SANDSTONE CONSOLIDATION ANALYSIS TO DELINEATE AREAS OF HIGH-QUALITY RESERVOIRS SUITABLE FOR PRODUCTION OF GEOPRESSURED GEOTHERMAL ENERGY ALONG THE TEXAS GULF COAST

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ABSTRACT

Analysis of reservoir quality of lower Tertiary sandstones along the Texas Gulf Coast delineates areas most favorable for geopressured geothermal exploration. Reservoir quality is determined by whole core, acoustic log, and petrographic analyses.

Wilcox sandstones exhibit no regional reservoir quality trends. In Lower and parts of Middle and Upper Texas Gulf Coast the sandstones are relatively well consolidated, but in other parts of Middle and Upper Texas Gulf Coast they show a reversal toward increased porosity at depth. Vicksburg sandstones have the poorest reservoir quality of sandstones of any formation prospective for geothermal energy. Frio sandstones show a systematic increase in reservoir quality from Lower to Upper Texas Gulf Coast. This increase in reservoir quality correlates to changes in rock composition and cementation. Acoustic log analysis substantiates a progression of greater consolidation from Upper to Lower Texas Gulf Coast.

Wilcox sandstones are poorly to moderately sorted, fine-grained, quartzose lithic arkoses, becoming more quartz-rich from Upper to Lower Texas Gulf Coast. Most rock fragments are metamorphic and volcanic. Vicksburg sandstones are poorly sorted, fine-grained lithic arkoses. Rock fragments are mainly volcanic clasts with lesser carbonate and minor metamorphic clasts. Frio sandstones range from poorly sorted, fine-grained, feldspathic litharenites to lithic arkoses in Lower Texas Gulf Coast to poorly sorted, fine-grained, quartzose lithic arkoses to subarkoses in Upper Texas Gulf Coast. Volcanic rock fragments predominate in all areas; carbonate rock fragments are common in Lower Texas Gulf Coast.

In spite of variations in composition, lower Tertiary sandstones exhibit a similar diagenetic sequence idealized as follows:

Surface to shallow subsurface diagenesis (0 to 1,200 m$^{\pm}$; 0 to 4,000 ft$^{\pm}$) begins with formation of pedogenic clay coats, leaching of feldspar, and replacement of

feldspar by calcite. Minor amounts of kaolinite, feldspar overgrowths, and Fe-rich carbonate are locally precipitated. Porosity is commonly reduced by compaction from the original 40 percent to less than 30 percent.

Moderate subsurface diagenesis (1,200 to 3,400 m±; 4,000 to 11,000 ft±) involves leaching of early carbonate cements and subsequent cementation by quartz overgrowths and later by carbonate cement. Cementation commonly reduces porosity to 10 percent or less, but this trend may be reversed by later leaching of feldspar grains, rock fragments, and carbonate cements. Resurrection of porosity to more than 30 percent can occur, but this may be reduced once more by later cementation by kaolinite, Fe-rich dolomite, and ankerite.

Deep subsurface diagenesis (>3,400 m±; >11,000 ft±) is a continuation of late Fe-rich carbonate cement precipitation.

Differences in intensity of diagenetic features that may correspond to changes in rock composition distinguish areas of high reservoir quality along the Texas Gulf Coast. Lower Texas Vicksburg and Frio reservoirs have extensive late carbonate cementation, whereas in the Upper Texas Gulf Coast carbonate cementation is minor. Wilcox reservoirs show no simple trend; quartz and lesser carbonate are the dominant porosity-reducing cements for which precipitation is governed by local chemical and physical conditions.

The Wilcox Group has good reservoir potential for geopressured geothermal energy in the Middle Texas Gulf Coast and possibly in adjacent areas, but other Wilcox areas are marginal. The Vicksburg Formation in the Lower Texas Gulf Coast is not prospective. Reservoir quality in the Frio Formation increases from very poor in lowermost Texas, to marginal into the Middle Texas Gulf Coast and to good through the Upper Texas Gulf Coast. The Frio Formation in the Upper Texas Gulf Coast has the best deep-reservoir quality of any unit along the Texas Gulf Coast.

INTRODUCTION

General Statement

Reservoir quality controls production of hydrocarbons and methane-saturated geothermal waters from sandstones. Economically attractive reservoirs must have porosities and permeabilities 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 enables prediction of depth range and of areas suitable for exploration, for enhanced development of known fields, and for application of most effective enhanced oil recovery methods.

The onshore Texas Gulf Coast lower Tertiary stratigraphic section is an area of active exploration for hydrocarbons and geothermal energy. Abundant information is available on structure, stratigraphy, and depositional systems of the area, but minimal data are available on reservoir quality from limited investigations made in recent years (Loucks, Bebout, and Galloway, 1977; Lindquist, 1977; Stanton, 1977). A regional assessment of reservoir quality to outline the distribution of high-quality reservoirs in the onshore Texas Gulf Coast lower Tertiary section and to determine factors controlling their creation and preservation was initiated by the Bureau of Economic Geology with subsequent funding by the U. S. Department of Energy.

Objectives and Scope of Study

The major objective of this regional investigation is the delineation of the sandstone consolidation history of the onshore Texas Gulf Coast lower Tertiary stratigraphic section with emphasis on formation, preservation, and vertical and lateral distribution of porosity and permeability to develop a predictive tool for recognition of favorable reservoir areas. The study emphasizes the Wilcox Group and the Vicksburg and Frio Formations in which geothermal fairways have been delineated (fig. 1). The results of this investigation can be used with those of the regional geopressured geothermal studies (Bebout, Agagu, and Dorfman, 1975; Bebout, Dorfman and Agagu, 1975; and Bebout and others, 1976) to indicate the most favorable areas to search for geothermal prospects.

Specific objectives are

1. to delineate the mineralogical composition of sandstones in each of the major lower Tertiary units in the onshore Texas Gulf Coast stratigraphic section,
2. to delineate a general sandstone consolidation sequence for the entire lower Tertiary section and a specific sandstone consolidation sequence for each formation prospective for geothermal energy,
3. to relate interval transit time from acoustic logs to the sandstone consolidation sequence in order to predict the sandstone consolidation sequence and its effects in areas where acoustic logs are the only available data, and
4. to outline areas within each formation where high-quality reservoirs exist at depths suitable for geothermal exploration.

Methodology

The onshore Texas Gulf Coast was divided geographically into 6 areas (fig. 1). Areas 1 and 2 (Lower Texas) include the Rio Grande Embayment, Areas 3 and 4 (Middle Texas) correspond to the area of the San Marcos Arch, and Areas 5 and 6 (Upper Texas) correspond to the Houston Embayment. The stratigraphic section was divided vertically into 6 stratigraphic units as shown in figure 2.

The primary data base for the sandstone consolidation study consisted of diamond cores and core plugs from 179 wells (figs. 3 and 4), core analyses from 253

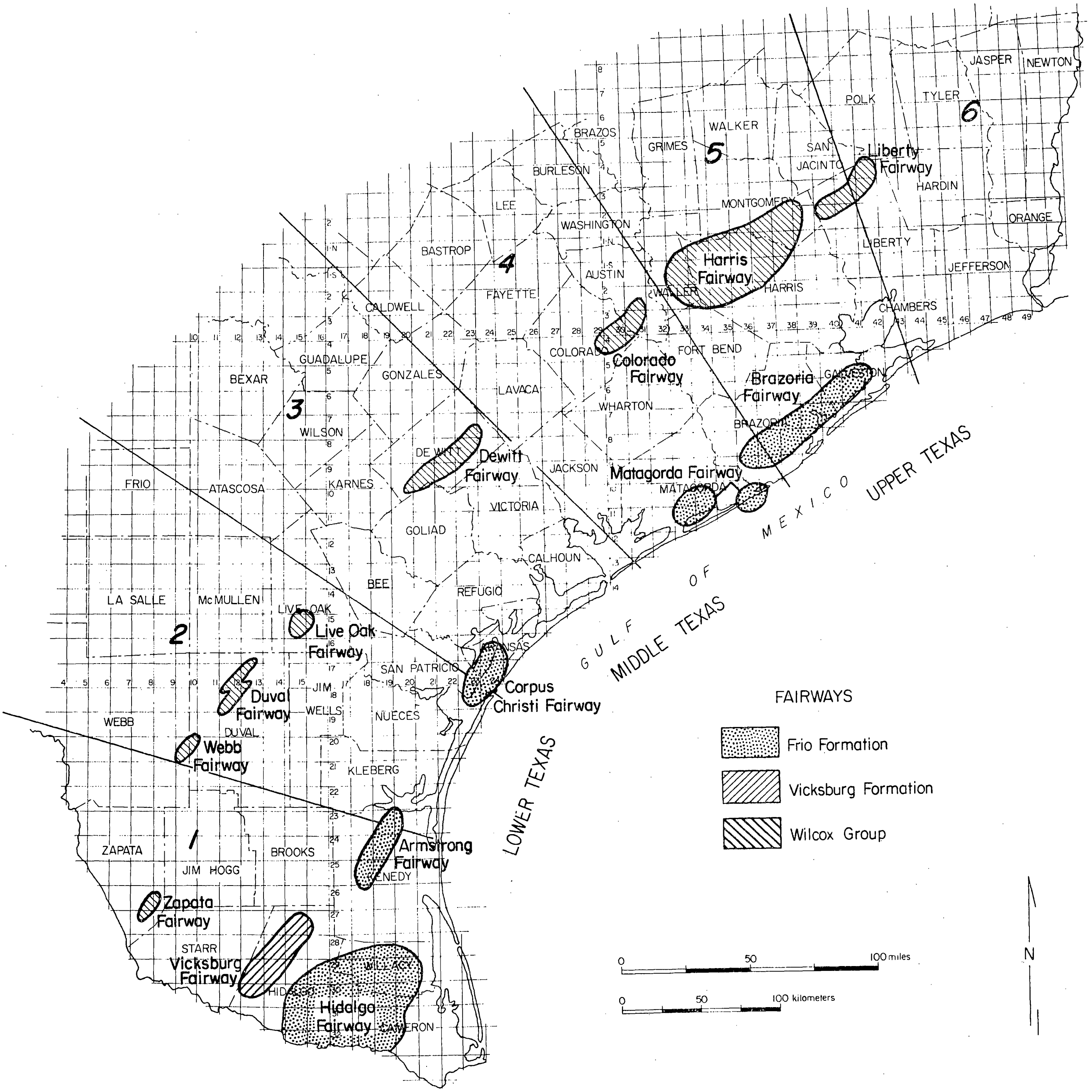


Figure 1. Area of investigation showing geopressured geothermal fairways and division of Lower, Middle, and Upper Texas Gulf Coast areas.

CENOZOIC — TEXAS GULF COAST

SYSTEM	SERIES	GROUP / FORMATION	INTERVAL
Quaternary	Recent	Undifferentiated	F
	Pleistocene	Houston	
Tertiary	Pliocene	Goliad	
	Miocene	Fleming	
	? —— ?	Anahuac	
	Oligocene	Frio	E
		Vicksburg	D
	Eocene	Jackson / Yegua	C
		Claiborne	B
		Wilcox	A
		Midway	

Figure 2. Cenozoic stratigraphic section, Texas Gulf Coast.

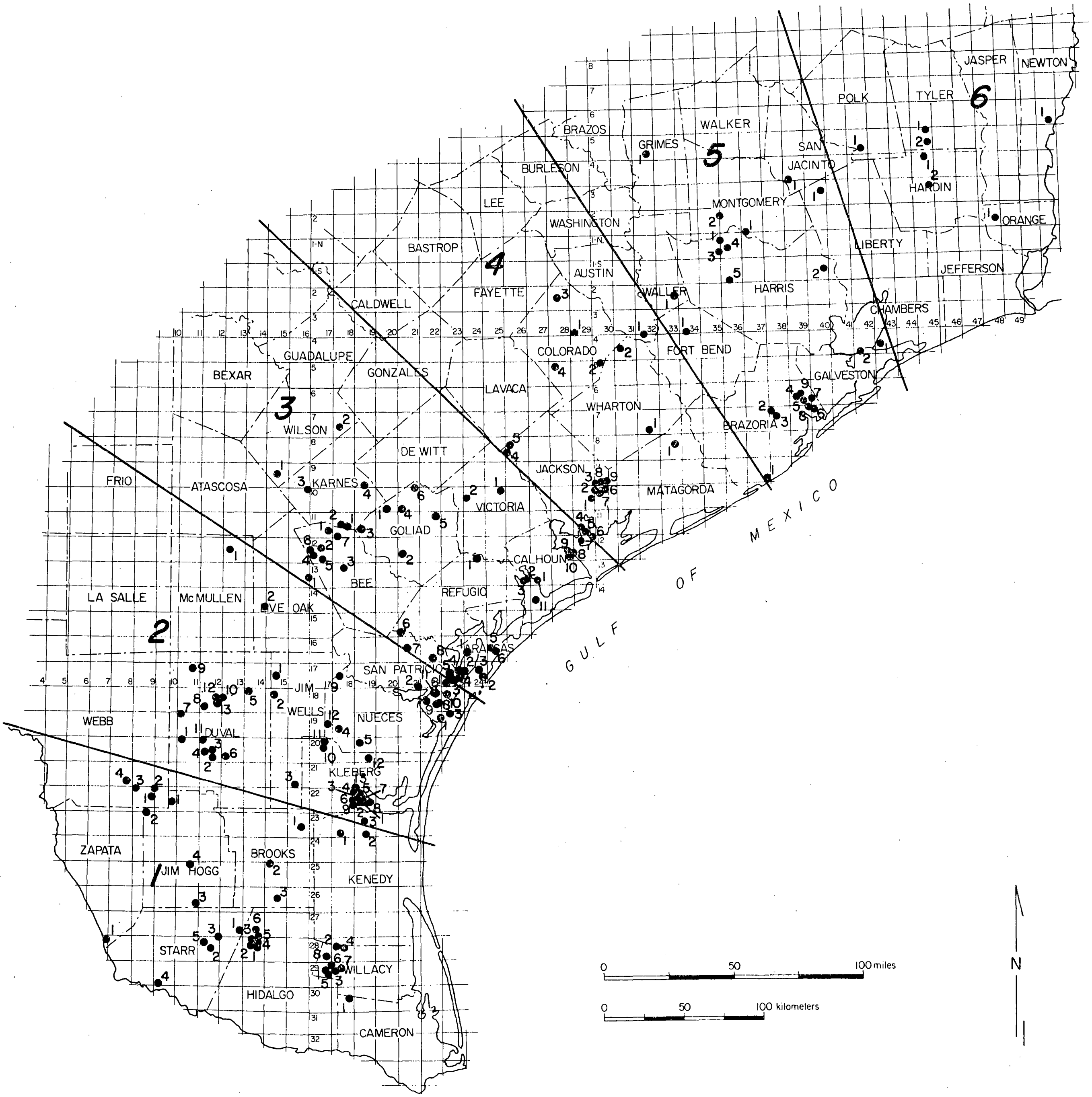


Figure 3. Location of wells with whole core samples.

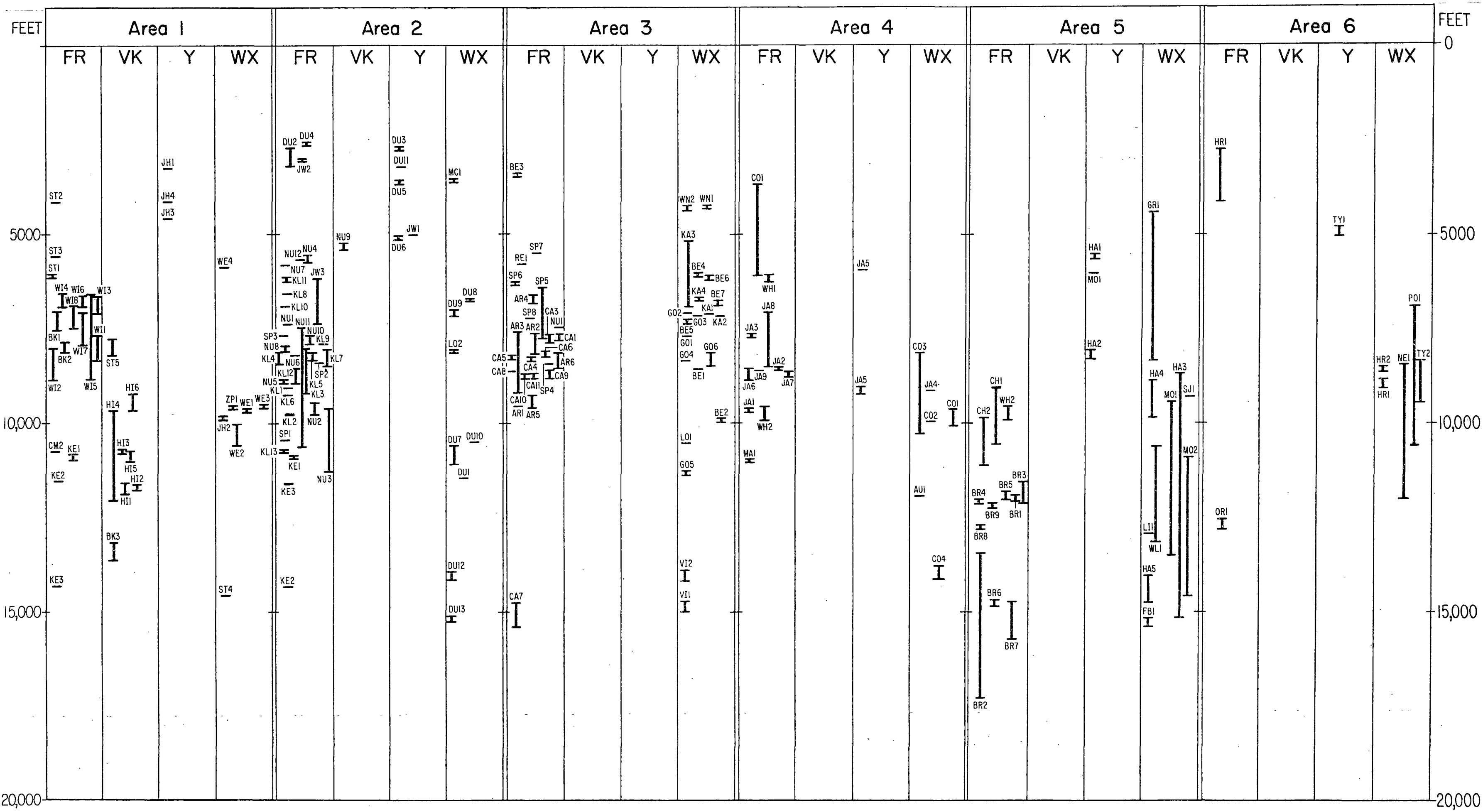


Figure 4. Distribution of whole core by area, formation, and depth.
FORMATIONS: FR-Frio, VK-Vicksburg, Y-Yegua, WX-Wilcox.

County names are abbreviated as follows:

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

wells, and acoustic logs from 86 wells. Lithology and primary structures of the cores were described (figs. 3 and 4) and environments of deposition were interpreted from corresponding electrical logs. Nine hundred and sixty-one thin sections were prepared from texturally mature matrix-poor sandstones at approximately 15 m (50 ft) intervals. Five hundred and forty of these thin sections were impregnated with blue-dyed epoxy, and 200 points per slide were counted for grain types, cement composition, and porosity types. Grain size, sorting, and packing proximity (compaction factor) were also determined. All thin sections were treated with amaranth solution to stain Ca-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 and ferroan calcite blue, using the method of Lindholm and Finkelman (1972). Selected samples were then analyzed in detail with the electron microprobe for carbonate composition, with the scanning electron microscope for mineral composition and diagenetic features, with the mass spectrometer for carbon and oxygen isotopes, and with the x-ray diffractometer for mineral composition.

Porosity and permeability data were obtained from both whole core and sidewall core analyses (fig. 5). One hundred and fifty-six wells with whole cores (7,564 data points) and 156 wells with sidewall cores (3,559 data points) were used. For each data point the corresponding pressure was calculated from mud weight and depth.

Interval transit time for sands and sandstones was calculated from acoustic logs at one hundred to two hundred foot depth intervals (fig. 6). Graphs of interval transit time versus depth were prepared for each well. Interval transit times were also grouped by area and by trend (fig. 6). The updip trend corresponds to wells drilled to the Wilcox Group, and the downdip trend corresponds to wells drilled to the Vicksburg or Frio Formations.

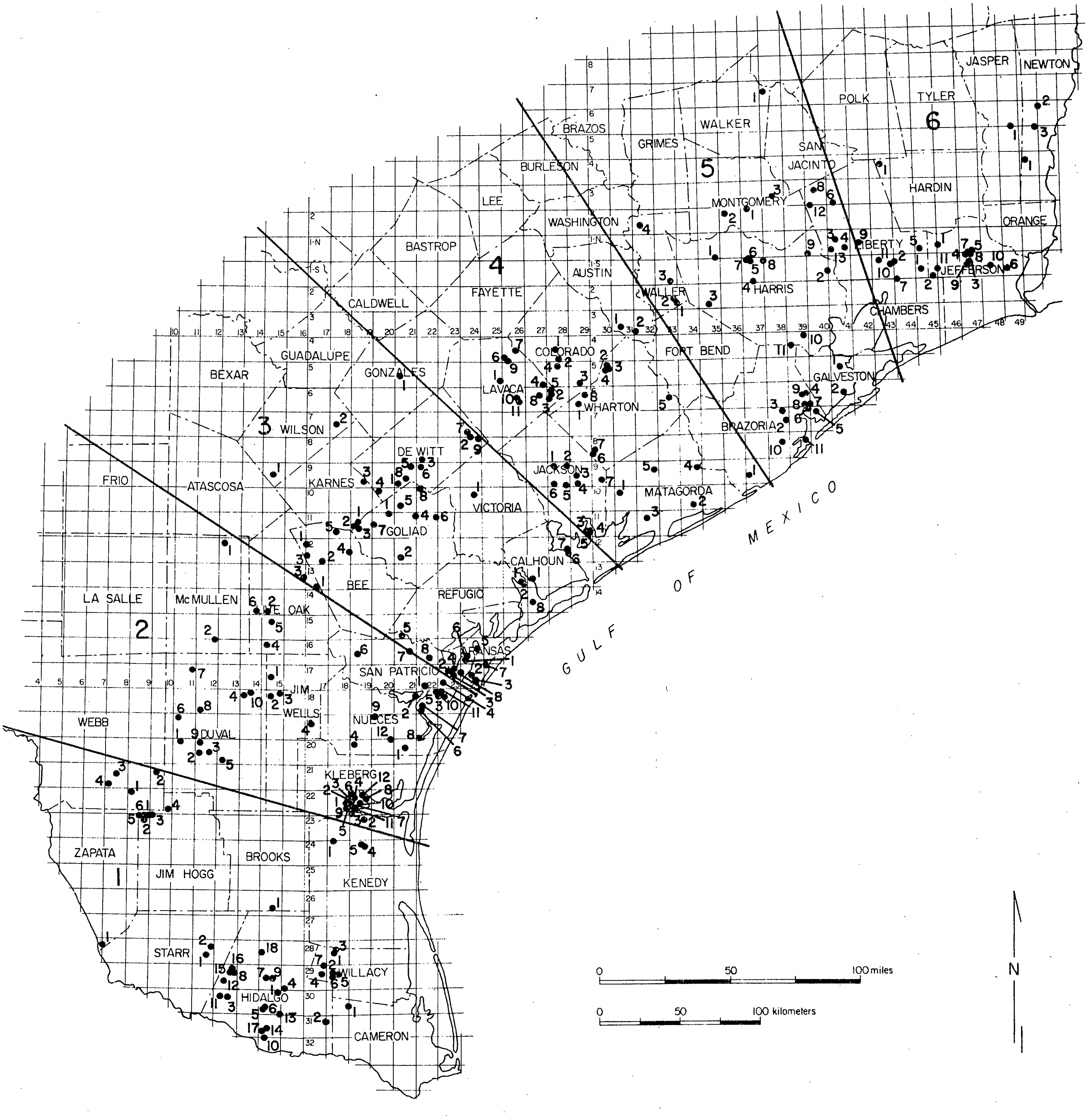


Figure 5. Location of wells with porosity and permeability data.

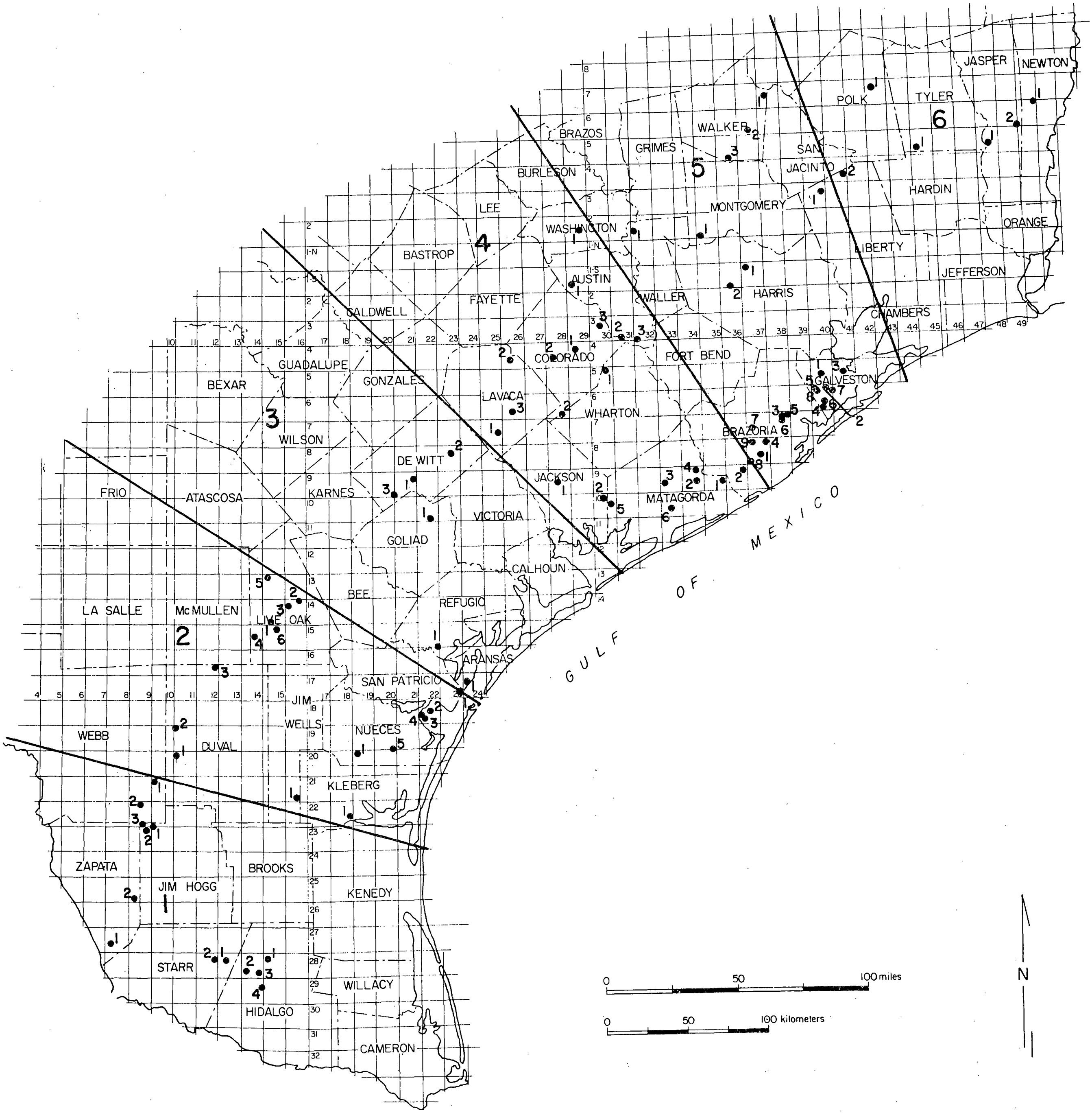


Figure 6. Location of wells with acoustic logs.

REGIONAL GEOLOGY

The onshore lower Tertiary Gulf Coast section is composed of a large number of terrigenous clastic wedges, which thicken downdip toward the Gulf of Mexico. Rapid loading of sediment on water-saturated muds (prodelta and shelf muds) resulted in contemporaneous growth faulting and subsequent accumulation of large quantities of deltaic and strandplain sands and muds (fig. 7). The sediments updip remained in the relatively shallow subsurface, whereas sediments downdip were subjected to more rapid subsidence and deep burial. Continuous movement along growth faults resulted in isolation of these large sections of sand and mud and in entrapment of their fluids. Flowage and diapirism of deeper Jurassic salt was caused by differential loading, which created linear trends of salt domes (fig. 8).

A number of distinct clastic wedges have been identified along the Gulf Coast (fig. 7) of which the Wilcox Group and the Vicksburg and Frio Formations are of most interest as potential onshore geothermal reservoirs. These wedges were formed from deposition of sediments in several depositional systems.

The Wilcox Group is divided into two parts on the basis of recognition of two progradational cycles (Bebout, Gavenda, and Gregory, 1978). The Upper Wilcox includes the Carrizo Formation, upper Wilcox, and middle Wilcox, which are described by Fisher and McGowen (1967), and it was deposited as a high-destructive delta system with an associated strandplain-barrier bar sequence (Fisher and others, 1969). The lower Wilcox corresponds to the lower Wilcox described by Fisher and McGowen (1967), and it was deposited as a high-constructive delta complex with associated strandplain sands (Fisher and McGowen, 1967). Sandstone content is high everywhere except for the downdipmost wells where growth faults are abundant and the proportion of shale increases markedly (Bebout, Gavenda, and Gregory, 1978).

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

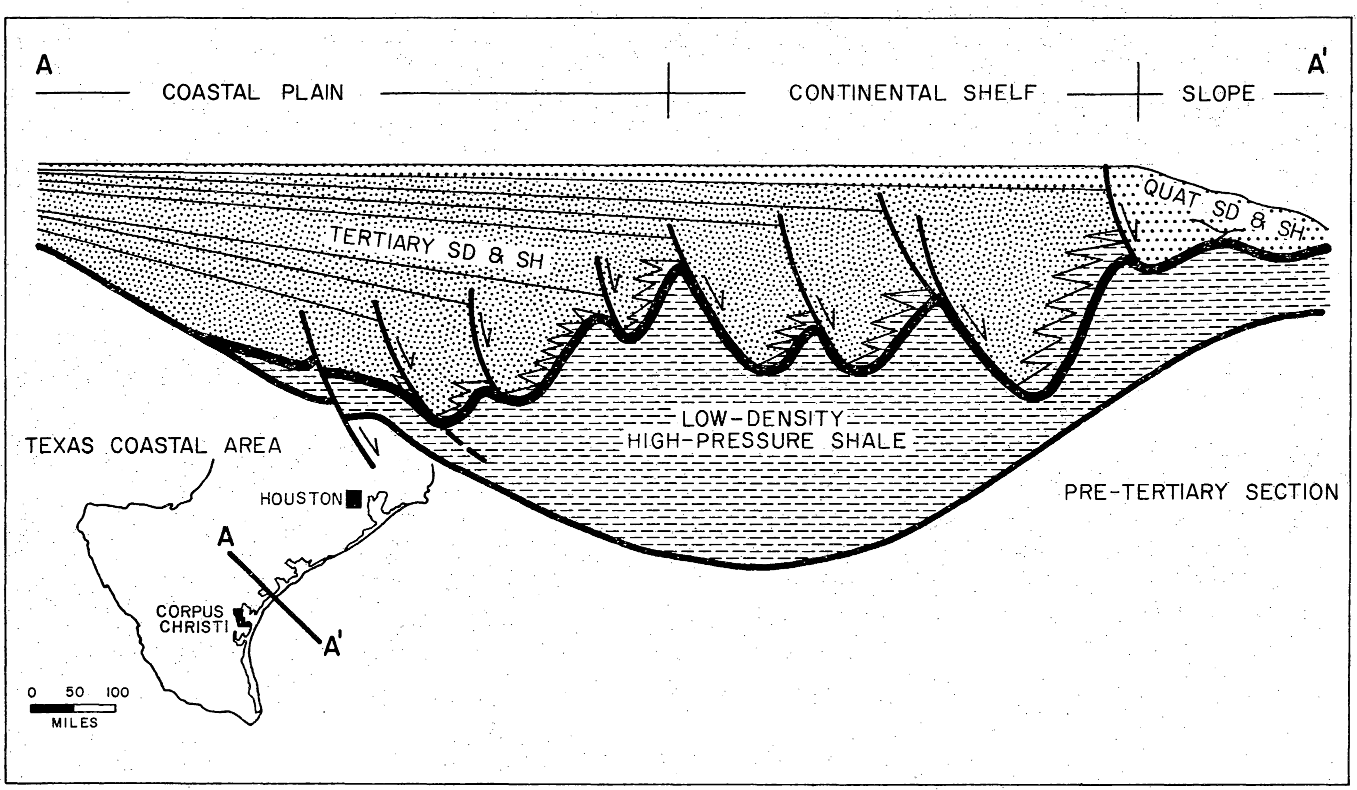


Figure 7. Depositional style of Cenozoic strata along the Texas Gulf Coast (Bruce, 1973).

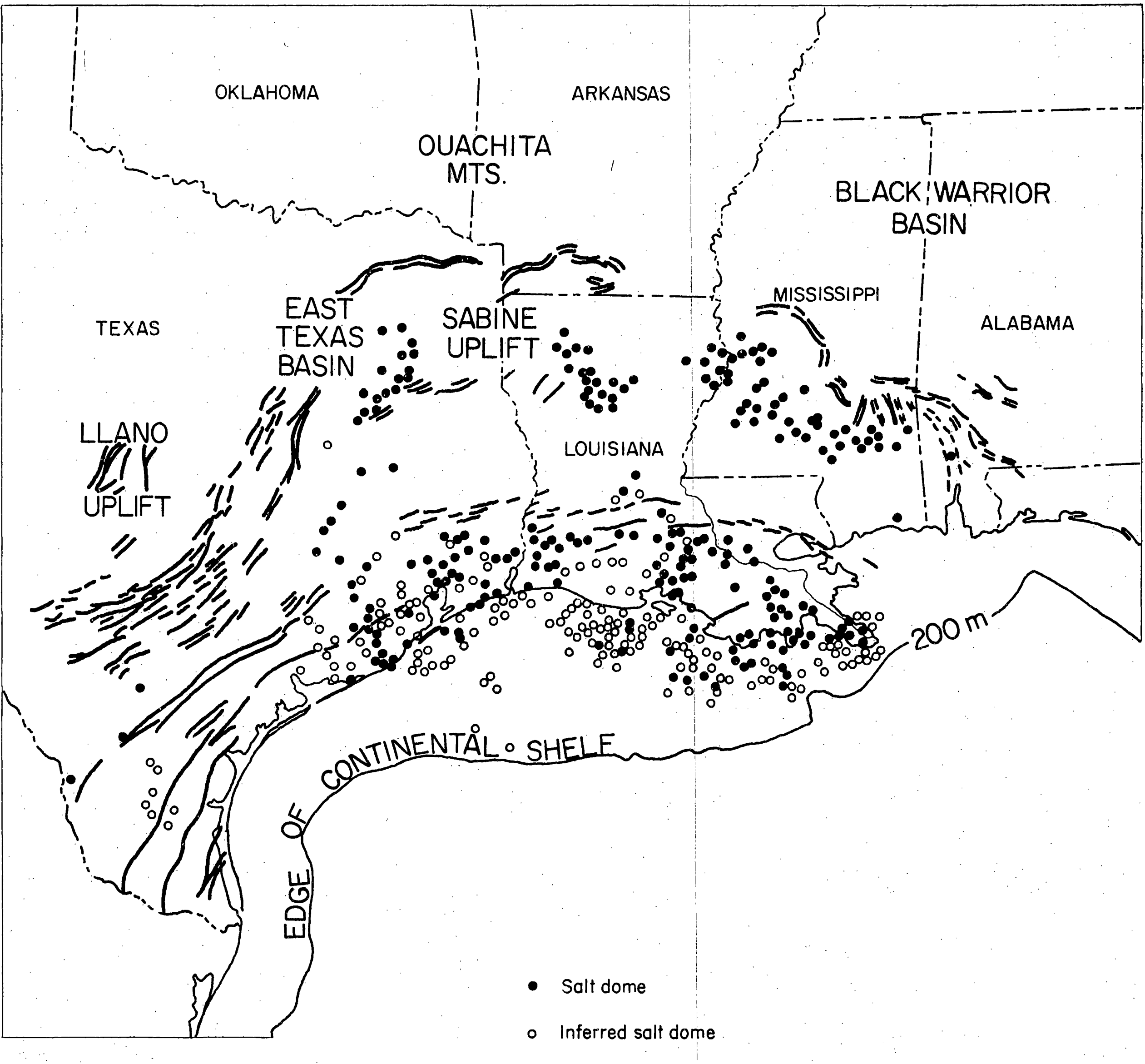


Figure 8. Salt domes and other structural features of the Gulf of Mexico region (from Tectonic map of North America; Jones, 1975).

Coast. Vicksburg sandstones along the Lower Texas Gulf Coast were deposited in a large, high-constructive deltaic system with a strong dip orientation and poor lateral continuity (Ritch and Kozik, 1971; Loucks, 1978).

In the Frio Formation lobate sandstone bodies along the Lower and Upper Texas Gulf Coasts are probably 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). Vertically, the Frio Formation has been divided into three parts. Thick sand units deposited in delta and barrier bar environments occur generally from 1,800 to 2,700 m (6,000 to 9,000 ft) below present sea level, shifting gulfward with successively younger units. The section updip from the main sand depocenter is a fluvial sequence of thin, discontinuous sandstones interspersed in thick shales. The downdip section is dominantly shale deposited in prodelta and shelf environments (Bebout, Loucks, Gregory, 1978).

RESERVOIR QUALITY

General Statement

Core analysis data from 253 wells were examined in this study. They are the best measure of reservoir quality, short of production tests. The principal drawback of core analysis is that porosity and permeability measurements are made at atmospheric pressures and temperatures apart from the original pore fluid. The results give values that are often an order of magnitude too high. Of these 253 wells, only 156 wells from which whole core (core plug) analyses were made 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. A sidewall core is taken by blasting a small hollow metal cylinder horizontally into the side of the well. The explosive impact of the cylinder into the rock often fractures the sample, and thin sections made from a sidewall core commonly show numerous fine, intragranular fractures. A sidewall core, therefore, tends to give a much higher porosity value than a whole core. Below a depth of 1,500 m (5,000 ft), porosity values from sidewall cores deviate significantly from those of whole cores, and erroneous readings increase with depth (fig. 9). Permeability as well as porosity readings are affected. Therefore, only porosity and permeability values from whole core analyses are used in this investigation.

Effect of Matrix

Clay matrix lowers reservoir quality at all depths (figs. 10 and 11). As high-quality reservoirs are essential in geothermal prospects, only matrix-free reservoirs should be sought.

General Porosity and Permeability Trends

Sandstone porosity and permeability generally decrease with depth through compaction and cementation, although this trend may be reversed by leaching of grains and cements. There is a general decrease in reservoir quality with depth in the Texas Gulf Coast section (figs. 12, 13, and 14), but there is a wide range of values at any given depth, indicating the complexities involved in understanding controls on reservoir quality.

A comparison of permeability and porosity for the Wilcox Group and the Vicksburg and Frio Formations shows the direct relationship between permeability and porosity (fig. 15). At 20 millidarcys (log 20 md =1.3), a lower ideal limit for geothermal type reservoirs, (Bebout, Loucks, and Gregory, 1978), porosity in the Wilcox and Frio averages 21 percent. In the Vicksburg a minimal 20 millidarcy

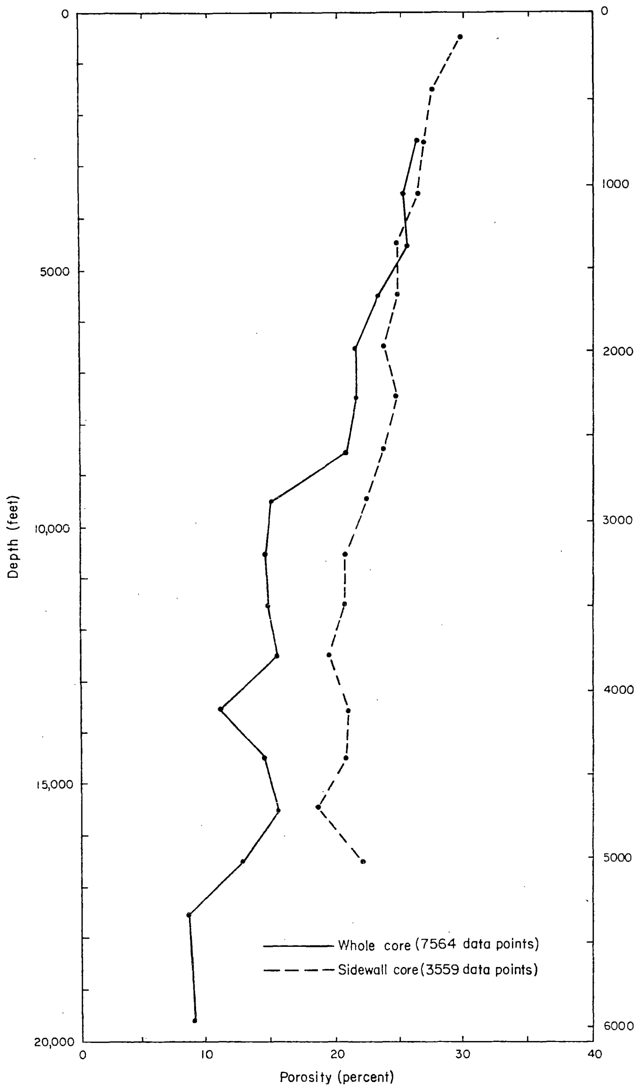


Figure 9. Mean porosity versus depth from both whole core and sidewall core for lower Tertiary sandstones from along the Texas Gulf Coast.

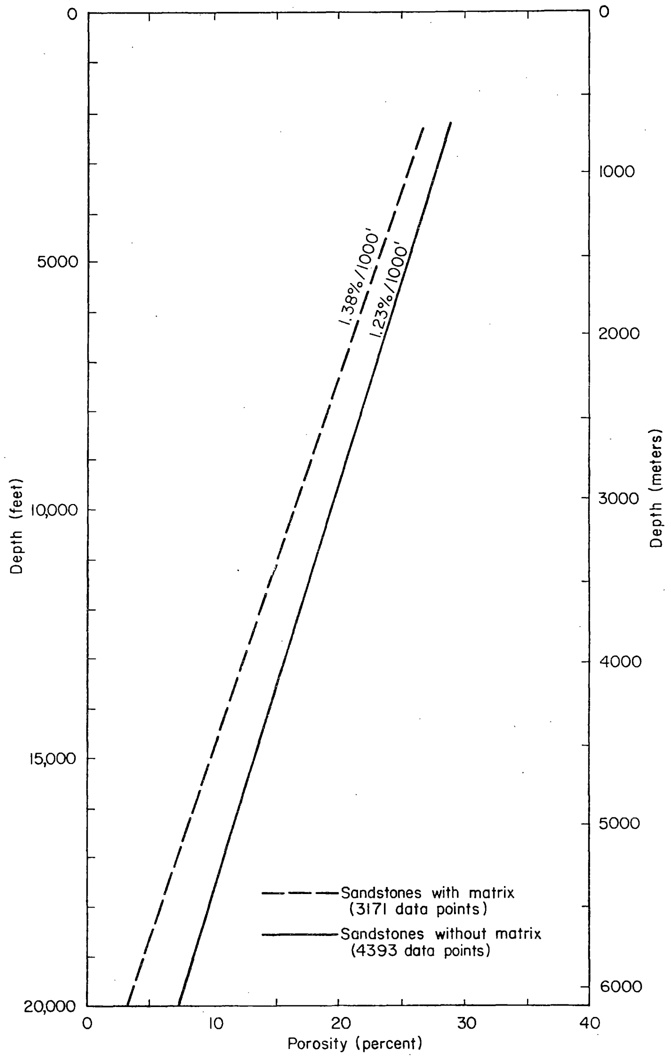


Figure 10. Mean porosity versus depth for lower Tertiary sandstones with and without clay matrix from along the Texas Gulf Coast.

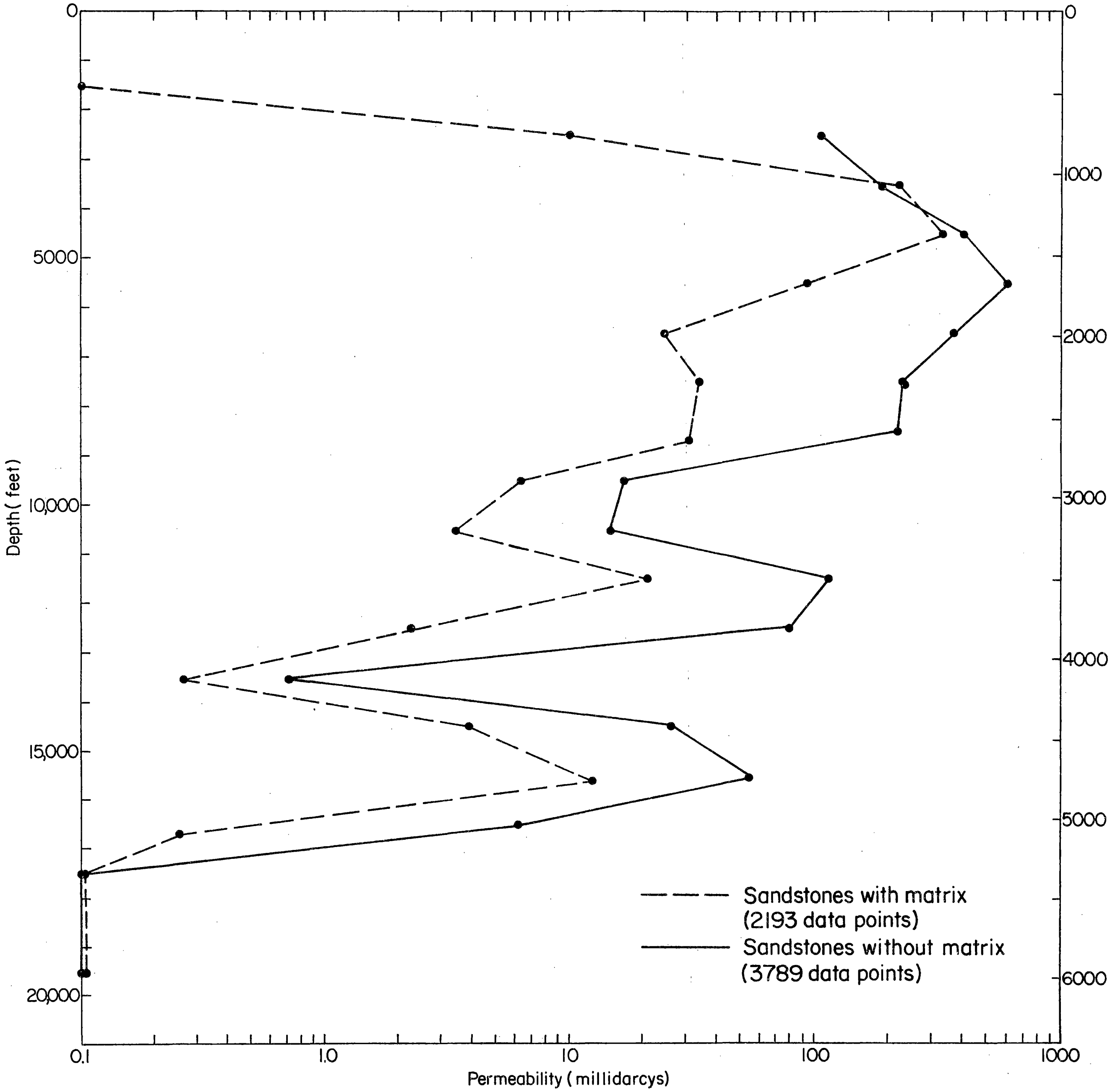


Figure 11. Mean permeability versus depth for lower Tertiary sandstones with and without clay matrix from along the Texas Gulf Coast.

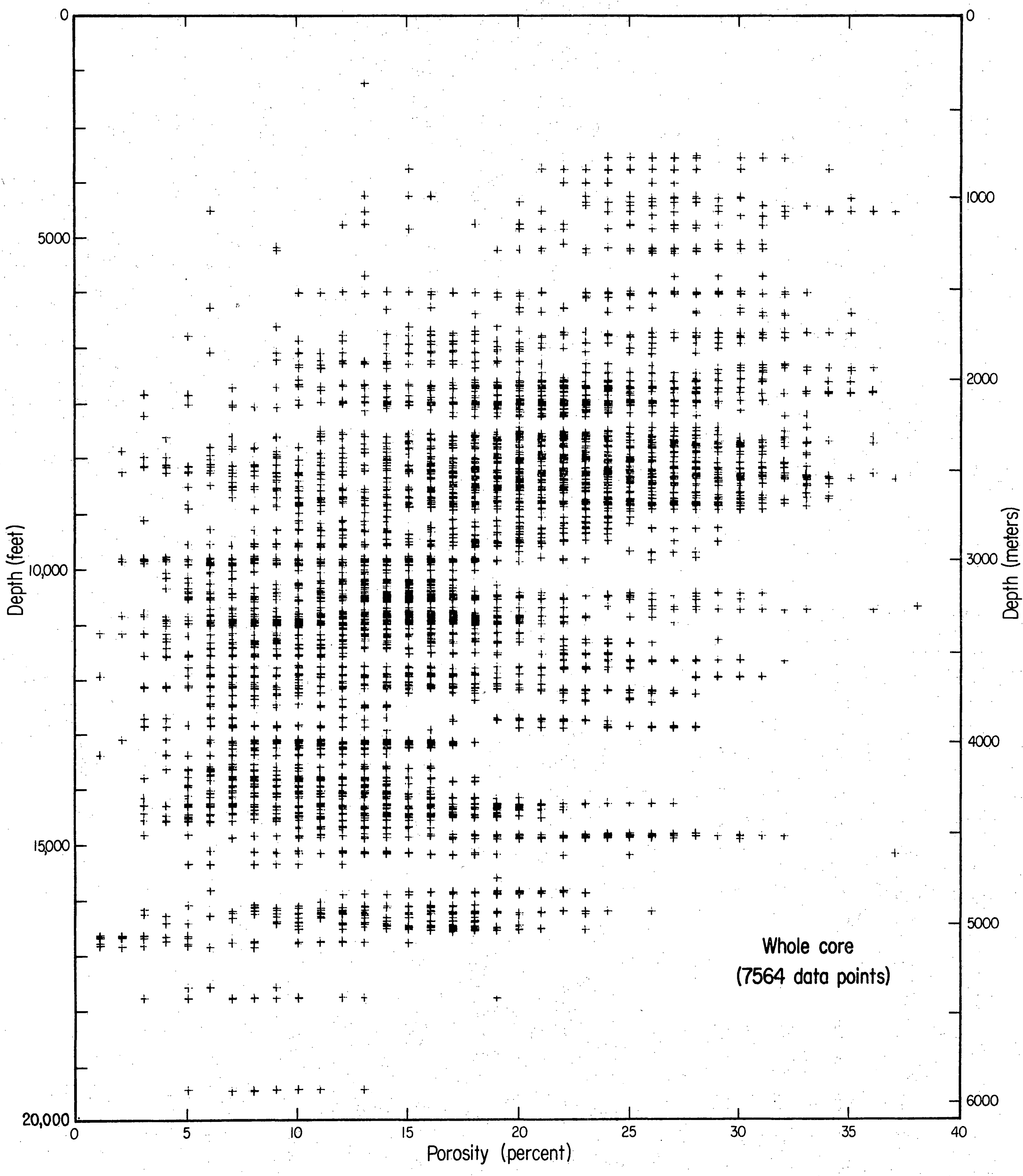


Figure 12. Sandstone porosity versus depth from whole core analyses for lower Tertiary formations along the Texas Gulf Coast. Sandstones with and without matrix are included.

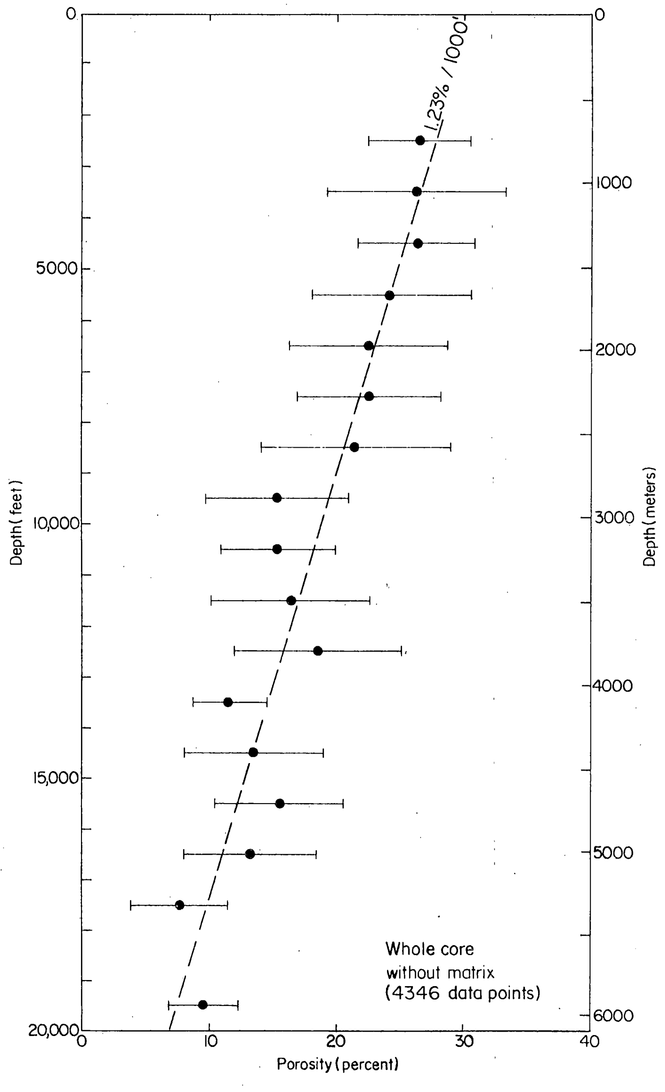


Figure 13. Mean sandstone porosity versus depth from whole core analyses for lower Tertiary formations along the Texas Gulf Coast. Only values from sandstones without matrix are used.

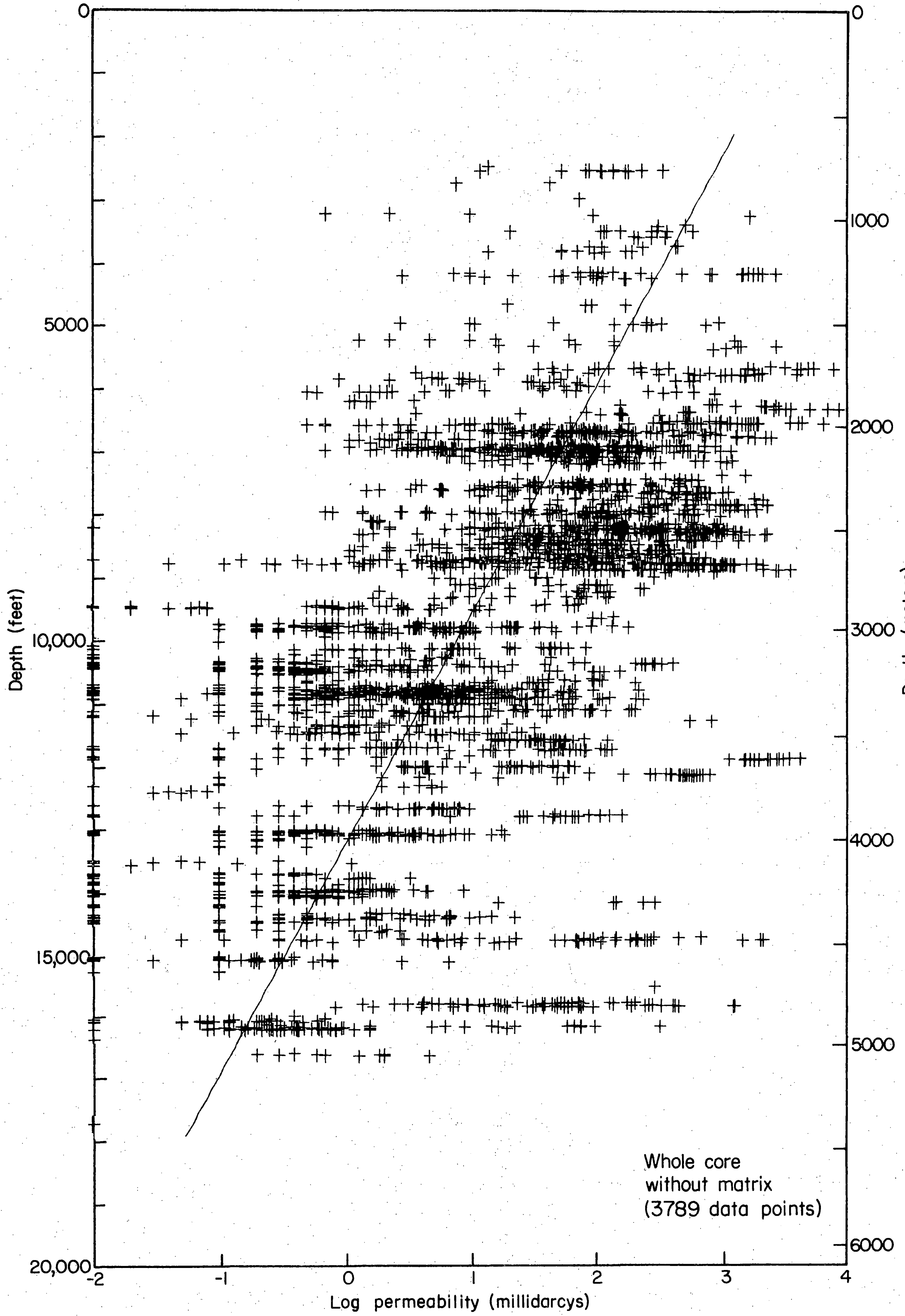


Figure 14. Permeability versus depth from whole core analyses for lower Tertiary formations along the Texas Gulf Coast.

permeability is present at approximately 25 percent or more porosity, if the least-square-fit line is extended to that range (fig. 15).

Porosity by Formation and Area

By superimposing plots of porosity versus depth upon each formation, variation in reservoir quality among formations can be compared (fig. 16). 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 fall together. However, if the Frio is grouped by Areas 1 through 3 and Areas 4 through 6 (fig. 16), the Frio Formation, along the Upper Texas Gulf Coast, has the highest reservoir quality of any formation. This is the area in which the world's first geopressured geothermal well was drilled (Bebout, Loucks, and Gregory, 1978).

Porosity-versus-depth plots for the six areas of the Wilcox Group and the Frio Formation indicate no regional porosity trend in the Wilcox (fig. 17) and a strong regional porosity trend in the Frio (fig. 18). The Frio Formation shows a systematic increase in reservoir quality from Area 1 north to Area 5. This increase in reservoir quality correlates to changes in rock composition and cementation, which are discussed in the section entitled Mineralogic and Diagenetic Controls on Reservoir Quality.

REGIONAL CONTROLS ON RESERVOIR QUALITY

General Statement

Possible regional controls on reservoir quality include time, subsidence rate, pressure, temperature, pore fluid composition, depositional environment, mineral composition of the sand and surrounding muds, texture, and diagenetic components. Each affects final reservoir quality; it is seldom possible to isolate one as the

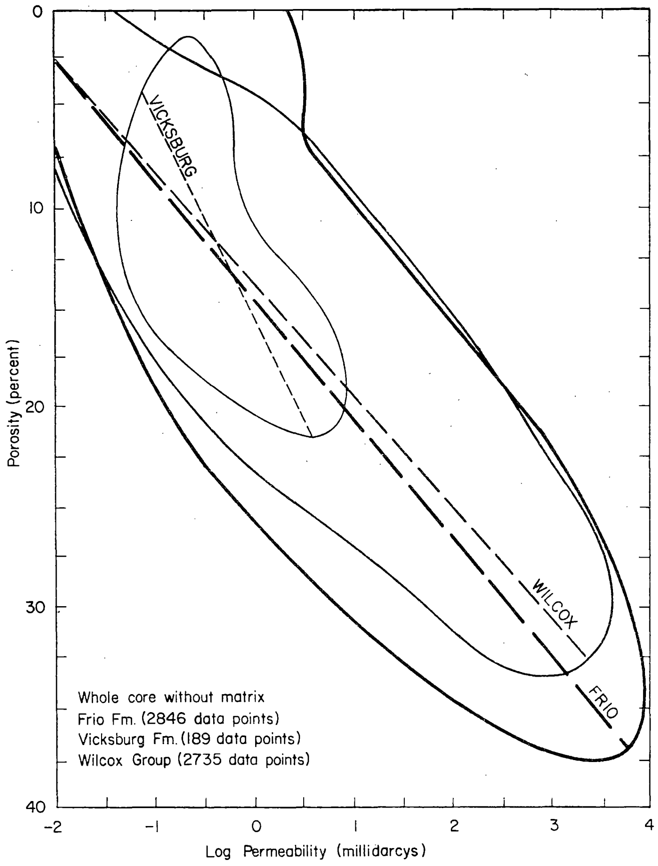
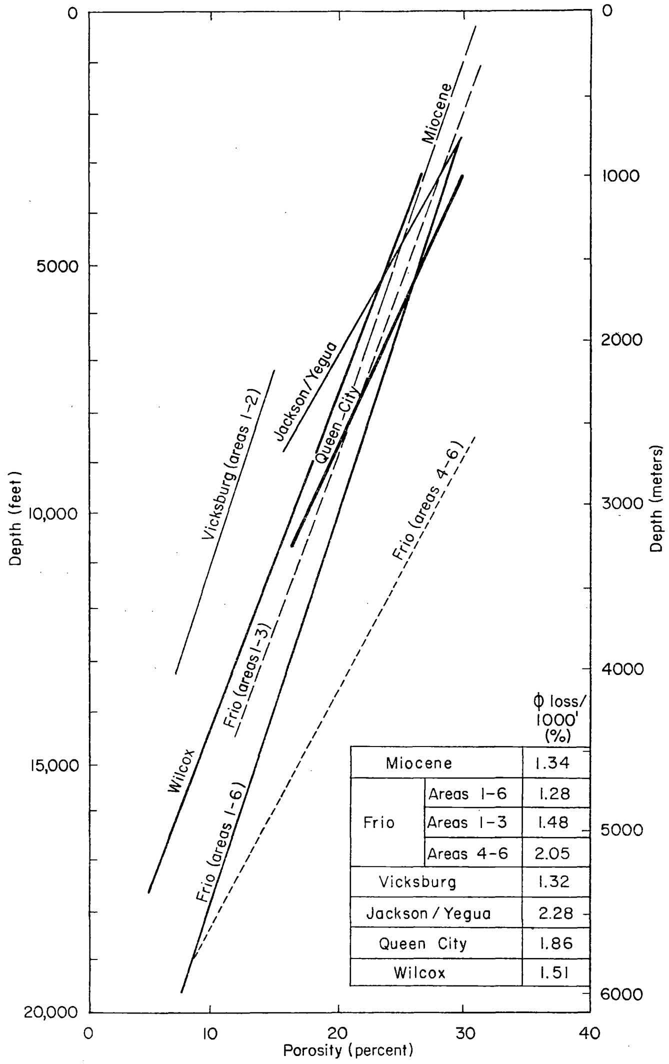


Figure 15. Relationship of porosity to permeability for Wilcox Group and Vicksburg and Frio Formations.



		ϕ loss/ 1000' (%)
Miocene		1.34
Frio	Areas 1-6	1.28
	Areas 1-3	1.48
	Areas 4-6	2.05
Vicksburg		1.32
Jackson / Yegua		2.28
Queen City		1.86
Wilcox		1.51

Figure 16. Mean sandstone porosity versus depth by formation for lower Tertiary formations along the Texas Gulf Coast. Table in lower right hand corner shows porosity loss per thousand feet for each formation.

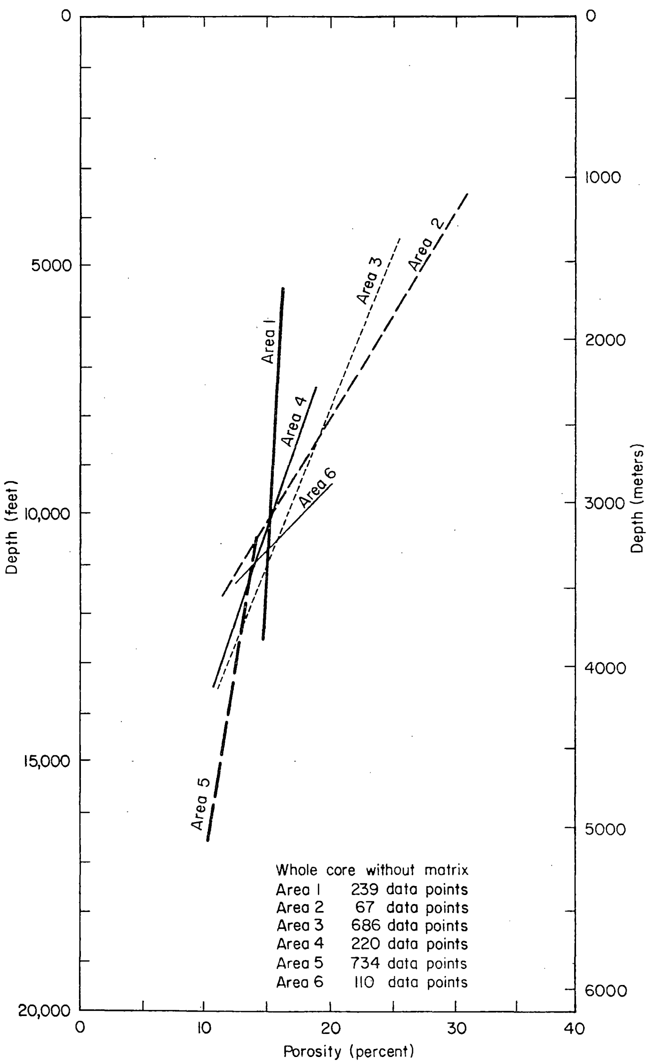


Figure 17. Mean Wilcox sandstone porosity by area.

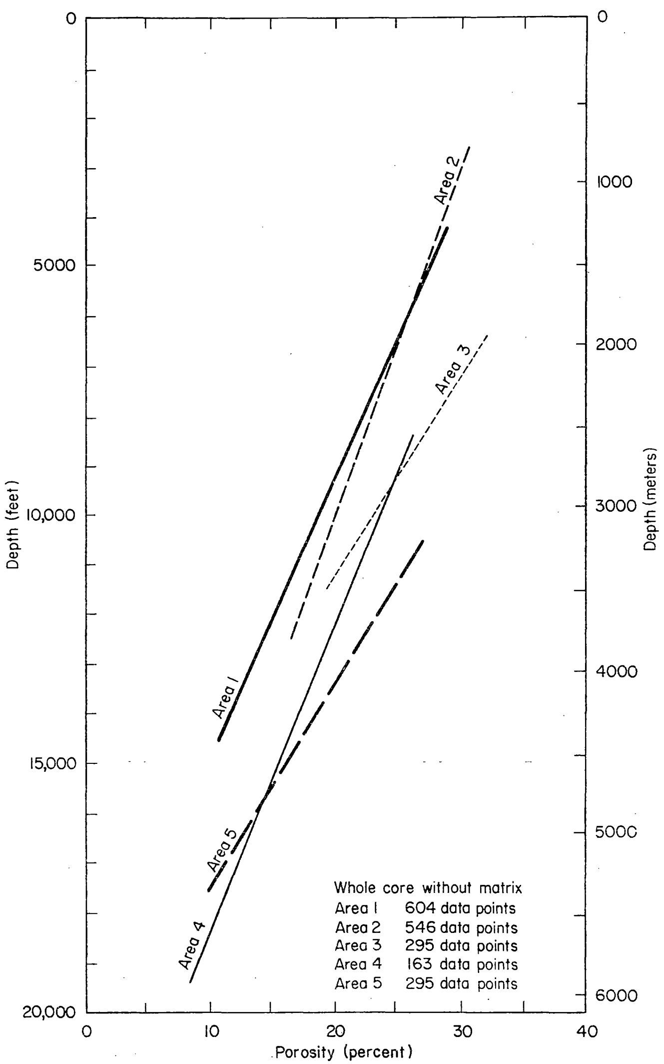


Figure 18. Mean Frio sandstone porosity by area.

dominant control. The influence of pore-fluid composition was not studied in this investigation. Depositional environments show no correlation with reservoir quality on a regional scale. Framework mineralogy and diagenetic controls on reservoir quality are important in determining reservoir quality in the Texas Gulf Coast, and they are discussed in this report. Time, subsidence, fluid pressure, and temperature are discussed for the lower Tertiary section as a whole in the following sections.

Time

Loss and resurrection of primary porosity and creation of secondary porosity are functions of time. Compaction increases with deeper burial, and the opportunity for cementation increases with duration of burial. Both lead to loss of primary porosity. Ideally, the Wilcox Group (50 to 55 million years BP), the oldest Tertiary formation, should have the least porosity, but, in fact, the Vicksburg Formation (30 to 35 million years BP) has the least porosity. These porosity-reducing processes are counteracted by dissolution or leaching of framework grains and cement, processes also dependent on time. Thus, time per se is not a meaningful factor in controlling reservoir quality along the Texas Gulf Coast.

Pressure

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

The effect of partial support of the rock column by pore fluids is indicated by undercompaction of shales in the geopressured zone (fig. 19). It has been postulated by

Jones (1975) that sandstones in the geopressured zone are also undercompacted (fig. 19). Ideally this is true if sands are uncemented; high pore pressures in the geopressured zone should reduce physical compaction and allow higher porosities to exist at greater depth. However, in rocks that are well-cemented before entering the geopressured zone, such as most pre-Miocene sediments in the Gulf Coast, high pore pressure probably does not have a significant effect because cementation has already arrested compaction and produced a rigid matrix. However, if abundant secondary porosity is developed in the geopressured zone, higher pressures may prevent large pores from collapsing owing to the weight of overburden. Therefore, an increase in sandstone porosity at the top of geopressure as shown in figure 19 would occur probably only in uncemented sands owing to the lack of compaction or in cemented sandstones owing to the formation of secondary leached porosity. Also, an increase in pore pressure can increase interval transit time on acoustic logs and result in the incorrect interpretation of an increase in porosity.

Friedman (1977) concluded from working with data of Atwater and Miller (1965) on uncemented Miocene sands in Louisiana that pore pressure affects the rate of porosity decline. Atwater and Miller's porosity data were plotted without regard for pore pressure, and they plotted on a straight line (fig. 20). Friedman replotted the data according to pressure gradient increments (fig. 21). He noted that the rate of porosity decline decreases with increasing pressure gradient. Therefore, in uncemented sediments, areas with higher pressure may indicate favorable areas for porosity preservation because of the lack of compaction. A similar analysis of sandstones of the Texas lower Tertiary section does not show a simple decrease in rate of porosity loss with depth (fig. 22). The data were sorted according to formation to better define porosity/pressure relationships, but sufficient data for reliable results are only available from the Wilcox Group and the Frio Formation (fig. 23). Porosity is not related to pressure gradient in Wilcox sandstones, and porosity has a roughly

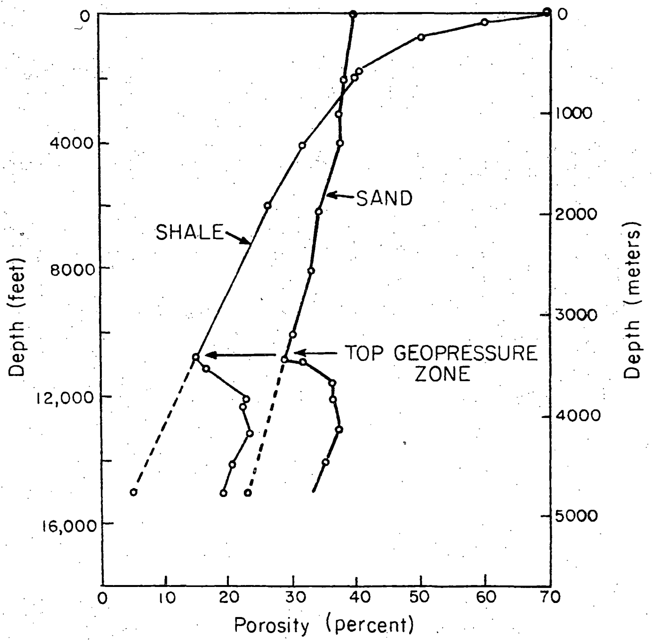


Figure 19. Relation of porosity to depth of burial in Cenozoic sands and sandstones in Cenozoic shales in the hydropressure zone and in the geopressure zone in the Gulf basin (adapted from Stuart, 1968).

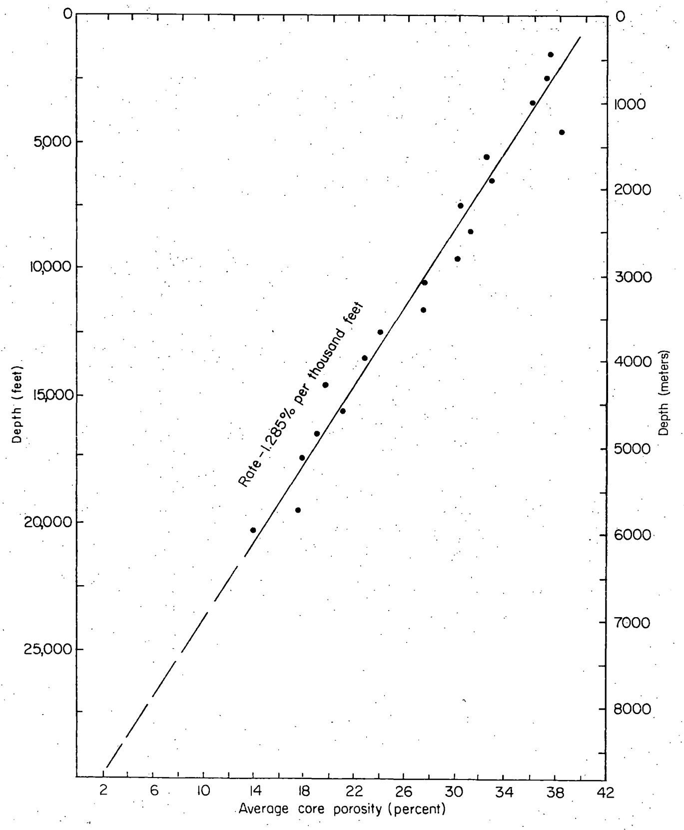
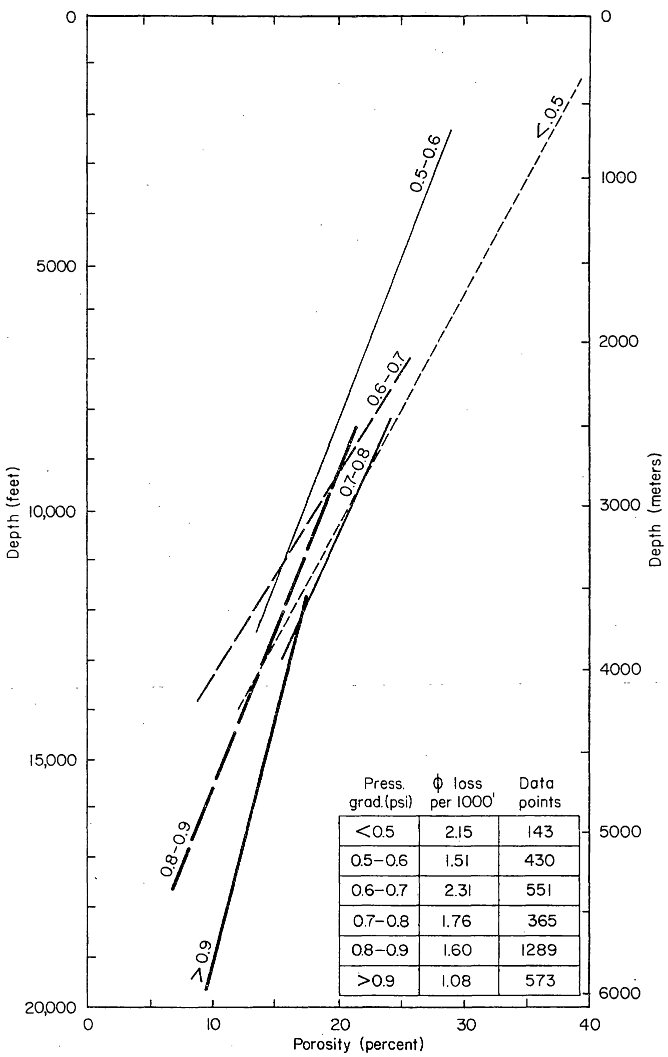


Figure 20. Mean porosity versus depth for south Louisiana sandstone (adapted from Atwater and Miller, 1965, by Jones and McBride, 1977).

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



Press. grad.(psi)	ϕ loss per 1000'	Data points
<0.5	2.15	143
0.5–0.6	1.51	430
0.6–0.7	2.31	551
0.7–0.8	1.76	365
0.8–0.9	1.60	1289
>0.9	1.08	573

Figure 22. Porosity loss relative to pressure gradient for lower Tertiary 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

Figure 23. Porosity loss relative to pressure gradient for Wilcox and Frio sandstones along the onshore Texas Gulf Coast.

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

Maps of bottom-hole pressure at depths of 3,048 and 3,810 m (10,000 and 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. 24 and 25). From Bee County the ridge shifts gulfward and follows the present day shoreline to the Texas-Louisiana border. The high pressure area in Lower Texas Hidalgo and Brooks Counties corresponds to the deep, thick, low-porosity sandstone trend of the Vicksburg Formation. North of the Vicksburg sandstone trend, porosity distribution along the Gulf Coast does not seem to be related to regional pressure differences.

Depth to the top of the geopressured zone in the Wilcox Group is deeper than in other formations in the Texas Gulf Coast (Bebout, Gavenda, and Gregory, 1978). The Wilcox Group is the oldest Tertiary sandstone unit (fig. 2), and fluids have had more time to leak out, thus lowering the top of the geopressured zone.

Temperature

Temperature is believed by many to be a major control on diagenesis in some sandstone suites and, hence, on porosity preservation (Galloway, 1974). Porosity in the Wilcox Group and Frio Formation decreased with increasing temperature (figs. 26 and 27). Because temperature increases with depth, this correlation is simply a restatement of the previously demonstrated relationship of decreasing porosity with depth. Regional relationships between porosity and temperature are more significant. Tem-

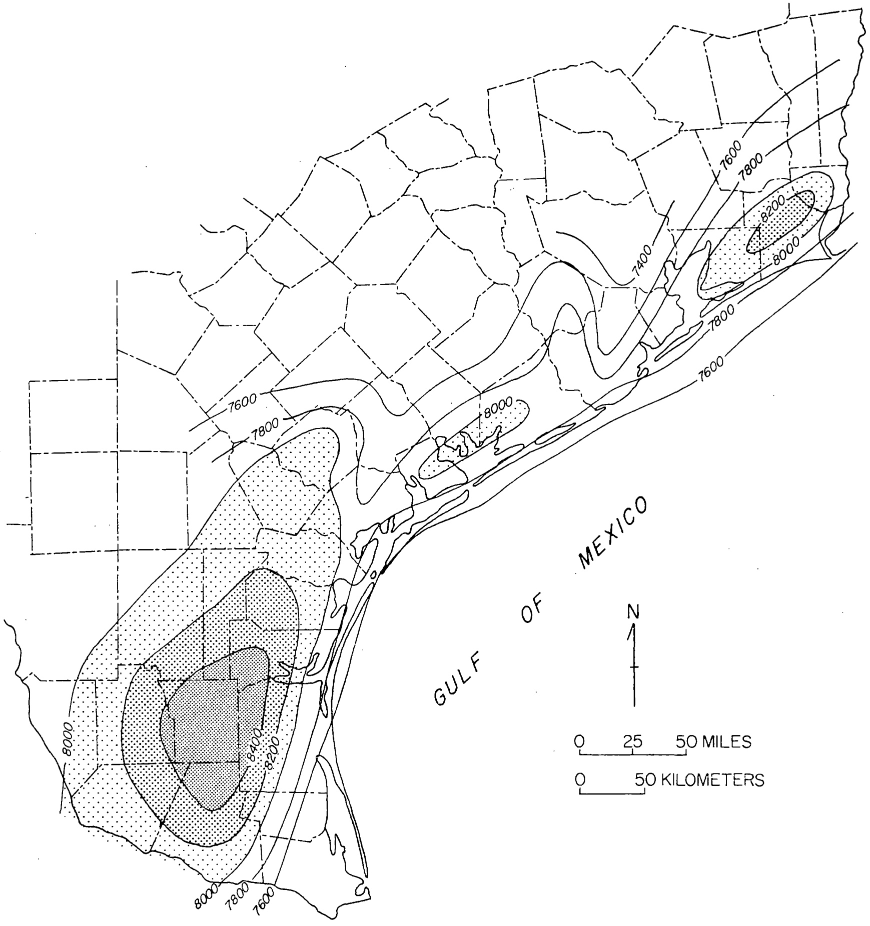


Figure 24. Pressure (psi) at 3,050 m (10,000 ft) in the geopressured zone. Pressures are calculated from drilling mud weights.

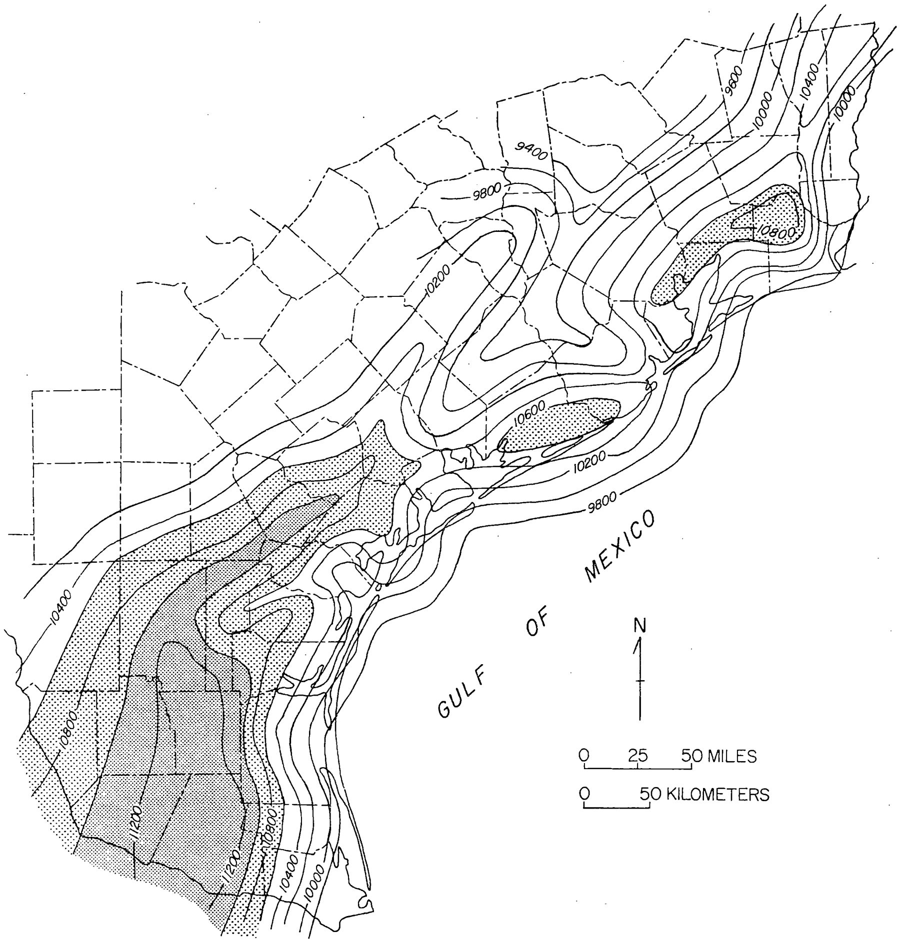


Figure 25. Pressure (psi) at 3,660 m (12,500 ft) in the geopressured zone. Pressures are calculated from drilling mud weights.

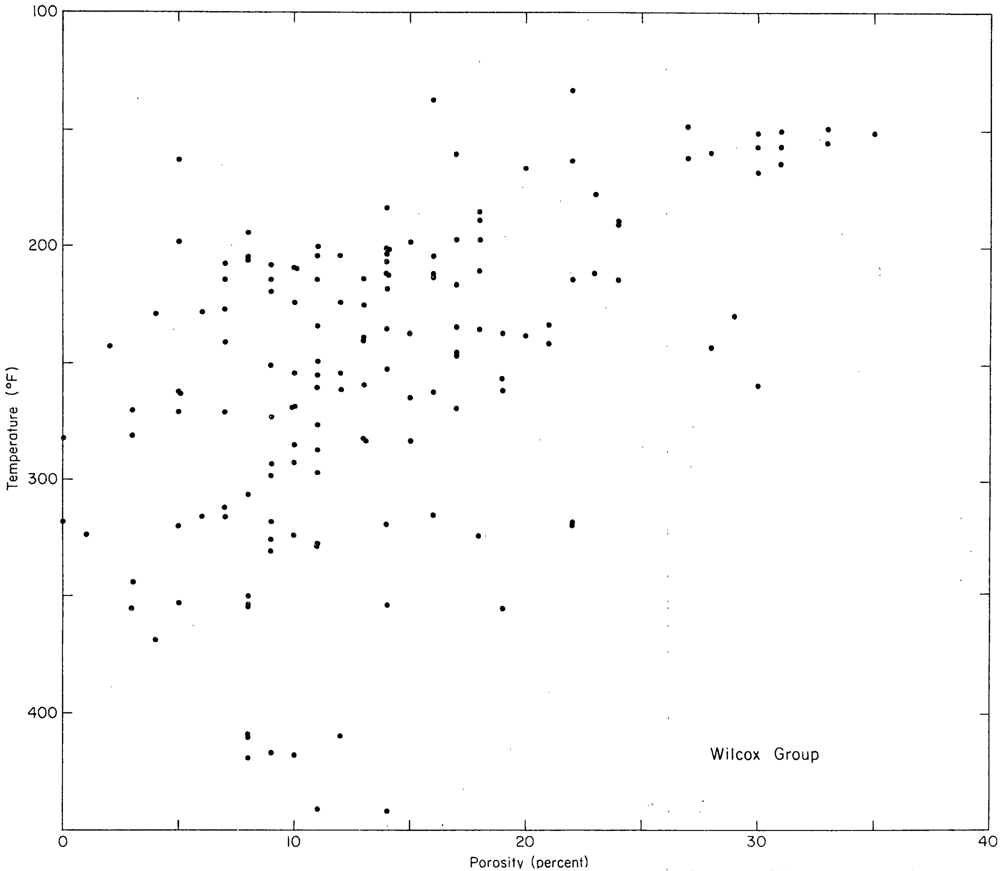


Figure 26. Porosity versus temperature for Wilcox sandstones.

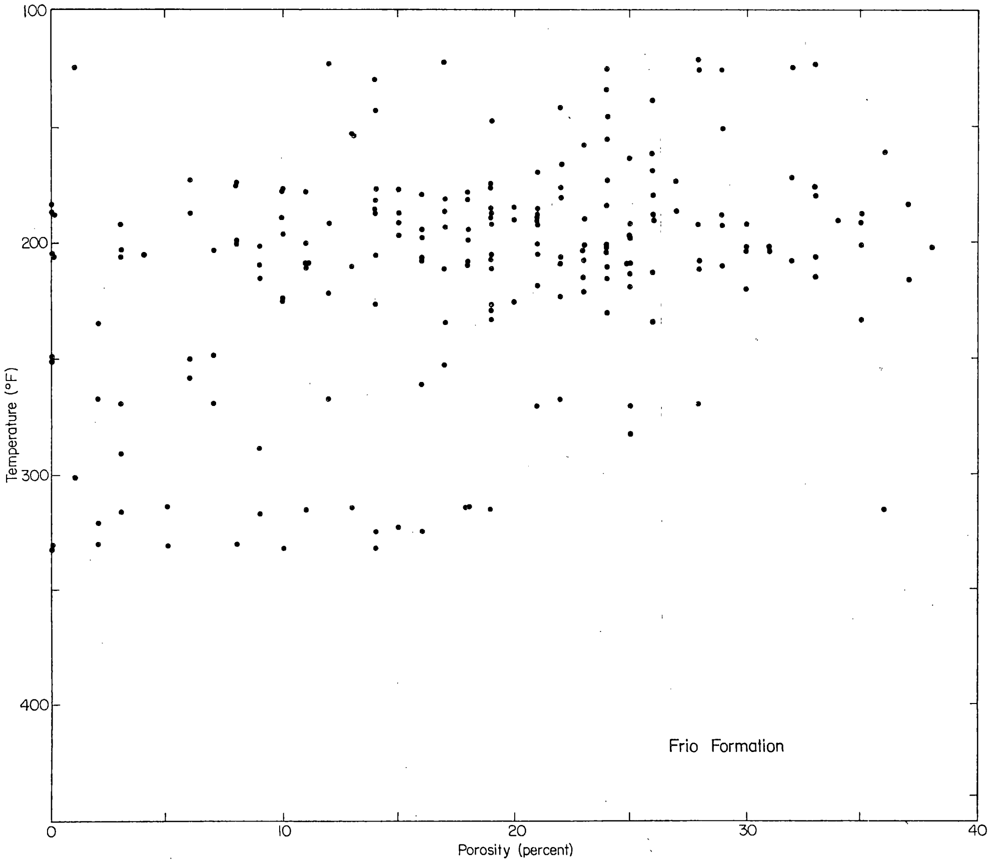


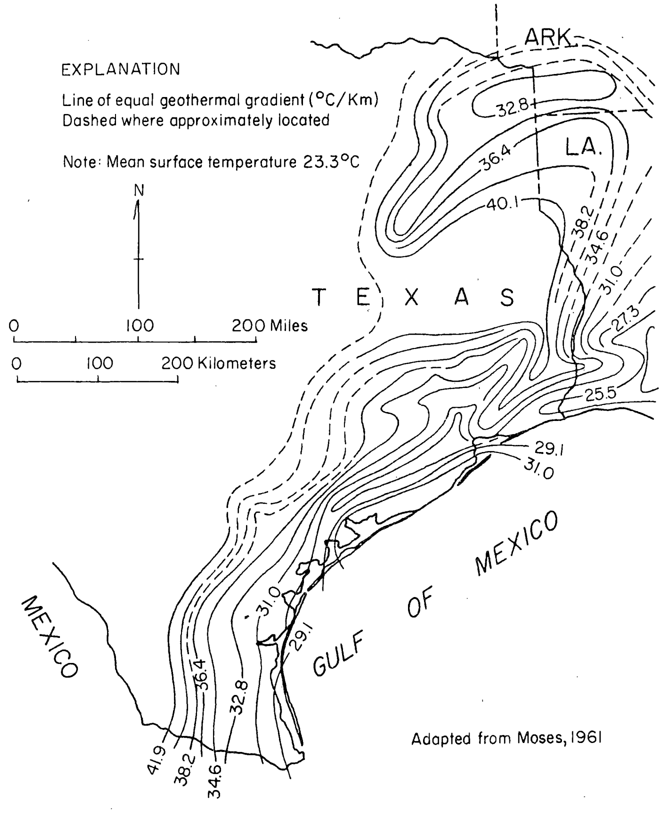
Figure 27. Porosity versus temperature for Frio sandstones.

perature distribution along the Texas Gulf Coast shows two regional trends (figs. 28 to 34): a decrease in temperature from Lower to Upper Texas Gulf Coast and a decrease in temperature gulfward. The Upper Texas Coast trend toward cooler temperatures corresponds to an increase in porosity in the Frio Formation (fig. 18). The high inland temperature relative to that near the coast corresponds to lower porosities in the Wilcox Group inland compared to that of the Frio Formation along the coast (fig. 16).

Mineralogic And Diagenetic Controls On Reservoir Quality

General Statement

Major factors controlling 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 become altered to achieve equilibrium within their environment, enhancing or lessening reservoir quality. The degree of instability is determined by initial mineral composition relative to fluid chemistry. Final reservoir quality is a complex result of initial mineralogical composition and the specific geochemical and physical history of re-equilibration to changing conditions. The most important aspects of alteration or diagenesis that determine final reservoir quality are the loss of and, conversely, preservation of primary porosity and the creation of secondary porosity. Primary porosity is the original porosity created by spaces left between grains during sediment deposition. This type of porosity decreases through time and burial through compaction and cementation. Secondary porosity is created by leaching of cements, by leaching of authigenic replacement products of grains, and by leaching of detrital grains. Secondary porosity can increase with depth and is the dominant form of porosity in the moderate and deep subsurface in the Gulf Coast lower Tertiary



Adapted from Moses, 1961

Figure 28. Temperature gradient in the hydropressure zone (adapted from Moses, 1961, by Jones, 1975).

Figure 29. Temperature (°F) at 1,520 m (5,000 ft) in the hydropressure zone.

Figure 30. Temperature (°F) at 2,290 m (7,500 ft) in the hydropressure zone.

Figure 31. Temperature (°F) at 3,050 m (10,000 ft) in the hydropressure zone.

Figure 32. Temperature (°F) at 3,050 m (10,000 ft) in the geopressure zone.

Figure 33. Temperature (°F) at 3,660 m (12,500 ft) in the hydropressure zone

Figure 34. Temperature (°F) at 3,660 m (12,500 ft) in the geopressure zone.

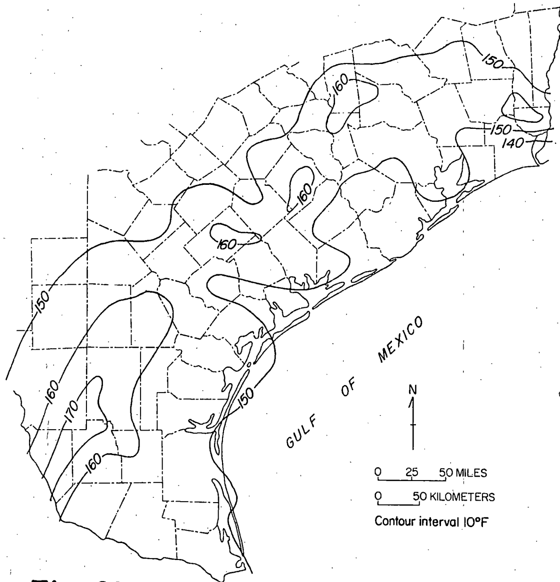


Fig. 29

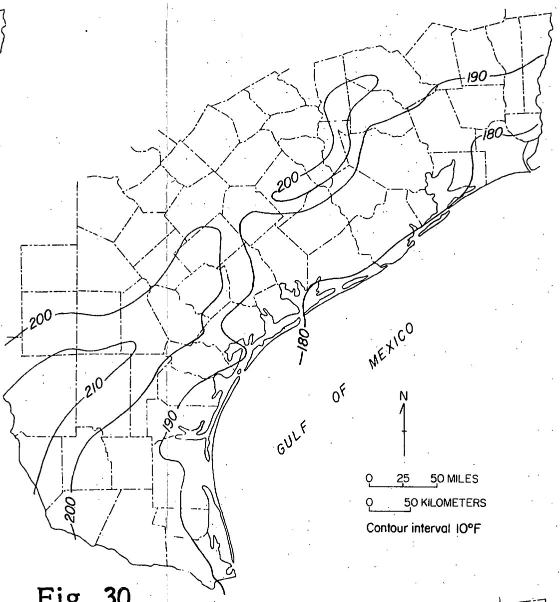


Fig. 30

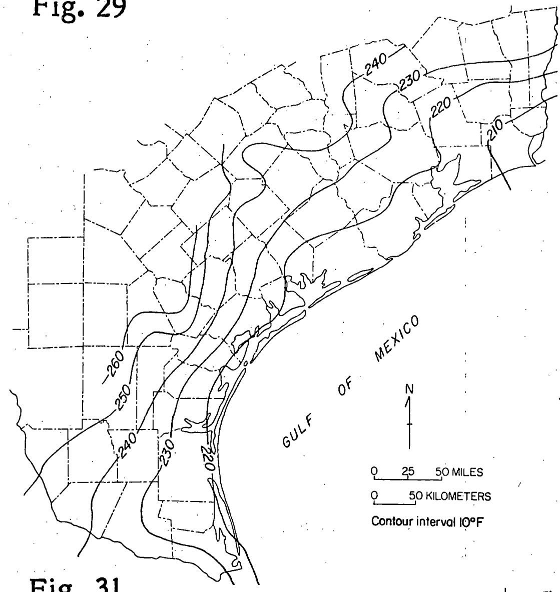


Fig. 31

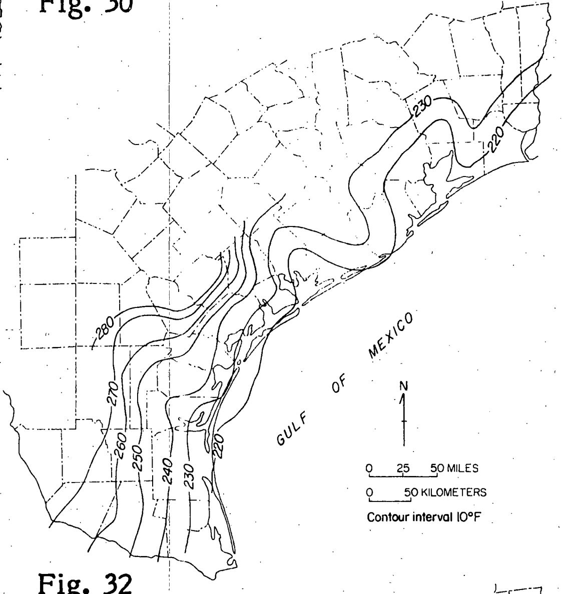


Fig. 32

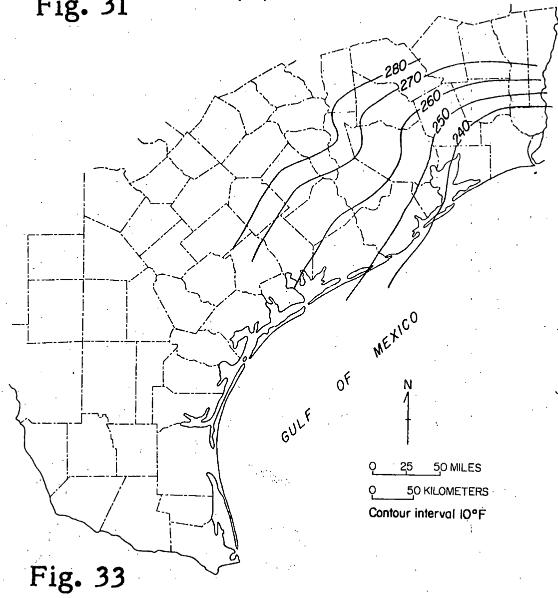


Fig. 33

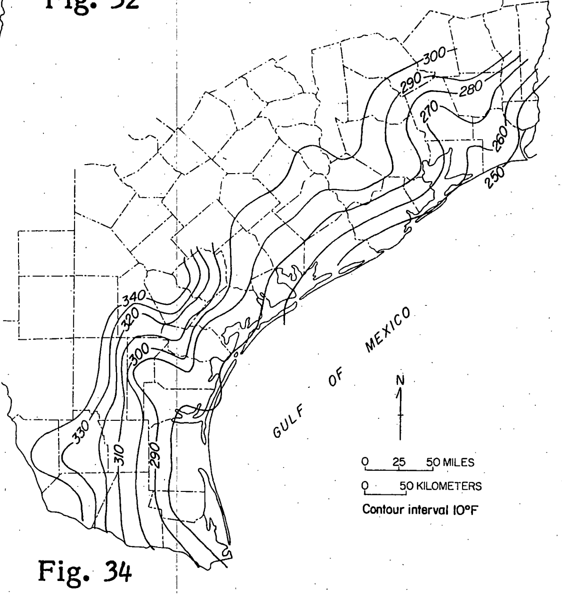


Fig. 34

stratigraphic section (fig. 35, Lindquist, 1977; Loucks, Bebout, and Galloway, 1977; and Stanton, 1977). Criteria for recognition of secondary porosity were developed by McBride (1977); Schmidt, McDonald, and Platt (1977); and Loucks, Bebout, and Galloway (1977) and include

1. Partial to complete leaching of cements. Calcite, dolomite, and ankerite cements are leached, resulting in patchy remnants with corroded boundaries.

2. Partial to complete dissolution of grains. Most leached grains are feldspars and volcanic rock fragments. Feldspars are commonly honeycombed and the original grain outline is preserved only by clay coats or rims.

3. Oversized pore spaces. Oversized pore spaces result when a grain is completely leached, leaving a pore space larger than adjacent grains. This process commonly creates the appearance of packing inhomogeneity.

4. Embayments in quartz overgrowths. Embayments in quartz with overgrowths result when grains around which the overgrowths precipitated are leached.

Secondary porosity in lower Tertiary Gulf Coast sandstones has been recognized in several different diagenetic stages. These stages are delineated later in the subsection on general diagenetic sequence.

Sandstone Classification

Folk's (1968) sandstone classification, based on three end-members--quartz, feldspar, and rock fragments (fig. 36)--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 the classification useful in grouping sandstones as 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 Texas lower Tertiary section is commonly difficult to distinguish from silicified volcanic rock fragments. The term quartzose has been added to Folk's

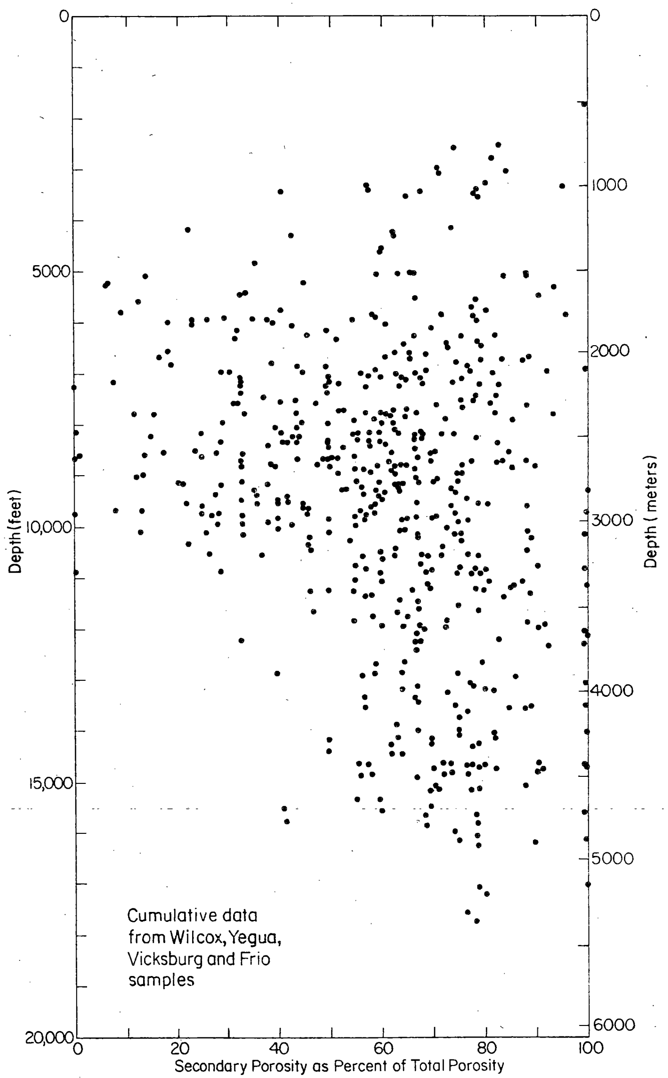


Figure 35. Secondary porosity as a percent of total porosity versus depth for lower Tertiary sandstones.

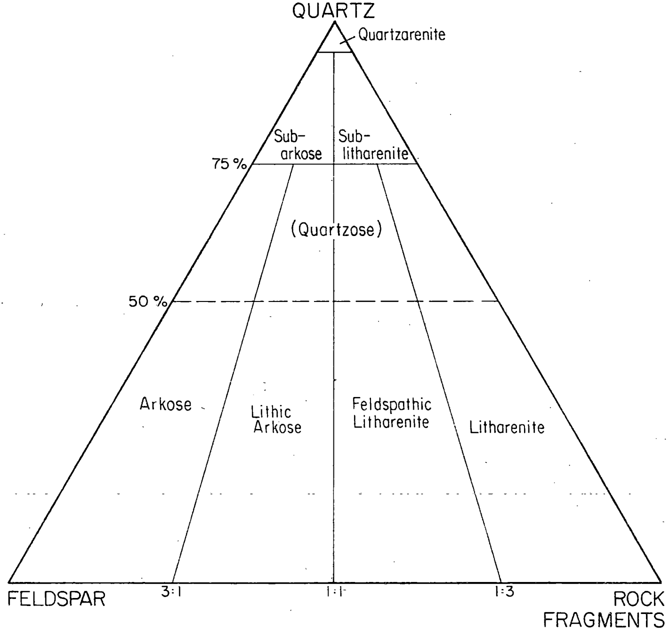


Figure 36. Sandstone classification from Folk (1968). "Quartzose" modifier added by this report.

classification in this paper to modify sandstone types with 50 percent or more quartz but less than 75 percent quartz.

General Diagenetic Sequence

Lower Tertiary formations along the Texas Gulf Coast have undergone a similar diagenetic sequence (fig. 37). A few formations have features that are not seen in others, and depths at which diagenetic features first occur differ among formations, but the general diagenetic sequence is consistent. The paragenetic sequence and its relationship to depth was delineated by noting depth to first occurrence and relative position of diagenetic features to each other. Most diagenetic features were well developed before the rock was buried to 3,000 m (10,000 ft)(fig. 37), indicating that most diagenesis occurs above the top of the geopressured zone. Porosity, however, continues to decrease in the geopressured zone (fig. 13), so some cementation must be taking place there.

Lower Tertiary formations display the following general diagenetic sequence:

Surface to shallow subsurface diagenesis (0 to 1,200 m$^{\pm}$; 0 to 4,000 ft$^{\pm}$) begins with formation of clay coats (probably smectite) formed by mechanical infiltration of colloidal clay-rich waters through the porous zone (Burns and Ethridge, 1977; Galloway, 1974) (centerfold a). Although clay coats occupy only a small volume of pore space, they can be detrimental to permeability by reducing pore-throat diameter and causing resistance to fluid flow (Galloway, 1977a). Clay rims, precipitated clay cement around grains, are present in minor amounts and can also similarly reduce permeability.

Alteration of feldspars begins in the source area, continuing at the depositional surface and into the subsurface. Feldspars are either leached or replaced with Fe-poor calcite (centerfold b and c). Fe-poor calcite is a common pore-filling cement in the Catahoula (updip equivalent of the Frio Formation; Galloway, 1977) and Frio Formations; it is a common diagenetic feature in paleosoil zones in Frio outcrop (McBride and others, 1968; Galloway 1977b). Fe-poor calcite is rarely poikilotopic

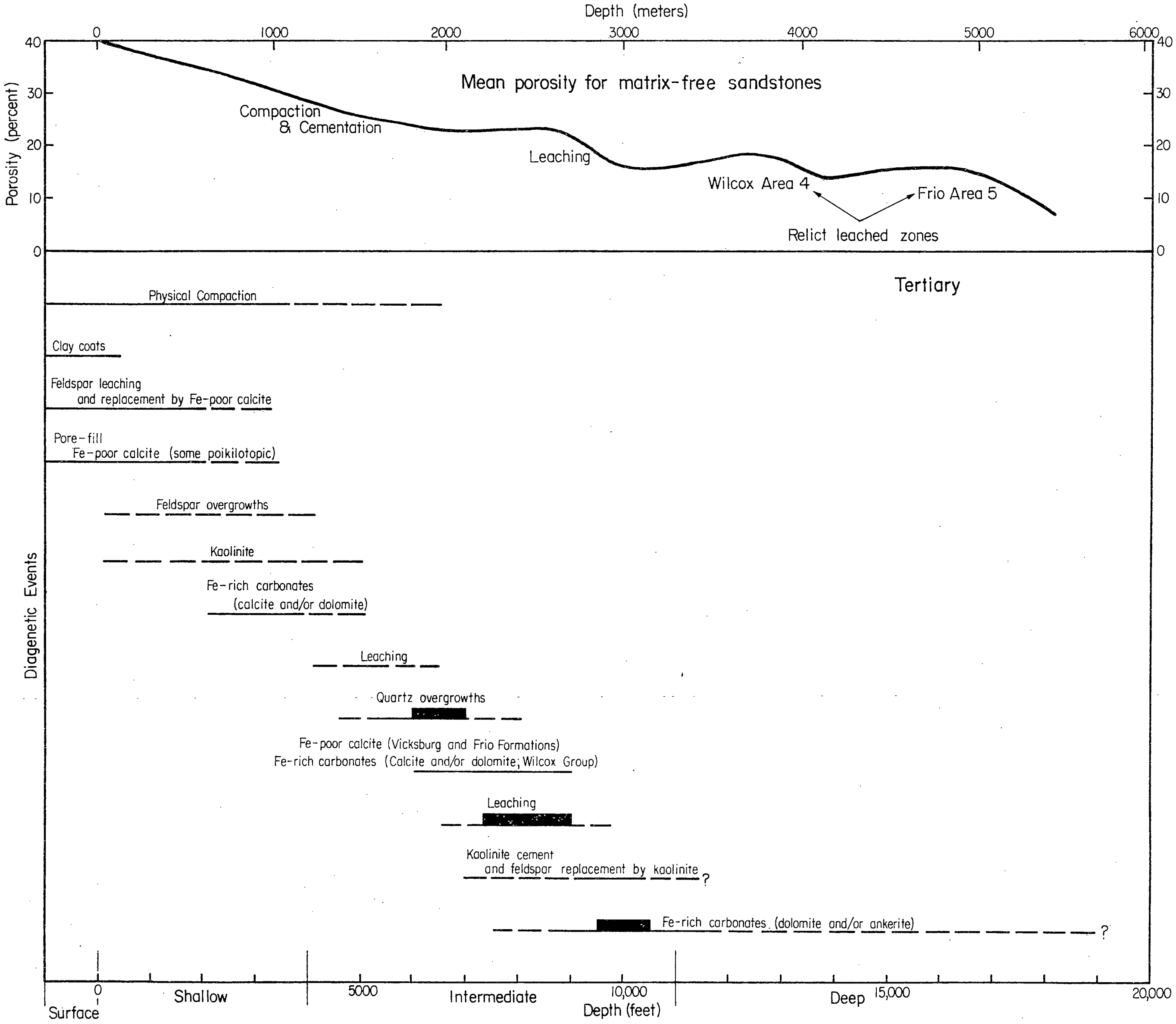


Figure 37. General rock consolidation stages with increasing depth of burial. Porosity curve at top of figure is for matrix-free sandstone.

(centerfold d).

Feldspar overgrowths around detrital feldspars and, less commonly, around volcanic rock fragments are also a near-surface feature. Overgrowths of plagioclase and orthoclase were precipitated on feldspars of all compositions. In one example, an orthoclase overgrowth was precipitated on a plagioclase overgrowth that had been precipitated on a volcanic rock fragment (centerfold e). Overlap of early leaching and feldspar cementation was observed in some samples. Volumetrically, this cement is not very significant.

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

Fe-rich carbonate cement (calcite and dolomite) begins to precipitate at approximately 600 m (2,000 ft) in pores and in molds of feldspar grains leached at a shallower depth (centerfold h).

Throughout the shallow subsurface, sediments are undergoing relatively rapid compaction because of the lack of significant cementation. The early Fe-poor calcite is the first major compaction-arresting cement. By 1,200 m (4,000 ft) porosity is reduced from the original 40 percent to approximately 30 percent.

Moderate subsurface diagenesis (1,200 to 3,400 m ±; 4,000 to 11,000 ft±) comprises a complex stage of cementation and leaching. Compaction is arrested during this stage because of abundant cementation.

Fe-rich carbonate precipitated at the end of the shallow subsurface stage, feldspar grains, and early calcite that replaced feldspars undergo dissolution which creates secondary leached porosity (centerfold i and j). This is the first of two important leaching stages in the moderate subsurface.

Quartz overgrowths are an important diagenetic feature in the consolidation history of Tertiary sandstones (centerfold k). Overgrowths arrest compaction and occlude pore space, and they are resistant to later dissolution. In many areas in the Wilcox Group, quartz overgrowths have occluded all or nearly all pore space, eliminating any potential for development of high-quality reservoirs. Quartz overgrowths are less abundant in other lower Tertiary formations, but locally they are still an important porosity-reducing cement.

Carbonate cementation occurs after formation of quartz overgrowths. In the Vicksburg and Frio Formations, carbonate cementation is Fe-poor (centerfold 1), and in the Wilcox Group, carbonate cementation is Fe-rich. This carbonate cementation is also a major porosity reducing event.

After these last stages of quartz and carbonate cementation, porosity is commonly reduced to 10 percent. This reduction in porosity may be reversed later, however, by a second intense leaching stage. Components that are leached are feldspars, volcanic rock fragments, and carbonate cements. Evidence for this stage of leaching is the dissolution of post-quartz overgrowth carbonate cement (centerfold m) and the formation of embayments in quartz overgrowths where grains have been dissolved (centerfold n). Continued leaching during this stage may resurrect porosities to more than 30 percent. This moderate subsurface stage of leaching is important in deep reservoir development.

After leaching, kaolinite is precipitated as a cement and also replaces feldspars (centerfold o and p). Commonly, replaced feldspars are nuclei for development of the cement. Kaolinite, composed of crystalline booklets consisting of single crystals several microns in size (plate 1a), forms a meshwork in the pore spaces that does not significantly reduce porosity but does reduce permeability. Fortunately, kaolinite cementation is neither abundant nor widespread.

The last stage of cementation observed in the lower Tertiary section is precipitation of Fe-rich dolomite and ankerite (centerfold q). The amount of this late cement is the variable that controls deep reservoir preservation in all lower Tertiary formations except the Wilcox Group in which quartz overgrowths are more important in reducing porosity than these late carbonate cements.

Deep subsurface diagenesis (>3,400 m±; >11.000 ft±) is a continuation of the precipitation of late Fe-rich carbonate cements. In some sections, such as in the Frio in Upper Texas, the late carbonate stage is minor, and high-quality reservoirs exist at depth.

Reservoir development in the lower Tertiary Sandstones of the Texas Gulf Coast is controlled by a series of porosity-reducing and porosity-enhancing events. In shallow reservoirs, porosity is mainly primary in origin with lesser secondary porosity. Much of this porosity is lost through compaction and cementation. Two different stages of leaching resurrect porosity, and reservoirs are now composed mainly of secondary porosity (fig. 35). These reservoirs may be destroyed by precipitation of significant quantities of late Fe-rich carbonate cement.

Although a general diagenetic sequence applicable to all Tertiary formations in the Texas Gulf Coast is apparent from petrographic analyses, there are significant differences among formations in mineral composition and in importance of each diagenetic event that have bearing on the existence of high-quality reservoirs at depth. It is necessary, therefore, to consider each formation separately to evaluate its potential for producing geothermal energy.

Wilcox Group

Texture and Mineralogy

Wilcox sandstones are typically poorly to moderately sorted, fine-grained quartzose lithic arkoses (figs. 38 to 41). Quartz content increases from Upper to Lower

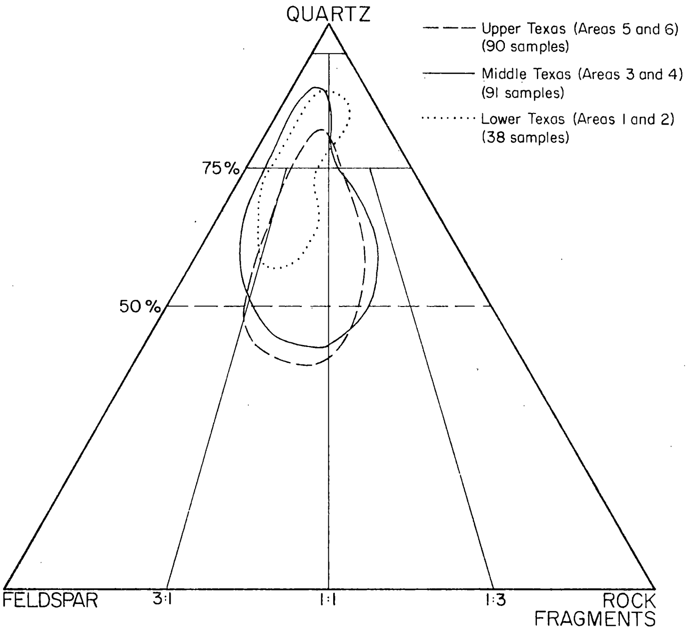
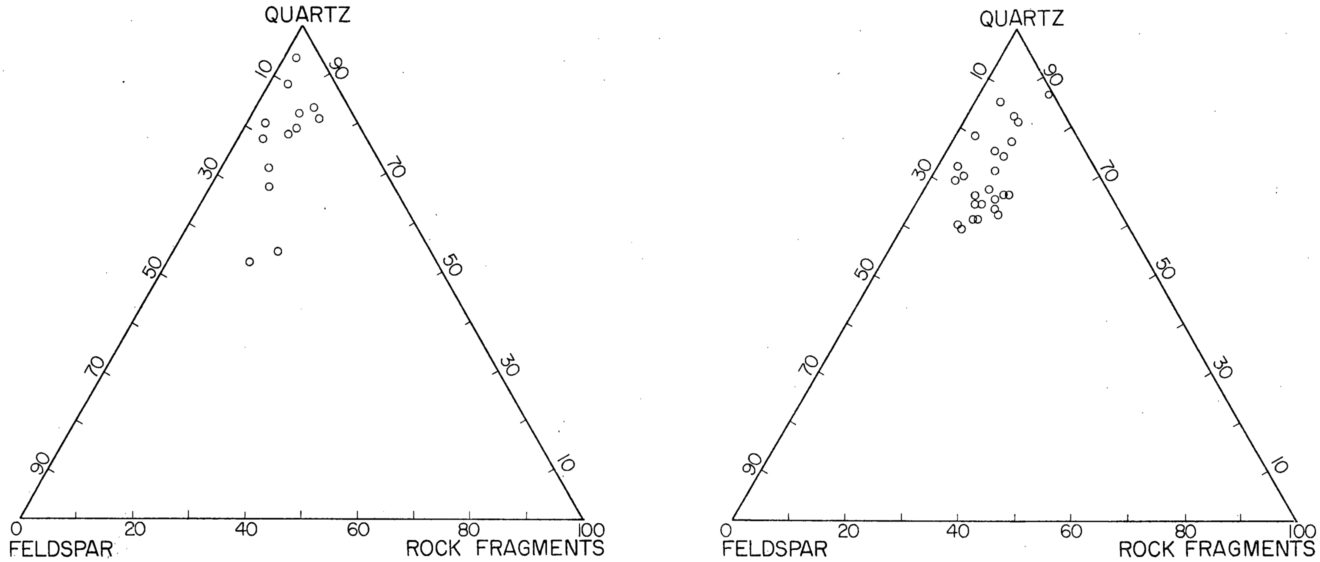
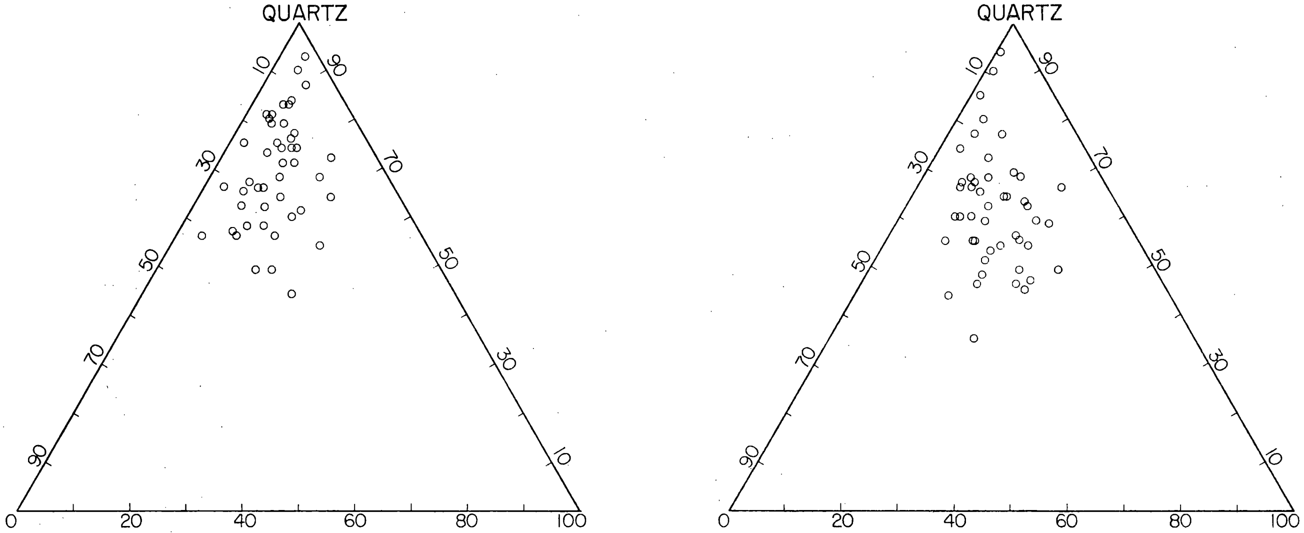


Figure 38. Wilcox sandstone composition.



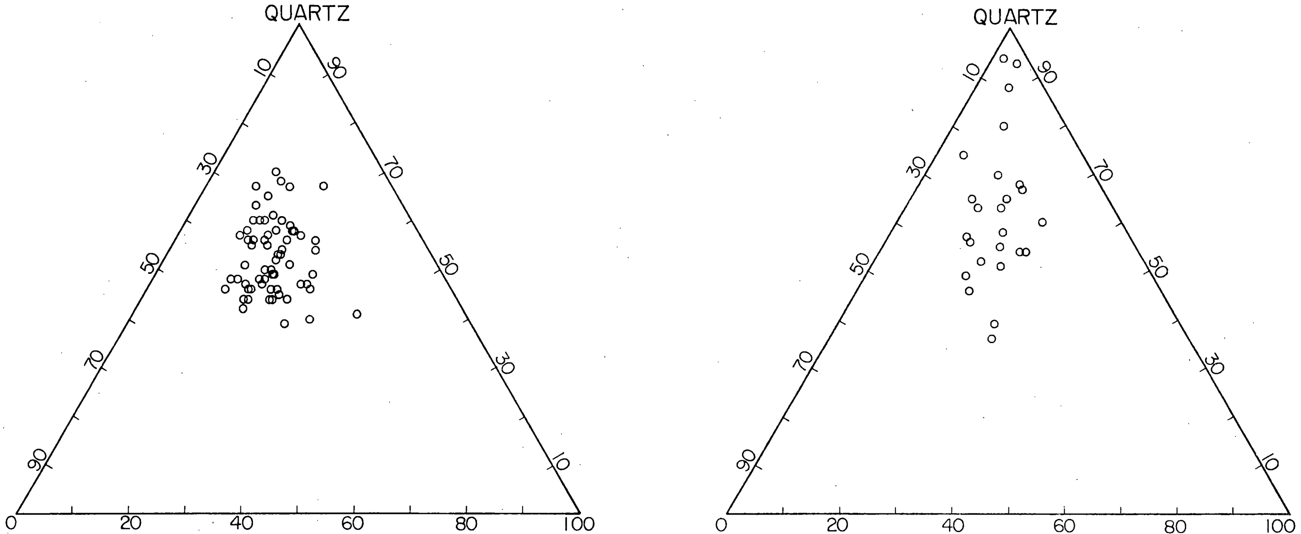
Area 1 (13 samples)

Area 2 (25 samples)



Area 3 (45 samples)

Area 4 (46 samples)



Area 5 (65 samples)

Area 6 (25 samples)

Figure 39. Basic data for Wilcox sandstone composition by area.

Texas Gulf Coast probably owing to a source area to the north. Orthoclase also has a regional trend, but in the opposite direction. It is found in more samples and is more abundant in each sample in Middle and Upper Texas. In Lower Texas the amount of orthoclase decreases significantly, and in Area 1 a minor amount of orthoclase occurs in only one sample. There is also an increase in sorting and a slight decrease in grain size (figs. 40 and 41) from north to south. If the major direction of transport were from Upper to Lower Texas, the more mechanically stable component, quartz, should have survived the transport, and the less stable components, such as orthoclase, should not have survived. An increase in sorting and a decrease in grain size are also to be expected with a greater distance of transport. Metamorphic and volcanic rock fragments are the major lithic debris in the Wilcox sandstones (fig. 42). Metamorphic rock fragments are low to medium grade, ranging from slates to quartzites and muscovite schists. Muscovite is a common accessory mineral. Most volcanic rock fragments are highly altered, usually by silicification (plate 1b). Many grains identified in the past as chert may actually be silicified volcanic rock fragments. Unaltered volcanic rock fragments are very similar to those identified in the Frio Formation as predominantly rhyolitic in composition (Lindquist, 1977). The Lower Texas Gulf Coast has approximately equal amounts of volcanic and metamorphic rock fragments; in Middle and Upper Texas Gulf Coast sandstones, metamorphic rock fragments predominate. The volcanic rock fragments probably came from West Texas, southern New Mexico, and/or northern Mexico (Shell Oil Company, 1975). A source for the metamorphic rock fragments is still in dispute. Todd and Folk (1957) 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 the Upper Texas Gulf Coast, probably locally derived from Cretaceous rocks from the Llano Uplift.

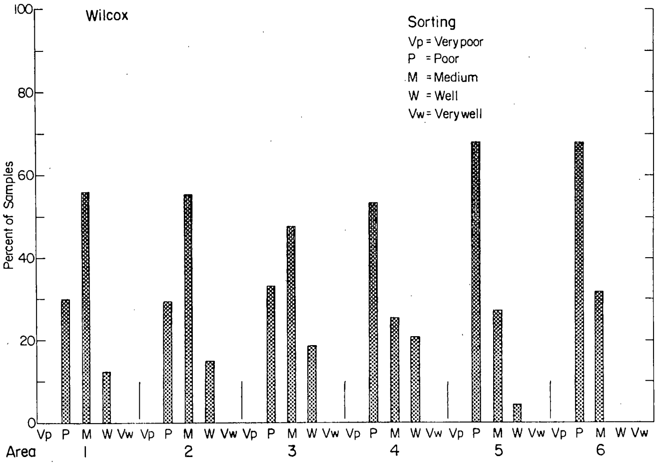


Figure 40. Distribution of sorting in Wilcox sandstones by area.

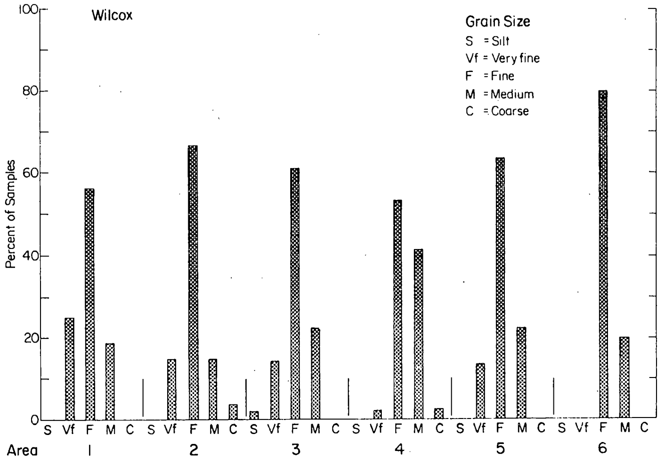


Figure 41. Distribution of grain size in Wilcox sandstones by area.

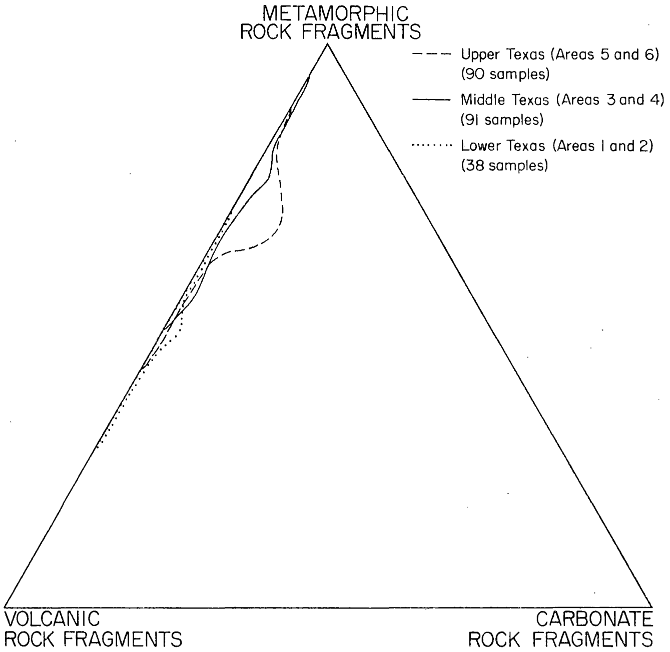


Figure 42. Wilcox sandstone rock fragment composition.

Diagenesis

Diagenesis in Wilcox sandstones progresses according to the general rock consolidation sequence outlined above (figs. 37 and 43). Features in the moderate subsurface, however, originate at shallower depths than in other formations, caused perhaps by a higher thermal gradient in the Wilcox Formation relative to other lower Tertiary formations.

Todd and Folk (1957) described diagenesis in Wilcox outcrop samples from Bastrop County in Central Texas. They noted clay coats, abundant feldspar leaching , feldspar overgrowths, and authigenic kaolinite booklets. Each of these features is common in shallow subsurface diagenesis. It is interesting, though, that Todd and Folk did not observe any near-surface Fe-poor calcite replacement of feldspars, which is common in the shallow subsurface in other formations. Neither was Fe-poor calcite observed in this study. Carbonate that has replaced feldspars or filled in leached feldspars in the Wilcox Group is Fe-rich, and it is rare above a depth of approximately 8,000 ft (2,440 m). It is possible that feldspars were leached at the surface, but carbonate associated with them was not precipitated until the moderate subsurface.

Stanton (1977) studied a Wilcox core from the moderate subsurface 1,552 m (5,094 ft) to 2,278 m (7,474 ft) from Karnes County, Texas. He outlined a paragenetic sequence as follows: quartz overgrowths, kaolinite, Fe-poor calcite, leaching, Fe-rich calcite, and dolomite. Stanton's observations are similar to those of this study for moderate subsurface diagenetic features (plate 1c). However, we found no Fe-poor carbonate cement following quartz overgrowths--only Fe-rich carbonate cements (fig. 43). Also, kaolinite in our sequence comes after or during the end of the major leaching stage, not before it.

Boles (1978), in a study of Wilcox sandstones of southwest Texas (Thompsonville area), recognized three stages of carbonate diagenesis. Calcite occurs to a depth of 2,300 m (7,600 ft). Ankerite (greater than 20 mole percent iron) is present from 2,560 m (8,400 ft) to at least 4,650 m (15,250 ft); shallower than 3,200 m (10,500 ft), the

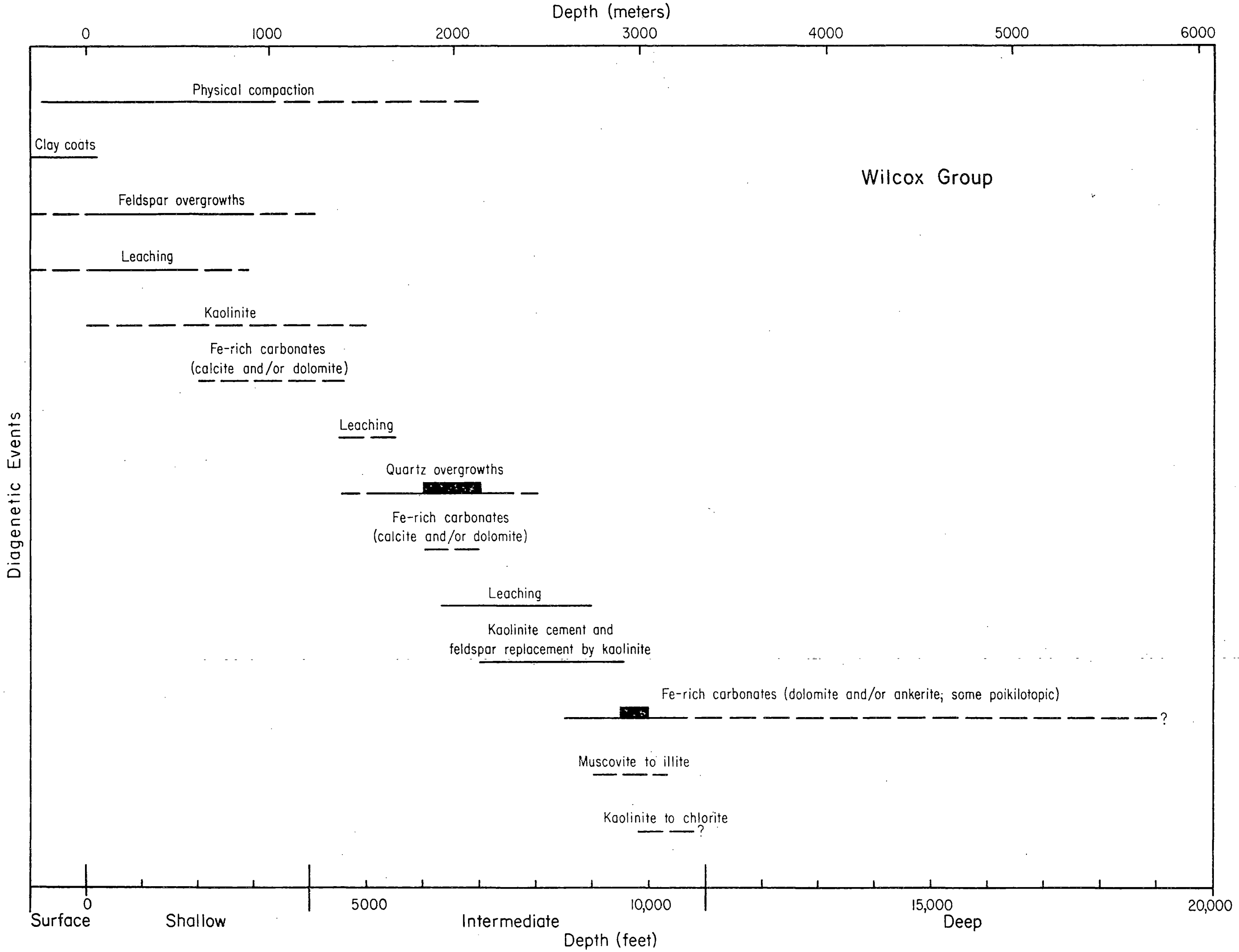


Figure 43. Diagenetic events versus depth for Wilcox sandstones.

carbonate cement is calcium-rich (similar to protodolomite). Boles and Frank believe ankerite forms by addition of iron and magnesium to previously precipitated calcite.

Our data suggest carbonate cementation occurs during three separate events in the Wilcox Group; the first of four carbonate events in the general diagenetic sequence, early Fe-poor calcite, was not noted. Twenty-eight percent of Wilcox samples studied 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, 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 around 2,600 m (8,500 ft) in depth. Above this depth, leaching may have reduced the amount of carbonate cement. This late carbonate cementation destroys reservoir quality in the deep subsurface.

Twenty-six carbonate-cemented sandstones from different depths were treated with potassium ferricyanide to stain Fe-rich calcite blue and with alizarin red-S to stain Fe-poor calcite red. Ankerite stains blue, and Fe-free dolomite remains colorless. Dolomite is present in some samples, but most stained dark blue, indicating the presence of iron. Among examples of the last stage of Fe-rich cementation two types of blue stain were noted: a deep, true blue and a less intense, slightly greenish-blue that stained the carbonate which had highly undulose extinction and curved crystal faces. The latter color likely indicates the presence of ankerite.

Late Fe-rich carbonate cements in four samples ranging in depths from 3,003 m (9,852 ft) to 4,480 m (14,700 ft) were analyzed by electron microprobe for calcium, iron, and magnesium. These cements are predominantly Fe-rich dolomite ($Ca_{0.58-0.59}Fe_{0.16-0.19}Mg_{0.23-0.25}CO_3$) and less commonly, ankerite ($Ca_{0.51}Fe_{0.22}Mg_{0.29}CO_3$). No Fe-rich calcite is present.

As noted above, kaolinite forms in two stages in the shallow subsurface and in the moderate subsurface. A plot of kaolinite abundance versus depth shows that most of the kaolinite is precipitated during the moderate subsurface stage of diagenesis. Petrographic evidence indicates that much of the kaolinite is associated with leached plagioclase and is probably an alteration product of the plagioclase. A plot of kaolinite abundance versus plagioclase abundance indicates a reverse relationship between them. Replacement of kaolinite by chlorite was noted beginning at a depth of 2,960 m (9,700 ft) (plate 1d).

Quartz overgrowths first appear at a depth of 1,370 m (4,500 ft), but they do not become common until around 1,830 m (6,000 ft). There is no direct relationship between amount of quartz grains and quartz overgrowths. A relationship may be present, but the amount of quartz overgrowths may be inaccurate because of difficulty in recognizing quartz overgrowths where no clay coats separate them from quartz grains. Samples containing more than 10 percent quartz overgrowths vary from a low of 11 percent of the total suite in Area 3 (area with the highest permeability in the Wilcox deep subsurface) to as high as 55 percent of the total suite in Area 5.

Reservoir Quality

Vertical porosity distribution in the Wilcox Group (fig. 17) shows no regional trend. Plots of permeability versus depth by geographic area indicate that Area 3 has the highest maximum permeabilities at any depth (fig. 44). It is the only area that has permeabilities over 20 millidarcys at depths where temperatures are greater than 300°F. Area 3 also has the best developed secondary leached porosity. It is interesting to note again that Area 3 has the lowest percentage of quartz overgrowths. Areas 1, 2, and 4 have permeabilities as high as 10 millidarcys at depths below the 300°F isotherm. No data were recorded for Area 6 below the 300° isotherm.

Secondary leached porosity resulting from leaching of feldspars, shale clasts, and carbonate cements is the dominant porosity type in the Wilcox Group in the moderate

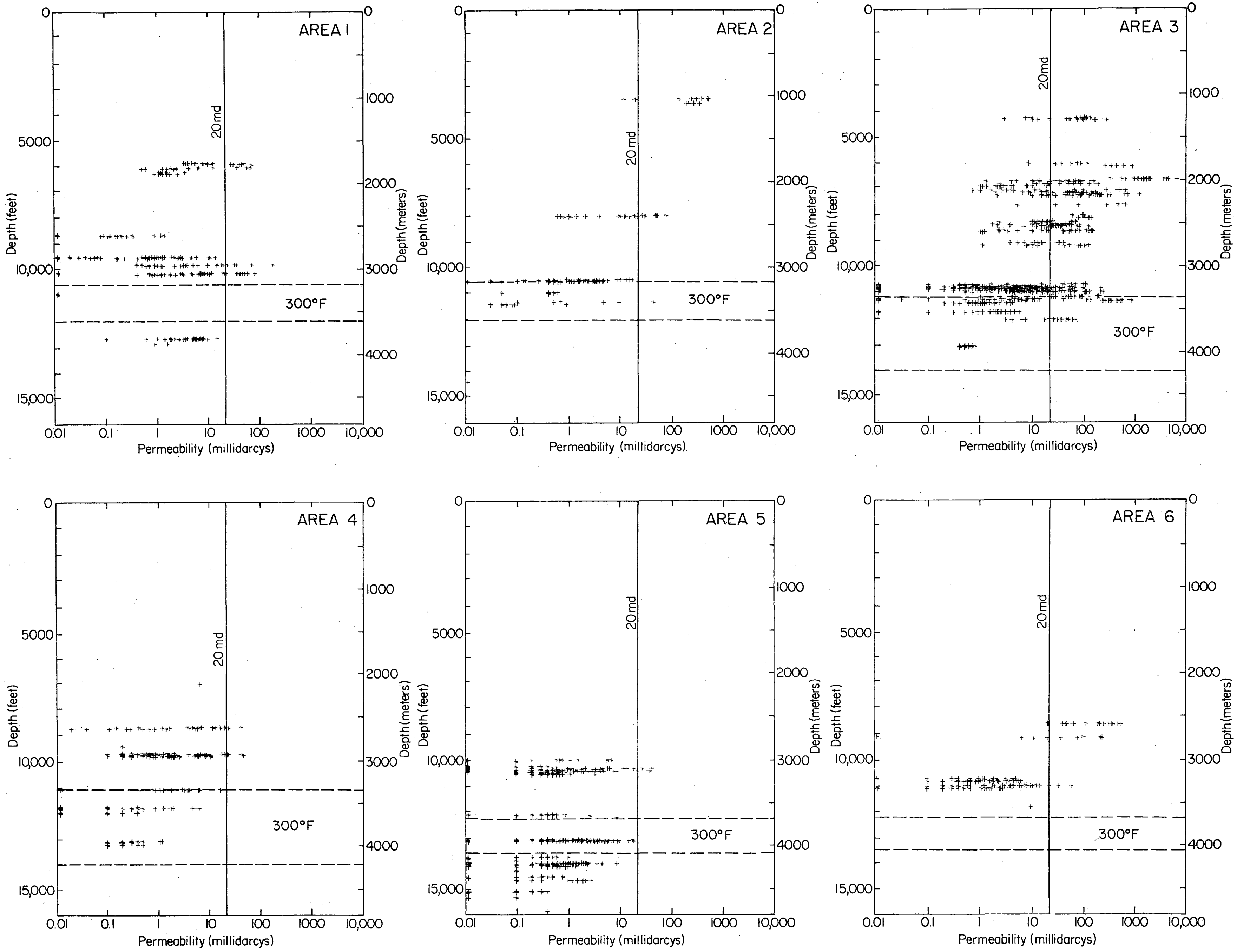


Figure 44. Permeability (whole core) versus depth by area for Wilcox Group.

and deep subsurface (fig. 45). Plots of primary and secondary porosity with depth show that at 3,500 m (11,500 ft), primary porosity is less than 4 percent, whereas secondary porosity is as high as 10 percent.

Quartz cementation is the major cause of porosity reduction in the Wilcox Group. It can be massive enough to occlude pore spaces totally, and because it is not susceptible to leaching, destruction of reservoirs is permanent. Carbonate cementation, which does not necessarily permanently destroy the reservoir, is not reponsible for as much porosity loss. Leaching of carbonate cements is important in resurrection of porosity and creation of high-quality reservoirs at depth.

No strong regional trend in distribution of quartz and carbonate cements was found in the Wilcox Group. This is probably because of no significant regional variation in sand composition. Locally, porosity depends upon the extent of leaching of feldspars and carbonate cement. More unstable components and less quartz result in development of more secondary porosity and, hence, greater total porosity (plate 1e and f).

Yegua Formation

Texture and Mineralogy

Sandstones of the Yegua Formation are moderately sorted, fine-grained, lithic arkoses to quartzose lithic arkoses (figs. 46 to 49). They become more quartz-rich from the Lower to Upper Texas Gulf Coast. In the Lower Texas Gulf Coast, volcanic and carbonate rock fragments are the dominant rock-fragment types (fig. 50). Volcanic rock fragments are similar in appearance to those in the Frio Formation and are probably rhyolitic in composition. In the Middle and Upper Texas Gulf Coast, rock fragments are composed of approximately equal amounts of metamorphic and volcanic rock fragments, and carbonate rock fragments are rare (fig. 50). Metamorphic rock fragments are similar to those in the Wilcox Group. Carbonate rock fragments are composed of micrite, probably eroded caliche fragments. The appearance of caliche

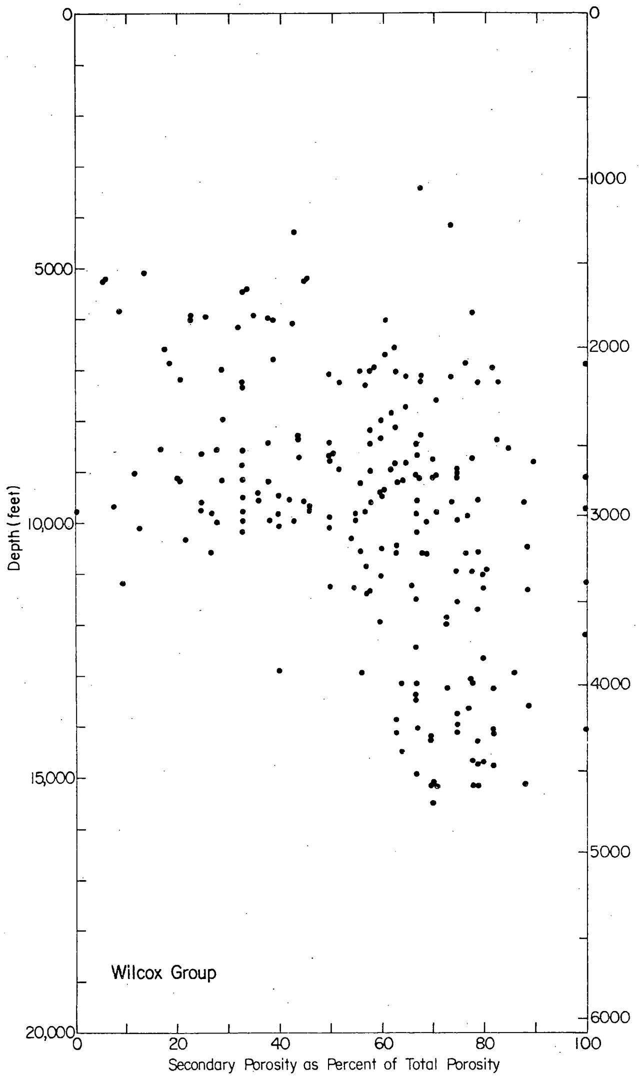


Figure 45. Secondary porosity as a percent of total porosity versus depth for Wilcox sandstones.

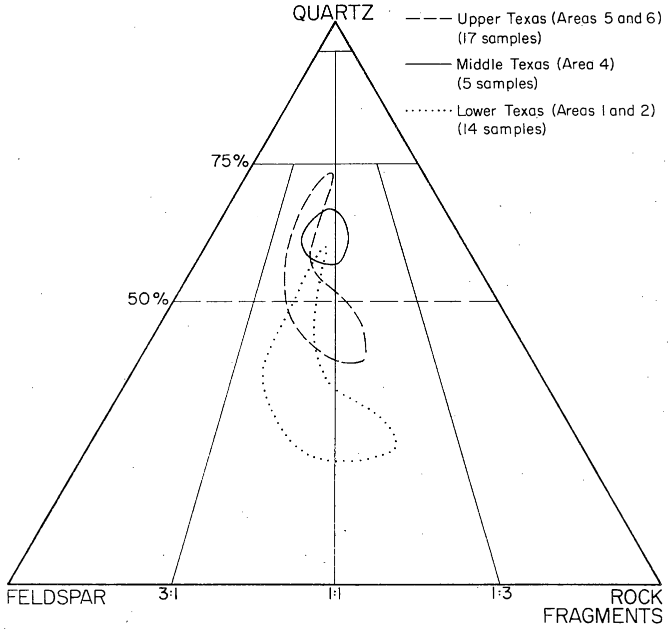
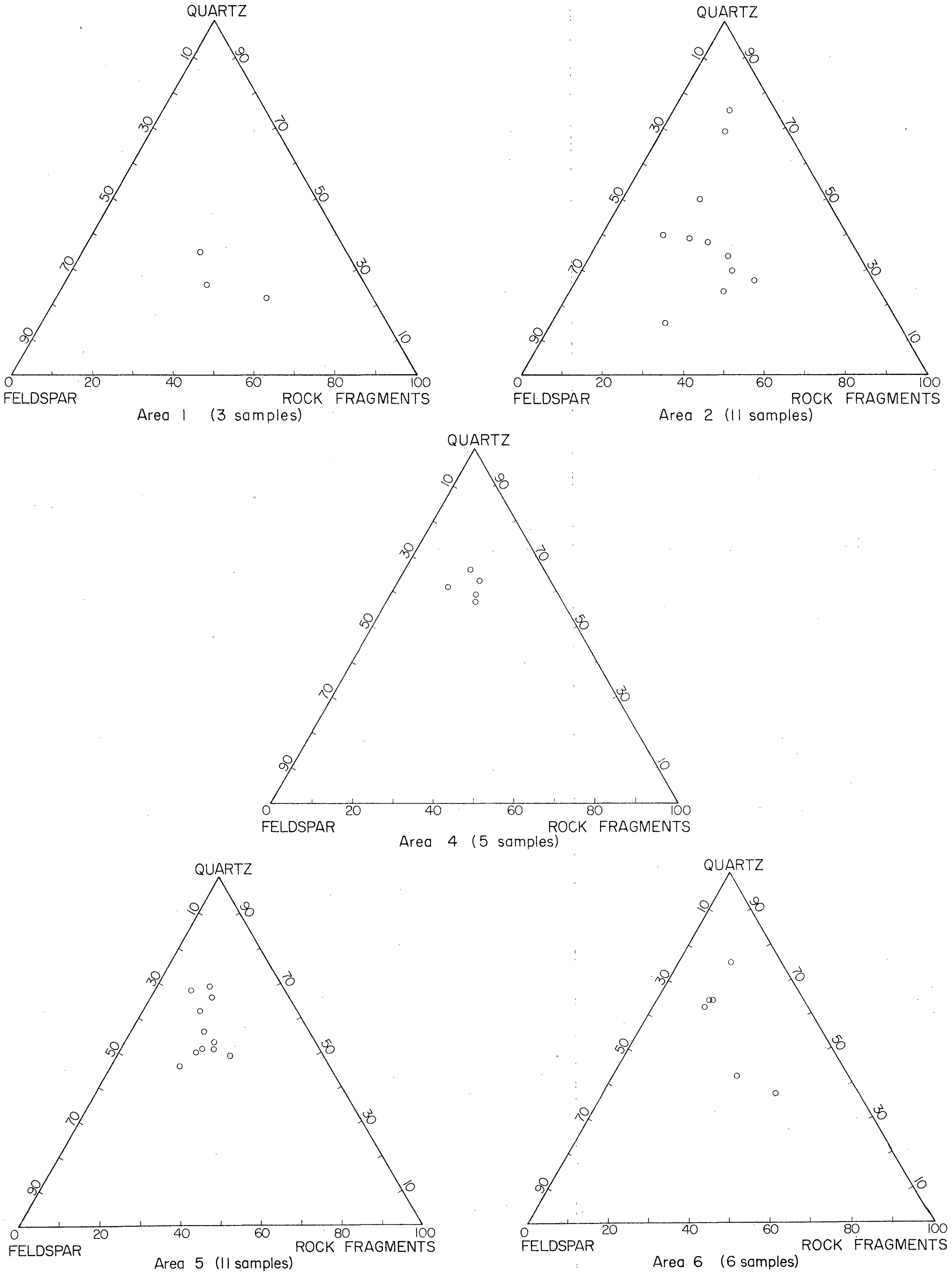


Figure 46. Yegua sandstone composition.



Area 1 (3 samples)

Area 2 (11 samples)

Area 4 (5 samples)

Area 5 (11 samples)

Area 6 (6 samples)

Figure 47. Basic data for Yegua sandstone composition by area.

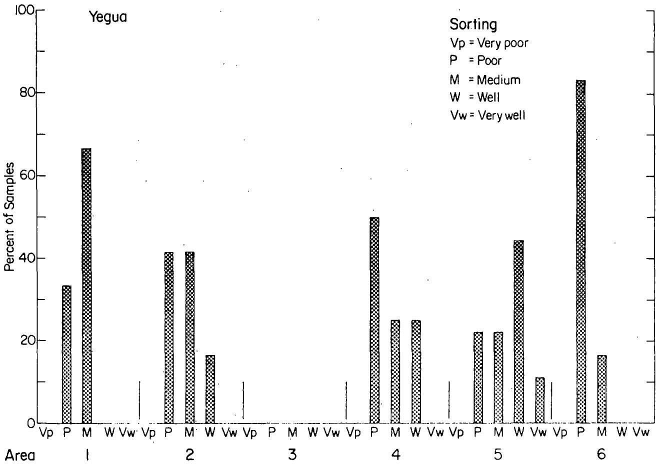


Figure 48. Distribution of sorting in Yegua sandstones by area.

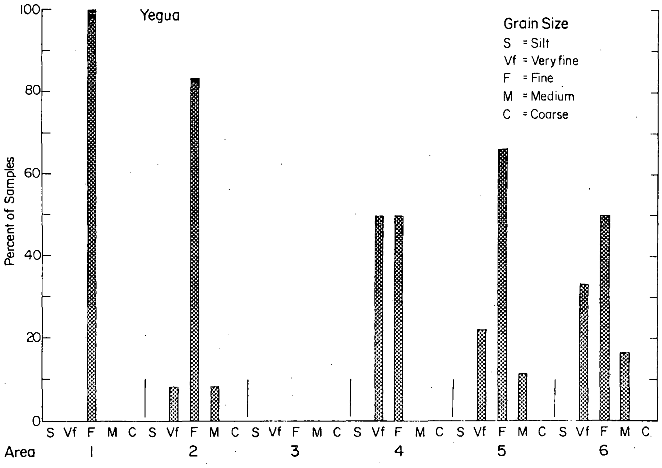


Figure 49. Distribution of grain size in Yegua sandstones by area.

clasts in the Yegua Formation may indicate a major change in climate from that during deposition of the Wilcox. During Wilcox time the entire Texas coast probably was subhumid; from Yegua time to the present the climate ranged from arid in the Lower Texas Gulf Coast to subhumid in the Upper Texas Gulf Coast. Texturally, Yegua sandstones decrease slightly in grain size from the Lower to Upper Texas Gulf Coast, but no sorting trends are apparent (figs. 48 and 49).

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

Diagenesis

In the shallow subsurface, feldspars were leached and replaced with Fe-poor calcite (figs. 37 and 51). Much of this early calcite associated with feldspars is leached in the moderate 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 are precipitated.

Precipitation of Fe-rich carbonate continues into the moderate subsurface. It also fills some leached pores within the early calcite that replaced feldspar grains. Carbonate cement in the Yegua Formation is most abundant in the Lower Texas Gulf Coast. This coincides with the occurrence of carbonate rock fragments in the Lower Texas Gulf Coast. The carbonate rock fragments may act as nuclei for the precipitation of carbonate cements. A similar relationship occurs in the Vicksburg and Frio Formations.

The pre-quartz-overgrowth-moderate-subsurface-leaching stage attacks feldspars and earlier carbonate cements. Silica diagenesis takes place in the form of quartz overgrowths on quartz grains. Quartz overgrowths begin to precipitate after this leaching stage at 1,370 m (4,500 ft) and are common by 1,980 m (6,500 ft). In a

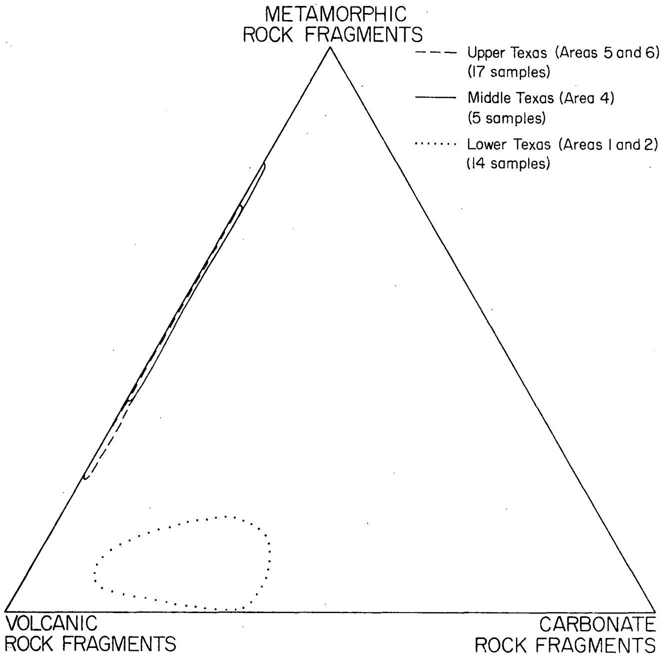


Figure 50. Yegua sandstone rock fragment composition.

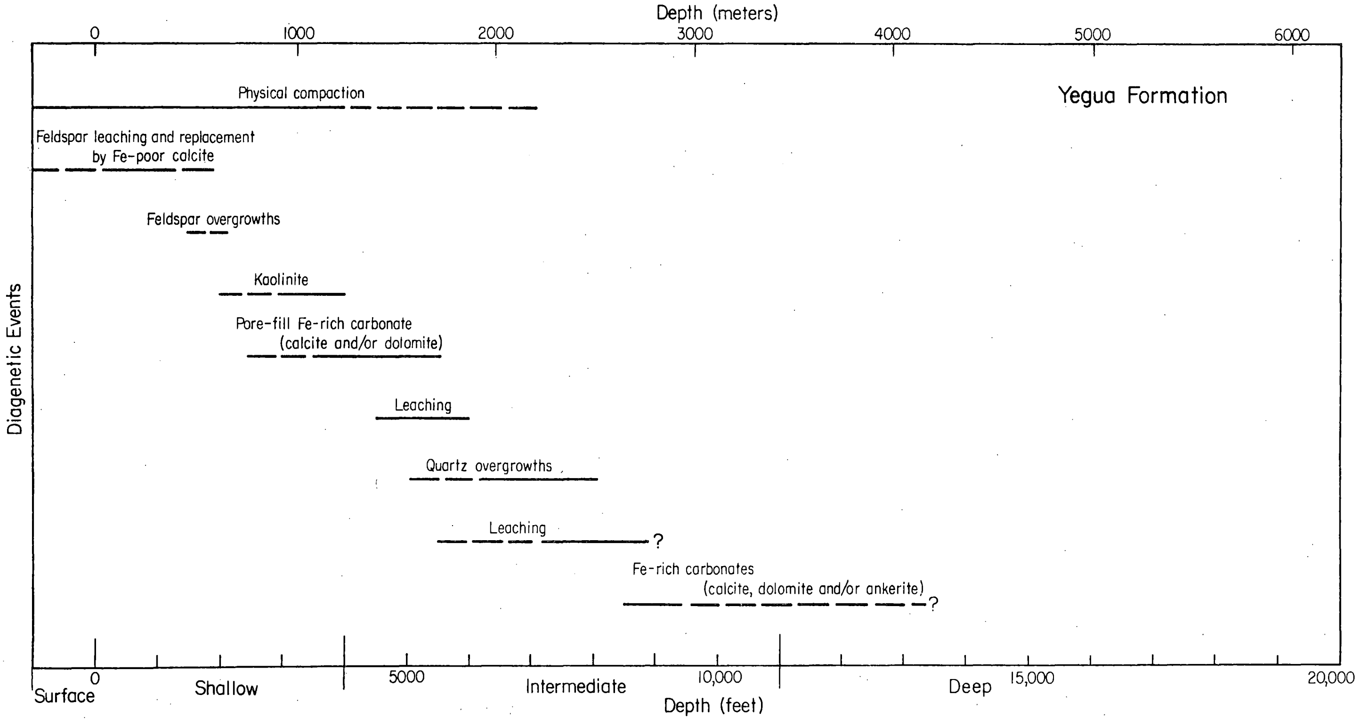


Figure 51. Diagenetic events versus depth for Yegua sandstones.

leaching stage after quartz overgrowths, feldspars and calcite that replace feldspars in the shallow subsurface decrease markedly in abundance.

The last stage of diagenesis in the moderate subsurface is Fe-rich carbonate cementation. No samples from the Yegua deep subsurface were obtained because of lack of control and because the Yegua is generally shale at depths greater than 3,350 m (11,000 ft.)

Reservoir Quality

The Yegua Formation is not prospective for geopressured geothermal energy because it is too shallow. The sandstones are neither hot enough nor geopressured. However, Yegua samples are included in this study to increase our understanding of reservoir quality in other formations that are prospective.

Yegua Formation porosity is intermediate between that of the Vicksburg Formation and the Wilcox Formation. In the moderate subsurface, primary porosity is as common as secondary porosity (fig. 52). Secondary porosity results from leaching of feldspars and carbonate cements. Late Fe-rich carbonate cement somewhat lessens porosity, but quartz overgrowths may be the major porosity-reducing factor at depth. With deeper burial, the Fe-rich carbonate cement, which probably is still being precipitated, may further reduce porosity.

Vicksburg Formation

Texture and Mineralogy

Vicksburg sandstones were sampled from the Lower Texas Gulf Coast (Areas 1 and 2) where the only deep sandstones in this formation occur. These sandstones are poorly sorted, fine-grained lithic arkoses (figs. 53 to 56). Rock fragments are mainly volcanic clasts, reflecting more extensive volcanism in West Texas and in Mexico during Vicksburg deposition; lesser amounts of carbonate rock fragments and metamorphic rock fragments occur in the Vicksburg Formation (fig. 57). The ancient Rio Grande transported this volcanic material into the rapidly subsiding Rio Grande

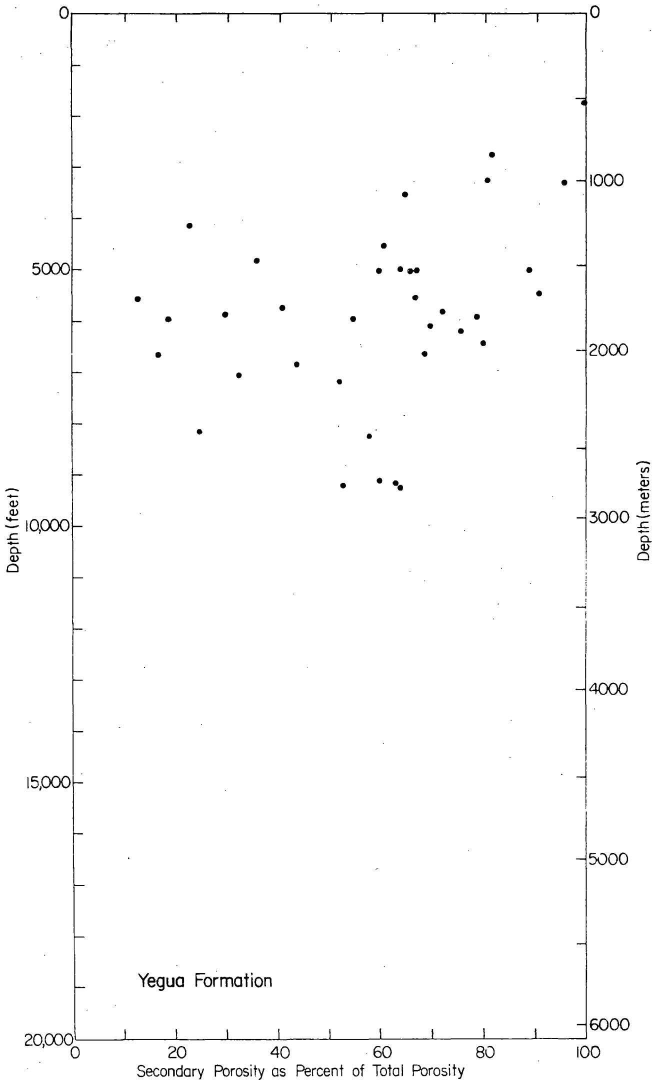


Figure 52. Secondary porosity as a percent of total porosity versus depth for Yegua sandstones.

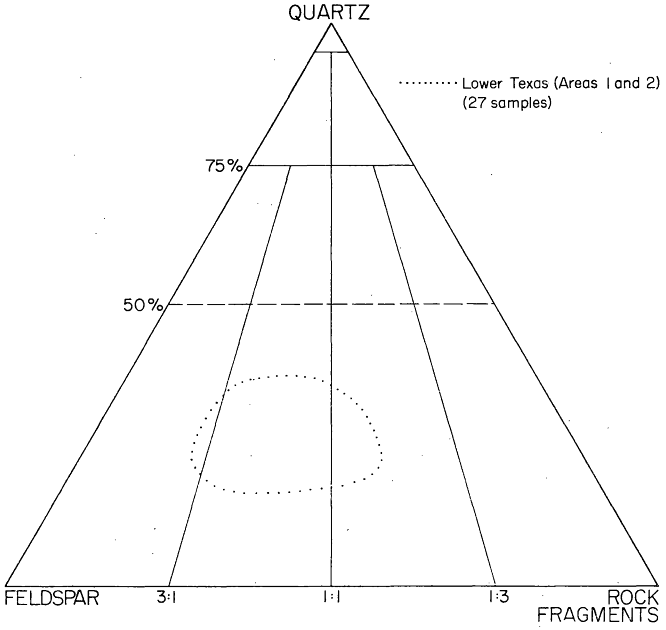
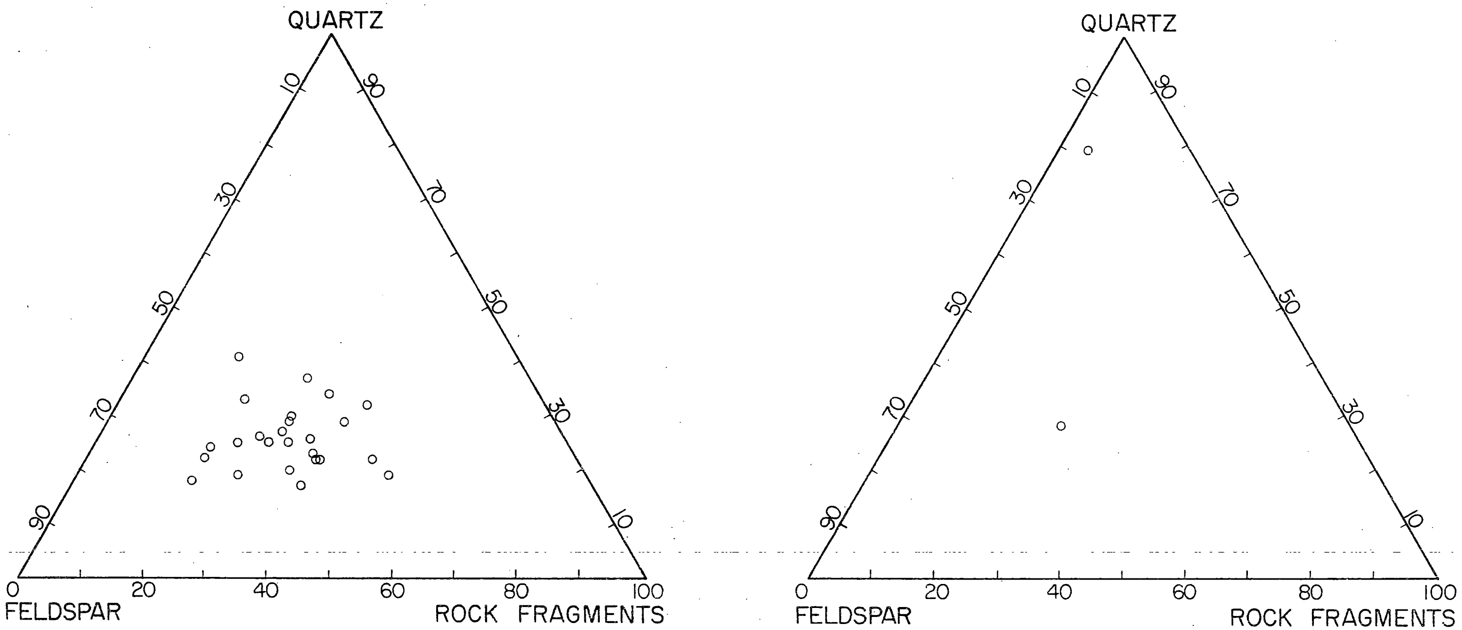


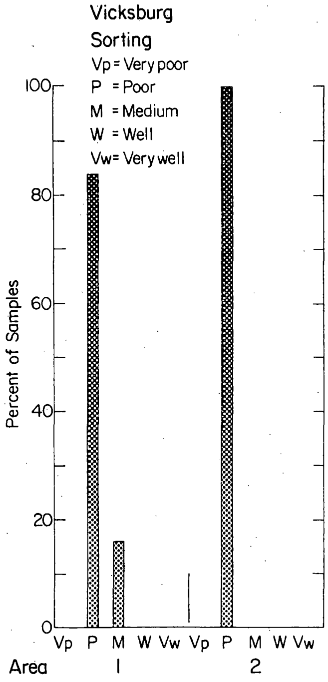
Figure 53. Vicksburg sandstone composition.



Area 1 (25 samples)

Area 2 (2 samples)

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



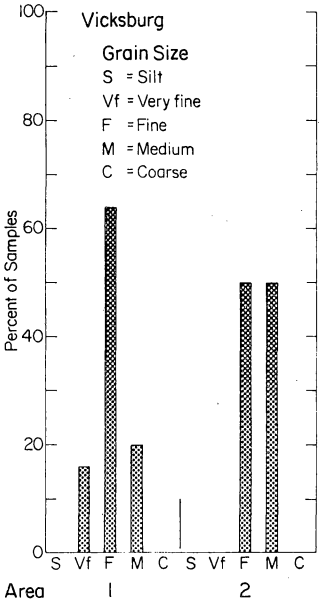


Figure 55. Distribution of sorting in Vicksburg sandstones by area.

Figure 56. Distribution of grain size in Vicksburg sandstones by area.

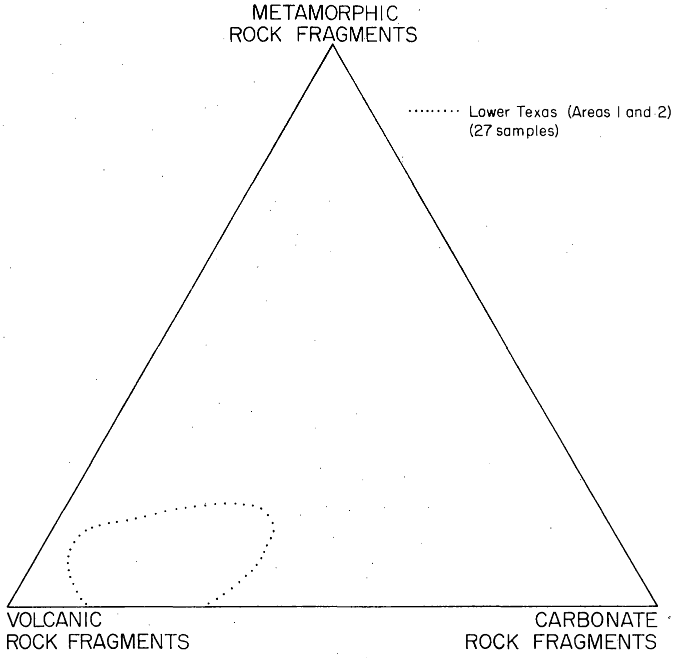


Figure 57. Vicksburg sandstone rock fragment composition.

Embayment in Lower Texas. Carbonate rock fragments are eroded caliche clasts similar to those of the Yegua and Frio Formations and indicate continued arid conditions in the Lower Texas Gulf Coast. The Rocky Mountain area may have been the source of the metamorphic rock fragments.

Diagenesis

Twenty-five of the 27 samples in the Vicksburg Formation are from depths of 2,440 m (8,000 ft) or more (fig. 4); thus direct information on diagenesis shallower than 2,440 m (8,000 ft) in this formation is not available. Rock composition and paragenetic sequences in the Vicksburg Formation are very similar to those in the Lower Texas Frio Formation, however, and depths at which shallow diagenetic events occur in the Vicksburg and Frio Formations are likely to be similar.

Diagenetic features in Vicksburg sandstones record essentially the same events as the general lower Tertiary diagenetic sequence, with the exception of a minor amount of zeolite cement precipitated during shallow subsurface diagenesis and the relative rarity of kaolinite (figs. 37 and 58). Early Fe-poor calcite replaces plagioclase, and a late stage of Fe-poor calcite appears after the quartz overgrowths. Quartz overgrowths are not common, generally constituting less than three percent of the rock volume. This low volume of quartz overgrowths is directly related to the low volume of quartz grains. Post-quartz overgrowth leaching is a major stage of reservoir development in the subsurface. Secondary porosity results from leaching of feldspars, volcanic rock fragments, and carbonate cements. This leached porosity is destroyed in most samples by late Fe-rich carbonate cementation. Abundant caliche clasts in the Vicksburg may have acted as nuclei for carbonate cement.

Reservoir Quality

The Vicksburg Formation has the poorest reservoir quality of any lower Tertiary formation (figs. 16 and 59). This is the result of fine grain size, poor sorting, abundant unstable rock fragments, pervasive carbonate cementation, and greater compaction

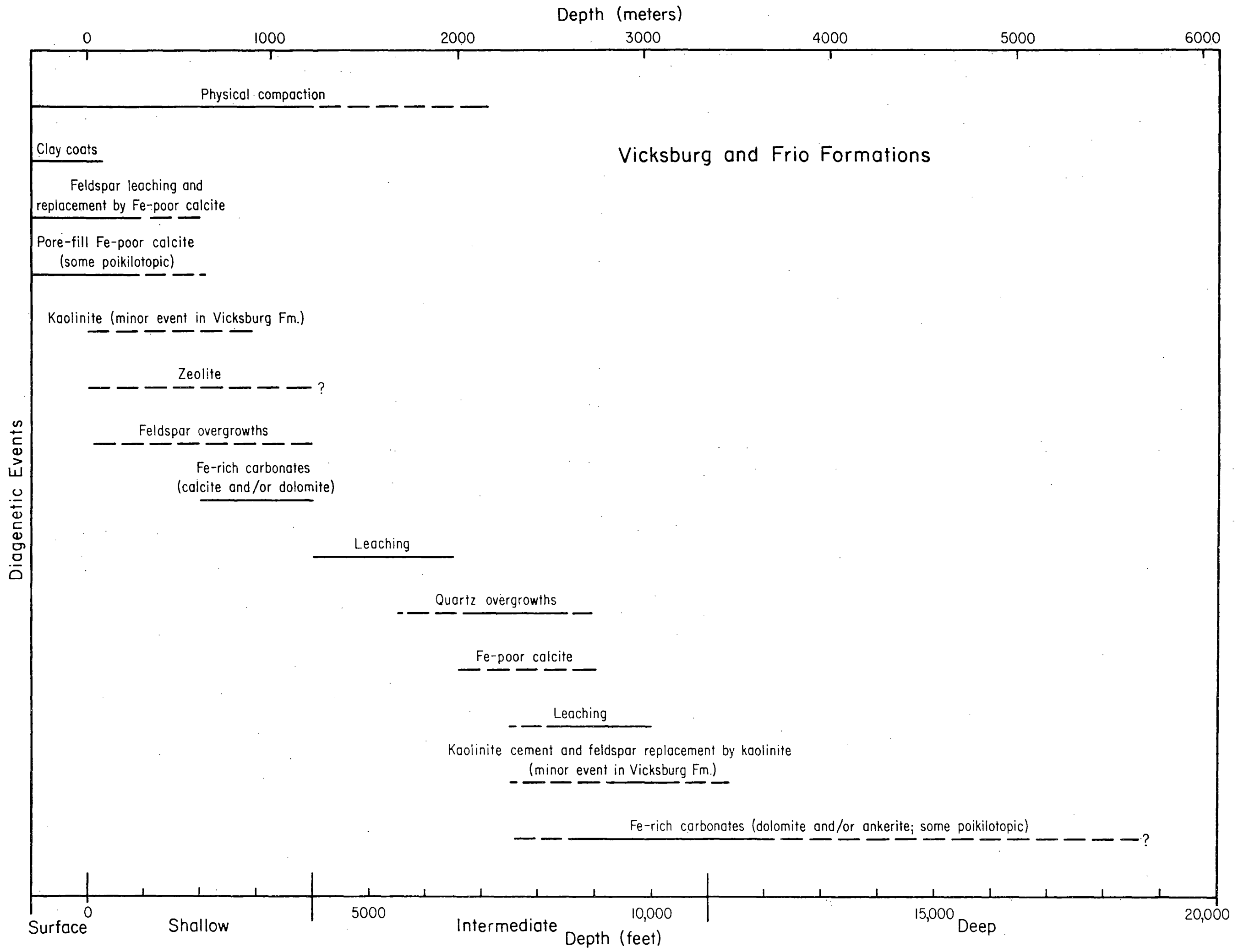


Figure 58. Diagenetic events versus depth for Vicksburg and Frio sandstones.

from rapid subsidence in the Lower Texas Gulf Coast. A typical Vicksburg sandstone is shown in plate 2a.

Most porosity beneath 2,440 m (8,000 ft) in depth is secondary porosity (fig. 60). Primary porosity is reduced to less than 5 percent, whereas secondary porosity may be up to 15 percent.

Frio Formation

Texture and Mineralogy

Of the lower Tertiary formations, the Frio Formation shows the most regional variation in mineral composition. In the Lower Texas Gulf Coast (Areas 1 and 2), Frio sandstones are poorly sorted, fine-grained, feldspathic litharenites to lithic arkoses (figs. 61 to 64). Middle Texas Gulf Coast (Areas 3 and 4) Frio sandstones are moderately to well-sorted, fine-grained, quartzose lithic arkoses. Upper Texas Gulf Coast (Areas 5 and 6) Frio sandstones are poorly sorted, fine-grained, quartzose lithic arkoses to subarkoses. This regional change in composition is independent of grain size (fig. 65).

Lower, Middle, and Upper Texas Frio sandstones have distinct rock fragment populations (fig. 66). In 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 volcanic rock fragments predominate, but some samples are rich in metamorphic rock fragments. Sandstones in the Middle Texas Gulf Coast also contain carbonate rock fragments, but such fragments are much less common than in the Lower Texas Gulf Coast. Rock fragments in the Upper Texas Gulf Coast sandstones are mainly volcanic rock fragments; amounts of metamorphic and carbonate rock fragments are much lower.

Lower Texas Gulf Coast sandstones 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. These volcanic rock fragments are dominantly

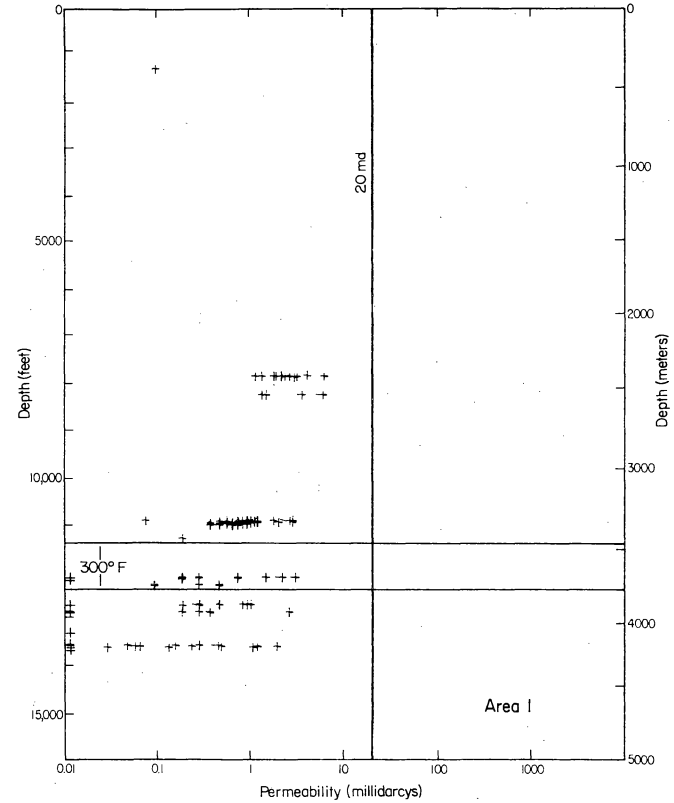


Figure 59. Permeability (whole core) versus depth by area for Vicksburg Formation.

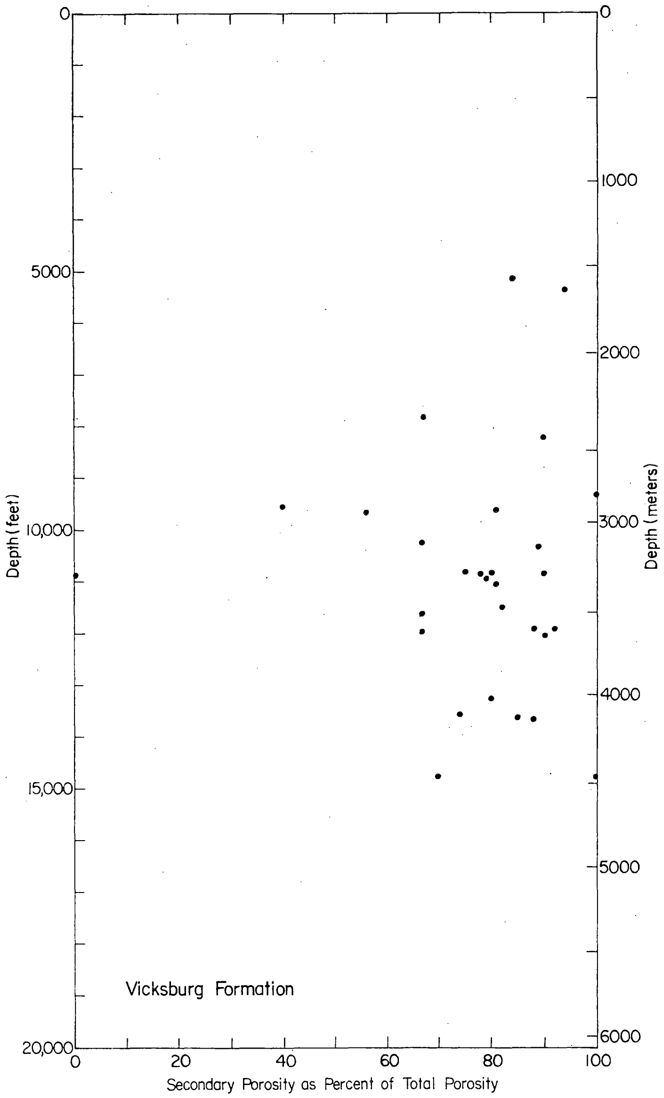


Figure 60. Secondary porosity as a percent of total porosity versus depth for Vicksburg sandstones.

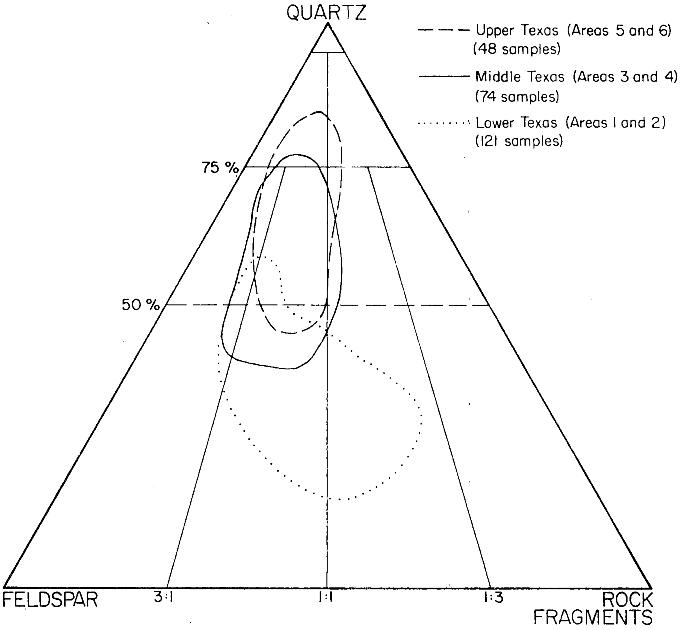
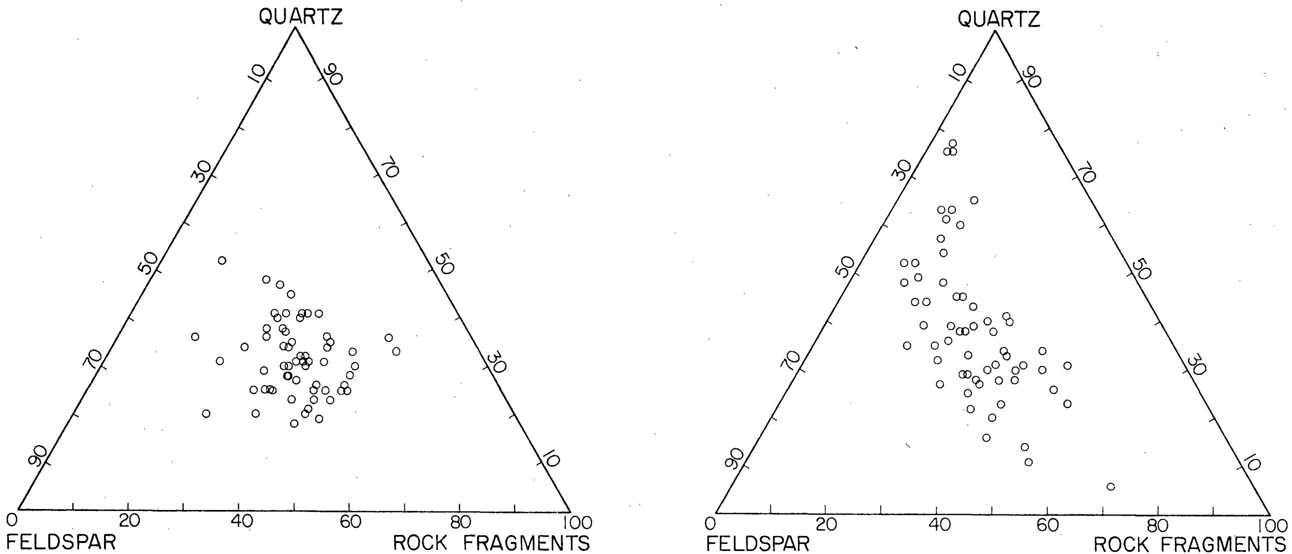
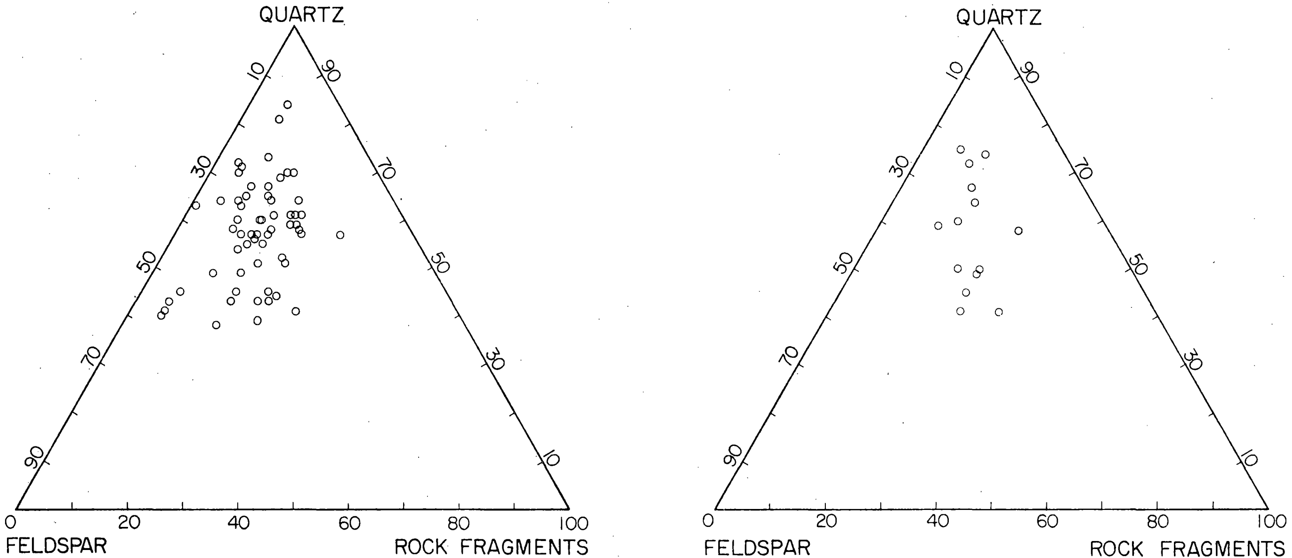


Figure 61. Frio sandstone composition.



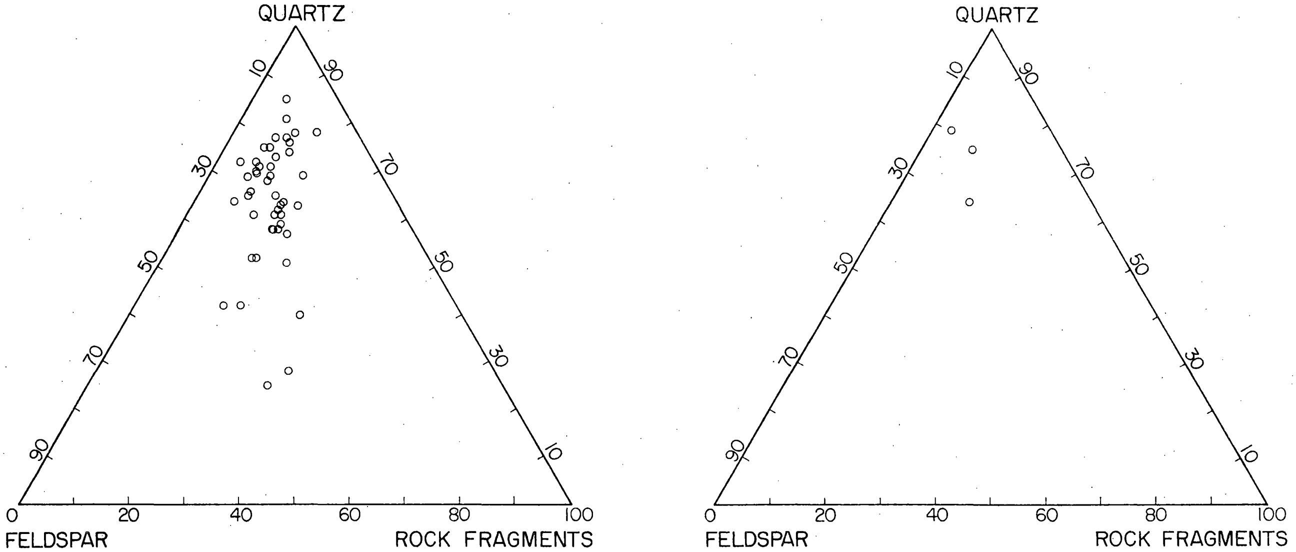
Area 1 (61 samples)

Area 2 (60 samples)



Area 3 (60 samples)

Area 4 (14 samples)



Area 5 (45 samples)

Area 6 (3 samples)

Figure 62. Basic data for Frio sandstone composition by area.

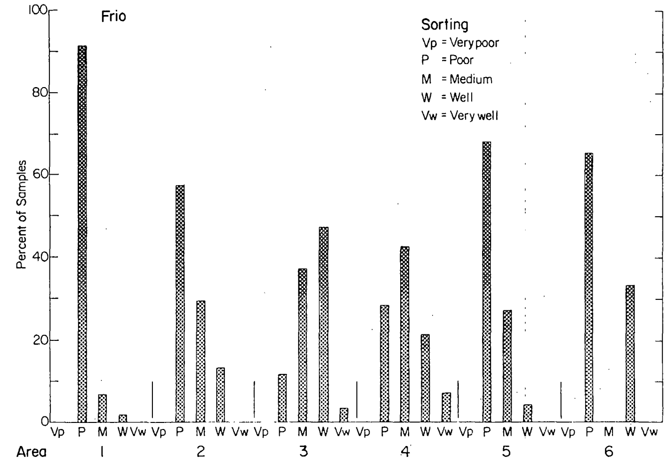


Figure 63. Distribution of sorting in Frio sandstones by area.

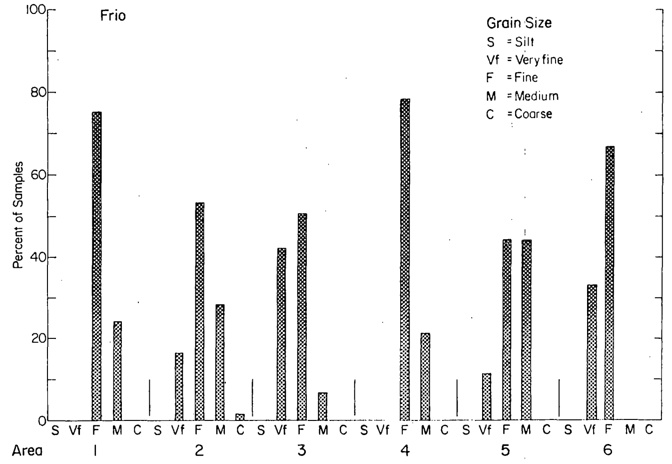


Figure 64. Distribution of grain size in Frio sandstones by area.

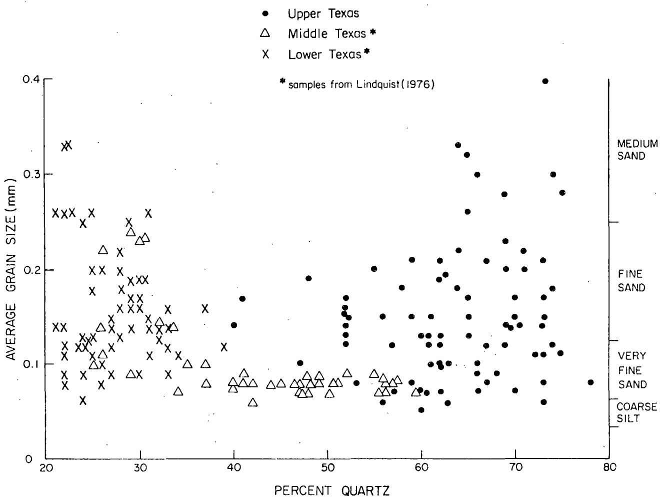


Figure 65. Relationship of percent quartz to average grain size for Frio sandstones along the Texas Gulf Coast.

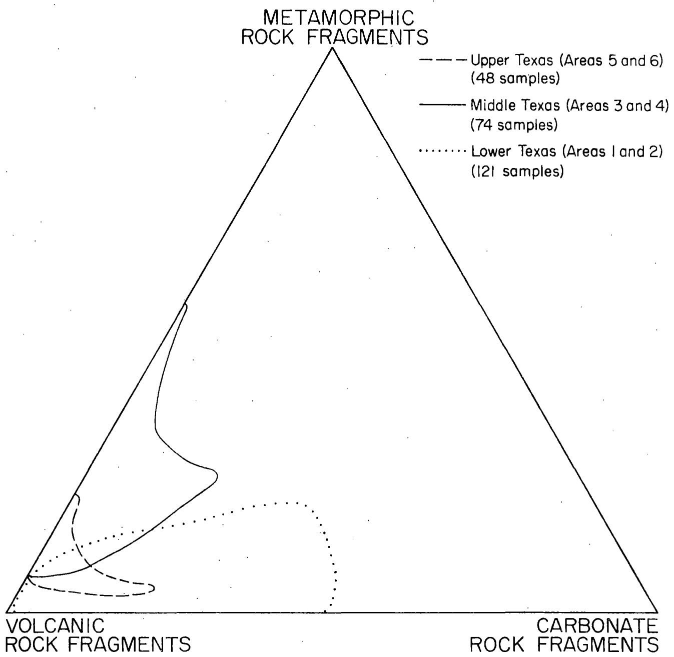


Figure 66. Frio sandstone rock fragment composition.

rhyolites and trachytes (Lindquist, 1977) and are usually silicified or altered to chlorite. Lesser amounts of these volcanics survived transport to Middle and Upper Texas Gulf Coast. The abundant carbonate rock fragments in Lower Texas Gulf Coast are caliche clasts, locally derived from caliche soils as the result of an arid climate. Caliche soils did not form in the more humid environment of Upper Texas Gulf Coast, and the abundance of carbonate rock fragments decreases in that direction. The source of abundant metamorphic rock fragments in Middle Texas Frio is debatable. If they were related to drainage from the Rocky Mountains, Upper Texas Frio should contain more metamorphic rock fragments as well. Middle Texas Frio also contains more orthoclase, suggesting a western source of metamorphic rock fragments such as the Llano Uplift, but the Uplift is believed to have been covered by Cretaceous carbonates until Miocene time.

Diagenesis

Changes in mineral composition and temperature along the Texas Gulf Coast determine the volume of diagenetic products in the Frio Formation and the depths at which they occur (figs. 38 and 59). The Frio Formation rock consolidation sequence has been delineated in earlier studies by Lindquist (1977) and Loucks, Bebout, and Galloway (1977). This study modifies these earlier investigations by adding newly recognized diagenetic features in the shallow and moderate subsurface and by adjusting depths of occurrence of these diagenetic features.

Clay coats occur in the shallow subsurface in only about 20 percent of the samples and usually contribute to only a small percentage of the volume of the sample. The coats commonly form thin layers and are discontinuous around grains. Clay rims are less abundant. Also in the shallow subsurface, feldspar grains and feldspar in volcanic rock fragments are leached and/or replaced by Fe-poor calcite. Some plagioclase grains have been selectively leached along one twin orientation. Minor pore-fill 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 (plate 2b), probably clinoptilolite (Galloway, 1977), is most common in the Lower Texas Gulf Coast (up to 13 percent of rock volume). The amount of zeolite cement is directly related to abundance of volcanic rock fragments.

At a depth of about 600 m (2,000 ft) an Fe-rich carbonate cement begins to precipitate. This is the first major subsurface cement in the Frio, but it is probably localized because most Frio sediments do not become well consolidated until a depth of 1,830 m (6,000 ft) or more.

The moderate subsurface stage of diagenesis begins with the leaching of early carbonate cements and feldspar. This leaching stage is followed by quartz cementation that begins around a depth of 1,520 to 1,830 m (5,000 to 6,000 ft). Quartz overgrowths are more abundant in samples having a greater number of quartz grains, and they are more common in the Upper Texas Gulf Coast where Frio sandstones are quartz-rich.

After the formation of quartz overgrowths, an Fe-poor calcite cement is precipitated. This calcite, with earlier carbonate cements and feldspar grains, enters the most extensive leaching stage in the diagenetic history of the Frio Formation. It is in this stage that porosities may be resurrected to more than 30 percent.

After this post-quartz leaching stage, cementation again becomes the dominant diagenetic process. Some of the remaining feldspars are replaced by well-developed booklets of kaolinite (centerfold o and p). Commonly kaolinite will grow out from replaced feldspars to fill surrounding pore space (centerfold o and p). In samples with higher percentages of kaolinite, the percentage of feldspar generally decreases. This correlation may be due to complete destruction of feldspar by kaolinite. Kaolinite cement forms up to as much as 5 percent of a sample.

The last cements to be precipitated are carbonates in the form of Fe-rich dolomite ($Ca_{0.54-4.58}Fe_{0.18}Mg_{0.24-0.28}CO_3$) and ankerite. These cements are especially common in the Lower Texas Gulf Coast where the abundance of carbonate rock fragments probably enhances precipitation by acting as nuclei. Rarely, leaching attacks Fe-rich dolomite (plate 2c).

Reservoir Quality

The Frio Formation has the best deep-reservoir quality in the lower Tertiary stratigraphic 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. 16, 18, and 67). Samples from Areas 5 and 6 from depths greater than the 300°F isotherm commonly have permeabilities greater than 29 millidarcys. In the northern part of Area 1 some permeability readings as high as 18 millidarcys are recorded, but the majority of readings are less than a few millidarcys. Porosity in the Frio Formation in the deep subsurface is dominantly secondary leached porosity (fig. 68).

The increase in reservoir quality from the Lower to Upper Texas Gulf Coast (fig. 18) corresponds to other trends in rock composition, climate, and geothermal gradient. The change in Frio rock composition is probably the most important of these. In the lower Texas Gulf Coast, where reservoir quality is poor, Frio sandstones are low in quartz and rich in volcanic and carbonate rock fragments (plate 2d). In the Upper Texas Gulf Coast, where reservoir quality is good, Frio sandstones are rich in quartz, lower in volcanic rock fragments, and lacking in carbonate rock fragments (plate 2e). The abundance of chemically unstable volcanic and carbonate rock fragments in the Lower Texas Gulf Coast accentuates diagenetic processes that destroy porosity. Zeolite cements are associated with high volumes of volcanic rock fragments, and chloritized volcanic rock fragments commonly are deformed in a manner that blocks

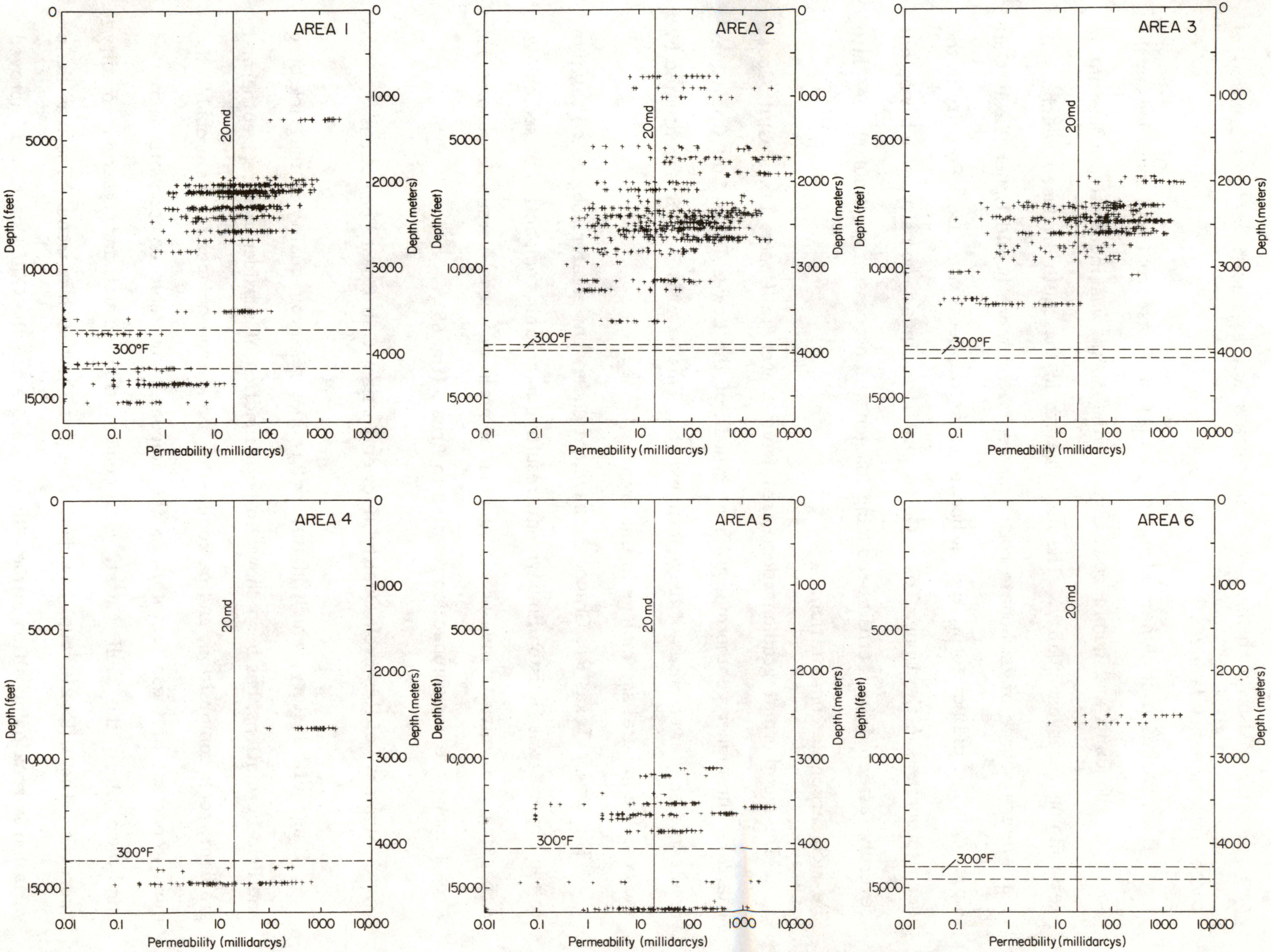


Figure 67. Permeability (whole core) versus depth by area for Frio Formation.

pore throats. Also, carbonate rock fragments act as nuclei for precipitation of carbonate cements (plate 2f).

Thus, variation in climate along the Texas Gulf Coast from arid conditions in the south to subhumid and humid conditions in the north was indirectly influential in determining reservoir quality. The arid climate in the south produced caliche soils that were a source of carbonate rock fragments. In more humid Upper Texas Gulf Coast caliches did not form, and carbonate rock fragments are rare. Porosity in the deep subsurface in the Upper Texas Gulf Coast is secondary porosity, which was not severely affected by porosity-reducing diagenetic processes, particularly by late Fe-rich carbonate cementation.

The geothermal gradient decreases from Lower to Upper Texas Gulf Coast (fig.28). The higher geothermal gradient typical of the Lower Texas Gulf Coast may result in a shallower onset of diagenetic events. This trend is further accentuated by the unstable mineral assemblage in this area.

The Lower Texas Rio Grande Embayment underwent greater subsidence relative to the Upper Texas Houston Embayment, resulting in greater compaction of sediments. A packing proximity (a measure of number of grain contacts)-versus-depth plot for Area 1 shows greater compaction relative to Area 5 (fig. 69).

Summary of Reservoir Quality in lower Tertiary Gulf Coast Formations

Diagenetic history, which in turn determines reservoir quality in the Vicksburg and Frio Formations, has been shown to be a function of subsidence rate, geothermal gradient, rock composition, and paleoclimate. Sandstone composition is probably the most important of these factors. As the amount of unstable components decreases northward along the Gulf Coast, less cementation occurs and reservoir quality improves. The Wilcox Group, however, does not show such a trend. There is little variation in rock composition in the Wilcox Group along the Gulf Coast, and improved

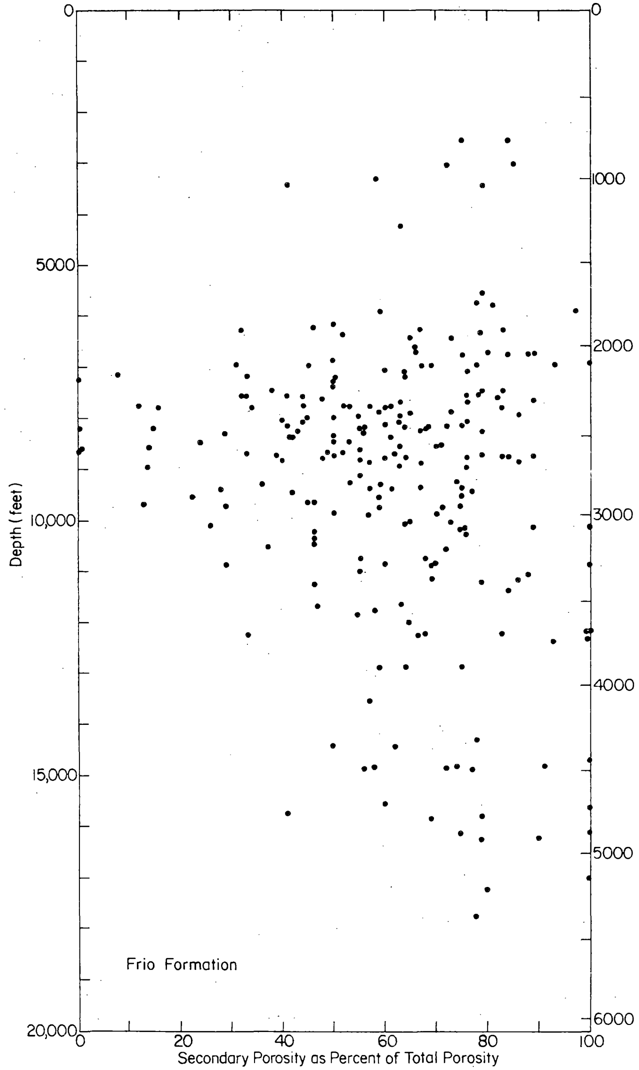


Figure 68. Secondary porosity as a percent of total porosity versus depth for Frio sandstones.

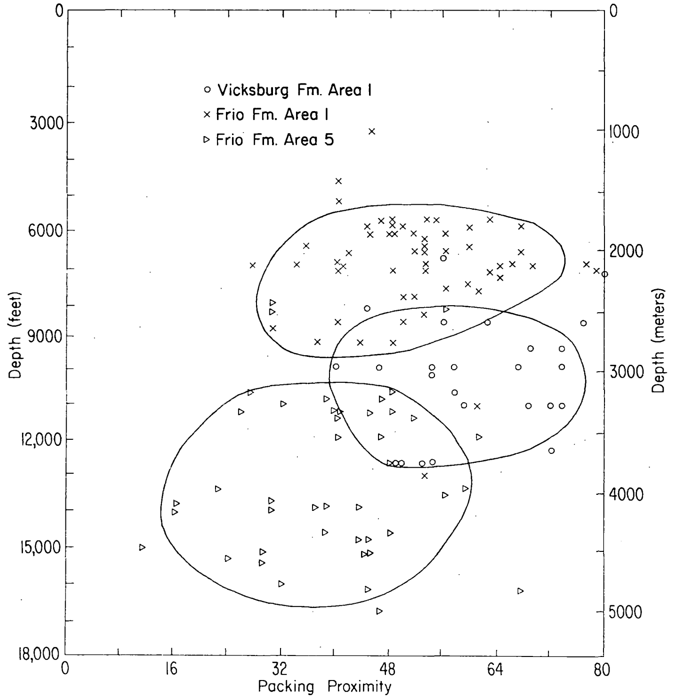


Figure 69. Packing proximity (a measure of the number of grain contacts) versus depth for Vicksburg sandstones from Area 1 and Frio sandstones from Areas 5 and 6.

reservoir quality appears to be determined by local rather than regional conditions. However, the best reservoir quality in the Wilcox Formation is found in Area 3 where the least amount of quartz overgrowths was noted. In the Frio Formation a higher percentage of quartz usually correlates with a lower percentage of unstable rock fragments and, therefore, less cementation. Locally in the Wilcox Group, more quartz usually correlates with less feldspar, and, therefore, less secondary porosity. These local differences in reservoir quality cannot be predicted by regional investigations. They are probably related to flux and composition of waters expulsed from nearby shales during shale diagenesis and compaction.

PETROPHYSICAL PARAMETERS AND DIAGENESIS

General Statement

Interval transit times for sandstones from acoustic logs (fig. 6) were plotted against depth to show the relationship between consolidation history and interval transit time. Two trends of data can be separated from the area paralleling the coast (fig. 6): 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.

At shallow depths, interval transit time in sandstones depends on porosity, rock composition, grain sorting, clay content, and overburden pressure; but at high overburden pressures, corresponding to deeper burial, only porosity and rock composition are important (Gregory, 1977). In abnormally high-pressured 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.

This phenomenon must be distinguished from increases in interval transit time owing to an increase in porosity.

Rock Consolidation History from Interval Transit Time Plots

Gardner, Gardner, and Gregory (1974) present an example of acoustic velocity versus depth for a normally pressured Louisiana Miocene sandstone sequence (fig. 70). The plot reflects low velocity characteristic of unconsolidated sediments in the shallowest strata. With increasing depth, velocity increases as a function of pressure and cementation at grain contacts. At about 2,130 m (7,000 ft) the rocks are relatively well consolidated, and velocity is inversely related to porosity. In this plot, divergence of true velocity (solid line) from velocity related to pressure (dotted line) is attributed to consolidation (fig. 70).

Interval transit time-versus-depth plots from the Texas Gulf Coast area exhibit the same compaction/consolidation curve as those of Gardner and others (1974) except for an increase in interval transit time at the top of the geopressured zone (fig. 71). The situation in the Texas Gulf Coast is more complicated, however, because the top of the geopressured zone may coincide with a zone of well-developed secondary leached porosity, causing an 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 interval transit time of sandstone versus depth (fig. 72) for Tertiary Gulf Coast sandstones shows an initial rapid decrease in interval transit time owing to compaction of unconsolidated sediments. As cementation is initiated, compaction decreases and eventually stops, and the rate of porosity loss decreases. This corresponds to an increase in slope on the interval transit time plot. At the major, post-quartz overgrowth leaching stage a reversal in the interval transit time slope occurs. Finally, if the Fe-rich carbonate cementation stage is prominent, the interval transit time curve will decrease again.

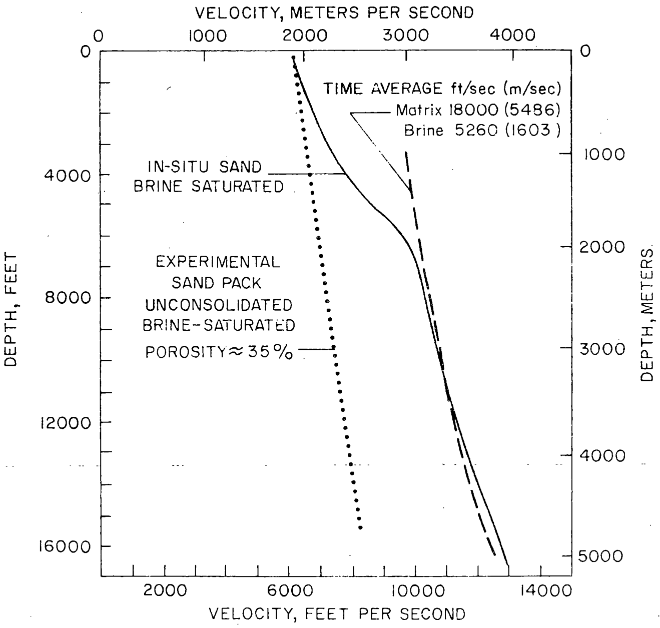


Figure 70. Velocity as a function of depth showing consolidation effect for Louisiana Tertiary sandstones. (From Gregory, 1977).

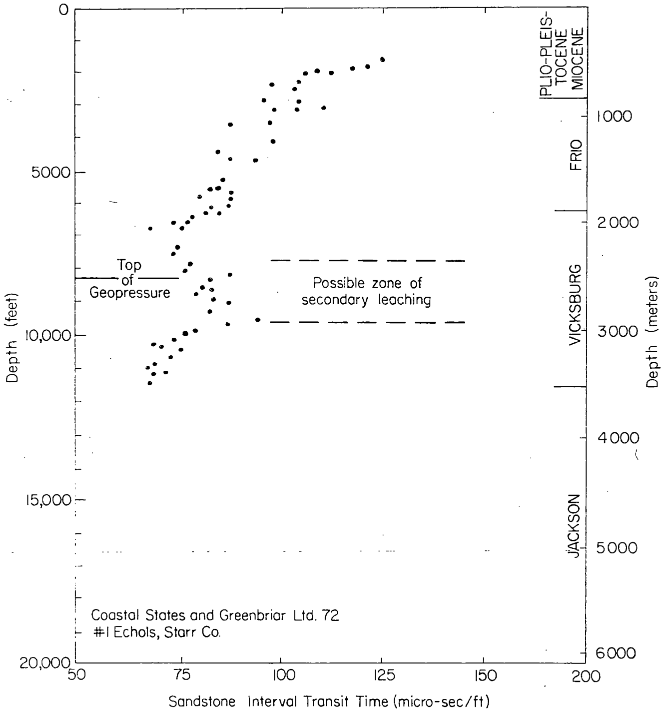


Figure 71. Sandstone interval transit time versus depth for the Coastal States and Greenbriar Ltd. 72 No. 1 Echols in Starr County. Zone of possible secondary leaching is marked.

Only a few plots of interval transit time from acoustic logs along the Texas Gulf Coast have a curve similar to the idealized plot. One of these wells is shown in figure 71. The possible zone of secondary leached porosity in this well also occurs at the top of the geopressured zone. The increase in interval transit time may be the result of both leached porosity (see Vicksburg diagenetic sequence in figure 58) and high fluid pressures. There are also slight breaks in slope in this plot 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 the basal Frio sandstones, respectively. Formational changes commonly show some effect on interval transit time (fig. 73).

Regional Variation in Rock Consolidation History

The acoustic logs used in this project were grouped by Areas 1 through 6 and further divided by updip Wilcox trend and downdip Vicksburg/Frio trend. All plots in each area for each trend were combined to produce an average or representative sandstone interval transit time-versus-depth plot (figs. 74 to 77).

Sandstones from the Vicksburg/Frio trend show progressively greater compaction and consolidation rates from Upper Texas to Lower Texas Gulf Coast (figs. 74 and 75), further substantiating conclusions based on core analyses and petrographic descriptions. Integration of sonic log-derived reservoir data greatly expands the base on which generalizations are made. These changes correspond to high reservoir quality in the Upper Texas Gulf Coast and poor reservoir quality in the Lower Texas Gulf Coast. Reservoir quality improves northward at all depths.

At a depth greater than 3,050 m (10,000 ft) interval transit time-versus-depth plots for the Wilcox Group in Areas 1, 2, 4, and 6 indicate relatively well consolidated sandstones, but similar plots for Areas 3 and 5 show a reversal toward apparent increased porosity at depth (figs. 76 and 77). Core analyses in Area 3 indicate high porosities and permeabilities deeper than 3,050 m (10,000 ft).

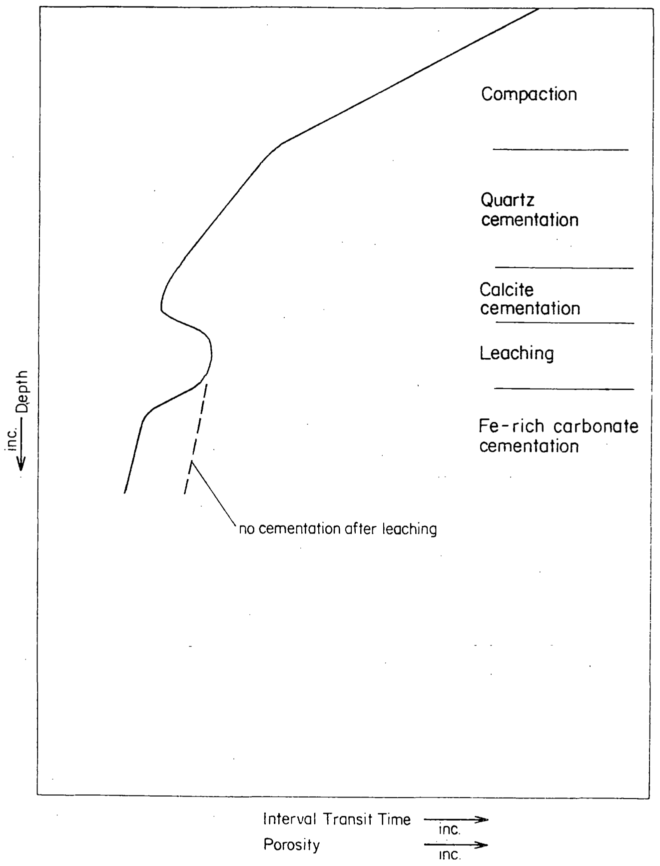


Figure 72. Idealized sandstone interval transit time plot versus depth showing possible relationship to major diagenetic stages.

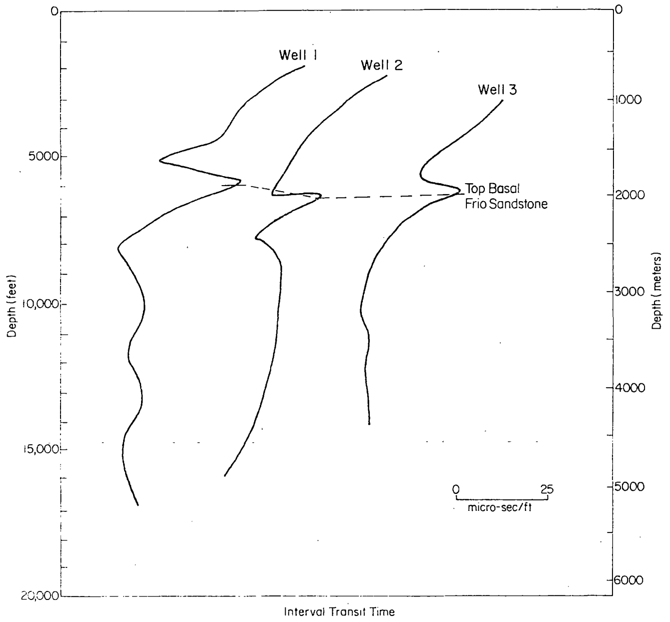


Figure 73. Sandstone interval transit time versus depth for 3 wells in Area 1 of the Vicksburg/Frio trend showing effect of formation changes.

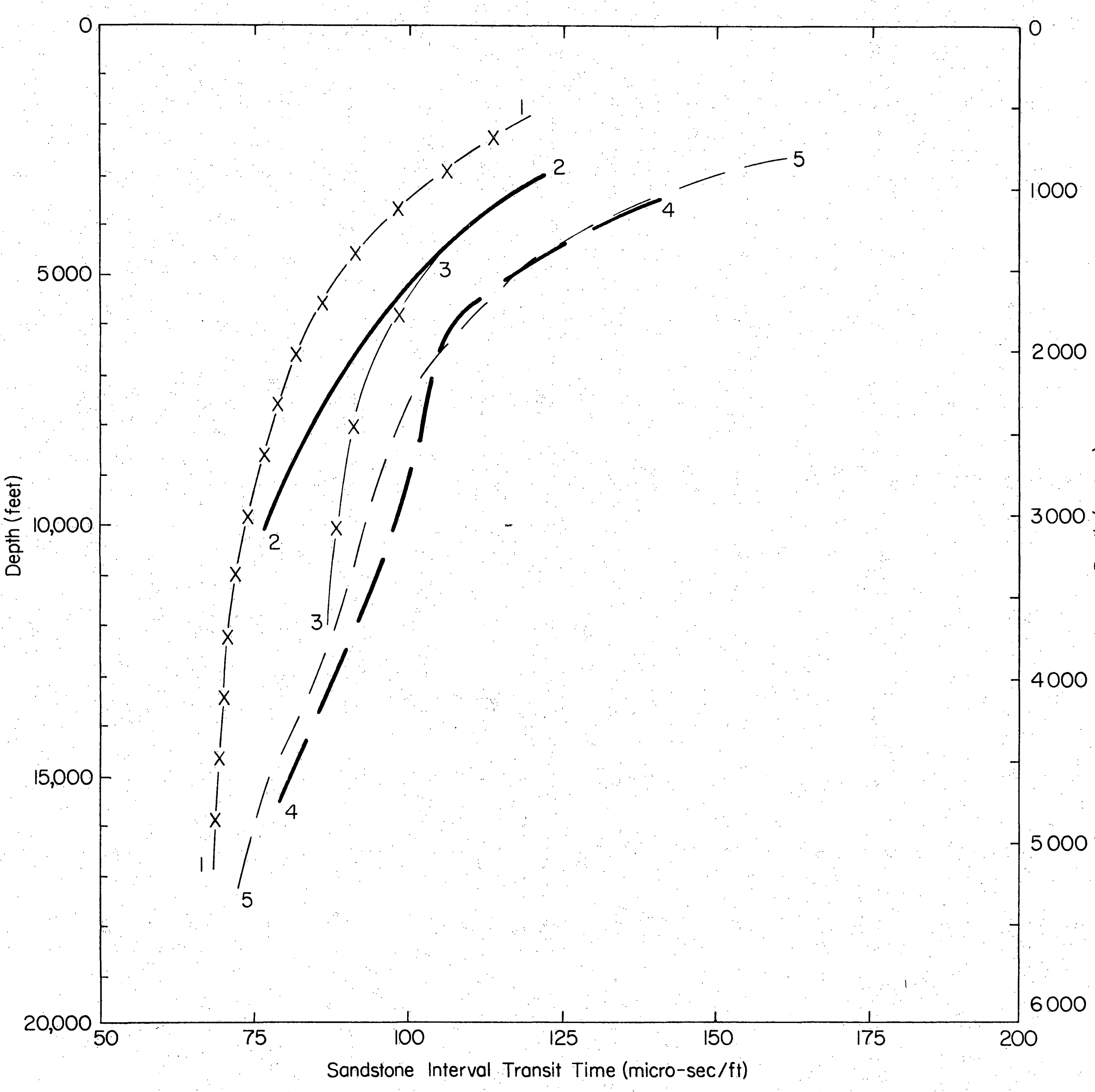


Figure 74. Sandstone interval transit time versus depth by area for the Vicksburg/Frio trend.

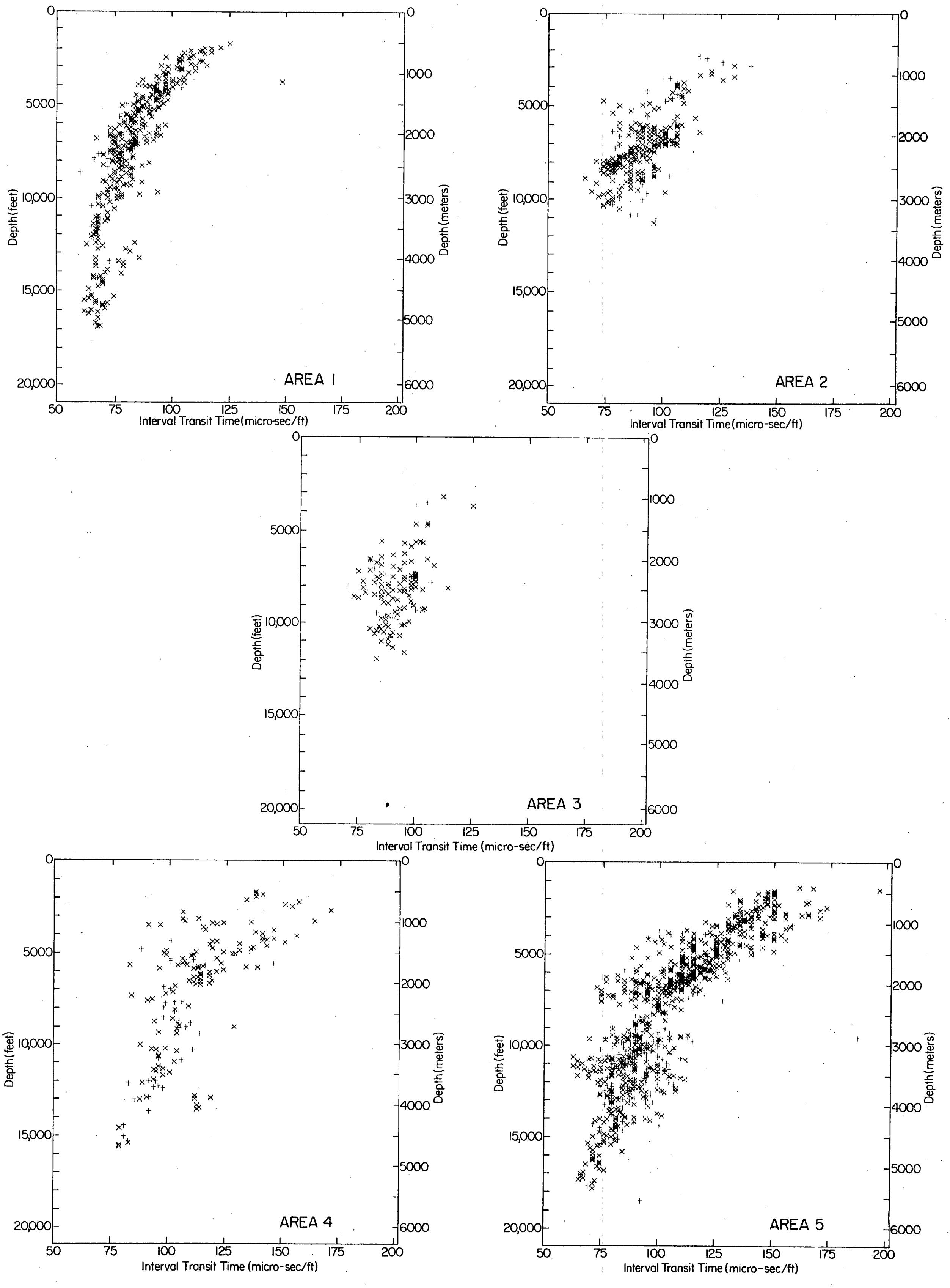


Figure 75. Basic data for Vicksburg/Frio trend sandstone interval transit time-versus-depth plot.

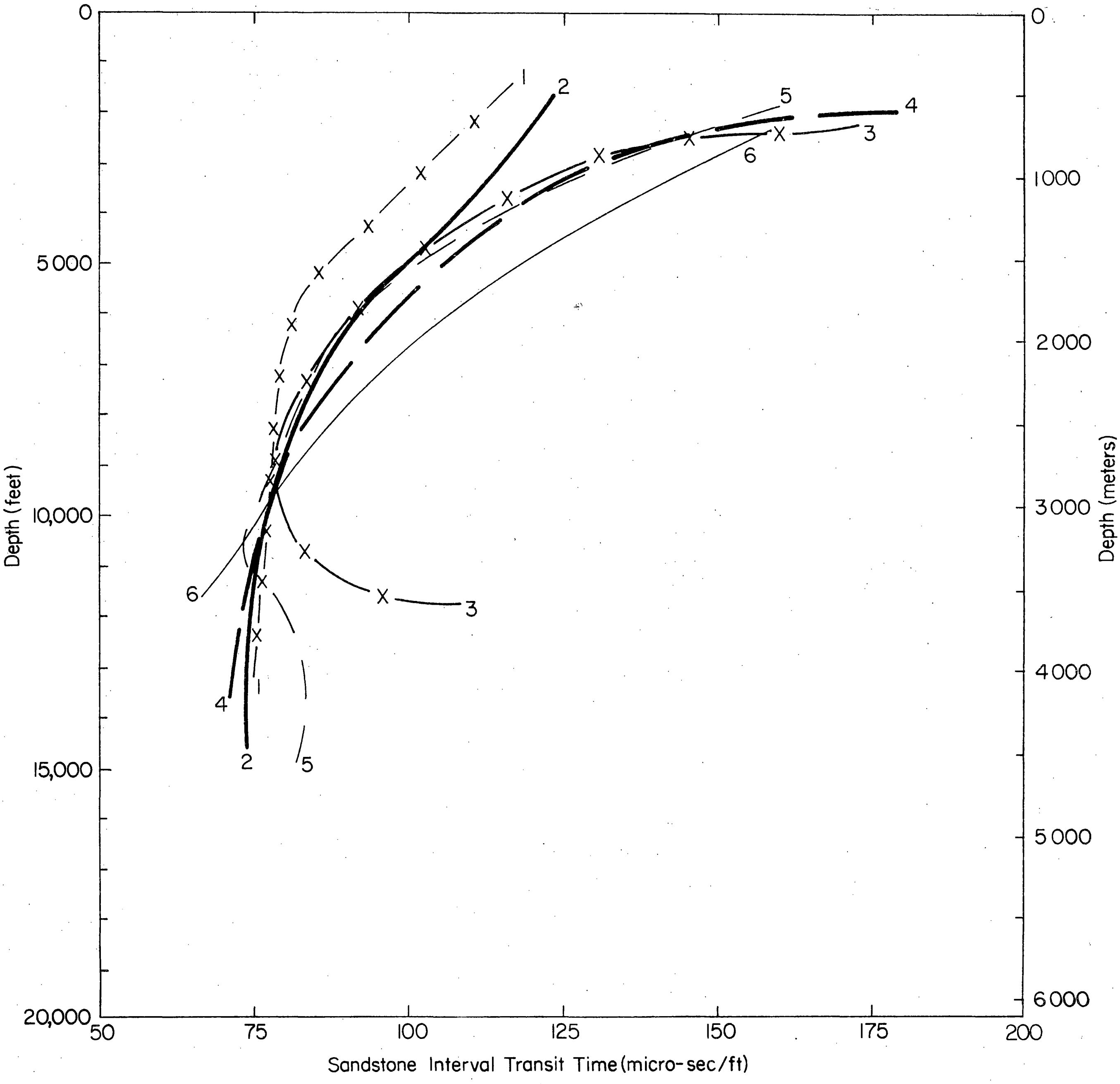


Figure 76. Sandstone interval transit time versus depth by area for the Wilcox trend.

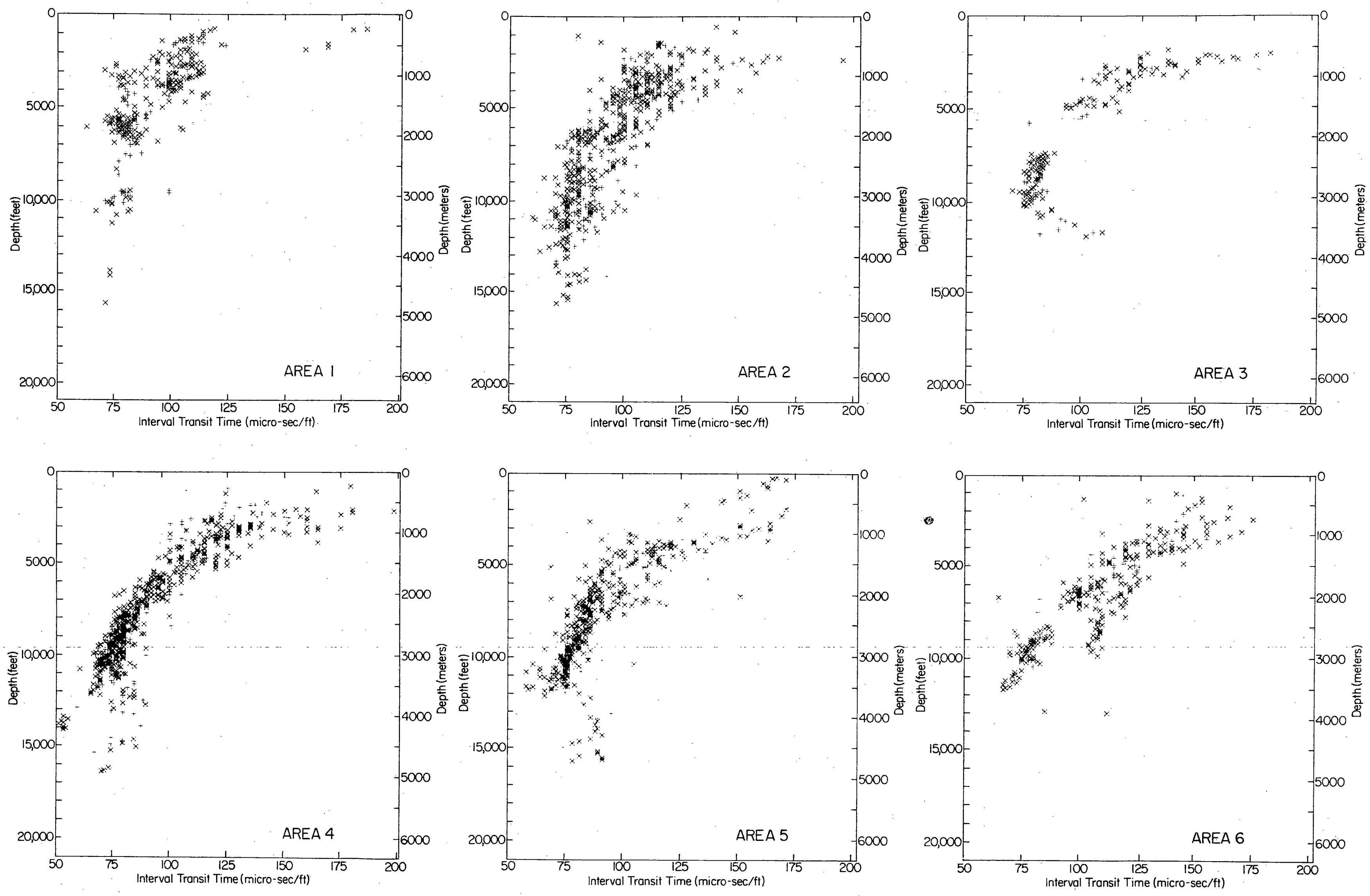


Figure 77. Basic data for Wilcox trend sandstone interval transit time-versus-depth plot.

Many of the sandstones shallower than 3,050 m (10,000 ft) in the updip Wilcox trend are younger than the Wilcox Group, and they exhibit a more rapid rate of compaction and consolidation in Lower Texas relative to Upper Texas Gulf Coast. This trend is the same for similar rocks in the downdip Vicksburg/Frio trend.

At depths shallower than 2,130 m (7,000 ft) both the Wilcox and the Vicksburg/Frio interval transit time trends are similar (figs. 74 and 76). At depths greater than 2,130 m (7,000 ft) Areas 1 and 2 of the Vicksburg/Frio trend have interval transit time curves similar to those in the Wilcox trend; all these curves correspond to low reservoir quality in the deep subsurface. Samples 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. These areas with higher interval transit time correspond to areas with highest-quality deep reservoirs. The Vicksburg/Frio trend in Area 3 has data to a depth of only 3,350 m (11,000 ft); beneath this depth, reservoir quality may be poor. In summary, the deep Vicksburg/Frio trend generally has more area of high-quality deep reservoirs suitable for geothermal geopressured exploration than the Wilcox trend.

CONCLUSIONS

Reservoir quality in sandstones deeper than the 300°F isotherm in the onshore Texas Gulf Coast lower Tertiary section is variable. Most of the sandstone reservoirs have permeabilities of less than 1 millidarcy, but in a few areas permeabilities are higher than 1,000 millidarcys.

Porosity and permeability are controlled by a complex series of diagenetic events consisting of compaction, cementation, and leaching. Many physical and chemical parameters potentially influence these diagenetic events. Each formation along the onshore Texas Gulf Coast exhibits a similar diagenetic history. Most diagenesis occurs in the hydropressured zone, but some carbonate cementation continues into the geopressured zone, as indicated by continued loss of porosity.

Primary porosity predominates in the shallow subsurface, but secondary leached porosity is dominant in the deeper subsurface. Any potential geopressured geothermal reservoir, therefore, is characterized, most importantly, by secondary porosity.

Reservoir quality trends in the lower Tertiary section along the Texas Gulf Coast are indicated by whole core analyses, sandstone interval transit times, changes in grain composition of the sandstones, and changes in intensity of diagenetic features. The potential for high-quality reservoirs to occur in the geopressured geothermal fairways is shown in figure 78. Outlines of fairways indicate areas where cumulative sandstone thickness is greater than 300 feet and the formation fluid temperatures are hotter than 300°F.

The Wilcox Group has good reservoir potential in Area 3 and possibly in adjacent parts of Areas 2 and 4. Other Areas in the Wilcox Group are marginal for development of high-quality reservoirs at depth. A few high-quality sandstones 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 is not prospective for geopressured geothermal energy because of very poor reservoir quality. Predictions of reservoir quality in other areas of the Vicksburg Formation were not made because of the lack of sandstones in the geopressured zone in these areas.

Reservoir quality in the Frio Formation increases from very poor in the southern two-thirds of Area 1 to marginal through Area 3 and 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.

These predictions about the occurrence of high-quality reservoirs at depth in the Tertiary section serve two purposes: they indicate areas where successful geopres-

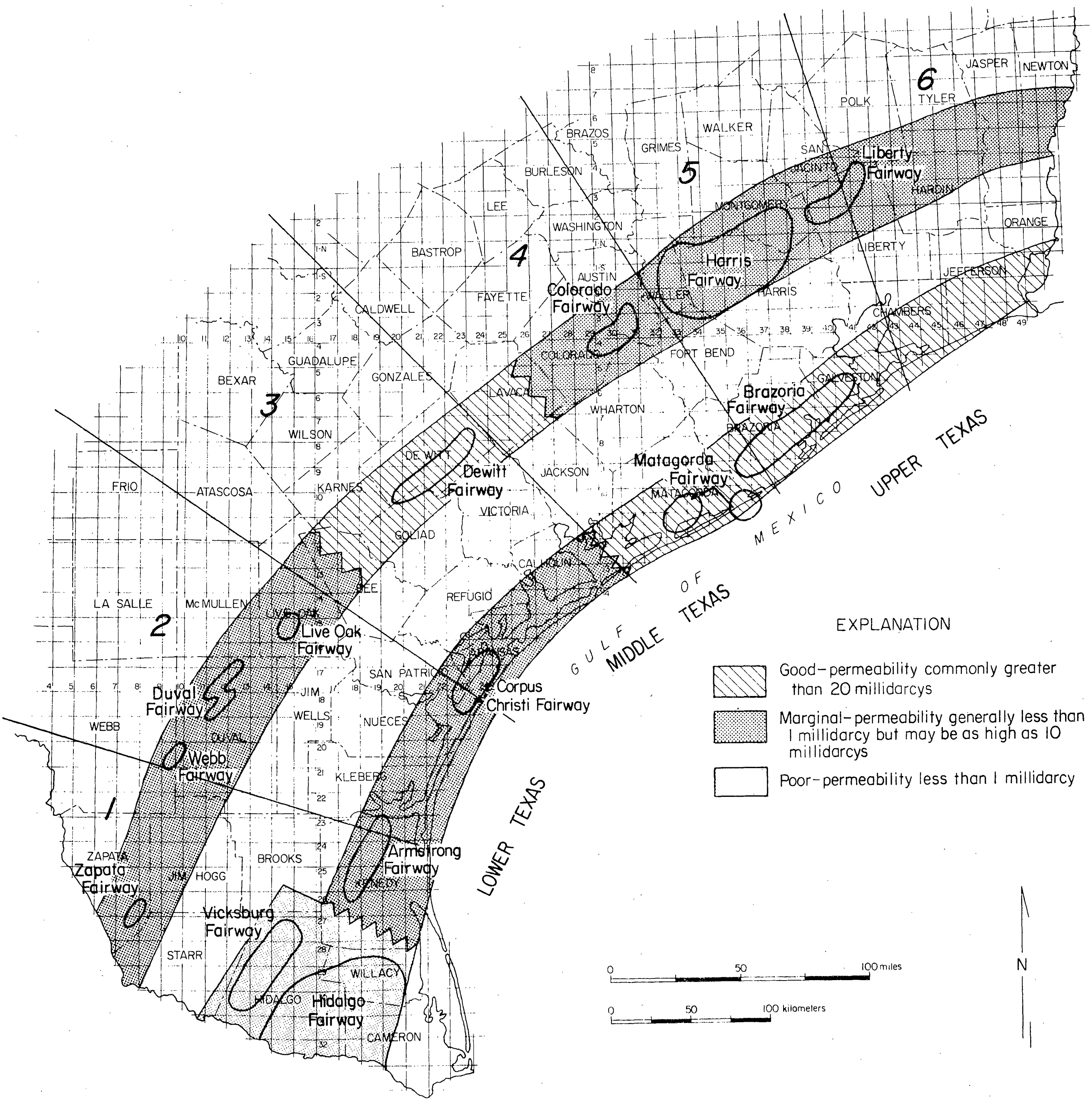


Figure 78. Potential for high-equality reservoirs suitable for the production of geopressured geothermal energy in the lower Tertiary stratigraphic section along the Texas Gulf Coast.

sured geothermal prospects are most likely, and they substantiate earlier decisions to eliminate prospects in areas that were believed to have poor potential for production of geopressured geothermal energy.

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Continental Oil Company
Core Service, Incorporated
Cox Drilling Company
Davis Oil Corporation
Dow Chemical Company, The
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Exxon Company, U.S.A.
D. D. Feldman Oil & Gas
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
W. C. McBride Silurian Oil Company
Maguire Oil Company
Miller & Fox Drilling Corporation
Mitchell Energy & Development Corporation
Mobil Oil Corporation
Mokeen Oil Company
Monsanto Company
Robert Mosbacher
Newmont Oil Company
Northern Pump Company
Oleum Incorporated
Oxy Petroleum, Incorporated
Phillips Petroleum Company
Quintana Petroleum Corporation
Rutherford Oil Corporation
Shell Oil Company
Sohio Petroleum Company
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REFERENCES

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, p. 334.

Bebout, D. G., Agagu, O. K., and Dorfman, M. H., 1975, Geothermal resources--Frio Formation, Middle Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 75-8, 43 p.

Bebout, D. G., Dorfman, M. H., and Agagu, O. K., 1975, Geothermal resources--Frio Formation, South Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 75-1, 36 p.

Bebout, D. G., Gavenda, V. J., and Gregory, A. R., 1978, Geothermal resources, Wilcox Group, Texas Gulf Coast: Geothermal Energy, U.S. Department of Energy, ORO/4891-3, 82 p.

Bebout, D. G., Loucks, R. G., Bosch, S. C., and Dorfman, M. H., 1976, Geothermal resources--Frio Formation, Upper Texas Gulf Coast: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 76-3, 47 p.

Bebout, D. G., Loucks, R. G., and Gregory, A. R., 1978, 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 91, 92 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, p. 498.

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., 1977, Petrology and diagenetic effects of graywacke sandstones: Eocene Umpqua Formation, Southwest Oregon (abs.): Rocky Mountain Section, American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, 26th Annual Meeting, Denver, Colorado, April 2-6, p. 51-52.

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, 102 p.

Fisher, W. L., and McGowen, J. H., 1967, Depositional systems in the Wilcox Group of Texas and their relationship to occurrence of oil and gas: American Association of Petroleum Geologists Bulletin, v. 53, p. 30-54.

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

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

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, p. 379-390.

Galloway, W. E., 1977, Diagenetic control of reservoir quality in arc-derived sandstones: implications for petroleum exploration (abs.): Rocky Mountain Section, American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, 26th Annual Meeting, Denver, Colorado, April 2-6, 1977, p. 47-48.

Galloway, W. E., 1977b, Catahoula Formation of the Texas Coastal Plain--depositional systems, mineralogy, structural development, ground-water flow history, and uranium distribution: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations 87, 59 p.

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.

Jonas, E. C., and McBride, E. F., 1977, Diagenesis of sandstone and shale: application to exploration for hydrocarbons: The University of Texas at Austin, Department of Geological Sciences, Continuing Education Program Publication Number 1, 165 p.

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.

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: Geological Survey Professional Paper 501, p. B152-B153.

Lindholm, R. C., and Finkelman, R. B., 1972, Calcite staining: semiquantitative determination of ferrous iron: Journal of Sedimentary Petrology, v. 42, p. 239-242.

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. 109-120.

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., Lindeman, 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 63, 122 p.

Moses, P. L., 1961, Geothermal gradients now known in greater detail: World Oil, v. 152, p. 79-82.

Murray, G. E., 1955, Midway Stage, Sabine Stage, and Wilcox Group: American Association of Petroleum Geologists Bulletin, v. 39, p. 671-96.

Ritch, H. J., and Kozik, H. G., 1971, Petrophysical study of overpressured sandstone reservoirs, Vicksburg Formation, McAllen Ranch Field, Hidalgo County, Texas: Society of Production Well Log Analysis 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: Bulletins of Canadian Petroleum Geologists, v. 25, p. 271-290.

Shell Oil Company, 1975, Stratigraphic Atlas, North and Central America: Shell Oil Company, Exploration Department, Houston, Texas.

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. 147-207.

Storm, L. W., 1945, Resume of fact and opinions on sedimentation in Gulf Coast region of Texas and Louisiana: American Association of Petroleum Geologists Bulletin, v. 29, p. 1304-35.

Stuart, C. A., 1970, Geopressures, in Proceedings of the Second Symposium on Abnormal Subsurface Pressure, Louisiana State University, Baton Rouge, Louisiana, January 1970, 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, p. 2545-2566.

Plate 1

(a) Scanning electron photomicrograph of kaolinite booklets. Frio Formation, Phillips No. 1 Houston "JJ" (4,826 m; 15,833 ft), Brazoria County, Texas.

(c) Precipitation of quartz overgrowths (1) was followed by emplacement of dead oil (2). Feldspar was replaced by kaolinite, or it was leached and kaolinite precipitated in the pore space. Fe-rich carbonate (3) precipitated in micropore spaces in the kaolinite. Wilcox Group, Pure No. 1 Vogelsang (2,975 m; 9,760 ft), Colorado County, Texas.

(e) Leaching of unstable components such as feldspar (1) and minor quartz cementation (2) resulted in significant total porosity (3) (20 percent). Wilcox Group, Area 3, Texas.

(b) Silicified volcanic rock fragment. Wilcox Group, Texas Eastern No. 2 Bruni Est. (1,790 m; 5,874 ft), Webb County, Texas.

(d) Chlorite rosette (1) has replaced kaolinite. Wilcox Group, Atlantic Refining No. C-1 Bruni (2,980 m; 9,778 ft), Webb County, Texas.

(f) Fewer unstable components such as feldspar (1) and more quartz (2) than in plate 1e resulted in less leaching and more quartz cementation (3). Total porosity is low (13 percent). Wilcox Group, Area 3, Texas.

Plate 1

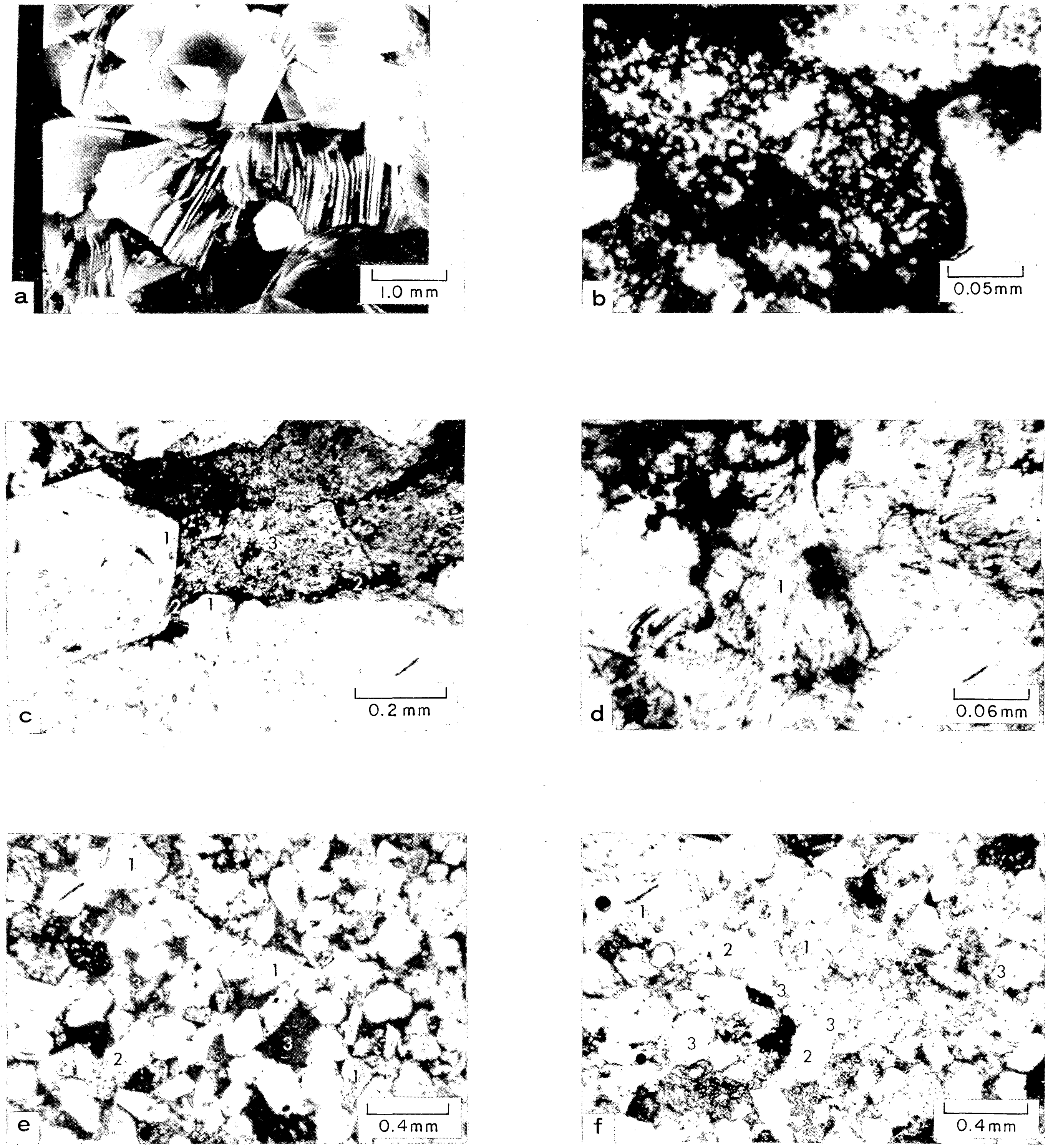
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Plate 2

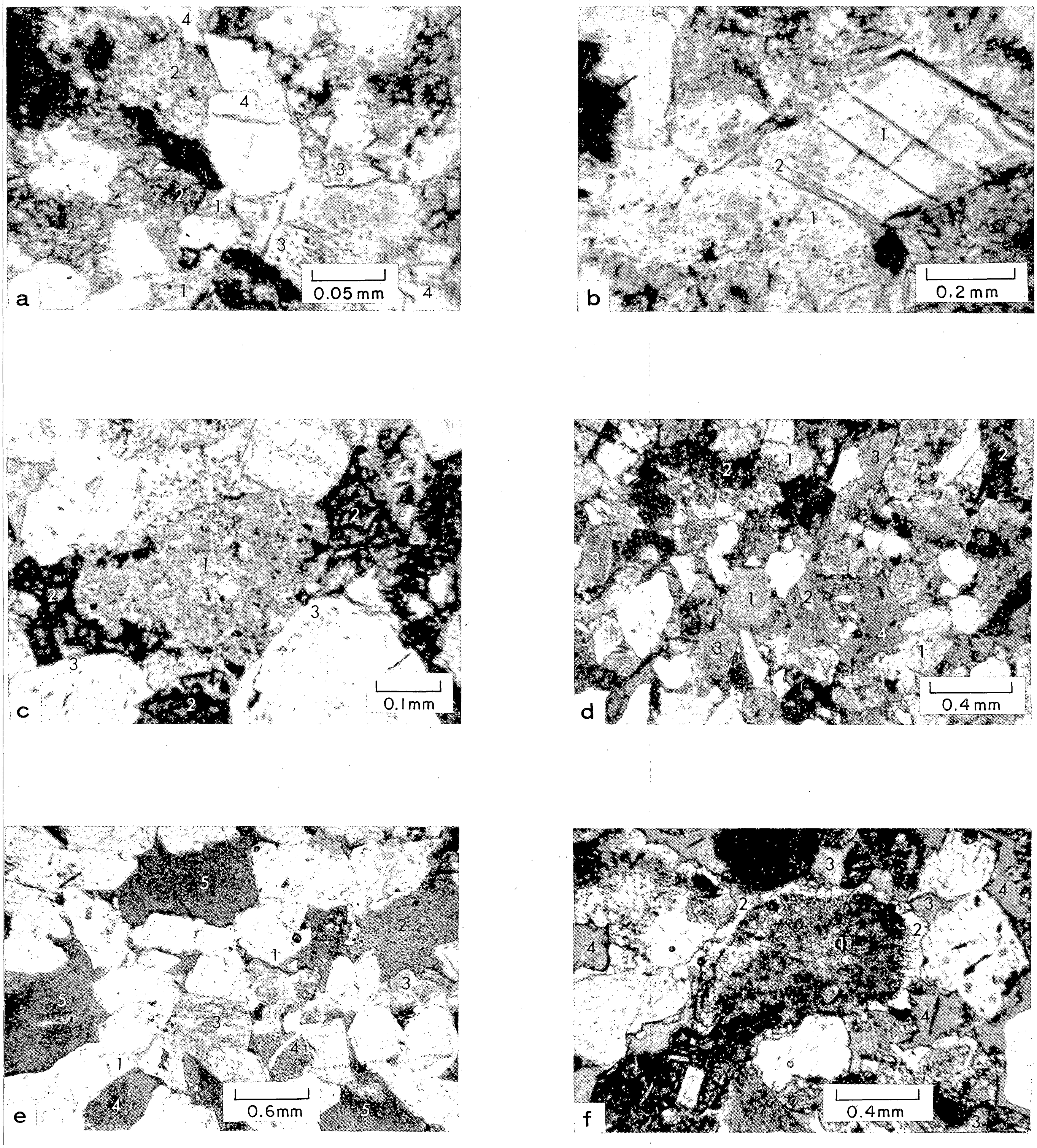
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Plate 2

(a) Vicksburg Formation sandstone. Note the high degree of compaction and low total porosity (9 percent) (1). Unstable volcanic rock fragments (2) and feldspar (3) are abundant, and carbonate cement (4) is present. Vicksburg Formation, Shell No. 6 Woods Christian (3,143 m; 10,311 ft), Hidalgo County, Texas.

(b) Zeolite cement (1), probably clinoptilolite, replaced feldspar without replacing an orthoclase overgrowth (2). Frio Formation, Shell No. B-2 Cage (2,427 m; 7,964 ft), Brooks County, Texas.

(c) Leaching of unknown grain (1) after precipitation of Fe-rich dolomite (2). Quartz overgrowths (3) are also present. Frio Formation, Phillips No. 1 Houston "GG" (4,517 m; 14,821 ft), Brazoria County, Texas.

d) Frio Formation sandstone, Area 1, showing high degree of compaction, large amount of unstable components, and low total porosity (12 percent). Feldspar (1), volcanic (2) and caliche (3) rock fragments and secondary porosity (4) are labeled. Humble No. J-3 Kenedy (4,392 m; 14,410 ft), Kenedy County, Texas.

(e) Frio Formation sandstone, Area 5, showing the small amount of unstable components and cement and abundant secondary porosity (13 percent). Quartz overgrowths (1), kaolinite cement (2), feldspar (3), volcanic rock fragments (4), and secondary porosity (5) are present. Phillips No. 1 Houston "GG" (4,539 m; 14,891 ft), Brazoria County, Texas.

(f) Caliche clast (1) acts as a nucleus for carbonate cement (2). Primary (3) and secondary (4) porosity are abundant. Frio Formation, Miller and Fox No. 6 Garcia (920 m; 3,017 ft), Jim Wells County, Texas.