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Relationship of Porosity Formation and Preservation to Sandstone Consolidation History- Gulf Coast Lower Tertiary Frio Formation

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RELATIONSHIP OF POROSITY FORMATION AND PRESERVATION TO SANDSTONE CONSOLIDATION HISTORY—GULF COAST LOWER TERTIARY FRIO FORMATION[1]

R. G. Loucks[2], D. G. Bebout[2], and W. E. Galloway[2]

ABSTRACT

Reservoir quality of lower Teritary sandstone reservoirs along the Texas Gulf Coast is controlled by sandstone depositional environment, mineralogical composition, and consolidation history (compaction, cementation, and leaching). In general, shallow reservoirs have primary porosity that is reduced by compaction and cementation, whereas deeper reservoirs result from late subsurface leaching.

Frio sandstones have the following idealized consolidation history:

Near-surface to shallow subsurface compaction and cementation stage (0 to 4,000 feet ±) starts with early feldspar leaching and replacement by calcite followed by precipitation of poikilotopic pore-filling calcite cement, clay coats and rims, feldspar overgrowths, and initial quartz overgrowths. Sand is compacted until arrested by cementation. Reservoir porosity is reduced from 40 percent to approximately 25 percent.

Moderate subsurface cementation stage (4,000 to 8,000 feet ±) consists of general precipitation of quartz overgrowths, localized welding by massive quartz overgrowths, and development of sparry pore-fill calcite cement. Porosity is commonly reduced to 10 percent.

Moderate subsurface leaching stage (8,000 to 11,000 feet ±) results in massive leaching of feldspars, volcanic and carbonate rock fragments, and calcite cements. Continued leaching may resurrect porosities to as high as 30 percent.

Deep subsurface cementation stage (>1,000 feet ±) involves reduction of leached porosity by precipitation of pore-filling kaolinite and iron-rich carbonate cements; resulting porosities depend on the amount of this late cement.

This rock consolidation history can be modified by residence time in each burial stage, thermal gradient, pore-fluid changes, and mineralogical differences. Deep Frio production, then, is not from simple primary porosity between grains, as in shallow reservoirs, but is from secondary leached porosity.

INTRODUCTION

The quality of sandstone reservoirs in the Gulf Coast lower Tertiary Frio section (Figs. 1 and 2) varies from a few percent porosity in well-cemented sandstones to as high as 40 percent in uncemented sands, and corresponding permeabilities vary from less than 0.01 millidarcy to as high as several thousand millidarcys. Reservoir quality depends on a complex relationship between the sandstone depositional environment, mineralogical composition, and consolidation history (compaction, cementation, and leaching). This report is a preliminary study of Frio sandstone consolidation history which exerts a major control on reservoir development and preservation at increasing depths of burial.

In general, shallow Frio reservoirs exhibit primary porosity that is reduced by compaction and cementation, whereas deeper reservoirs display secondary porosity resulting from moderate to deep subsurface leaching of grains and cements. It is proposed that this generalized sandstone-consolidation sequence can be applied to other lower Tertiary formations in the Gulf Coast area to predict reservoir quality.

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FACTORS CONTROLLING SANDSTONE RESERVOIR QUALITY

General

Depositional environment not only controls the initial porosity in a sand through sorting, but also controls the areal distribution and geometry of the reservoir. Superimposed on porosity variations resulting from depositional

CENOZOIC – TEXAS GULF COAST

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

FIGURE 1. Cenozoic stratigraphic chart of the Texas Gulf Coast.

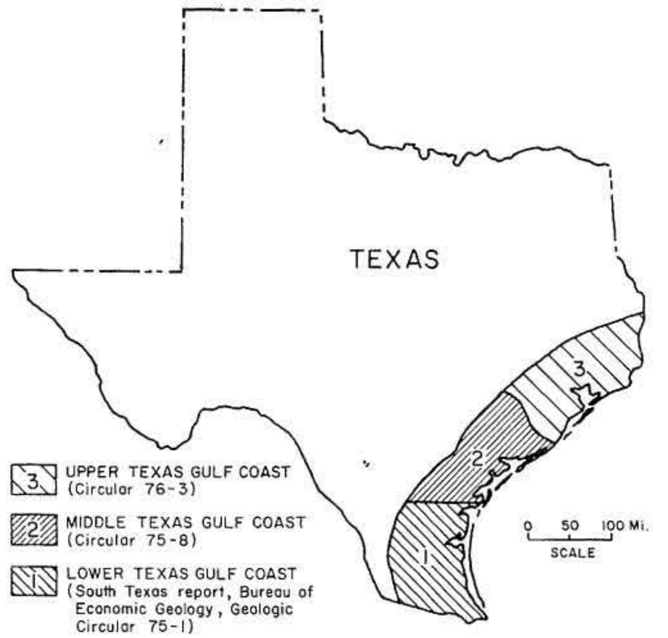

FIGURE 2. Areas of study in the Frio Formation of the Texas Gulf Coast. Circulars 75-1 (Bebout and others, 1975b), 75-8 (Bebout and others, 1975a), and 76-3 (Bebout and others, 1976) refer to regional investigation on the geothermal potential of the Frio Formation published by the Bureau of Economic Geology, The University of Texas at Austin.

environments is the structural setting, which affects the rate of subsidence and the residence time that a sand remains in a particular diagenetic state. Mineralogical composition determines the nature and rate of chemical and physical diagenesis. The relationship of depositional and structural setting, within the context of the thermal, geochemical, and pore-fluid history of the depositional basin, defines the sandstone consolidation history.

Sandstone Depositional Environment

Along the upper Texas Gulf Coast in Brazoria County, the sandstone and shale section of the *Anomalia bilateralis* sandstone interval (T5 to T6 interval of Bebout and others, 1976) was deposited as a series of depositional events consisting of high-constructive lobate deltas in an active salt-withdrawal basin (Bebout and others, in press) (Fig. 3). Reservoir quality (porosity and permeability) varies both vertically within each depositional event and also laterally from one part of the salt-withdrawal basin to another. The best Frio reservoir sandstones occur at the top of deltaic progradational facies in distributary-mouth bar and distributary-channel sandstones; poor reservoir quality characterizes the proximal delta front and distal delta front sandstones (Fig. 4).

In the area of the most rapid subsidence near the Danbury dome, the Frio sandstones were deposited in the proximal delta-front facies on the downthrown side of a large growth fault (Fig. 3). This rapid subsidence resulted in less early cementation of the sands at shallow depths, but with burial, subsequent increased compaction destroyed the potential reservoirs. Extreme loss of porosity with rapid burial of uncemented sands is well illustrated by Hsu (1977) in the Pliocene of the Ventura field in California. Probably a similar history typifies unconsolidated deltaic Pleistocene sands in the deep subsurface under the Gulf of Mexico. In the Chocolate Bayou area, on the other hand, slower subsidence of the Frio sands allowed early cementation which, in turn, prevented significant compaction; subsequent leaching resulted in formation of excellent reservoirs at depths greater than 16,000 feet. Other studies by Morris and others (1977) and Tillman and Almon (1977) have documented the role of the depositional environment in determining sandstone reservoir quality.

Sandstone Mineralogy

In defining diagenesis as related to reservoir quality, Galloway (1977a) stressed that sandstones are a mixture of discrete grains with different chemical and physical stabilities. The grains are stable in some chemical and physical environments and are unstable in others. As the grains stabilize in new diagenetic environments, the alteration products may reduce or enhance reservoir quality. Therefore, it is important to know the regional as well as the local variation in the mineralogy of a sandstone unit.

Sandstone reservoirs in the downdip Frio (9,000 feet and deeper) comprise quartz, feldspar, (plagioclase and orthoclase) and volcanic and carbonate rock fragments. The relative proportions of these rock components vary from the upper to lower Texas Gulf Coast (Fig. 5). The Frio sandstones of the upper Texas Gulf Coast contain more quartz and less feldspar and volcanic rock fragments (quartzose feldspathic volcanic litharenite and quartzose lithic arkose), and those of the lower Texas Gulf Coast are higher in volcanic rock fragments and feldspar than in quartz (feldspathic volcanic litharenite). Carbonate rock fragments are more common along the lower Texas Gulf Coast and decrease in abundance northward (Lindquist, 1976a; 1977). The Frio sandstones of the middle Texas Gulf Coast have a transitional composition between those of the lower and upper Texas Gulf Coast. This regional change in composition occurs independently of grain size (Fig. 6). The Catahoula Formation, the updip outcropping equivalent of the Frio, exhibits these same regional compositional variations (Galloway, 1977b).

Average reservoir quality increases in the deep Frio sandstones from the lower to the upper Texas Gulf Coast. The improved quality in upper Texas is attributed to fewer carbonate rock fragments and to greater mineralogical stability; this trend will be discussed in greater detail in the section concerning sandstone consolidation case histories.

Sandstone Consolidation History

The sandstone consolidation history for the downdip Frio Formation has been worked out by Lindquist (1976a, 1976b, 1977) and Bebout and others (in press). Both of these studies emphasize reservoir quality in deep Frio sandstones. The consolidation sequence and case histories elucidate where and how to search for the best sandstone reservoirs in the deep Frio, and with some modification these principles should be applicable in other lower Tertiary units.

The Frio sandstone consolidation sequence is based mainly on outcrop, shallow core (less than 100 feet) and deep core (9,000 to 17,000 feet) data; a few samples between 100 to 9,000 feet have been examined. The depth range for different diagenetic stages is only estimated, but even if the depth ranges are modified with future work, the

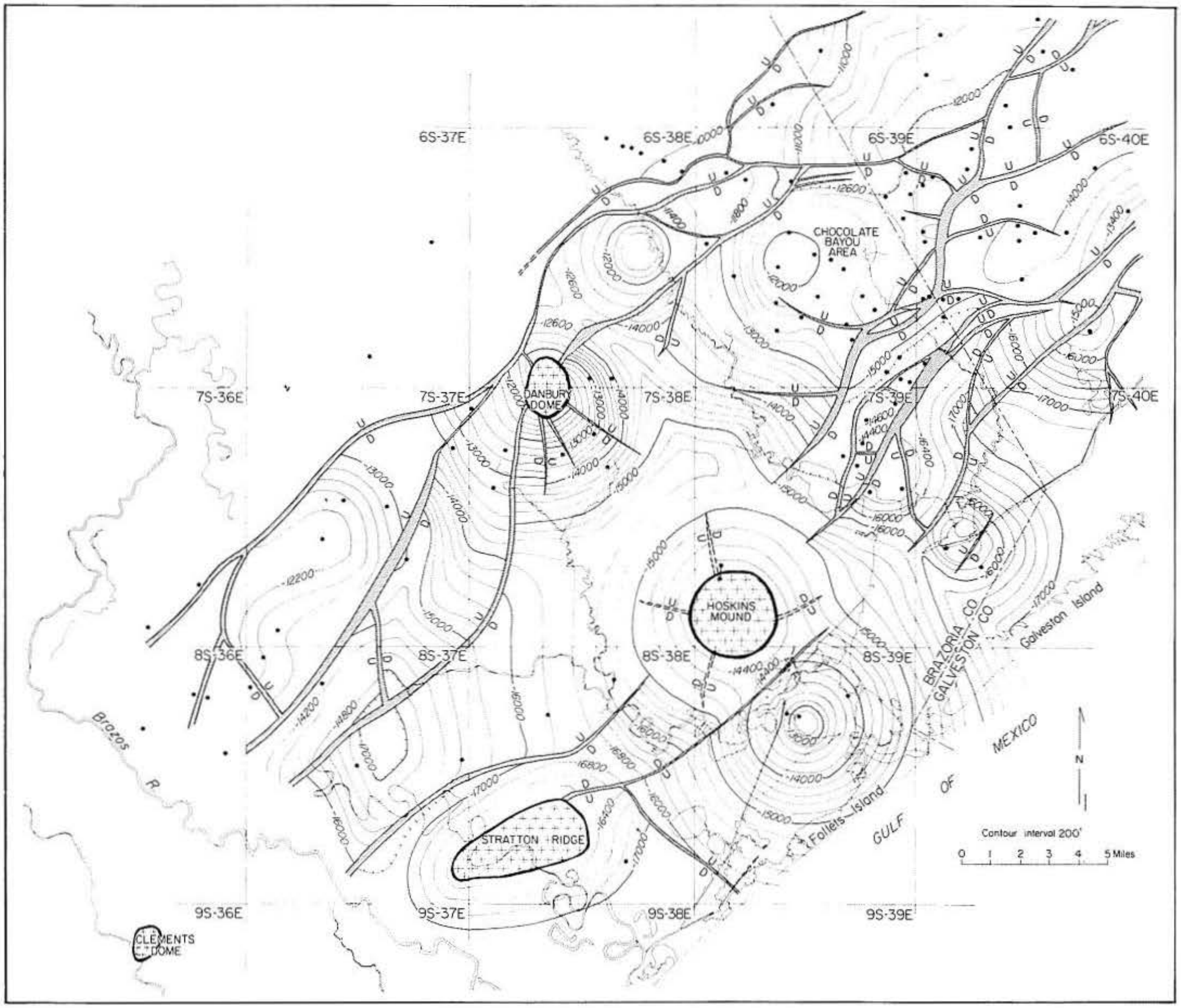

FIGURE 3. Structure map of the *Anomalia bilateralis* zone of the Frio Formation in Brazoria and Galveston Counties, Texas. A large salt-withdrawal basin is indicated by the structurally low area in the center of the map.

overall paragenetic sequence will remain the same. The basis for the paragenetic sequence and estimation of depth is given in Table 1. Other authors (Stanton and McBride, 1976; Stanton, 1977) have noted that some of the following diagenetic features occur at shallower depths in the Wilcox Formation of the Texas Gulf Coast.

Frio sandstones have the following idealized consolidation sequence (Fig. 7):

Near-surface to shallow subsurface compaction and cementation stage (0 to 4,000 feet ±) starts with early feldspar leaching and replacement by calcite (Fig. 8). This authigenic calcite is a common diagenetic feature in the paleosoil zones in the Frio outcrop (Galloway, 1977b). Also, the early precipitation of poikilotopic pore-fill calcite cement is indicated by the loose packing of enclosed grains and the lack of any other cement type around the grains (Fig. 9). Fortunately this massive pore-filling cement is a localized phenomenon and does not affect any appreciable amount of the reservoir. Clay coats (Galloway, 1974) are formed by mechanical infiltration (Fig. 10) of clay-rich waters into the porous soil zone (Burns and Ethridge, 1977), whereas the clay rims (Fig. 11) are precipitated from pore fluids during shallow burial (Galloway, 1974; Burns and Ethridge, 1977). Although clay rims occupy only a small volume of pore space, they can be detrimental to permeability by reducing pore-throat diameter (Galloway, 1977a). Feldspar overgrowths are precipitated in the shallow subsurface but are minor by volume (Fig. 12). Quartz overgrowths and clay rims tend to arrest compaction of the sandstones. Reservoir poros-

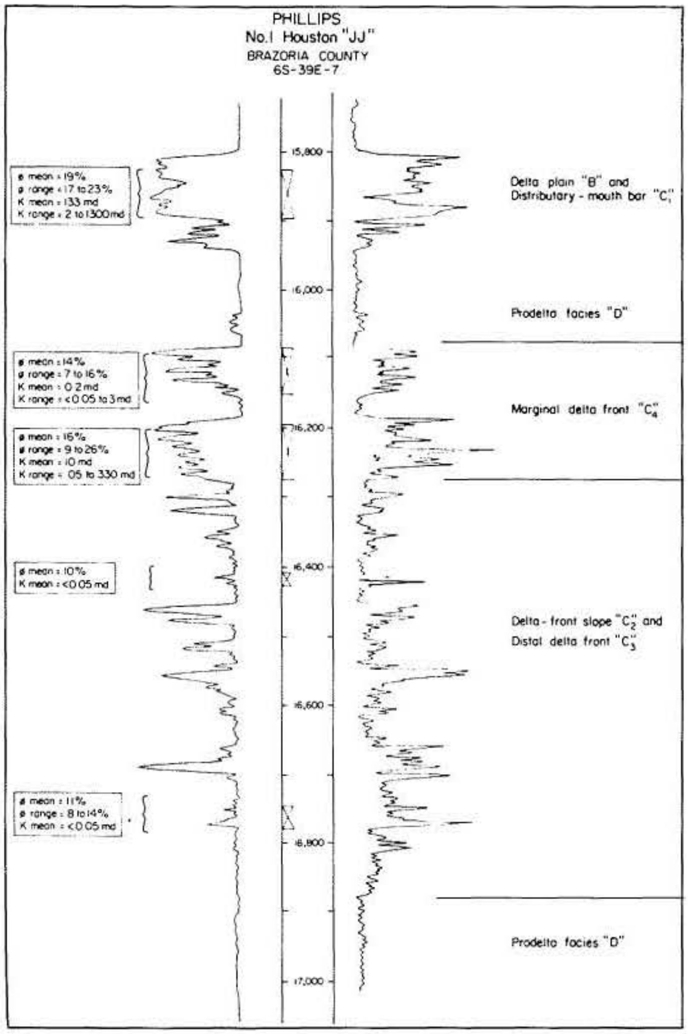

FIGURE 4. Depositional facies of high-constructive lobate delta systems interpreted from the electrical log of the Phillips No. 1 Houston "JJ." The highest porosity and permeability occurs at the top of the deltaic cycles in distributary-channel and distributary-mouth bar facies.

ity is reduced from the original 40 percent to approximately 25 percent during this near-surface to shallow subsurface consolidation stage by compaction and early cementation (Fig. 7).

Moderate subsurface cementation stage (4,000 to 8,000 feet ±) continues the precipitation of quartz overgrowths (Fig. 13). Well-developed quartz overgrowths have been identified at a depth of 5,300 feet. In areas where there was rapid compaction of sands, welding by massive quartz overgrowths occluded the pore space and destroyed any potential reservoir (Fig. 14). Following development of the quartz overgrowths is the formation of sparry pore-fill calcite cement (Fig. 15) which is extremely common during this stage of diagenesis in the lower Texas Gulf Coast Frio (Lindquist, 1976a, 1976b, 1977). Porosities are commonly reduced to 10 percent by cementation in the moderate subsurface (Fig. 7).

Moderate subsurface leaching stage (8,000 to 11,000 feet ±) results in massive leaching of feldspars (Figs. 16, 17), volcanic and carbonate rock fragments (Fig. 18), and calcite cements (Fig. 19). Some of the feldspar leaching may actually be the result of solution of the early calcite that replaced the feldspars in the soil zone (Lindquist, 1976a, 1976b, 1977). Continued leaching may resurrect porosities to as high as 30 percent (Fig. 7). This moderate subsurface stage is important for deeper reservoir development.

Deep subsurface cementation stage (11,000 feet ±) causes reduction of leached and remaining primary porosity (Figs. 16, 17) by precipitation of pore-fill kaolinite (may also be replacing feldspars) and iron-rich calcite and dolomite cements (Figs. 19, 20). The iron in the carbonates was identified by potassium ferrocynide stain. The kaolinite, composed of crystalline booklets several microns in size, forms a meshwork in the pore spaces that does not significantly reduce porosity but is detrimental to permeability. The late iron-rich carbonates commonly form single euhedral crystals (Fig. 20) or form as an outer layer on earlier iron-poor calcite cement (Fig. 19). The amount of late cementation in this deep subsurface stage determines whether reservoirs will exist at depth (Fig. 7).

This sandstone consolidation sequence can be modified by residence time in each burial state, thermal gradient, changes in pore-fluid chemistry, and mineralogical differences. Comprehensive discussions of probable pore-fluid history in the Frio sandstones are given by Galloway (1977b) for the shallow subsurface and by Lindquist (1976a, 1977) for the deeper subsurface. Criteria for recognition of sandstone consolidation stages relative to the zone of secondary leached porosity are presented in Table 2.

FRIO SANDSTONE CONSOLIDATION CASE HISTORIES

The reservoir quality of Frio sandstones vary regionally. Along the lower Texas Gulf Coast (Fig. 2) permeability in sandstone cores deeper than 13,000 feet averages 1 to 2 millidarcys; Lindquist (1976a, 1976b, 1977) concluded that most of the deep reservoirs are cemented with late-forming kaolinite and iron-rich calcite and dolomite. To the northeast along the upper Texas Gulf Coast (Fig. 2), however, permeability in deep Frio sandstones ranges up to hundreds of millidarcys. This higher permeability is interpreted as the result of less well-developed late carbonate cementation. Compositional variation is believed to be one of the major factors controlling late carbonate precipitation and consequent reservoir quality of the Frio sandstones. Abundant carbonate rock fragments along the lower Texas Gulf Coast probably provided nuclei for the late carbonate cement that destroyed much of the porosity of these sandstones, whereas this type of cement is less well developed to the northeast along the upper Texas Gulf Coast where carbonate rock fragments are rare. This relationship is supported by a positive correlation between carbonate rock fragments and carbonate cement.

Preliminary diagenetic studies of the Frio in the area of Chocolate Bayou field and Danbury dome in Brazoria County, Texas (Fig. 2) by Bebout and others (in press) and a detailed diagenetic study of the lower Texas Gulf Coast Frio by Lindquist (1976a, 1976b, 1977) show a range of variations in diagenesis of the sandstones (Fig. 6), induced by regional and local variations in mineralogy, depositional environment, thermal history, and pore-fluid chemistry.

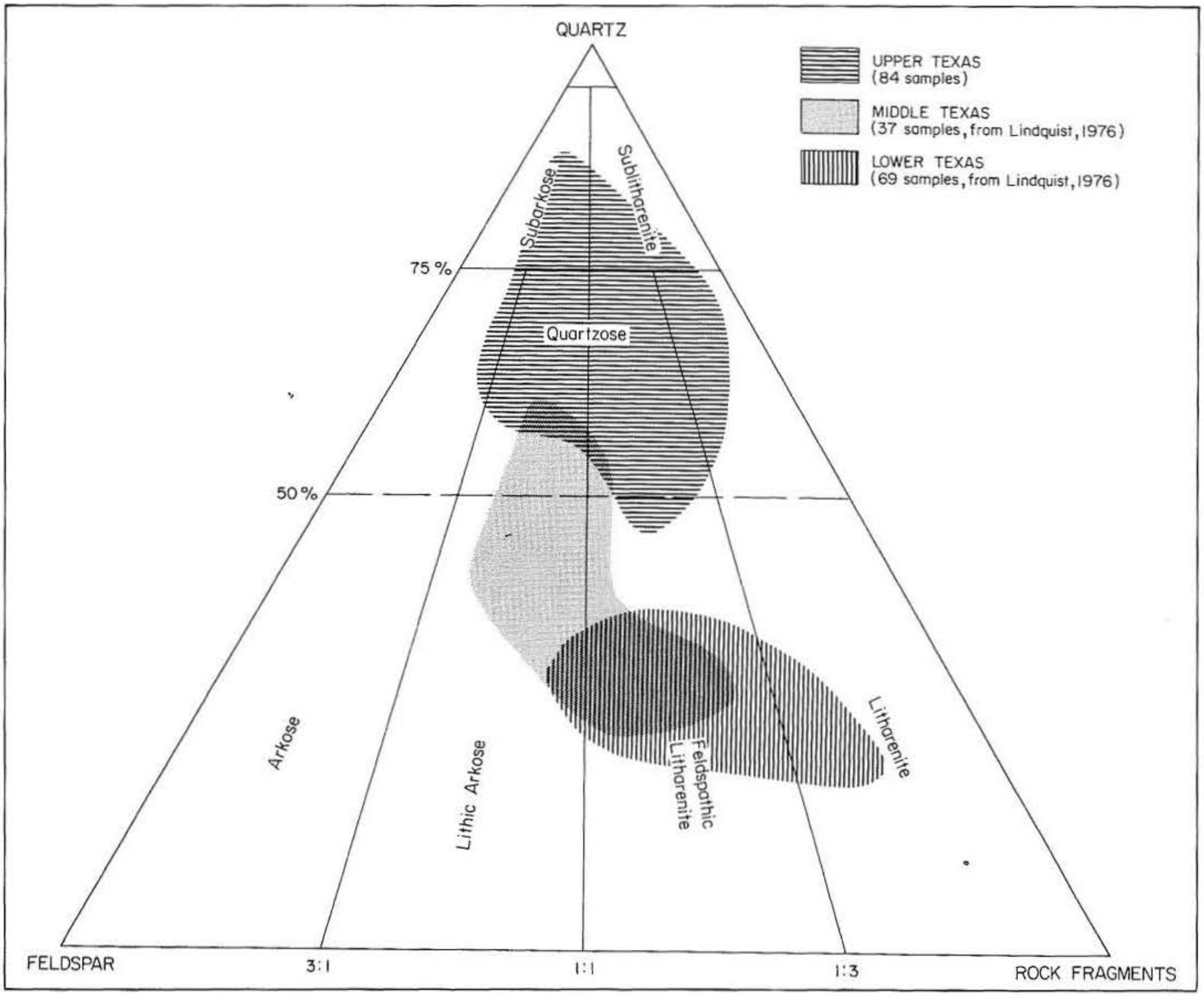

FIGURE 5. Sandstone composition of the Frio Formation along the Texas Gulf Coast. Sandstone classification after Folk, 1968.

Case I: Chocolate Bayou field area (Fig. 7). In the shallow and intermediate subsurface to a depth of approximately 9,000 feet, normal compaction and systematic early stages of cementation reduced porosity to less than 15 percent. At depths of 9,000 to 11,000 feet, the leaching stage increased porosity up to 30 percent. Much of the secondary porosity was preserved at greater depths but some kaolinite and iron-rich carbonate cements were deposited, reducing the average porosity to 25 percent or less.

Case II: Danbury dome area (Fig. 7). Early rapid subsidence in a salt-withdrawal basin prevented early stage cementation and resulted in greater-than-normal mechanical compaction. During the later stages of compaction at intermediate depths massive quartz cementation further reduced porosity to less than 10 percent (Fig. 14). The massive quartz cementation probably hindered the development of secondary porosity at greater depths. The final result is the lack of porous reservoirs in these overcompacted and cemented sandstones.

Case III: Lower Texas Gulf Coast (Fig. 7). Normal compaction and abundant early sparry calcite cementation formed in the intermediate depth zone and resulted in the reduction of porosity to less than 10 percent. In contrast to the less soluble quartz cement of the Danbury dome area, the comparatively abundant sparry calcite cement was leached and up to 30-percent porosity produced. Following this leaching stage kaolinite and iron-rich carbonate and zeolite (analcime) cements drastically reduced porosity to less than 15 percent.

These case histories indicate that variations in the consolidation sequences of sandstones from different areas along the Texas Gulf Coast ultimately produce a wide range of reservoir quality.

DIAGENETIC FEATURE	BASIS FOR PARAGENETIC SEQUENCE (RELATIVE TIMING)	BASIS FOR DEPTH ESTIMATION
Feldspar leaching and replacement by calcite (Fig. 8)	Common feature in paleosoils of the Catahoula Formation (Frio equivalent) (Galloway, 1977b). Feldspar overgrowths in leached voids of feldspars reveal early leaching.	Soil feature at or near surface.
Poikilotopic calcite cement (Fig. 9)	Lack of any other cements indicates very early "diagenetic freezing"; porosity was totally occluded before any other cementation stage took place. Immediately adjacent to poikilotopic calcite cement are sandstones that contain several cement types and the grains are normally compacted.	Evidence of early cementation and loose packing places this cement as a soil or very shallow subsurface feature.
Clay coats (Fig. 10)	Common feature in paleosoils of the Catahoula Formation (Galloway, 1977b). Also overlain by quartz overgrowths.	Soil feature at or near surface.
Clay rims (Fig. 11)	Quartz overgrowths are absent where chlorite clay rims are thick; similar situation as described by Tillman and Almon (1977).	Occur before quartz. Galloway (1974) documented their formation between 1,000 to 5,000 feet in sandstones of similar composition.
Feldspar overgrowths (Fig. 12)	Euhedral against quartz overgrowths which indicates they formed before quartz.	Occur before quartz.
Quartz overgrowths (Figs. 13 and 14)	Overlie clay coats, absent around clay rims, anhedral against feldspar overgrowths and absent where poikilotopic calcite is present. Euhedral against sparry calcite, kaolinite, and iron-rich carbonate cements. Also leached-grain embayments into the quartz overgrowth indicates leaching occurred after quartz cementation (Fig. 18A).	Galloway (1974), for sandstones of similar composition, found quartz overgrowths to start between 2,000 to 4,000 feet. Selected samples of Frio sandstones indicated no overgrowths at 2,500 feet and well-developed overgrowths at 5,300 feet.
Sparry calcite cement (Fig. 15)	Anhedral against quartz and feldspar overgrowths. Underwent dissolution during moderate subsurface leaching stage.	Timing relative to quartz and feldspar overgrowths and to leaching puts this cement later. Lindquist (1976a) noted sparry calcite to be well developed at depths of 8,000 ft.
Leaching of feldspars, volcanic rock fragments, and calcite (Figs. 16, 17, 18)	Leaching of calcite cement that replaced feldspars in soil zone and also leaching of sparry calcite cement. Leached feldspars, volcanic rock fragments, and leached-grain embayments in quartz overgrowths filled by kaolinite and iron-rich carbonate cements.	Lindquist (1976a) noted leaching starting around 8,500 feet. Also, if fluids released by the transformation of montmorillonite to illite caused the leaching, this approximates the leaching stage at around 8,000 to 9,000 feet.
Kaolinite cement, and feldspar replacement by kaolinite (Figs. 16, 17)	Replaces feldspars and fills leached porosity in feldspar, primary pore space, and resurrected primary pore space (previously filled with sparry calcite). Anhedral against quartz and fills leached-grain embayments in quartz overgrowths.	Occurs after leaching. In South Texas, kaolinite cementation begins around 10,000 feet.
Iron-rich calcite and dolomite cements (Figs. 19, 20)	Filled leached porosity. Also, pore fluids that leached the earlier calcites had to be acidic whereas pore fluids that deposited late iron-rich carbonate cements had to be basic; therefore, a period of time had to elapse while pore-fluid chemistry changed.	Occurs after leaching and after kaolinite cementation because, according to Lindquist (1976a), kaolinite is stable at a lower pH than carbonates.

* See Galloway (1974), Lindquist (1976a, 1977), Peterson (1977), and Stanton (1977), for similar sandstone consolidation sequences.

TABLE 1. Evidence for delineating paragenetic sequence and estimating depth of occurrence.*

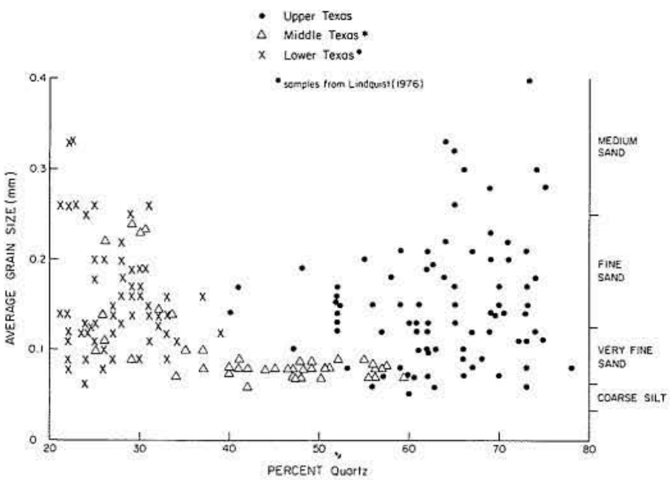

FIGURE 6. Relationship of percent quartz to average grain size between lower, middle and upper Texas Gulf Coast.

APPLICATIONS

General

The recognition of the consolidation sequence in a sandstone has direct application to exploration for both hydrocarbon and geopressured geothermal reservoirs. The applications are in predicting reservoir quality, both areally and with depth of burial, and in gaining insight into the relationship between timing and depth of the development of reservoir porosity to that of the generation of hydrocarbons.

Prediction of Reservoir Quality

In searching for potential geothermal reservoirs in the Frio Formation along the Texas Gulf Coast, Bebout and others (in press) found that there is considerable variation in reservoir quality. Their study used the sandstone consolidation history of the Frio Formation to explain the distribution of deep, high-quality reservoirs that have permeability greater than 20 millidarcys, which approximately corresponds to 20-percent porosity, and fluid temperatures greater than 300° F.

For example, along the lower Texas Gulf Coast porosity dropped below 20 percent, and permeability dropped to less than 1 millidarcy before the depth was reached where fluid temperatures are over 300° F (Fig. 7). Late kaolinite and iron-rich carbonate cements destroyed the potential reservoirs. From knowledge of both the mineralogy of this area (Fig. 5) and the sandstone consolidation history (Fig. 7), the prediction can be made that reservoir quality necessary for geopressured-geothermal prospects are unlikely to be found along the lower Texas Gulf Coast. Because of the similar mineralogy in the middle Texas Gulf Coast (Fig. 5), the same predictions of poor reservoir quality at depths greater than 13,500 feet can be made.

In the upper Texas Gulf Coast, however, mineralogy of the sandstones is more stable chemically than that of the sandstones in the lower and middle Texas Gulf Coast, and the sandstones lack carbonate rock fragments (Fig. 5). The rock consolidation history in the upper Texas Gulf Coast indicates that high-quality reservoirs exist at depth in the right structural setting. Good-quality reservoirs with porosities higher than 20 percent and fluid temperatures above 300° F exist below 13,500 feet in the Chocolate Bayou field area where compaction was normal because of initial slow subsidence and early cementation (Fig. 7). The lack of carbonate rock fragments to act as nuclei and the generally more stable quartz-rich mineral assemblage in the upper Texas Gulf Coast inhibited the formation of late carbonate cements. However, in areas of rapid subsidence, such as in the salt-withdrawal basin near the Danbury dome (Fig. 3), there was minor early cementation and the sediments were overcompacted. The compaction was finally arrested by massive quartz welding which results in poor-quality reservoirs below 13,500 feet. Poor-quality reservoirs are assumed to exist throughout the center of the salt-withdrawal basin.

As these case histories indicate, an analysis of sandstone consolidation provides a reliable estimate of reservoir distribution. This analysis can be accomplished through the study of a few wells in the area and by application of the sandstone consolidation sequence as outlined in this paper.

Relationship between Secondary Leached Porosity and the Generation of Hydrocarbons

The zone of well-developed secondary leached porosity occurs at depths and ambient temperatures that place it well within the liquid window of hydrocarbon generation and preservation (Fig. 7) as defined by Pusey (1973.) The liquid window encompasses the temperature/depth range within which major oil fields occur, unless there is significant vertical or lateral migration or post-accumulation changes in the thermal regime. The liquid window characteristically brackets oil production in Tertiary basins such as the Gulf Coast. The window, which extends from 150° F to 300° F, includes the minimal temperature (150° F) for generation of petroleum from source kerogen and the maximum temperature (300° F) of liquid preservation (LaPlante, 1972; Pusey, 1973). At temperatures above 300°F, only dry gas or gas with minor liquids are typically found (Klemme, 1972).

The high porosity produced by secondary leaching within a similar depth range as the liquid window suggests that most oil and essentially all deep gas and gas-plus-condensate production from the Frio is mainly from secondary porosity (Fig. 21). The most productive reservoirs should lie within the relatively narrow zone of maximum leached-porosity development, particularly in the lower Texas Gulf Coast Frio where porosities are enhanced by as much as 10 percent (Fig. 7). Productivity of deep Frio reservoirs that have experienced significant secondary porosity development and preservation (cases I and III; fig. 7), should be appreciably better than that of equivalent unleached sections. In fact, development and preservation of leached porosity must be a primary determinant of production economics. The ability to predict the occurrence and magnitude of leached porosity should be useful for efficient exploration for any production from lower Tertiary reservoirs in the deep subsurface.

CONCLUSIONS

Knowledge of the sandstone consolidation history is an important tool in predicting both areal and vertical reservoir quality. Also the realization that shallow reservoirs consist of primary porosity and that deep reservoirs are mainly composed of secondary leached porosity aids in

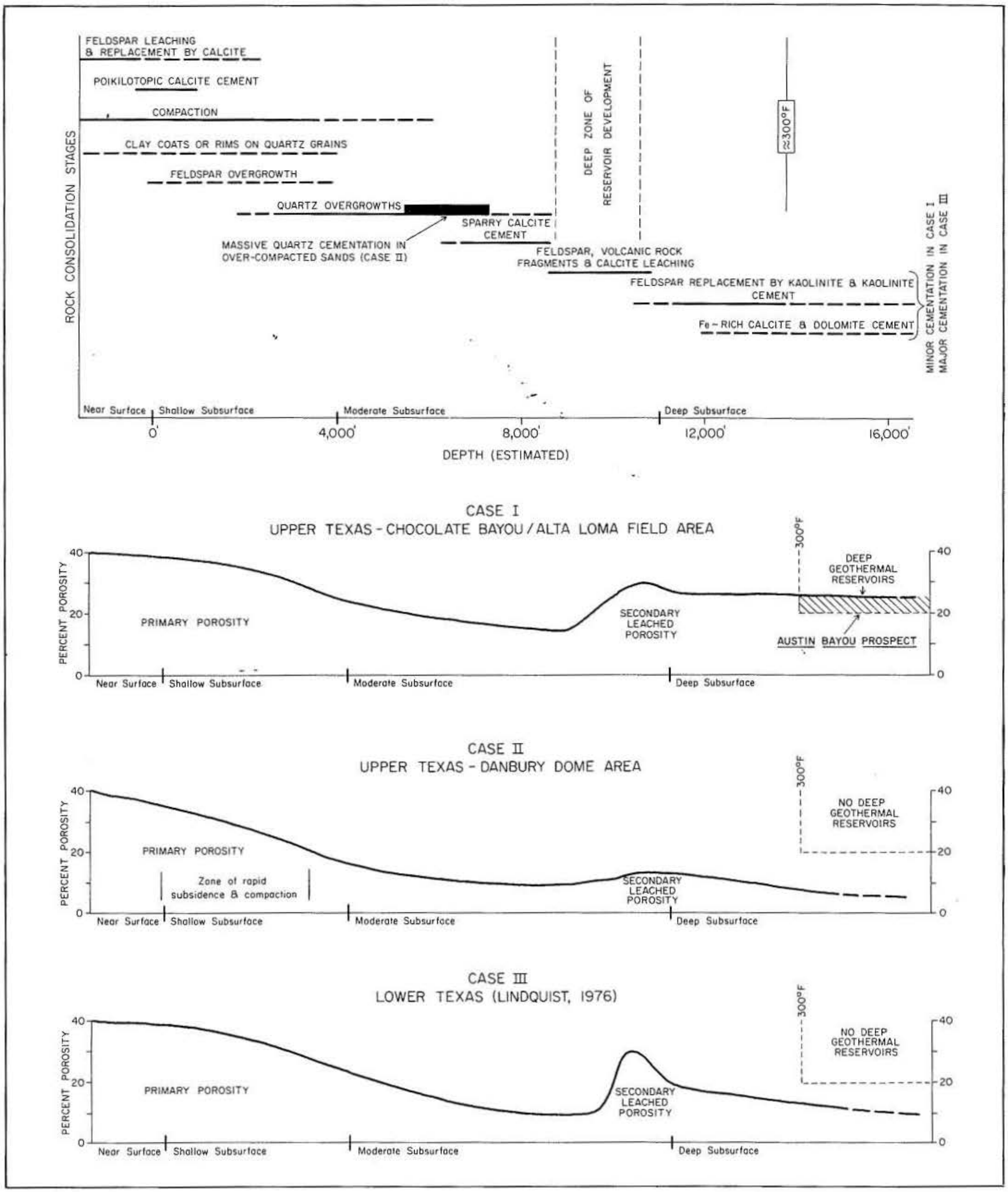

FIGURE 7. Rock consolidation stages with increasing depth and case histories of consolidation in the Chocolate Bayou/Alta Loma field areas, Danbury dome area, and lower Texas area.

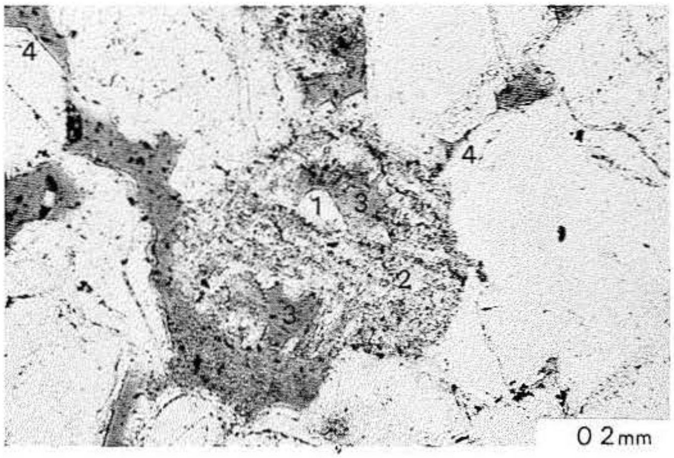

FIGURE 8. Authigenetic feldspar overgrowths (1) inside a leached feldspar grain (2) indicate that leaching occurred in the paleosoil horizon or in the shallow subsurface. Much of the porosity is secondary (3) quartz overgrowths (4) filled in most of the primary porosity. Frio Formation, Phillips No. 1 Houston "JJ" (15,869 feet), Brazoria, County, Texas.

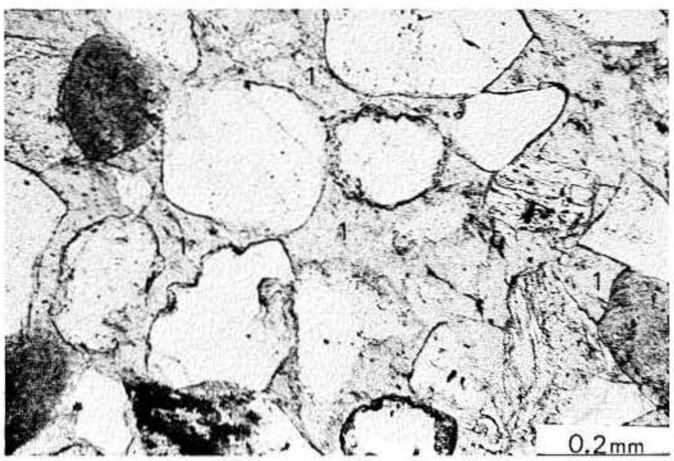

FIGURE 9. Poikilotopic calcite cement (1) formed early as indicated by loose packing of grains and absence of any other cements around grains. Frio Formation, Phillips No. 1 Gunderson (12,236 feet), Brazoria County, Texas.

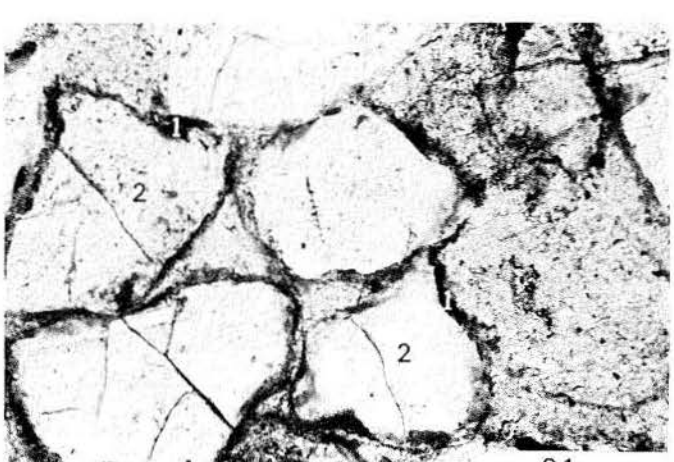

FIGURE 10. Montmorillonite clay coats (1) around quartz grains (2) Frio Formation, Exxon No. 152-A Galveston Bay St. (10,066), Galveston County, Texas.

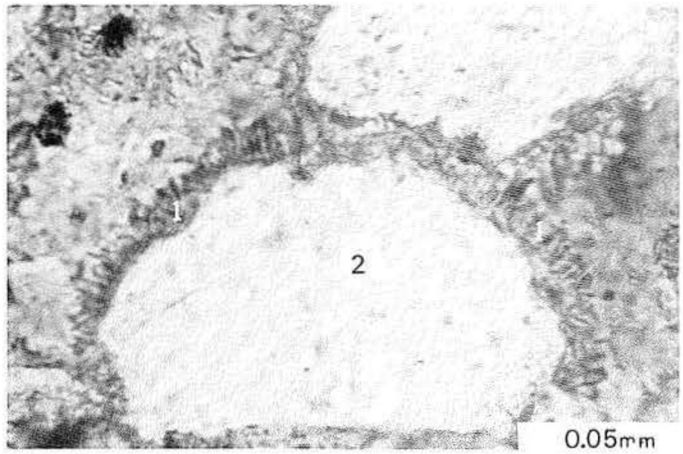

FIGURE 11. Chlorite clay rims (1) around quartz grains (2). Thick rims inhibited quartz overgrowths. Frio Formation, Exxon No. 152-A Galveston Bay St. (10,066), Galveston County, Texas.

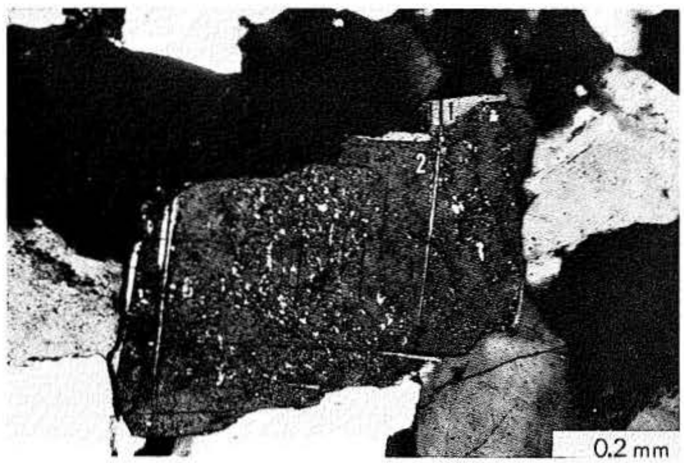

FIGURE 12. Authigenetic feldspar overgrowth (1) on plagioclase grain (2). Light specks in plagioclase grain are areas of calcite replacement. Crossed nicols. Frio Formation, Humble No. 1 Skrabanek (17,030-60 feet), Brazoria County, Texas.

understanding variations in reservoir quality throughout a section.

The sandstone consolidation sequence outlined in this paper should be recognizable throughout the Gulf Coast lower Tertiary section. The diagenetic processes are not unique to one area but are general in scope. Nevertheless, the processes can be modified by residence time in each diagenetic stage, thermal gradient, pore-fluid changes, and mineralogical differences which result in a wide range of reservoir quality.

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We would like to thank M. G. Moseley for an excellent job of point-counting thin sections used in this study and for helpful comments. Also thanks to W. R. Kaiser of the Bureau of Economic Geology who reviewed the draft of

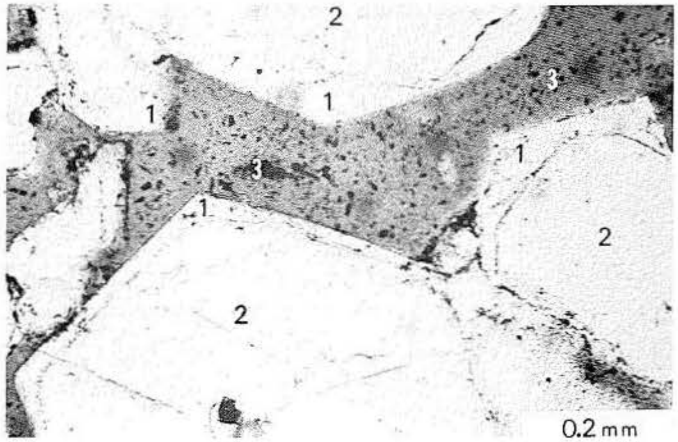

FIGURE 13. Euhedral quartz overgrowths (1) on quartz grains (2) projecting into a primary pore space (3). Frio Formation, Phillips No. 1 Houston "JJ" (15,869 feet), Brazoria County, Texas.

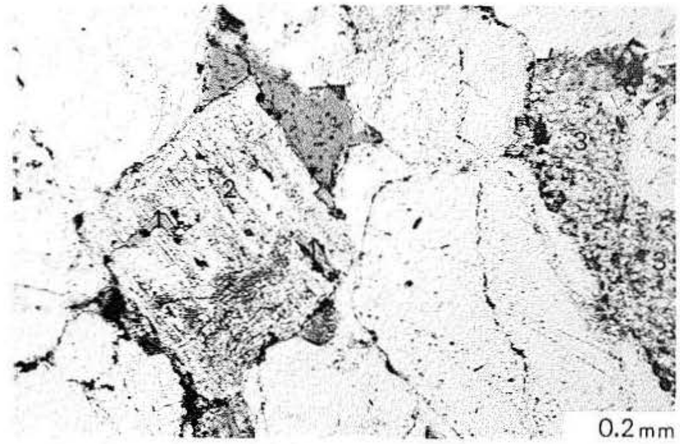

FIGURE 16. Secondary porosity (1) in leached plagioclase grain (2). Kaolinite clay (3) in a leached pore space. Frio Formation, Phillips No. 1 Houston "JJ" (15,829 feet), Brazoria County, Texas.

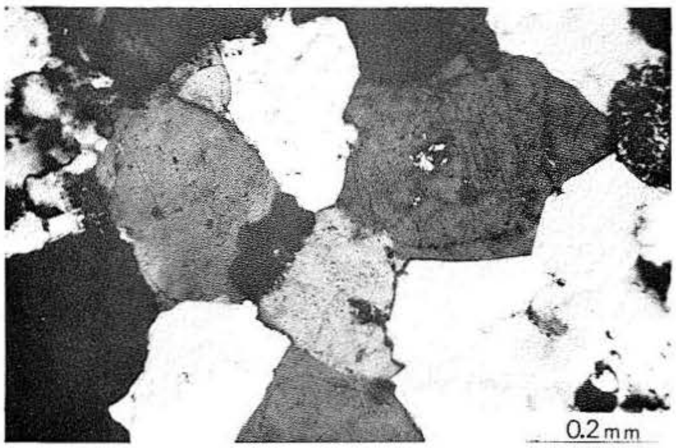

FIGURE 14. Massive quartz overgrowth welding has occluded the pore space. Crossed nicols. Frio Formation, Humble No. 1 Skrabanek (17,030-60 feet), Brazoria County, Texas.

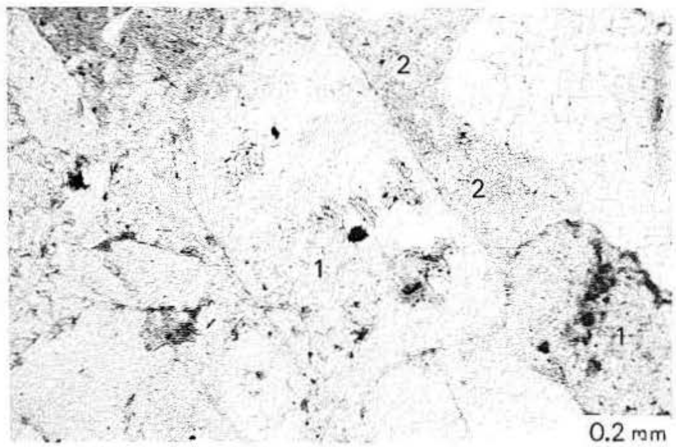

FIGURE 17. A. Kaolinite-clay fill in leached plagioclase grains (1) and in primary porosity (2).

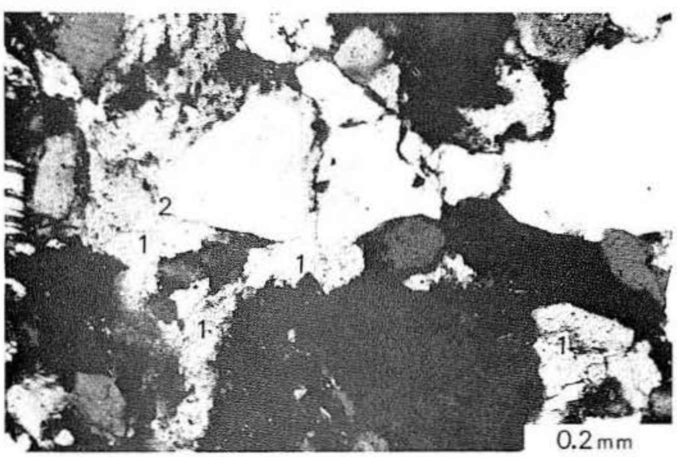

FIGURE 15. Sparry calcite cement (1) following quartz overgrowths (2). Pore space is totally filled. Crossed nicols. Frio Formation Humble No. 1 Skrabanek (16,130-60 feet), Brazoria County, Texas.

FIGURE 17. B. Crossed nicols of same thin section. Frio Formation, Phillips No. 1 Houston "JJ" (15,833 feet), Brazoria County, Texas.

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FIGURE18. A. leached porosity (1) in plagioclase-rich volcanic rock fragments (2). Leached-grain embayment into quartz overgrowth (3).

TABLE 2. Criteria for recognition of sandstone consolidation stages relative to the zone of secondary leached porosity. Some criteria for leaching is from Lindquist (1976, 1977) and McBride (1977).

Table 2

PRELEACHING STAGE:

1. Absence of oversized vugs.
2. Abundant calcite replaced feldspars.
3. Abundant sparry calcite cement.

LEACHING STAGE:

1. Partially to completely leached grains.
2. Leached sparry calcite cement.
3. Oversized pore spaces.
4. Leached-grain embayments into quartz overgrowths.

POSTLEACHING:

1. Kaolinite and iron-rich carbonate cements filling secondary leached porosity, primary porosity, and resurrected primary porosity.

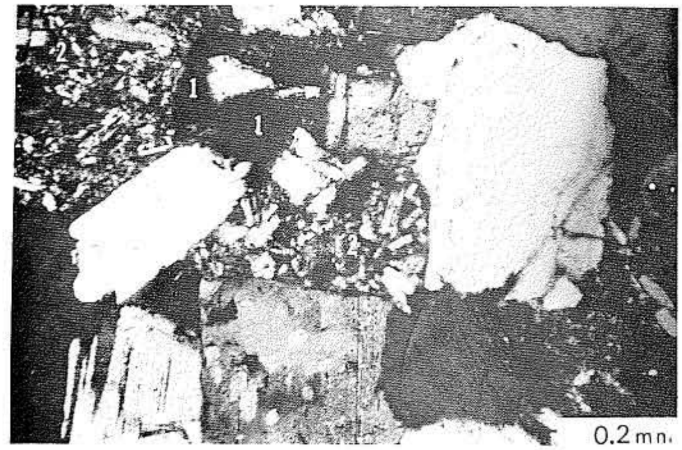

FIGURE 18. B. Crossed nicols of same thin section. Frio Formation, Phillips No. 1 Houston "JJ" (15,829 feet), Brazoria County, Texas.

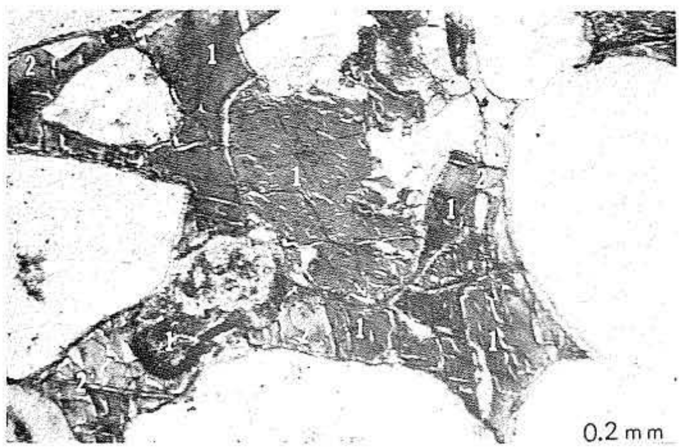

FIGURE 19. Partly leached iron-free calcite cement (1) surrounded by late iron-rich calcite cement (2) that has totally occluded porosity. Thin section stained with alizarin red-S and potassium ferrocyanide. Frio Formation, Phillips No. 1 Houston "JJ" (16,208 feet), Brazoria County, Texas.

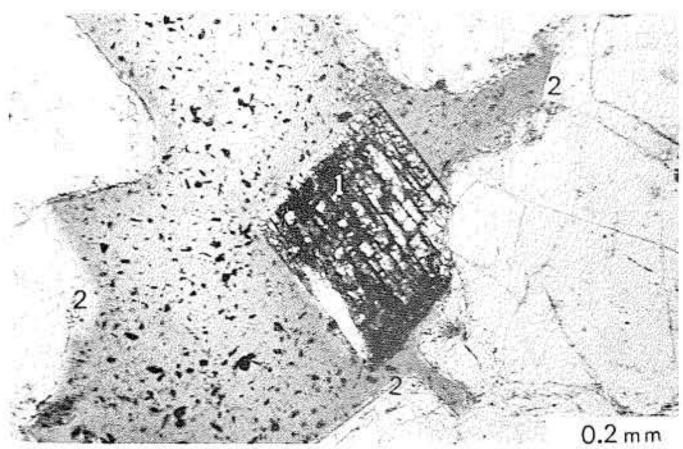

FIGURE 20. Late euhedral iron-rich dolomite (1) in oversized pore space. Oversized pore space indicates leached porosity; however, euhedral quartz overgrowths (2) indicate part of the pore space was primary. Thin section stained with potassium ferrocyanide. Frio Formation, Phillips No. 1 Houston "JJ" (15,809 feet), Brazoria County, Texas.

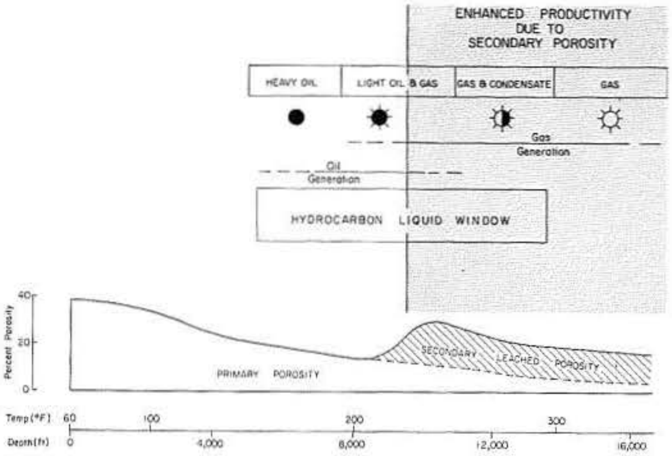

FIGURE 21. Schematic porosity versus depth/temperature curve for a Frio section intermediate between cases I and III (Fig. 7) showing relative significance of primary versus secondary leached porosity. The lower half of the hydrocarbon liquid window, which is characterized by the production of light liquids and distillate, as well as all of the deep gas productive section, lie within the zone of secondary porosity and permeability.

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