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FACTORS CONTROLLING GEOPRESSURED GEOTHERMAL RESERVOIR QUALITY--FRIO SANDSTONE FACIES, TEXAS GULF COAST*

R. G. LOUCKS and M. G. MOSELEY

ABSTRACT

Geopressured geothermal reservoir quality along the Texas Gulf Coast is controlled by sandstone depositional environment, mineralogical composition, and consolidation history (compaction, cementation, and leaching).

The best Frio reservoirs occur at the top of deltaic progradational sequences in distributary-mouth bar and distributary-channel sandstone facies. Poor reservoir quality characterizes proximal delta front and distal delta front sandstones. Sandstone mineralogical composition varies from quartzose feldspathic volcanic litharenite and quartzose lithic arkose along the upper Texas Gulf Coast to feldspathic volcanic litharenite rich in carbonate rock fragments along the lower Texas Gulf Coast.

Frio sandstones exhibit the following four major stages of consolidation:

1. Near-surface to shallow subsurface compaction and cementa-

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tion stage (0 to 4,000 feet $\pm$). Porosity is reduced from 40 percent to approximately 25 percent.

2. Intermediate subsurface cementation stage (4,000 to 8,000 feet $\pm$). Porosity is commonly reduced to 10 percent.
3. Intermediate subsurface leaching stage (8,000 to 11,000 feet $\pm$). Leaching of grains and cements may resurrect porosities to as high as 30 percent. This is the zone of geothermal reservoir development.
4. Deep subsurface cementation stage (11,000 feet $\pm$). High reservior quality necessary for geothermal prospects depends on the absence of this late cement.

Geothermal reservoirs are not composed of simple primary porosity between grains, but rather consist of secondary leached porosity. Austin Bayou Prospect in Brazoria County, Texas, is a prospective geothermal reservoir that is the product of secondary leached porosity.

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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 upon a complex relationship between sandstone depositional environment, mineralogical composition, and consolidation history (compaction, cementation, and leaching). This report is part of an ongoing study of Frio sandstone consolidation history, which exerts a major control on geopressured geothermal reservoir development and preservation at increasing depths of burial.

In general, shallow Frio reservoirs exhibit primary porosity

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* This paper is a portion of the Bureau of Economic Geology publication by Bebout, Loucks, and Gregory (in press, 1977), "Frio Sandstone Reservoirs in the Deep Subsurface Along the Texas Gulf Coast--Their Potential for the Production of Geopressured Geothermal Energy."

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.

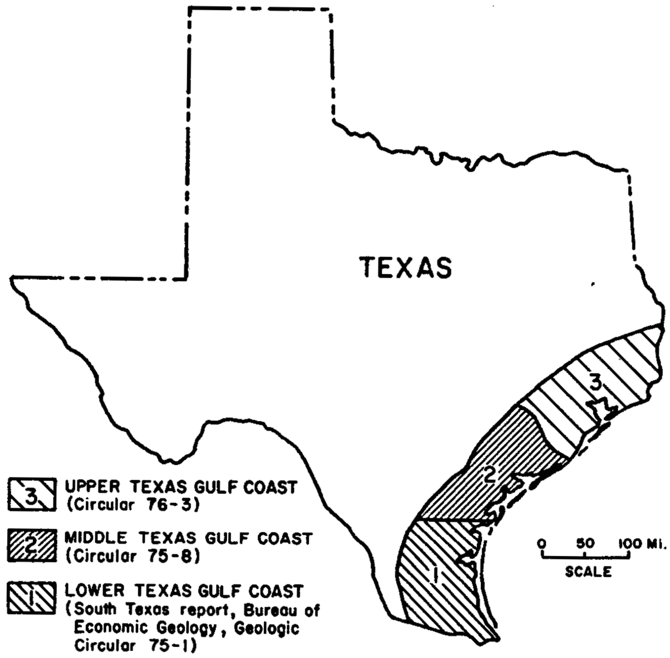


Figure 2. Areas of study in the Frio Formation of the Texas Gulf Coast. Circulars 75-1 (Bebout and others, 1975b), 75-8 (Bebout and others, 1975a), and 76-3 (Bebout and others, 1976) refer to regional investigation on the geothermal potential of the Frio Formation published by the Bureau of Economic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

that is reduced by compaction and cementation, whereas deeper potential geothermal 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 geothermal reservoir quality.

FACTORS CONTROLLING SANDSTONE RESERVOIR QUALITY

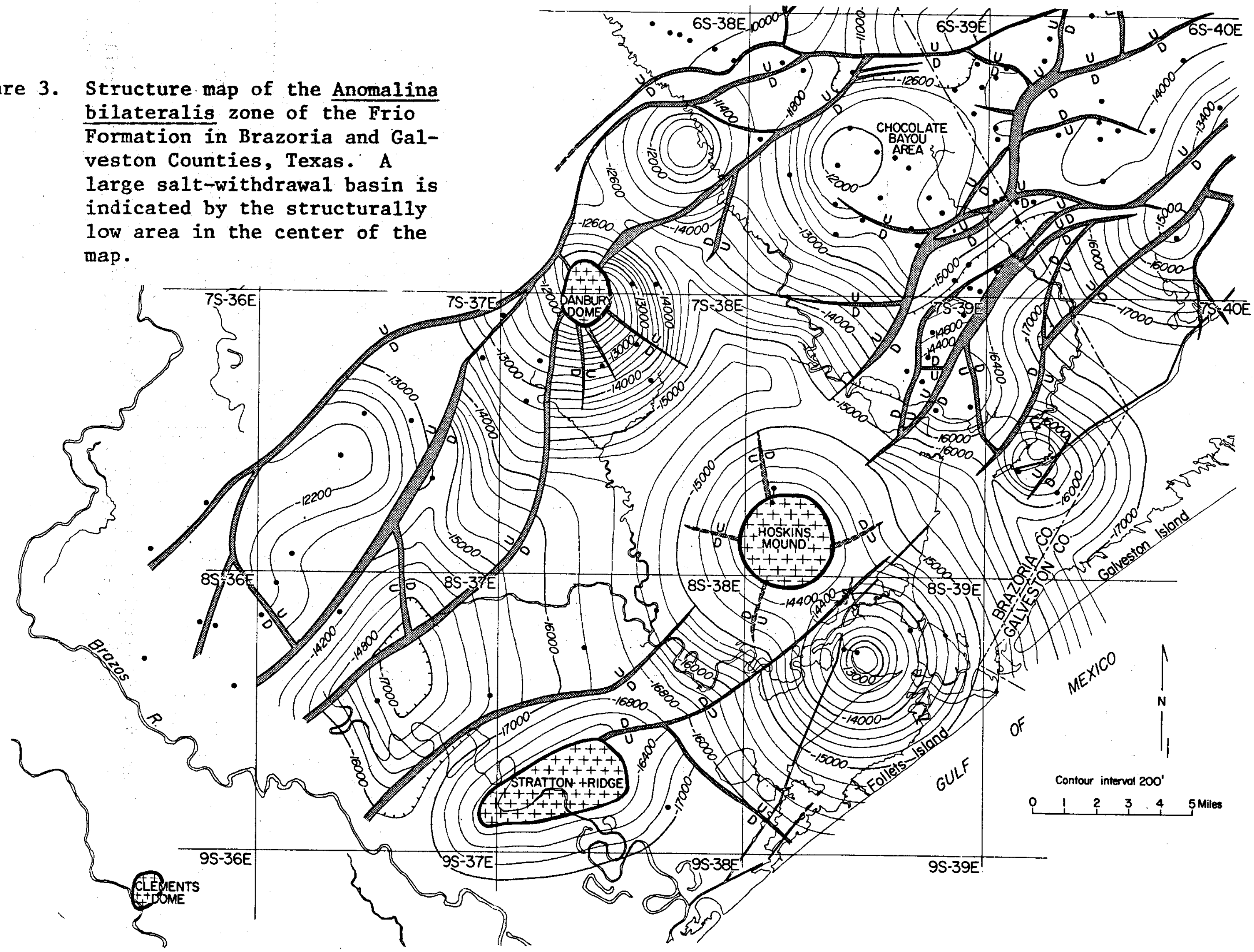
Depositional environment not only controls the initial porosity in a sand through sorting, but also controls the areal distribution and geometry of the reservoir. Superimposed upon porosity variations resulting from depositional environments is the structural setting, which affects the rate of subsidence 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 between 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

In the area of the Austin Bayou Prospect along the upper Texas Gulf Coast in Brazoria County, the sandstone and shale section of the *Anomalina 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 geothermal reservoir sandstones occur at the top of deltaic progradational facies in distributary-mouth bar and distributary-channel sandstones; poor reservoir quality characterizes both the proximal delta front and the 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. A similar history probably 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 by Tillman and Almon (1977), have docu-

Figure 3. Structure map of the *Anomalina 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.



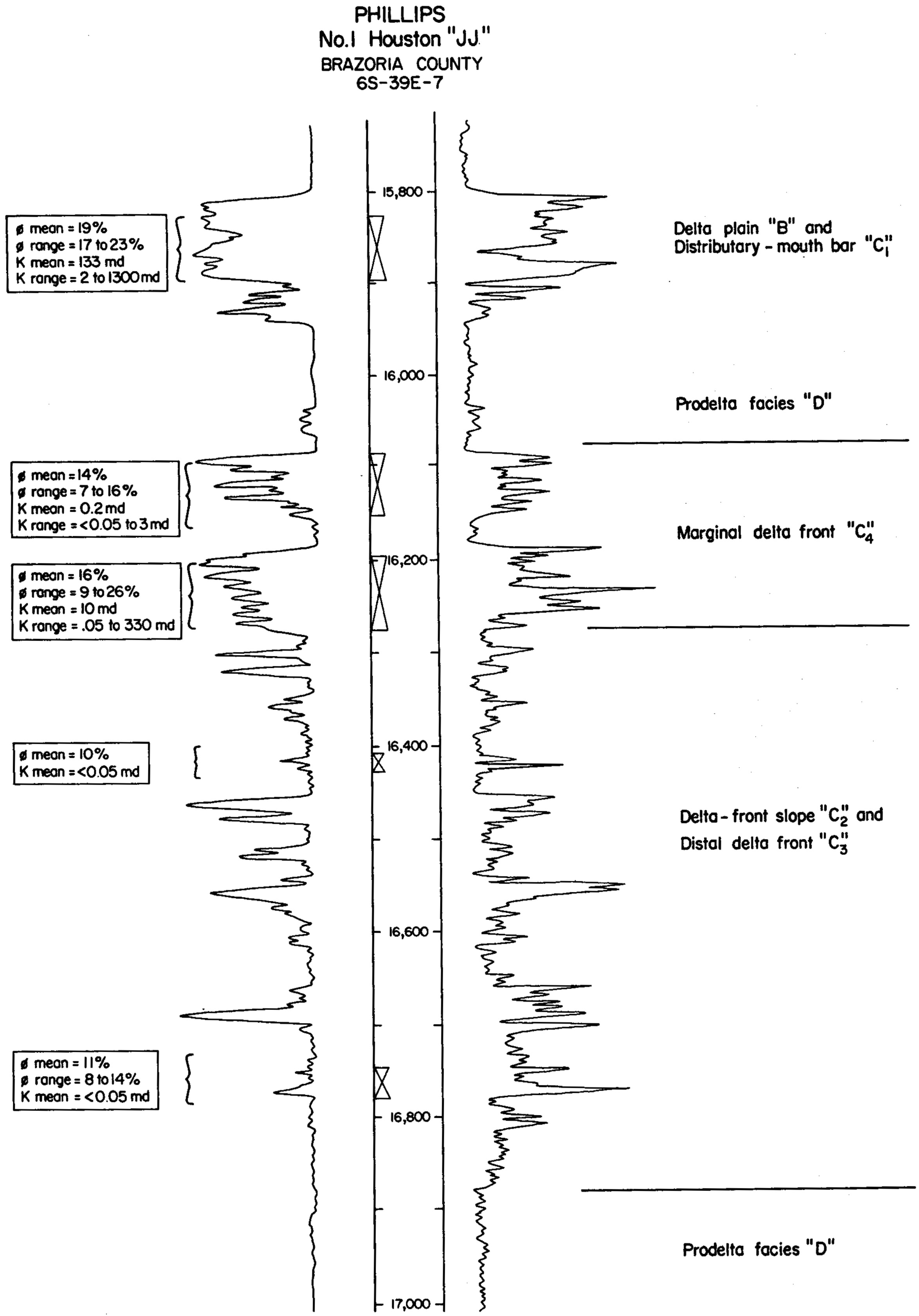


Figure 4. Depositional facies of high-constructive lobate delta systems interpreted from the electrical log of the Phillips No. 1 Houston "JJ." The highest porosity and permeability occur at the top of the deltaic cycles in distributary-channel and distributary-mouth bar facies.

mented 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.

Potential geothermal reservoirs in the downdip Frio are composed of quartz, feldspar (plagioclase and orthoclase), and volcanic and carbonate rock fragments. The relative proportions of these rock components vary from the upper to the 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 contain more volcanic rock fragments and feldspar than quartz (feldspathic volcanic litharenite). Carbonate rock fragments are more common along the lower Texas Gulf Coast, decreasing 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

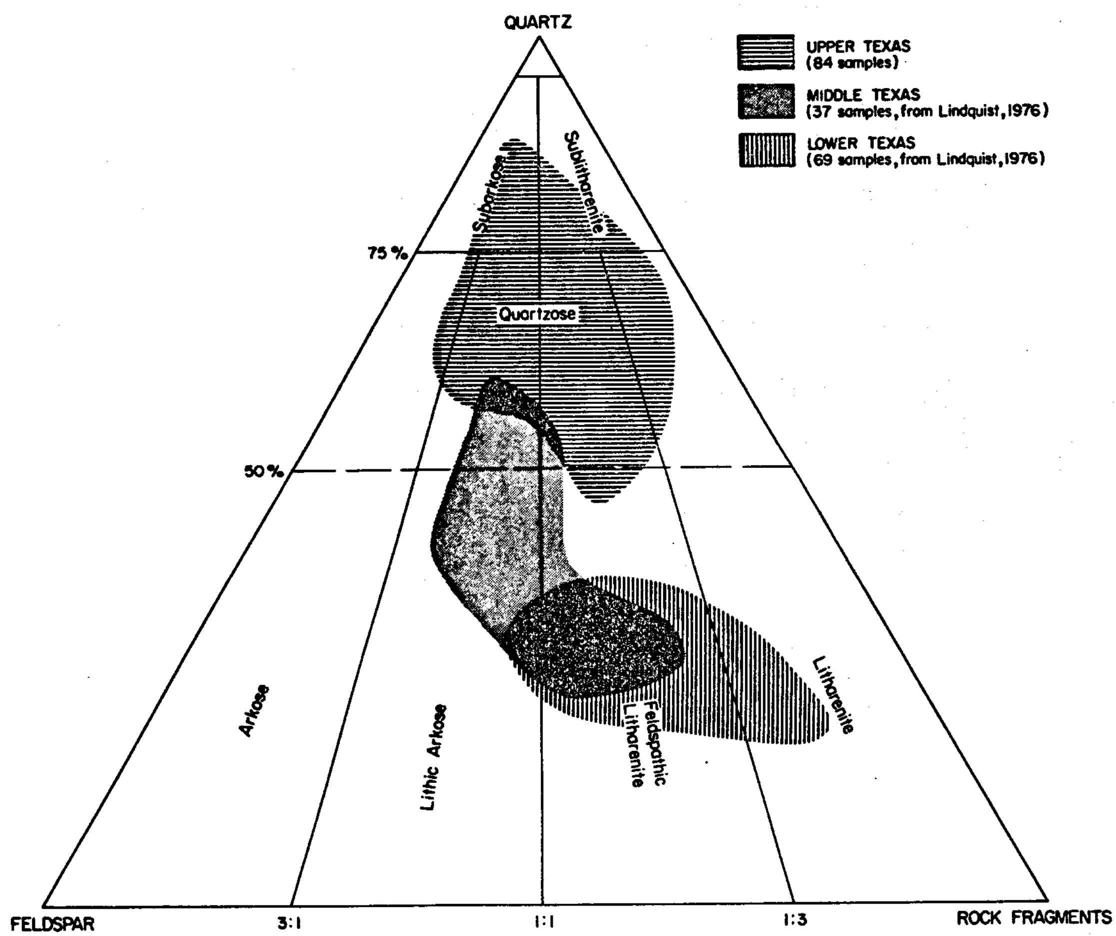


Figure 5. Sandstone composition of the Frio Formation along the Texas Gulf Coast. Sandstone classification after Folk, 1968.

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 reservoirs 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 by 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 geothermal 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 upon outcrop, shallow core (less than 100 feet), and deep core (9,000 to 17,000 feet) data; a few samples from between 100 and 9,000 feet have been examined. The depth range for different diagenetic stages is only estimated, but even if the depth ranges are modified by future work, the overall paragenetic sequence will remain the same. Other

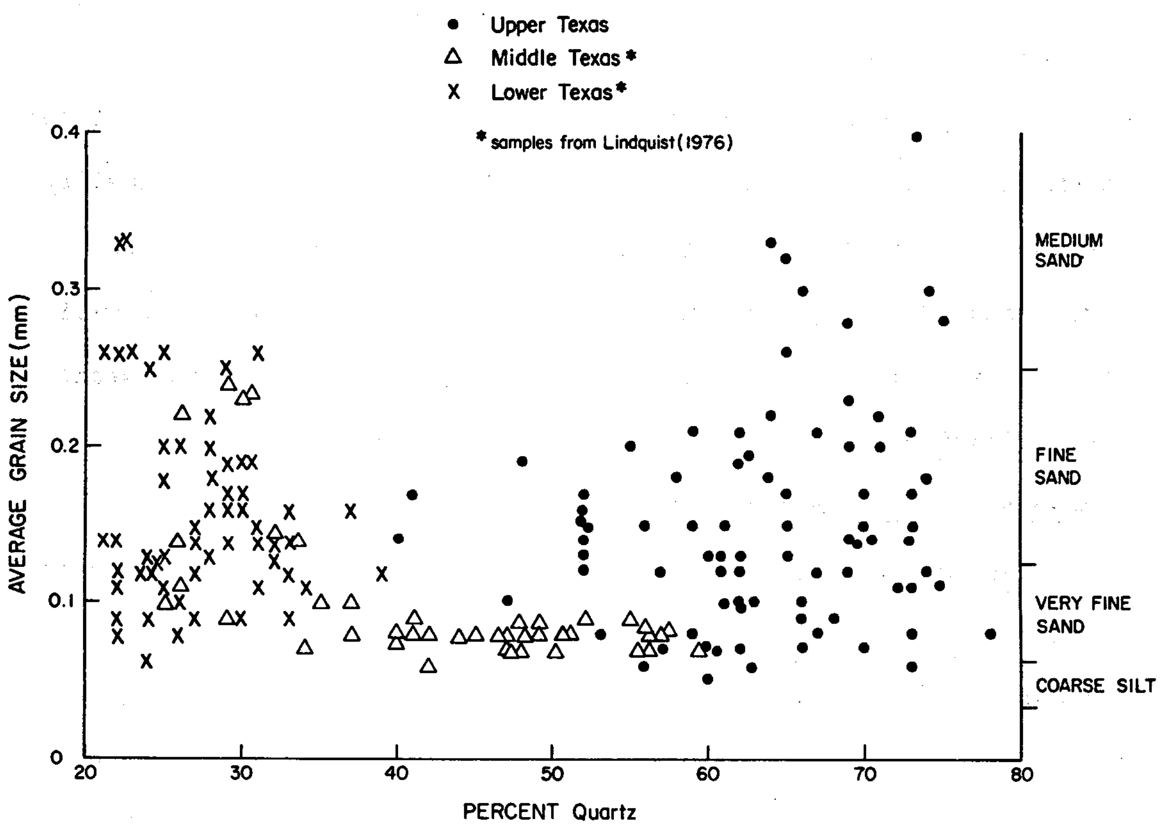


Figure 6. Relationship of percent quartz to average grain size between lower, middle and upper Texas Gulf Coast.

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 $\pm$) 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 by the lack of any other cement type around the grains (fig. 9). Fortunately, this massive pore-filling cement is a localized phenomenon which 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, minor by volume (fig. 12), are precipitated in the shallow subsurface. Quartz overgrowths and clay rims tend to arrest compaction of the sandstones. Reservoir porosity is reduced by compaction

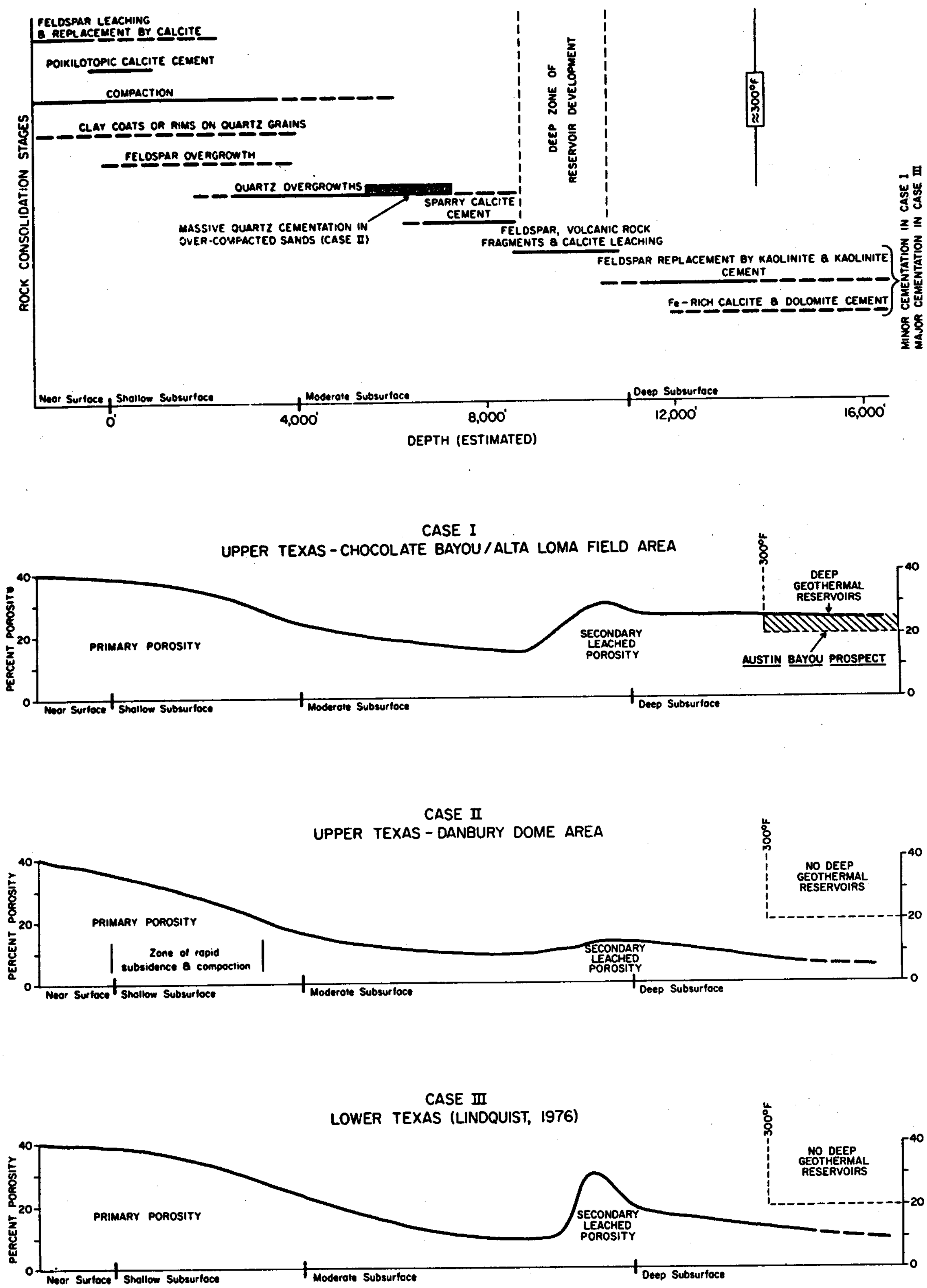


Figure 7. Rock consolidation stages with increasing depth and case histories of consolidation in the Chocolate Bayou/Alta Loma field areas, Danbury Dome area, and lower Texas area.

Figure 8. Authigenetic feldspar overgrowths (1) inside a leached feldspar grain (2) indicate that leaching occured 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 feet), 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 feet), Galveston County, Texas.

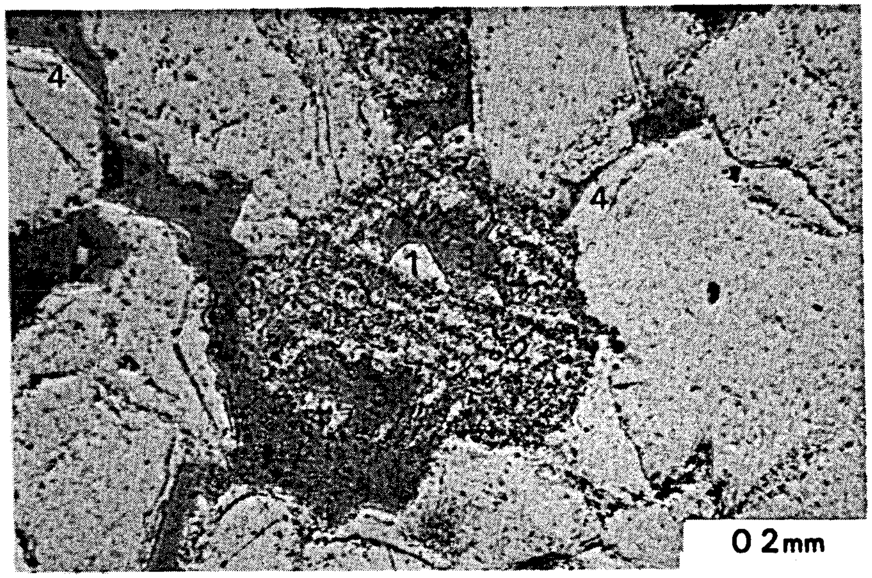


Figure 8

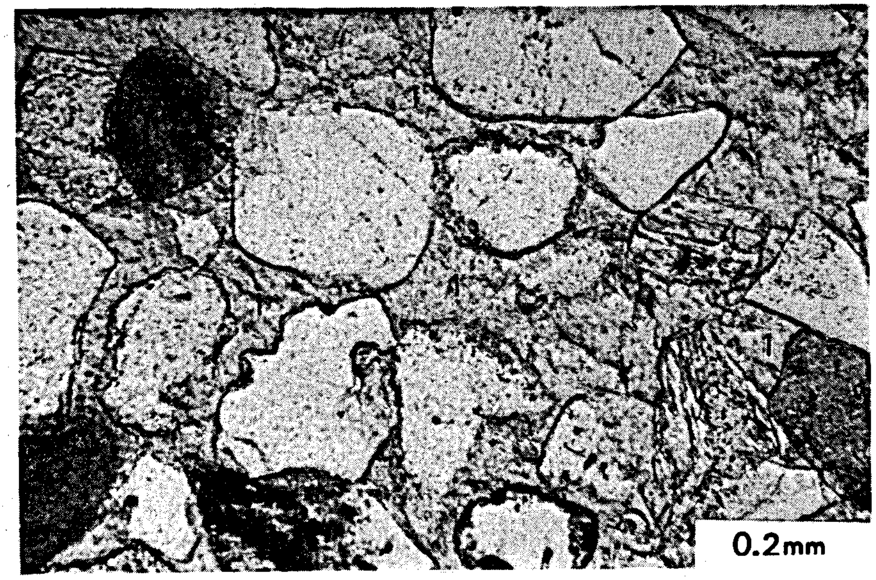


Figure 9

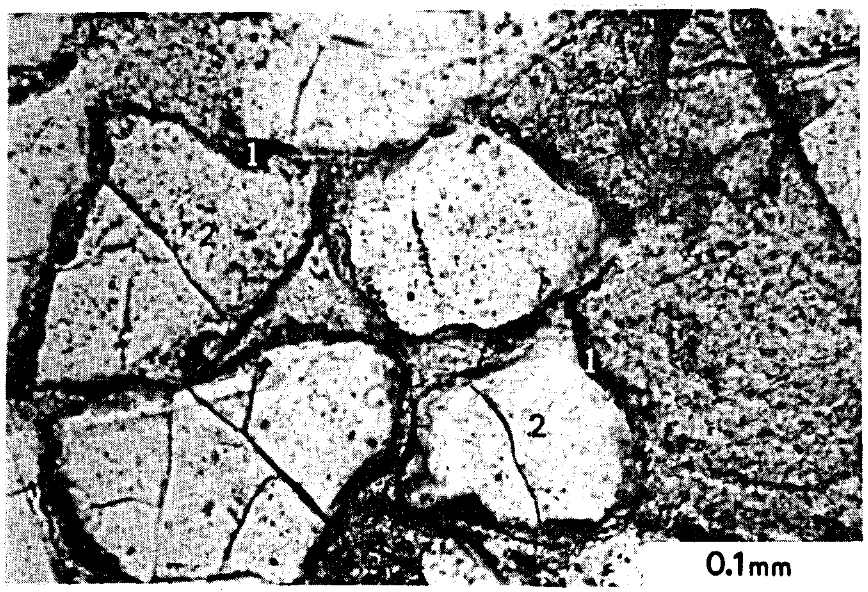


Figure 10

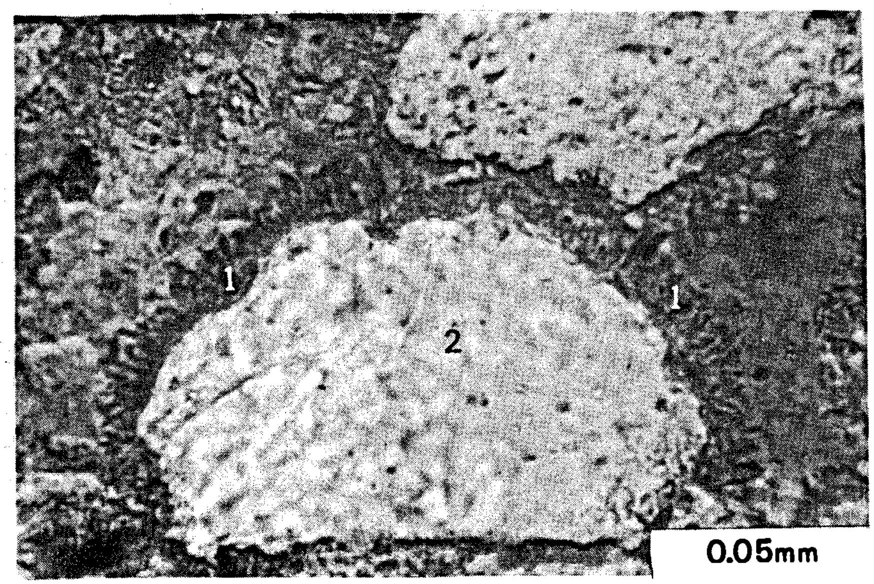


Figure 11

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 #1 Skrabanek (17,030-60 feet), Brazoria County, Texas.

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 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 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.

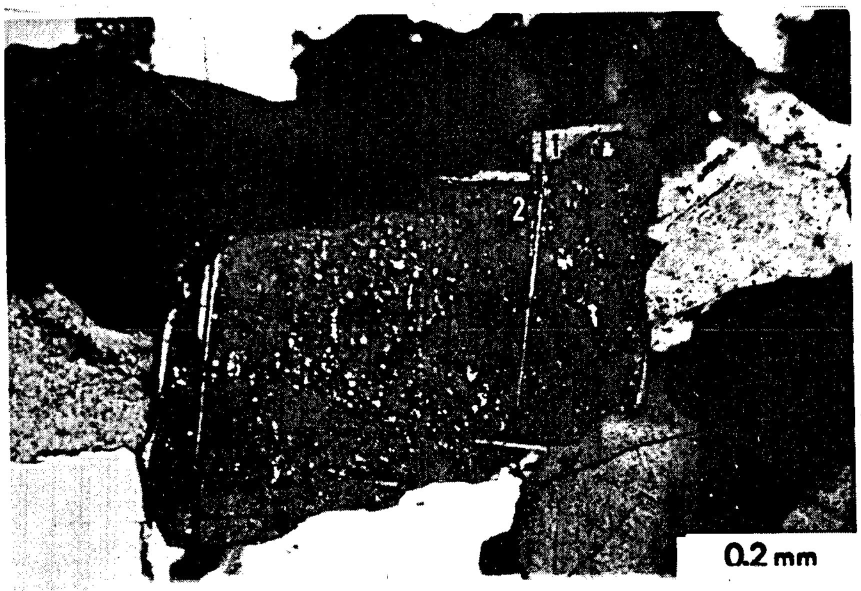


Figure 12

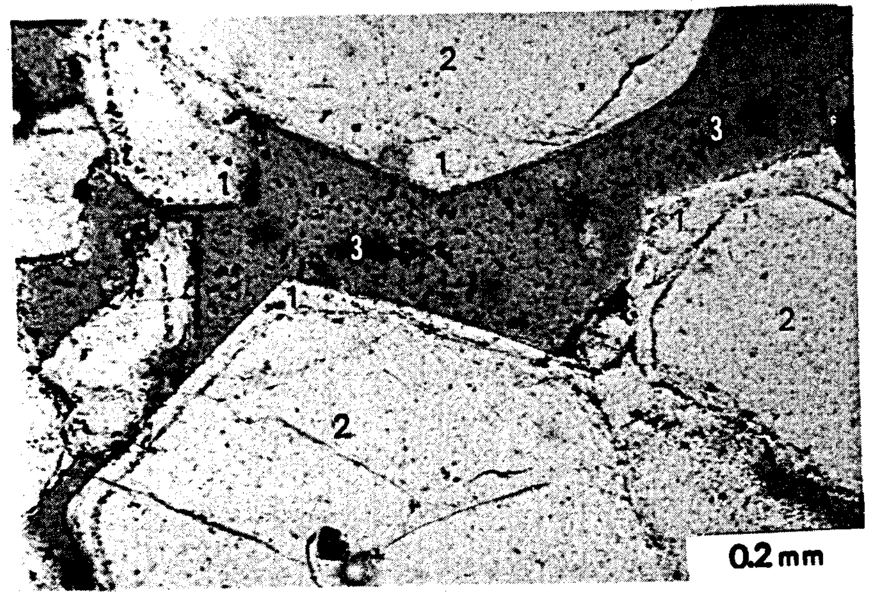


Figure 13

Figure 14

Figure 15

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 17. A. Kaolinite-clay fill in leached plagioclase grain (1) and in primary porosity (2). B. Crossed nicols of same thin section. Frio Formation, Phillips No. 1 Houston "JJ" (15,833 feet), Brazoria County, Texas.

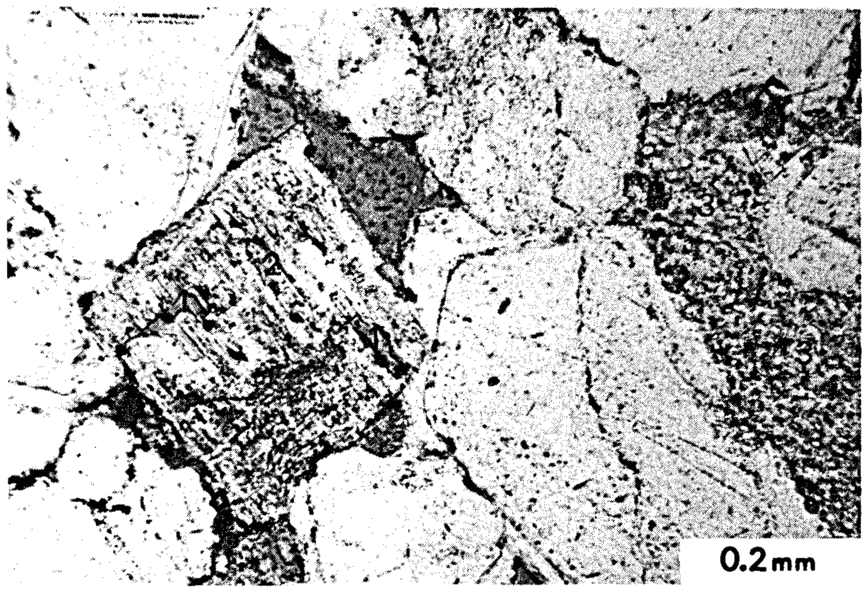


Figure 16

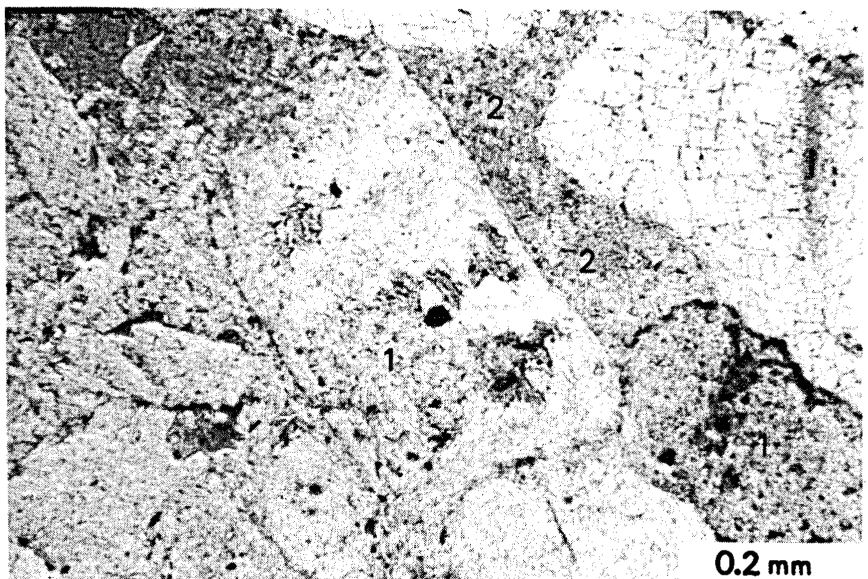


Figure 17a

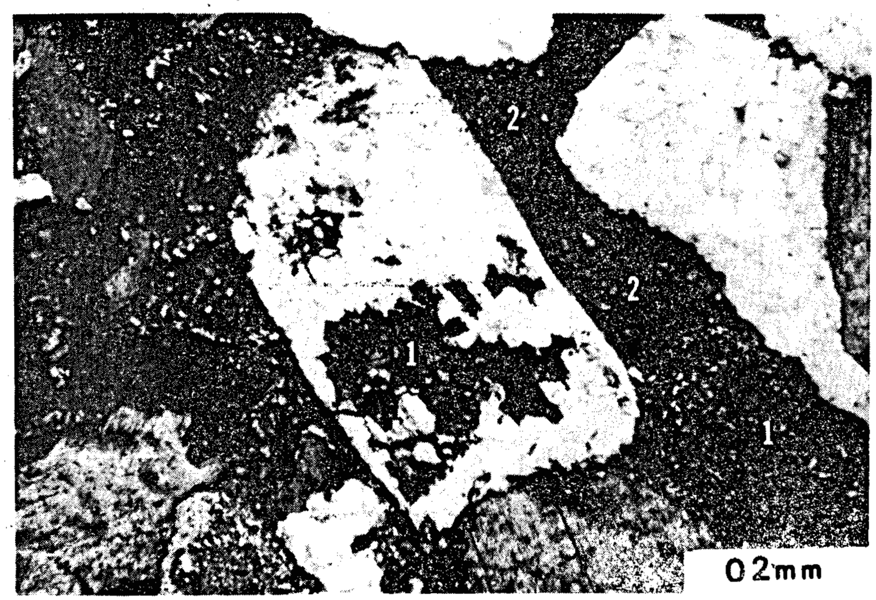


Figure 17b

Figure 18. A. Leached porosity (1) in plagioclase-rich volcanic rock fragments (2). Leached-grain embayment into quartz overgrowth (3). B. Crossed nicols of same thin section. Frio Formation, Phillips No. 1 Houston "JJ" (15,829 feet), Brazoria County, Texas.

Figure 19. Partly leached Fe-free calcite cement (1) surrounded by late Fe-rich calcite cement (2) that has totally occluded porosity. Dark color is due to staining with alizarin red-S and potassium ferrocyanide. Frio Formation, Phillips No. 1 Houston "JJ" (16,208 feet), Brazoria County, Texas.

Figure 20. Late euhedral Fe-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. Dark color of dolomite is due to staining with potassium ferrocyanide. Frio Formation, Phillips No. 1 Houston "JJ" (15,809 feet), Brazoria County, Texas.

Figure 18a

Figure 18b

Figure 19

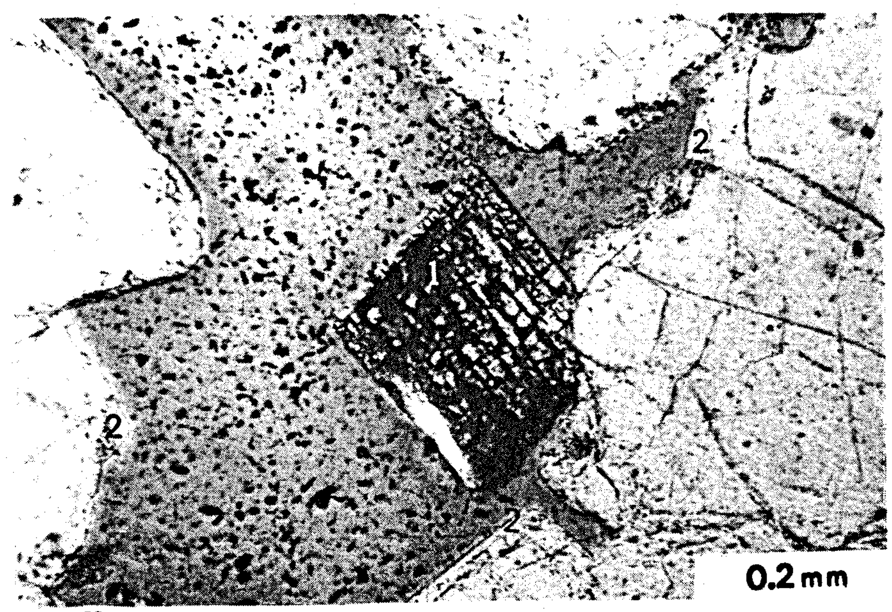


Figure 20

and early cementation (fig. 7) from the original 40 percent to approximately 25 percent during this near-surface to shallow subsurface consolidation stage.

Moderate subsurface cementation stage (4,000 to 8,000 ±) 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 the development of the quartz overgrowths is the formation of sparry pore-fill calcite cement (fig. 15), which is very common during this stage of diagenesis in the Frio in the lower Texas Gulf Coast (Lindquist, 1976a, 1976b, 1977). Porosities are generally 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 in deeper geothermal 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 Fe-rich calcite and dolomite cements (figs. 19, 20). The iron in the carbonates was identified by potassium ferrocyanide stain. The kaolinite, composed of crystalline booklets several microns in size, forms a meshwork in the pore spaces which does not significantly reduce porosity but which is detrimental to permeability. The late Fe-rich carbonates commonly form single euhedral crystals (fig. 20), or form as an outer layer on earlier Fe-poor calcite cement (fig. 19). The amount of late cementation in this deep subsurface stage determines whether geothermal reservoirs will exist at depth (fig. 7).

This sandstone consolidation sequence can be modified by residence time in each burial state, by thermal gradient, by changes in pore-fluid chemistry, and by mineralogical differences. Excellent 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 1.

FRIO SANDSTONE CONSOLIDATION CASE HISTORIES

The reservoir quality of Frio sandstones varies regionally. Along the lower Texas Gulf Coast (fig. 2) permeability in sandstone

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 Fe-rich carbonate cements filling secondary leached porosity, primary porosity, and resurrected primary porosity.

Table 1 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).

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 Fe-rich calcite and dolomite. To the northeast, in the area of the Austin Bayou Prospect 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. This type of cement, however, 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 potential geothermal reservoirs in the Frio in the area of the 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.

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 Fe-rich carbonate cements were deposited, reducing the average porosity to 25 percent or less. The Austin Bayou Prospect probably has a similar diagenetic history.

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). Massive quartz cementation probably hindered the development of secondary porosity at greater depths. The final result is the lack of potential geothermal 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 was produced. Following this leaching stage, kaolinite and Fe-rich carbonate and zeolite (analcime) cements drastically reduced porosity to less than 15 percent and destroyed all possibility of preserving potential geothermal reservoirs.

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.

PREDICTION OF GEOTHERMAL RESERVOIR QUALITY IN FRIO SANDSTONE FACIES

In searching for potential geothermal reservoirs in the Frio Formation along the Texas Gulf Coast, Bebout and others (in press) found 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 Fe-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 is unlikely to be found along the lower Texas Gulf Coast. Because of similar mineralogy in the middle Texas Gulf Coast (fig. 5), the same prediction can be made of poor reservoir quality at depths greater than 13,500 feet.

In the upper Texas Gulf Coast, however, the mineral assemblage in the sandstones is more stable chemically than that in 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^{o} F exist below 13,500 feet in the Chocolate Bayou field area where compaction was normal, due to 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 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 studying a few wells in the area, and by applying the sandstone consolidation sequence as outlined in this paper.

CONCLUSIONS

Knowledge of the sandstone consolidation history is an important tool in predicting both areal and vertical reservoir quality. Realization that shallow reservoirs consist of primary porosity and that deep potential geothermal reservoirs are composed primarily of secondary leached porosity also helps in 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, by thermal gradient, by pore-fluid changes, and by mineralogical differences, all of which result in a wide range of reservoir quality.

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