Geologists Memoir No. 37, p. 47-62.

Land, L. S., and Milliken, K. L., 1981, Feldspar diagenesis in the Frio Formation, Brazoria County, Texas Gulf Coast: Geology, v. 9, no. 7, p. 314-318.

Laniz, R. V., Stevens, R. E., and Norman, M. B., 1964, Staining of plagioclase feldspar and other minerals with F. D. and C. Red No. 2: U.S. Geological Survey Professional Paper 501, p. B152-B153.

LaPlante, R. E., 1972, Petroleum generation in Gulf Coast Tertiary sediments (abs.): American Association of Petroleum Geologists Bulletin, v. 56, no. 3, p. 635.

Lindholm, R. C., and Finkelman, R. B., 1972, Calcite staining: semiquantitative determination of ferrous iron: Journal of Sedimentary Petrology, v. 42, no. 1, p. 239-242.

Lindquist, S. J., 1976, Sandstone diagenesis and reservoir quality, Frio Formation (Oligocene), South Texas: The University of Texas at Austin, Master's thesis, 147 p.

Lindquist, S. J., 1977, Secondary porosity development and subsequent reduction, overpressured Frio Formation sandstone (Oligocene), South Texas: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 99-107.

Loucks, R. G., 1978, Sandstone distribution and potential for geopressure geothermal energy production in the Vicksburg Formation along the Texas Gulf Coast: Gulf Coast Association of Geological Societies Transactions, v. 28, p. 239-271.

Loucks, R. G., Bebout, D. G., and Galloway, W. E., 1977, Relationship of porosity formation and preservation to sandstone consolidation history—Gulf Coast lower Tertiary Frio Formation: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 109-120.

Loucks, R. G., Dodge, M. M., and Galloway, W. E., 1979a, Importance of secondary leached porosity in lower Tertiary sandstone reservoirs along the Texas Gulf Coast: Gulf Coast Association of Geological Societies Transactions, v. 29, p. 164-171.

Loucks, R. G., Dodge, M. M., and Galloway, W. E., 1979b, Sandstone consolidation analysis to delineate areas of high-quality reservoirs suitable for production of geopressured geothermal energy along the Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology, Report to U.S. Department of Energy, Division of Geothermal Energy, Contract No. EG-77-5-05-5554, 97 p.

Loucks, R. G., Richmann, D. L., and Milliken, K. L., 1980, Factors controlling porosity and permeability in geopressured Frio sandstone reservoirs, General Crude Oil/Department of Energy Pleasant Bayou test wells, Brazoria County, Texas, *in* Dorfman, M. H., and Fisher, W. L., eds., Fourth Geopressured Geothermal Energy Conference Proceedings: The University of Texas at Austin, Center for Energy Studies, v. 1, p. 46-82.

Loucks, R. G., Richmann, D. L., and Milliken, K. L., 1981, Factors controlling reservoir quality in Tertiary sandstones and their significance to geopressured geothermal production: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 111, 41 p.

McBride, E. F., 1977, Secondary porosity—importance in sandstone reservoirs in Texas: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 121-122.

McBride, E. F., Lindemann, W. L., and Freeman, P. S., 1968, Lithology and petrology of the Gueydan (Catahoula) Formation in South Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 63, 122 p.

Milliken, K. L., Land, L. S., and Loucks, R. G., 1981, History of burial diagenesis determined from isotopic geochemistry, Frio Formation, Brazoria County, Texas: American Association of Petroleum Geologists Bulletin, v. 65, no. 8, p. 1397-1413.

Moncure, G. K., Lahann, R. W., and Siebert, R. M., 1984, Origin of secondary porosity and cement distribution in a sandstone/shale sequence from the Frio Formation (Oligocene), *in* McDonald, D. A., and Surdam, R. C., eds., Clastic diagenesis: American Association of Petroleum Geologists Memoir No. 37, p. 151-161.

Murray, G. E., 1955, Midway Stage, Sabine Stage, and Wilcox Group: American Association of Petroleum Geologists Bulletin, v. 39, no. 5, p. 671-696.

Pusey, W. C., 1973, Paleotemperatures in Gulf Coast using the ESR-kerogen method: Gulf Coast Association of Geological Societies Transactions, v. 23, p. 195-202.

Richmann, D. L., Milliken, K. L., Loucks, R. G., and Dodge, M. M., 1980, Mineralogy, diagenesis, and porosity in Vicksburg sandstones, McAllen Ranch field, Hidalgo County, Texas: Gulf Coast Association of Geological Societies Transactions, v. 30, p. 473-481.

Ritch, H. J., and Kozik, H. G., 1971, Petrophysical study of overpressured sandstone reservoirs, Vicksburg Formation, McAllen Ranch field, Hidalgo County, Texas: Society of Professional Well Log Analysts, Twelfth Annual Logging Symposium, 14 p.

Schmidt, V., McDonald, D. A., and Platt, R. L., 1977, Pore geometry and reservoir aspects of secondary porosity in sandstones: Bulletin of Canadian Petroleum Geologists, v. 25, p. 271-290.

Stanton, G. D., 1977, Secondary porosity in sandstones of the lower Wilcox (Eocene), Karnes County, Texas: Gulf Coast Association of Geological Societies Transactions, v. 27, p. 197-207.

Storm, L. W., 1945, Resume of facts and opinions on sedimentation in Gulf Coast region of Texas and Louisiana: American Association of Petroleum Geologists Bulletin, v. 29, no. 9, p. 1304-1335.

Stuart, C. A., 1970, Geopressures, *in* Proceedings of the Second Symposium on Abnormal Subsurface Pressure: Baton Rouge, Louisiana State University, 121 p.

Todd, T. W., and Folk, R. L., 1957, Basal Claiborne of Texas, record of Appalachian tectonism during Eocene: American Association of Petroleum Geologists Bulletin, v. 41, no. 11, p. 2545-2566.

Wentworth, C. K., 1922, A scale of grade and class terms for clastic sediments: Journal of Geology, v. 30, p. 377-392.

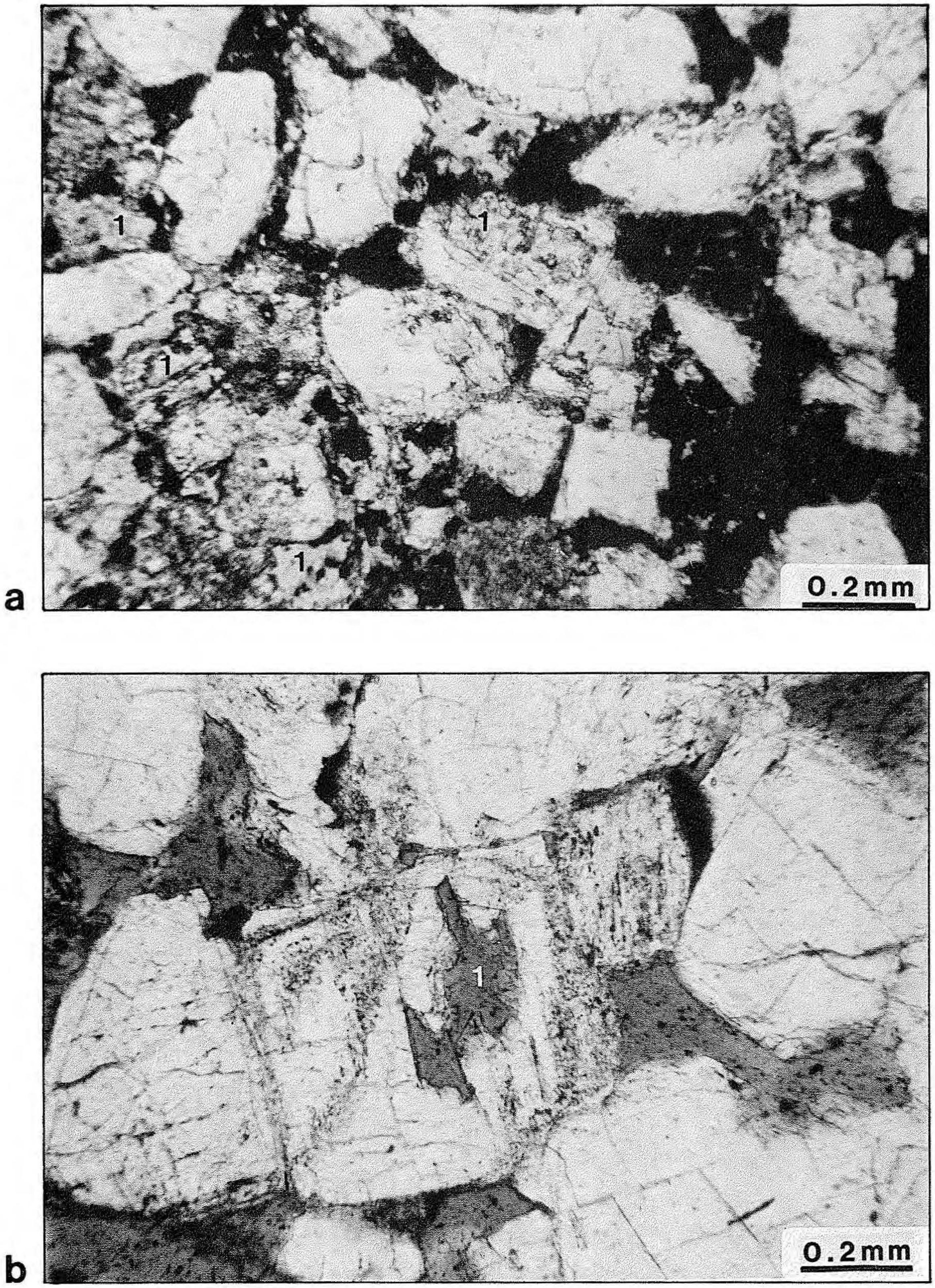


Plate 1. Criteria for recognition of secondary porosity. (a) Patchy remnants of Fe-rich carbonate cement (dark areas). All primary pore space was originally filled with carbonate cement. Some secondary porosity in feldspars (1) is also present. Yegua Formation, Sun No. 4 Ramirez "B" (1,383 m [4,536 ft]), Jim Hogg County, Texas. (b) Partial dissolution of a plagioclase grain (1) forming secondary porosity. Frio Formation, Phillips No. 1 Houston "GG" (4,518 m [14,823 ft]), Brazoria County, Texas.

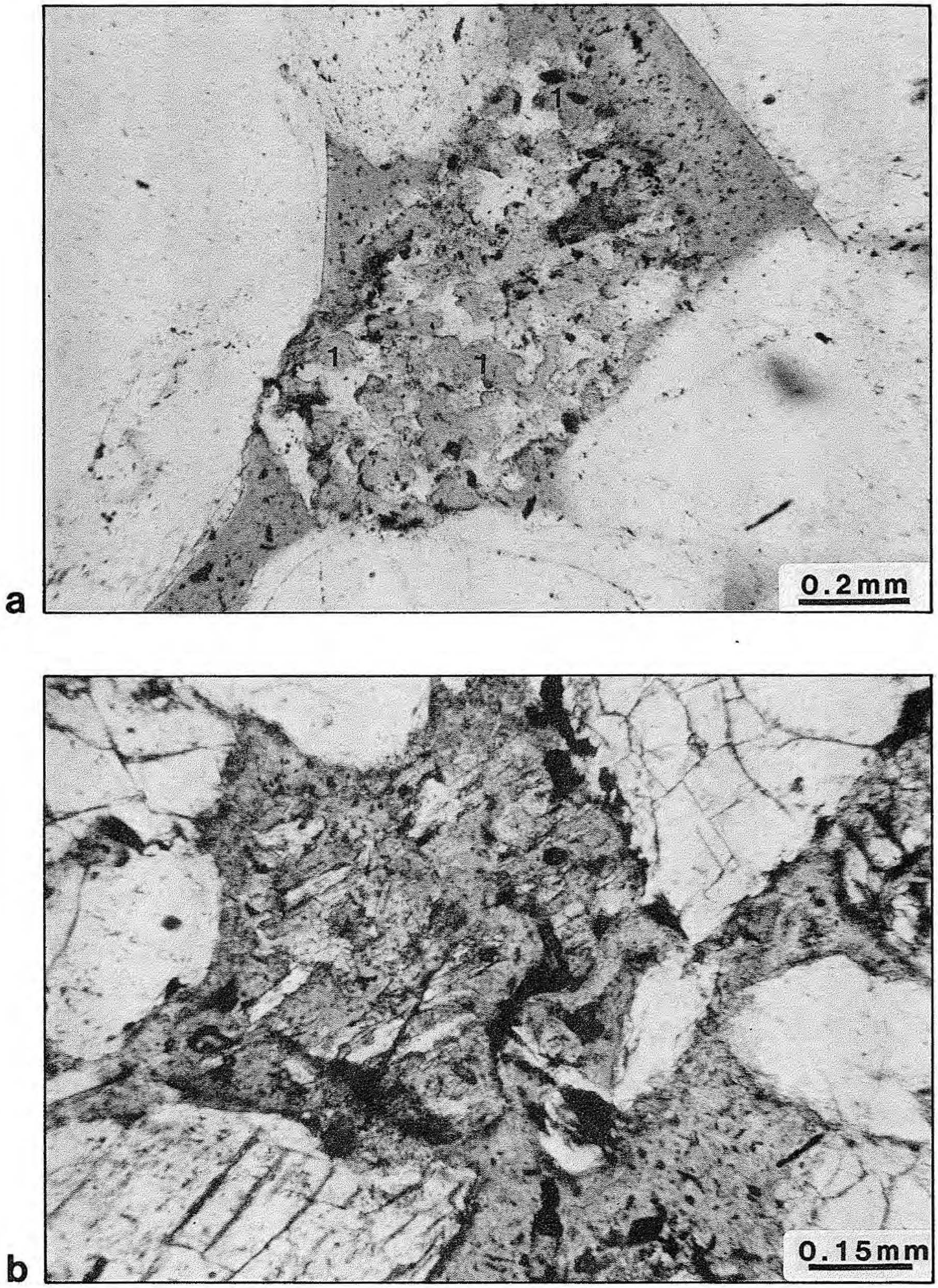


Plate 2. Criteria for recognition of secondary porosity. (a) Partial dissolution of a volcanic rock fragment forming secondary porosity (1). Frio Formation, Phillips No. 1 Houston "JJ" (4,837 m [15,870 ft]), Brazoria County, Texas. (b) Dissolution of feldspar grain forming honeycombed structure. Frio Formation, Phillips No. 1 Houston "JJ" (4,939 m [16,205 ft]), Brazoria County, Texas.

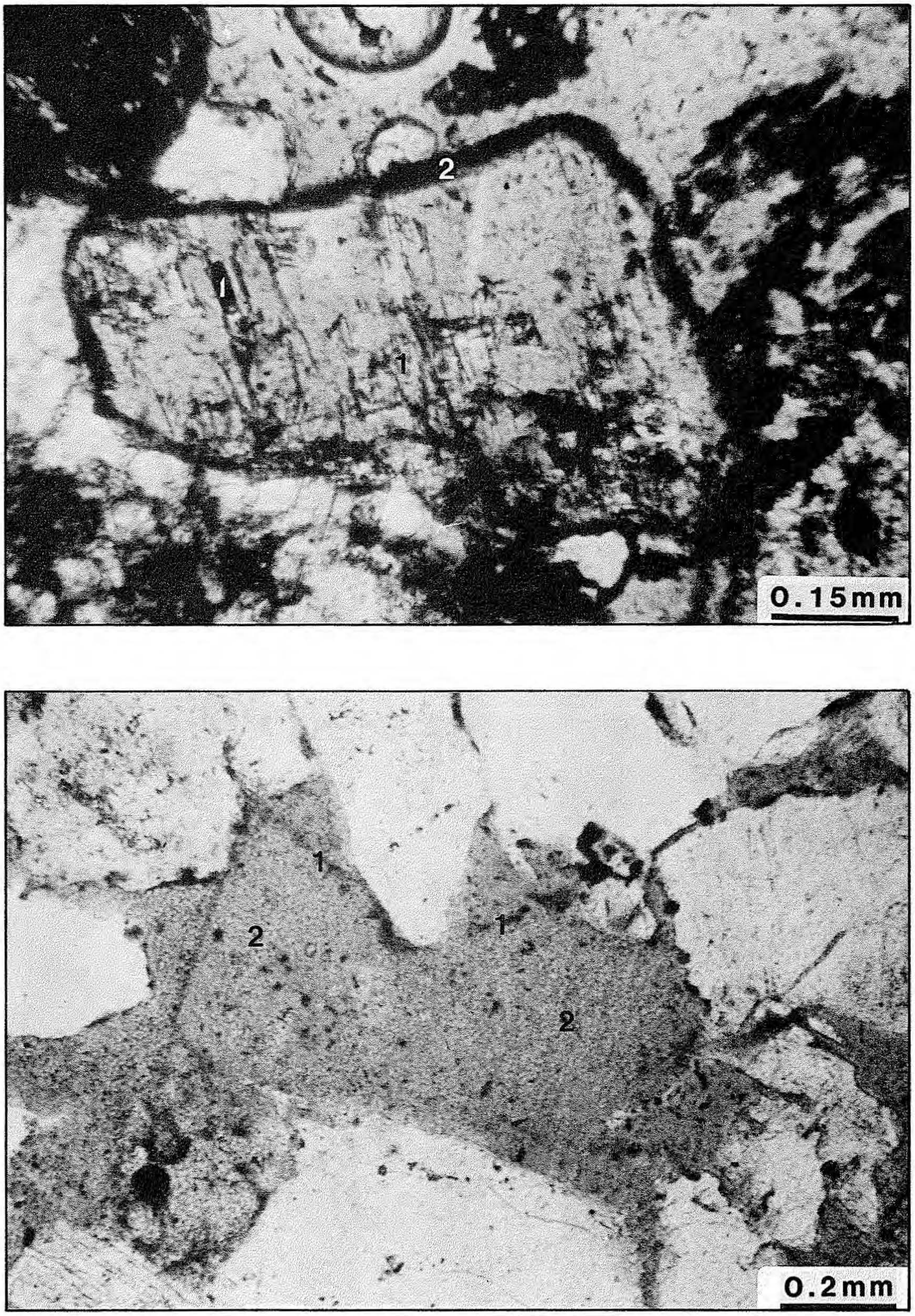
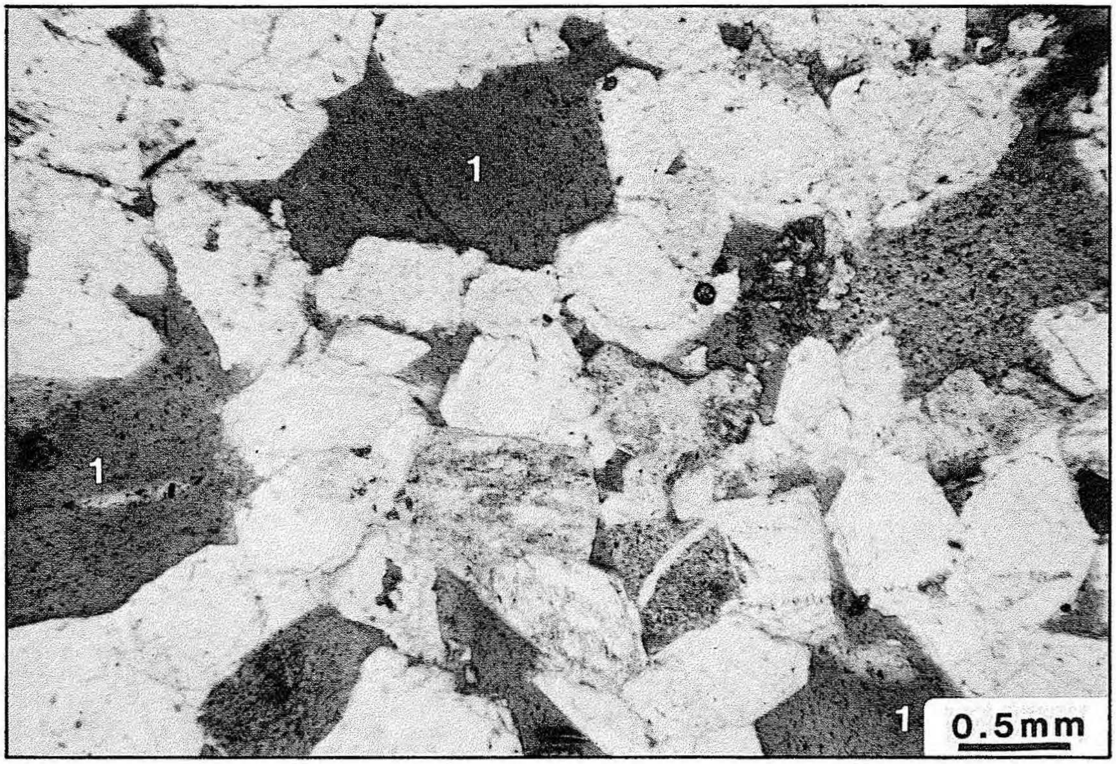
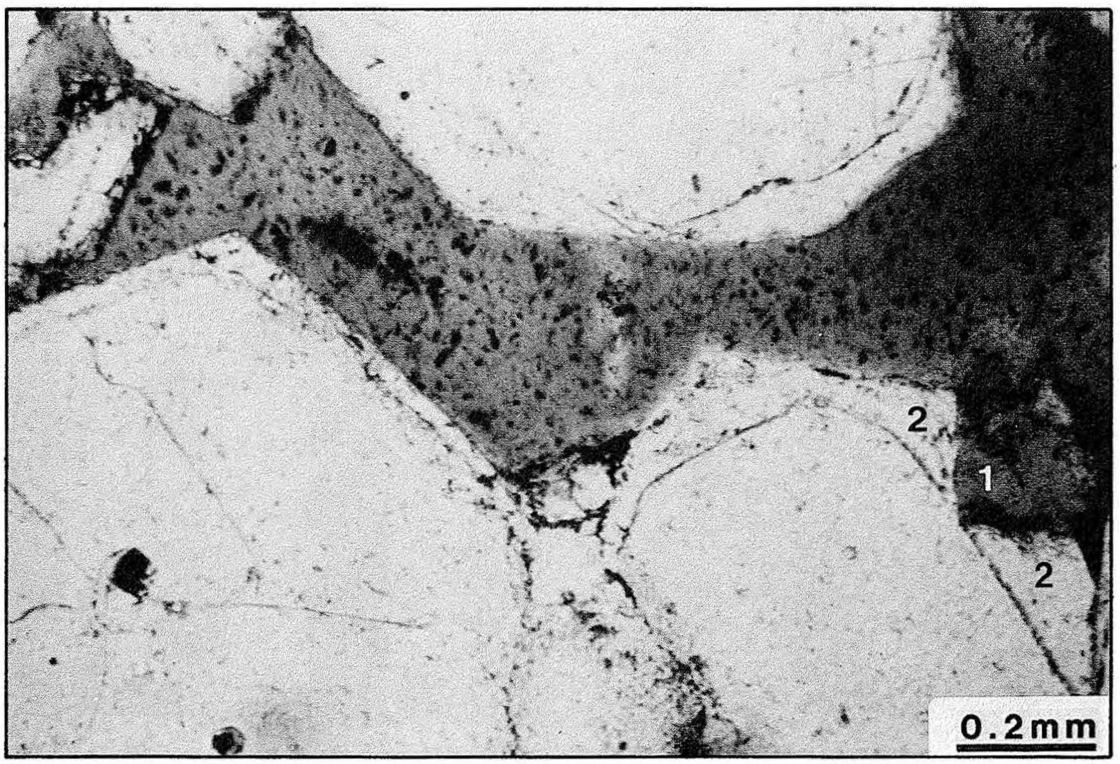
a
b


Plate 3. Criteria for recognition of secondary porosity. (a) Almost complete dissolution of feldspar grain with a minor honeycombed structure (1) and clay coat (2) remaining. Frio Formation, Miller and Fox No. 6 Garcia (920 m [3,017 ft]), Jim Wells County, Texas. (b) Dissolved feldspars outlined by clay coat (1) and partially filled with kaolinite cement (2). Frio Formation, Phillips No. 1 Houston "JJ" (4,826 m [15,833 ft]), Brazoria County, Texas.



a



b

Plate 4. Criteria for recognition of secondary porosity. (a) Sandstone showing oversized pore spaces (1) resulting from dissolution of feldspars. The complete dissolution of feldspars creates the appearance of packing inhomogeneity. Frio Formation, Phillips No. 1 Houston "GG" (4,539 m [14,891 ft]), Brazoria County, Texas. (b) Embayment (1) in quartz overgrowth (2) due to dissolution of grain around which the overgrowth previously precipitated. Frio Formation, Phillips No. 1 Houston "JJ" (4,837 m [15,870 ft]), Brazoria County, Texas.

APPENDIX: WELL DATA

Wells with Whole Core Samples

Aransas County

1. Arkansas Fuel Oil et al. No. 1 W. Rockport Unit 1
2. Cities Service No. 1 State Tract 242
3. Cities Service No. B-1 State Tract 260
4. Conroe Drilling, King & Heyne No. 1-A State Puerto Bay 4
5. Getty Oil Mission Corp., Ohio Oil No. 1 State Tract 125
6. Heep Oil No. 3 H. T. Sellers

Austin County

1. Southern Natural Gas No. 1 Frank Uhyrek

Bee County

1. Apache Corp., Southland Royalty & North Central Oil Corp. No. B-1 Burnell Tips
2. Frankfort Oil No. 10 W. D. Walton
3. Northern Pump No. 1 Dora Dugat
4. Northern Pump No. 1 R. L. House
5. Northern Pump No. 1 Alma Knight
6. Northern Pump No. 1 Gus Walters
7. Tennessee Gas Transmission No. B-1 A. N. Dahl

Brazoria County

1. Humble Oil No. 1 Freeport Sulfur
2. Humble Oil No. 1 J. M. Skrabanek
3. Humble Oil No. 1 R. W. Vieman
4. Phillips Petroleum No. 2 Gunderson
5. Phillips Petroleum No. F-3 Houston
6. Phillips Petroleum No. 1 Houston "GG"
7. Phillips Petroleum No. 1 Houston "JJ"
8. Phillips Petroleum No. 1 Houston "Z"
9. Phillips Petroleum No. 2 Rekdahl

Brooks County

1. Arkansas Fuel Oil No. 1 J. F. Dawson
2. Shell Oil No. B-2 Jimmie & Lenora Cage
3. Shell Oil No. 2 Lips

Calhoun County

1. Arkansas Fuel Oil, C. G. Glasscock, Tidelands Oil, and Ohio Oil No. 1 G. C. Bindewald
2. Arkansas Fuel Oil, C. G. Glasscock, Tidelands Oil No. 3 State Tract 72
3. C. G. Glasscock, Tidelands Oil, and Arkansas Fuel Oil No. 2 State Tract 72
4. Humble Oil No. 3 Elizabeth K. Hardie
5. Humble Oil No. 4 Elizabeth K. Hardie
6. Humble Oil No. 6 Elizabeth K. Hardie
7. Humble Oil No. 12 Elizabeth K. Hardie
8. Humble Oil No. 3 Lavaca Bay State Tract 45 (original)
9. Humble Oil No. 3 Lavaca Bay State Tract 45 (State Tract)
10. Sun Oil No. 1 Lavaca Bay State Tract 34
11. Texas Eastern Transmission No. 1 State Tract 127

Cameron County

1. Humble Oil No. 1 L. D. Austin

Chambers County

1. Humble Oil No. 15 M. E. Mayes
2. Humble Oil No. A-152 Galveston Bay State
3. Sun Oil No. 4 O. K. Winfree

Colorado County

1. Davis & Company No. 1 McLane
2. Magnolia Petroleum No. 1 Gracey Wegenhoft
3. Pure Oil No. 1 Frieda Vogelsang
4. Shell Oil No. 54 Sheridan Gas Unit

Duval County

1. Amerada Petroleum No. 1 Viggo Gruy
2. Continental Oil No. A-100 Robert Driscoll Estate
3. Continental Oil No. A-102 Robert Driscoll Estate
4. Continental Oil No. D-2 Clara Driscoll
5. Continental Oil No. 7 Ben Mew
6. Daubert Oil & Gas and Murphy Oil No. 2 Southland Life Insurance Company
7. Gulf Oil No. 1 Gulf Peters
8. Jake L. Hamon No. 15 Hoffman
9. Harkins & Company No. 1-100 D.C.R.C.
10. J. M. Hueber and Shell Oil No. 1 J. B. Stegal
11. Russell Maguire No. B-2 Driscoll
12. Shell Oil No. 1 J. B. Stegal "A"
13. Shell Oil No. 1 L. C. Weatherby "A"

Fort Bend County

1. Enserch Exploration No. 1 Foster Farms

Goliad County

1. Continental Oil No. 42 Pettus
2. Miller and Fox Minerals Corp. No. 1 J. S. Hodges
3. Miller and Fox Minerals Corp. No. 1 G. T. Powell
4. Robert Mosbacher and W. T. Mendell No. 1 Bettie Albrecht
5. Shell Oil No. 1-A R. W. Bego
6. Tennessee Gas Transmission No. 1 H. A. Bomba

Grimes County

1. Cockburn Company No. 1 Gayle
2. Shell Oil No. 2 Flora I. Johnson

Hardin County

1. Humble Oil No. 2 Southwest Lumber Company
2. Shell Oil No. 1 Kirby Lumber Company 10A

Harris County

1. Amerada Stanolind No. 1 Bode
2. Brewster & Bartle (Sun Oil) No. 1 Mrs. Z. S. Kratky
3. Humble Oil No. 10 Milo
4. Humble Oil No. 11 Tomball Gas Unit 1
5. Pan American No. 1 Dorothy D. Brown

Hidalgo County

1. Shell Oil No. 15 A. A. McAllen
2. Shell Oil No. 18 A. A. McAllen
3. Shell Oil and Delhi-Taylor Oil No. 4 Woods Christian
4. Shell Oil and Delhi-Taylor Oil No. 6 Woods Christian
5. Shell Oil and Delhi-Taylor Oil No. 7 Woods Christian
6. Shell Oil and Delhi-Taylor Oil No. 8 Woods Christian

Jackson County

1. Occidental Petroleum No. 3 George McHaney
2. Sun Oil No. 1 Arnolds Unit
3. Sun Oil No. 1 Dillie Unit
4. Sun Oil No. 1 McDaniels
5. Sun Oil No. 5 McDaniels
6. Sun Oil No. 1 Mauritz Unit 11
7. Sun Oil No. 1 Mauritz Unit 12
8. Sun Oil No. 1 Neisslie Unit
9. Sun Oil No. 1 Wright Unit

Jefferson County

1. Shell Oil No. 3 McFadden Ranch
2. Sun Oil No. 2 A. J. Mauboules

Jim Hogg County

1. D. D. Feldman Oil & Gas No. 1 C. W. Hellen
2. Gulf Oil No. 1 Fulbright Estate et al.
3. Sun Oil No. 4 A. Ramirez "B"
4. Sun Oil No. 35 Weil Bros.

Jim Wells County

1. Champlin Petroleum No. E-2 Shaeffer Ranch
2. Miller & Fox Minerals Corp. No. 6 Guadalupe B. Garcia
3. Shell Oil No. 21 Seeligson

Karnes County

1. Miller & Fox Minerals Corp. No. 1 Lott
2. Miller & Fox Minerals Corp. No. 1 Mary Lee Deer & Dorothy Carter
3. Seaboard Oil No. 1 Kulodjiejezyk
4. Texas Eastern Transmission Corp. No. 1 Ernest Waskow

Kenedy County

1. Arkansas Fuel Oil Corp. No. 2 H. F. McGill, Jr.
2. Humble Oil No. 3 Kenedy "J"
3. Humble Oil No. 18 S. K. East "B"

Kleberg County

1. Arkansas Fuel Oil Corp. No. 1 Beckman
2. Arkansas Fuel Oil Corp. No. 2 L. E. Bryant
3. Arkansas Fuel Oil Corp. No. C-1 V. A. Hubert
4. Arkansas Fuel Oil Corp. No. 2 V. A. Hubert
5. Arkansas Fuel Oil Corp. No. 1 Harry Langham
6. Arkansas Fuel Oil Corp. No. 1 A. T. Mittag
7. Arkansas Fuel Oil Corp. No. 1 Orr
8. Arkansas Fuel Oil Corp. and The Texas Company No. 1 J. L. Runnels
9. Arkansas Fuel Oil Corp. and Mokeen Oil No. 1 R. B. Womack
10. Champlin Oil No. 93 G. P. Wardner
11. Champlin Oil No. 101 G. P. Wardner
12. Sun Oil No. 376-1 Baffin State
13. Sun Oil & Morgan Minerals No. 2 Fimble Gas Unit

Liberty County

1. Pan American No. 1 Mabel Ott Howard

Live Oak County

1. Cities Service No. 1 Bailey "C"
2. Texas Eastern Transmission Corp. No. 2 Maxine Unit 11

McMullen County

1. J. S. Abercrombie No. 1 M. A. Tyler

Matagorda County

1. Sun Oil No. 27 Braman "C"

Montgomery County

1. Humble Oil No. 1 James C. Baldwin
2. Superior Oil No. 3 South Texas Development Company

Newton County

1. Humble Oil No. 1 W. W. Moore, Jr.

Nueces County

1. Arkansas Fuel Oil, Sunray Mid-Continent Oil No. 1 State Tract 10
2. Arkansas Fuel Oil No. 2 State Tract 751
3. Atlantic Richfield No. 4 State 45-47 Unit Tract 470
4. Champlin Oil No. 82 G. P. Wardner
5. Cities Service No. 1 Boggan "A"
6. Cities Service and Sunray DX Oil No. 4 State Tract
7. Cities Service, Ohio Oil, and Sunray Mid-Continent Oil No. 1 State Tract 61
8. Cities Service No. 2 State Tract 61
9. Delhi-Taylor Oil No. 2 L. J. Moore
10. Jake L. Hamon No. 2 State Tract 8
11. Jake L. Hamon No. 3 State Tract 8
12. Union Producing No. A-7 Driscoll

Orange County

1. Gulf Oil No. 3 Miller Victor Land Company Unit 2

Polk County

1. Humble Oil No. 1 J. C. Wittforth

Refugio County

1. Quintana Petroleum No. 63 Thomas O'Connor "C"

San Jacinto County

1. Shell Oil No. 11 Central Coal and Coke

San Patricio County

1. Conroe Drilling, D. D. Feldman, Del Mar Drilling, and King & Heyne No. 1 William E. Hunt
2. Conroe Drilling and King & Heyne No. 1 Billie Louise Chandler
3. Conroe Drilling and Jack Modeset No. A-1 Rosalie L. Stein
4. Conroe Drilling and Stanolind Oil & Gas No. 2 Bankers Mortgage
5. Conroe Drilling, Sunray Mid-Continent, Farenthold & Pitcairn et al. No. 1 A. J. Wheeler
6. Seaboard Oil No. 2 R. H. Welder Estate "A"
7. Superior Oil No. 61 Minnie S. Welder
8. The Texas Company No. 1 Alvin Becker

Starr County

1. Champlin Oil No. B-4 Arcadio Guerra
2. Continental Oil No. 4 W. I. Cameron "A"
3. Shell Oil No. 7 A. M. Garza St.
4. Shell Oil No. 1 H. W. Lehman
5. Texaco No. 5 Martinez State

Tyler County

1. Amerada Petroleum No. 1 Goolsbee
2. Humble Oil No. F-1 East Texas Oil Company Fee

Victoria County

1. Amerada Petroleum No. 1 Allan Kovak
2. Sun Oil No. 1 E. R. Urban

Waller County

1. Humble Oil No. 1 W-31 Katy GFU

Webb County

1. Atlantic Richfield No. C-1 Bruni Estate
2. Atlantic Richfield No. B-1 McLean Estate
3. Atlantic Richfield No. 1 Puig Gas Unit
4. Texas Eastern Transmission No. 2 A. M. Bruni Estate

Wharton County

1. Humble Oil No. 70 M. C. Cockburn
2. Humble Oil No. 1 Armit Thomas et al.

Willacy County

1. Shell Oil No. 2 Yturria
2. Superior Oil No. B-2 Clark-Cowden
3. Superior Oil No. 1 W. W. Ely
4. Superior Oil No. 2 W. W. Ely
5. Superior Oil No. 3 Chess Todd
6. Superior Oil No. 4 Chess Todd
7. Superior Oil No. 5 Chess Todd
8. Superior Oil No. 11 Yturria

Wilson County

1. Fitzpatrick Drilling No. 1 D. O. Poth et al.
2. Forest Oil No. 1 Mrs. T. D. Manford

Zapata County

1. Jake L. Hamon No. 1 Manuela Yzaguirre

Wells with Porosity and Permeability Data

Aransas County

1. Arkansas Fuel Oil et al. No. 1 W. Rockport Unit 1
2. Cities Service No. 1 State Tract 242
3. Cities Service No. B-1 State Tract 260
4. Conroe Drilling, King & Heyne No. 1-A State Puerto Bay 4
5. Getty Oil, Mission Corp. No. 1 State Tract 125
6. Heep Oil No. 3 H. T. Sellers
7. Phillips Petroleum No. 1 State Tract 163
8. Tenneco No. 2 W. G. McCampbell, Jr., et al.

Austin County

1. Robert Mosbacher and H. L. Brown, Jr., No. 1 Mrs. D. C. Hillboldt
2. Southern Natural Gas No. 1 Frank Uhyrek

Bee County

1. Northern Pump No. 1 R. T. House
2. Northern Pump No. 1 Alma Knight
3. Northern Pump No. 1 Gus Walters
4. Skelly Oil No. 1 A. W. Zook
5. Tennessee Gas Transmission No. B-1 A. N. Dahl

Brazoria County

1. Continental Oil No. 2 S. S. Perry
2. Humble Oil No. 1 J. M. Skrabanek
3. Humble Oil No. 1 R. W. Vieman
4. Phillips Petroleum No. 2 Gunderson
5. Phillips Petroleum No. 1 Houston "GG"
6. Phillips Petroleum No. 1 Houston "JJ"
7. Phillips Petroleum No. 1 Houston "Z"
8. Phillips Petroleum No. 3 Houston Farms "F"
9. Phillips Petroleum No. 2 Rekdahl
10. Texaco No. 2 Hoskins Mound Fee
11. Texaco No. 1 Tarpon Mound Fee

Brooks County

1. Shell Oil No. 2 C. S. Lips

Calhoun County

1. Arkansas Fuel Oil, C. G. Glasscock and Tidelands Oil No. 1 W. L. Bindewald
2. Arkansas Fuel Oil, C. G. Glasscock and Tidelands Oil No. 3 State Tract 72
3. Humble Oil No. 3 Elizabeth K. Hardie
4. Humble Oil No. 4 Elizabeth K. Hardie
5. Humble Oil No. 6 Elizabeth K. Hardie
6. Humble Oil No. 3 Lavaca Bay State Tract 45 (original)
7. Humble Oil No. 3 Lavaca Bay State Tract 45 (hole 2)
8. Texas Eastern Transmission No. 1 State Tract 127

Cameron County

1. Humble Oil No. 1 L. D. Austin

Chambers County

1. James B. Felder & Associates No. 1 Hawthorne

Colorado County

1. Dan J. Harrison, Jr., No. 1 Herman Jenkins
2. F. B. Lacy and Angelina Exploration No. 1 Hollis Massey
3. Shell Oil No. 1 Engstrom "EE"
4. Shell Oil No. 53 Sheridan Gas Unit

De Witt County

1. Atlantic Refining No. 1 Ella Lee Kirlick
2. Atlantic Refining No. 1-A Mathew-Newson Unit
3. Atlantic Refining No. 1 C. A. Schorre
4. Atlantic Refining No. 1 Myra A. Skinner
5. Austral Oil No. 1 Schroeter
6. Austral Oil and Crown Central No. 1 Ferguson
7. Lone Star Producing Company No. 1 J. F. Garrett
8. Monsanto No. 1 Kulawik
9. Shell Oil No. 1 W. M. Carroll

Duval County

1. Amerada Petroleum No. 1 Viggo Gruy
2. Continental Oil No. D-2 Clara Driscoll
3. Continental Oil No. A-100 Robert Driscoll
4. Continental Oil No. 7 Ben Mew
5. Daubert Oil & Gas and Murphy Oil of Oklahoma No. 2 Southland Life Insurance Company
6. Gulf Oil No. 1 Gulf-Peters
7. Harkins & Company No. 1-100 D.C.R.C.
8. Jake L. Hamon et al. No. 15 Duval-W. K. Hoffman
9. Russell Maguire No. B-2 Driscoll
10. Tex-Star Oil & Gas No. 1 A. E. Garcia

Galveston County

1. Humble Oil No. B-14 Bayou Development
2. Humble Oil No. 1 Jones Bay State Tract 81

Goliad County

1. Continental Oil No. 42 J. E. Pettus
2. Miller & Fox Minerals Corp. No. 1 J. S. Hodges
3. Miller & Fox Minerals Corp. No. 1 Gentry T. Powell
4. Robert J. Hewitt No. 1 Mrs. Frieda Hall
5. Robert J. Mosbacher and Mendell No. 1 Bettie Albrecht
6. Shell Oil No. 1-A R. W. Bego
7. Sunray DX Oil No. 1 F. R. Pereira
8. Tennessee Gas Transmission No. 1 K. A. Bomba

Gonzales County

1. Monsanto No. 1 N. H. Gas Kamp

Hardin County

1. Austral Oil S. A. 6722 No. 1

Harris County

1. Barousse & Barrett No. 1 R. C. Addicke
2. Brewster & Bartle No. 1 Mrs. Z. S. Kratky
3. Crown Central Petroleum No. 1 Lucille Fisher et al.
4. Currie Davis & Company No. 1 Susholtz Zieben Company
5. Houston Natural Gas Production No. 1 Claud B. Hamill Unit 1

6. Houston Natural Gas Production No. 1 Claud B. Hamill Unit 2
7. Houston Natural Gas Production No. 1 Claud B. Hamill Unit 3
8. Houston Natural Gas Production No. 1 J. E. Wilcox
9. Houston Oil No. C-2 Foster Lumber Company
10. Robinson Oil & Gas No. 1 J. E. Fleming
11. Robinson Oil & Gas No. 1 Webster Fleming Gas Unit 3

Hidalgo County

1. American Petrofina of Texas No. 1 E. P. Evans
2. American Petrofina of Texas No. 3 Graham Unit
3. Arco Oil Corp. and Mabee Royalties Inc. No. 1 F. M. Cole Estate
4. Atlantic Richfield No. 2 Smith Gas Unit
5. Bateman & Cooley No. 1 Knops et al.
6. Bentsen-Whittington Oil No. 1 Edinberg Improvement Company
7. The Cherryville Corp. No. 1 Jose Barrera
8. Cleary Petroleum Corp. No. 1-2 Wieseham-Walker
9. Coastal States Gas Producing No. 1 A. E. Austin
10. Coastal States Gas Producing No. 1 H. S. Alcorn
11. Coastal States Gas Producing No. 1 Peter Van Scherpe
12. Coastal States Gas Producing No. 1 Zamora "GG"
13. Gulf Oil No. 1 Wolcot Gas Unit et al.
14. R. W. McMahon & Associates No. 1 Boston, Texas Land Trust
15. Shell Oil No. 1 Dixie Mortgage Loan Company
16. Shell Oil No. 2 May Agnes Hopkins
17. Tenneco No. 43 McAllen Fieldwide Unit
18. Texaco No. 7 A. E. Guerra

Jackson County

1. Behemoth Petroleum and Dellwood Oil No. 1 Robert Zejicek
2. E. Cockrell, Jr., et al. No. B-4 Moody
3. Francitas Gas No. 2 Lovett Estate
4. George R. Brown No. 1 W. L. Moody, Jr.
5. Hass Brothers No. 2 Louis Kuretsch
6. Harper Smith and Associates No. 1-A W. T. Westhoff
7. Sun Oil Company No. 1 Mauritz Unit 11

Jasper County

1. Kerr, McGee, Sinclair No. B-1 Atlantic

Jefferson County

1. Atlantic Refining No. 1 Gilbert Estate
2. Cyprus Oil No. 1 Tyrrell
3. Meredith & Company No. 1 Boyt
4. Meredith & Company No. 1 A. P. Daniel
5. Meredith & Company No. 1 A. P. Daniel Unit 2
6. Meredith & Company No. 1 William Doornbos et al.
7. Meredith & Company No. 1 Guiterman
8. Meredith & Company No. 1 Quinn
9. Meredith & Company No. 1 Weed
10. Owen No. 2 Hebert
11. Texland Production Corp. and H. R. Dillion No. 1 Neuhaus

Jim Hogg County

1. Atlantic Richfield No. 3 Marrs McLean "C"
2. Atlantic Richfield No. 4 Marrs McLean "C"
3. Atlantic Richfield No. 6 Marrs McLean "C"
4. D. D. Feldman Oil & Gas No. 1 Hellen
5. Gulf Oil No. 1 Fulbright et al.
6. Shell Oil, Robert Mosbacher No. 1 J. E. Fulbright

Jim Wells County

1. Champlin Petroleum No. E-2 Shaeffer Ranch
2. Miller & Fox Minerals Corp. No. 6 Guadalupe de Garcia
3. Neville G. Penrose No. 1 A. G. Martinez
4. Skelly Oil No. 1 J. A. Hill

Karnes County

1. Miller & Fox Minerals Corp. No. 1 Mary Lee Deer and Dorothy Carter
2. Miller & Fox Minerals Corp. No. 1 Lott
3. Texas Eastern Transmission No. 1 Ernest Waskow

Kenedy County

1. Arkansas Fuel Oil No. 2 H. F. McGill, Jr.
2. Humble Oil No. 15 S. K. East "B"
3. Humble Oil No. 18 Mrs. S. K. East "B"
4. Humble Oil No. 3 John G. Kenedy, Jr., "J"
5. Humble Oil No. 2 Carl F. Risken

Kleberg County

1. Arkansas Fuel Oil No. 1 John R. J. Beckman
2. Arkansas Fuel Oil No. 2 L. E. Bryant
3. Arkansas Fuel Oil No. 2 V. A. Hubert
4. Arkansas Fuel Oil No. C-1 V. A. Hubert
5. Arkansas Fuel Oil No. 1 Langham
6. Arkansas Fuel Oil No. 1 T. A. Mittag
7. Arkansas Fuel Oil No. 1 R. W. Orr
8. Arkansas Fuel Oil, Argo, and Sun No. 1 Shonefeld
9. Arkansas Fuel Oil and Mokeen Oil No. 1 R. B. Womack
10. Arkansas Fuel Oil and The Texas Company No. 1 J. L. Runnels
11. Sun Oil No. 376-1 Baffin State
12. Sun Oil & Morgan Minerals Corp. No. 2 Fimble Gas Unit

Lavaca County

1. Fundamental Oil No. 1 J. O. Thigpen
2. George Mitchell and Associates No. 1 W. W. Allen
3. George Mitchell and Associates No. 1 W. W. & A. G. Allen Unit
4. George Mitchell and Associates No. 1 Sophia B. Jones
5. George Mitchell and Associates No. 1 Oldham
6. Shell Oil No. 1 Fielder
7. Shell Oil No. 1 Langenberg Unit
8. Shell Oil No. 7 E. T. Neubeve
9. Shell Oil No. 1 Daniel Struse
10. The Superior Oil Company No. 1 Julia Klinitchek
11. Union Texas Petroleum No. 1 T. Z. Sparks

Liberty County

1. American Republic Corp. No. 1 J. E. Broussard
2. Cabot Corp. No. 1 Rick Ranch
3. Corley & Geiselman No. 1 D. J. Harrison
4. Draper-Goodale & Company No. 1 Price Daniel
5. Humble Oil No. 1 Mary E. Pickett
6. Humble Oil No. 1 Woodrow Smith
7. L. P. Kelley No. 1 Pan-Am Fee
8. Oil and Gas Property Management No. 1 Quickel
9. Sanders Oil Operation No. 3 E. W. Pickett Lot 3

10. Shell Oil No. 1 Bill Daniel
11. Shell Oil No. 2 Bill Daniel
12. Starr Oil & Gas and J. M. Huber Corp. No. 1 A. R. Duke
13. Texaco No. 1 Paraffine

Live Oak County

1. Atlantic Refining No. 1 J. H. Coward
2. Atlantic Refining No. 1 T. J. Lyne
3. Cities Service No. 1 Bailey "C"
4. Jake L. Hamon No. 1 Marie C. Hefner
5. Neil E. Hanson & Harry Hurt No. 1 Bernice S. Sparkman
6. Texas Eastern Transmission No. 2 Marine Unit 11

McMullen County

1. J. S. Abercrombie No. 1 M. A. Tyler
2. Mokeen Oil No. 1 Henry L. Hart

Matagorda County

1. ADA Oil No. 1 C. C. Fletcher
2. Falcon Seaboard Drilling No. A-1 Baer Ranch
3. Falcon Seaboard Drilling No. A-2 Baer Ranch
4. Humble Oil No. 1 First City National Bank Trustee
5. Occidental Petroleum No. 1 J. E. Dawdy, Jr., et al.

Montgomery County

1. Humble Oil No. 45 A. A. & D. A. Madley
2. The Superior Oil Company No. 3 Lake Creek Unit
3. Texaco No. 1 B. D. Griffin

Newton County

1. Coastal States Gas Producing & North Central Oil No. 1 John White
2. Kerr-McGee Corporation No. 1 Sinclair-Atlantic Fee A
3. Kerr-McGee Corporation No. 2 Sinclair-Atlantic Fee A

Nueces County

1. A. O. Morgan et al. No. 1 Chapman Ranch "C"
2. Arkansas Fuel Oil No. 2 State Tract 751
3. Arkansas Fuel Oil and Sunray Mid-Continent No. 1 State Tract 10
4. Cities Service No. 1 Boggan "A"
5. Cities Service No. 4 State Tract 9
6. Cities Service No. 2 State Tract 61
7. Cities Service and Sunray Mid-Continent No. 1 State Tract 61
8. Cities Service and Sunray Oil No. 1 State Tract 51
9. Delhi-Taylor No. 2 L. J. Moore
10. Jake L. Hamon No. 2 State Tract 8
11. Jake L. Hamon No. 3 State Tract 8
12. Socony Mobil No. 1 Chapman Ranch "B"

Refugio County

1. C. G. Glasscock, Tidelands Oil, and Arkansas Fuel Oil Corp. No. 2 State Tract 72

San Patricio County

1. Conroe Drilling and D. D. Feldman Oil & Gas No. 1 W. E. Hunt
2. Conroe Drilling and King and Heyne No. 1 B. L. Chandler
3. Conroe Drilling and Stanolind Oil & Gas No. 2 Bankers Mortgage
4. Conroe Drilling, Sunray Mid-Continent, Farenthold & Pitcairn et al. No. 1 A. J. Wheeler
5. Seaboard Oil No. 2 R. H. Welder Estate "A"
6. Skelly Oil No. 3 Fannie Coates
7. The Superior Oil Company No. 61 Welder
8. The Texas Company No. 1 Alvin Becker

Starr County

1. Continental Oil No. 4 W. I. Cameron
2. The Texas Company No. 5 Martinez-State

Victoria County

1. Sun Oil No. 1 Wedemeier Gas Unit

Walker County

1. Humble Oil No. 1 Gibbs Brothers & Company

Waller County

1. Exxon No. 1 Katy Gas Field Unit W-35
2. Humble Oil No. 1 Katy Gas Field Unit W-32
3. Michel T. Halbouty No. 1 John W. Harris et al.
4. Pan American Petroleum No. 1 C. A. O'Conner

Webb County

1. Atlantic Refining No. 1 V. L. Puig Gas Unit
2. Cities Service No. 1 Benavides "A"
3. Skelly Oil No. 2-C J. O. Walker
4. Texas Eastern Transmission No. 2 A. M. Bruni Estate

Wharton County

1. Anderson & Coke No. 1 L. I. Rehfuss
2. General Crude No. 1 Wintermann
3. General Crude No. 2 Wintermann
4. General Crude No. 4 Wintermann
5. Miller and Ritter No. 1 Coye Mae Allen
6. Pure Oil No. 1 L. E. Lancaster
7. Pure Oil No. 6 W. L. Stewart
8. Sunray DX Oil Company No. 2 W. N. Lehrer

Willacy County

1. The Superior Oil Company No. B-2 Clark-Cowden
2. The Superior Oil Company No. 1 W. W. Ely
3. The Superior Oil Company No. 2 W. W. Ely
4. The Superior Oil Company No. 3 Chess Todd
5. The Superior Oil Company No. 4 Chess Todd
6. The Superior Oil Company No. 5 Chess Todd
7. The Superior Oil Company No. 11 Yturria

Wilson County

1. Fitzpatrick Drilling No. 1 D. O. Poth et al.
2. Forest Oil No. 1 Mrs. T. D. Manford

Zapata County

1. Jake L. Hamon No. 1 Manuela Yzaguirre

Wells with Acoustic Logs

Aransas County

1. Humble Oil No. 1 State Tract 222 E. Aransas Pass Gas Unit

Austin County

1. George Mitchell & Associates No. 1 Albert Peschel
2. Robert Mosbacher & Hillboldt No. 1 H. L. Brown
3. Southern Natural Gas No. 1 Frank Uhyrek

Brazoria County

1. Continental Oil No. 1 White Frost
2. Dow Chemical No. 1 C. C. Bell et al.
3. Humble Oil No. 1 M. E. Hunter
4. Humble Oil No. 1 Retrieve State Farm Tract 4
5. Humble Oil No. 1 J. M. Skrabanek
6. Humble Oil No. 1 R. W. Vieman
7. Humble Oil No. 1 A. B. Williamson
8. Mobil Oil No. 1 Hayden McNeill
9. Monsanto No. 1 Stasny

Colorado County

1. Anadarko No. 1 Wells "A"
2. Harrison No. 1 Herman Jenkins
3. Newmont Oil No. 1 Annabell Everett

De Witt County

1. Austral Oil No. 1 Schroeter
2. George R. Brown No. 1 Alfred Friar
3. Humble Oil No. 1 Guaranty Title and Trust Company Trustee

Duval County

1. Amerada No. 1 Viggo Gruy
2. Gulf Oil No. 1 Peters
3. P. R. Rutherford No. 1 Walter Pursch

Galveston County

1. Cities Service No. B-2 Stewart
2. Hassie Hunt No. 3 S. H. Green
3. Humble Oil No. B-14 Bayou Development Company
4. Mobil Oil No. 11 Halls Bayou Ranch
5. Phillips Petroleum No. 2 Pabst "B"
6. Phillips Petroleum No. 2 Jacquard "A" Sidetrack 1
7. Texas Eastern Transmission No. 1 Hitchcock
8. Texas Eastern Transmission No. 1 Nanna O. Newton

Goliad County

1. Atlantic Refining No. 1 G. F. Diebel

Harris County

1. Houston Natural Gas No. 1 Claud B. Hamill Unit 3
2. Pan American No. 1 Dorothy D. Brown

Hidalgo County

1. Shell Oil No. 1 Beaurline
2. Shell Oil No. 1 George Coates-Newmont Oil Company
3. Shell Oil No. C-1 McAllen Ranch
4. Tenneco No. 1 Harriman Ranch

Jackson County

1. Michel T. Halbouty No. B-1 L. R. Hollingsworth
2. Monsanto Chemical No. 1 Texas Gulf Sulfur Fee

Jasper County

1. Austral No. 1 S. A. 6732
2. Kerr-McGee Corp. No. B-1 Sinclair Atlantic

Jim Hogg County

1. Atlantic Richfield No. 2-C Marrs McLean Trust
2. Gulf Oil No. 1 Fulbright Estate
3. Mosbacher No. 1 J. E. Fulbright

Jim Wells County

1. Sun Oil No. 117 P. Canales

Kleberg County

1. Arkansas Fuel Oil No. 1 R. B. Womack

Lavaca County

1. Shell Oil No. 1 E. A. Sibley
2. Sohio No. 1 E. W. Ponish
3. Union Texas Petroleum, Alberville Operating Company, and Kiowa Minerals No. 1 T. E. Sparcks

Liberty County

1. Pan American No. 1 Kilburn Moore Estate
2. Pan American No. 1 Mabel Ott Howard

Live Oak County

1. Atlantic Refining No. 1 T. J. Lyne
2. Cities Service No. 1 Bailey "C"
3. Gulf Oil No. 1 John Lee
4. P. R. Rutherford No. 2-A Earl M. Baker et al.
5. Tenneco No. 1 C. G. B. Schultz
6. Tidewater Oil No. 1 Emmie Tullis

Matagorda County

1. Continental Oil No. 1 Nora Caldwell
2. Davis Oil No. 1 Helen K. Johnson
3. Humble Oil No. 1-B Pauline Huebner
4. Occidental Petroleum No. 1 First City National Bank of Houston Trustee
5. Pan American No. A-2 Silver Lake Ranch
6. Socony Mobil Oil No. 3 Janie Hawkins

Montgomery County

1. Pan American No. 1 R. A. Welch Foundation

Newton County

1. Kerr-McGee Corp. No. 1-A Sinclair Atlantic

Nueces County

1. Cities Service No. 1 Boggan "A"
2. Cities Service No. 4 State Tract 9
3. Cities Service No. 1 State Tract 61
4. Cities Service No. 2 State Tract 61
5. Socony Mobil No. 1 Chapman Ranch "B"

Polk County

1. Pan American No. A-1 Southland Paper Mill

Refugio County

1. Cox, et al. No. 1 Dammann

San Patricio County

1. Tenneco Oil No. 1 W. G. McCampbell

Starr County

1. Coastal States Producing and Greenbriar LTD 72 No. 1 George H. Echols
2. Sun Oil No. 3 C. M. Hall "C"

Tyler County

1. Shell Oil No. 1 Kirby Lumber Corp. Tract 53-A

Walker County

1. Humble Oil No. 1 Gibbs Bros. & Company
2. Marr & Morgan No. 3 Gibbs
3. Pure Oil and Moran Corp. No. 1 Central Coal and Coke Corp.

Waller County

1. Pan American No. 1 C. A. O'Conner

Washington County

1. Shell Oil No. 1 C. W. Jackson

Webb County

1. Cities Service No. A-1 Benavides
2. Coastal States Producing No. 1 V. L. Puig

Wharton County

1. General Crude No. 1 Wintermann
2. Sun Ray Oil No. 1 Hancock

Zapata County

1. Ashland Oil No. 1 Munon
2. Jake L. Hamon No. 1 Elizabeth McCampbell