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URANIUM FAVORABILITY OF LATE EOCENE THROUGH PLIOCENE ROCKS OF THE SOUTH TEXAS COASTAL PLAIN

BENDIX FIELD ENGINEERING CORPORATION
Grand Junction Operations
Grand Junction, Colorado 81501

February 1977

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PLATES (continued)

SUMMARY AND CONCLUSIONS

This report contains the results of a subsurface uranium favorability study of Tertiary rocks (late Eocene through Pliocene) in the Coastal Plain of South Texas. In ascending order, these rock units include the Yegua Formation, Jackson Group, Frio Clay, Catahoula Tuff, Oakville Sandstone, and Goliad Sand. These units are known to contain uranium deposits or to have lithologies potentially favorable as host rocks. The Vicksburg Group, Anahuac Formation, and Fleming Formation were not considered because they have unfavorable lithologies.

Successively younger sedimentary units were deposited throughout the study area and crop out progressively toward the Gulf Coast. Repeated transgressions and regressions, plus occasional overlap, modify this generalization. Environments of deposition include: fluvial, flood plain, deltaic, lagoonal, strand plain-barrier bar, and open shelf.

Four major fault zones were active during deposition of the Tertiary sediments. Sediments thicken rapidly downdip (coastward) of these fault zones. Faults within these zones, together with many smaller faults, may act either as barriers to ground-water movement or as conduits for reductants--both of which are important in the precipitation of uranium.

Volcanic activity began in Yegua time and climaxed in Catahoula time. This activity resulted in deposition of large volumes of volcanic tuff and ash. Uranium minerals were leached from the volcanic sediments and were carried downdip by alkaline ground water to reducing zones where the uranium was deposited. The largest uranium deposits are in unoxidized ore rolls.

Association of known ore deposits indicates that some environments are more favorable for uranium deposition than others. Well logs were used to prepare cross sections and maps to show structure, sandstone/shale ratios, total sandstone thickness, formation thickness, and number of optimum sands in order to show the presence and extent of potential sandstone host rocks and their environments of deposition. Conclusions were based principally on subsurface data.

The following conclusions were reached:

1. The Yegua Formation, Jackson Group, Frio Clay, Catahoula Tuff, Oakville Sandstone, and Goliad Sand contain sandstones that may be favorable uranium hosts under certain environmental and structural conditions. All except the Yegua are known to contain ore-grade uranium deposits.

2. Yegua and Jackson sandstones are found in strand plain-barrier bar systems that are aligned parallel to depositional and structural strike. These sands grade into shelf muds on the east, and lagoonal sediments updip toward the west. The lagoonal sediments in the Jackson are interrupted by dip-aligned fluvial systems. In both units, favorable areas are found in the lagoonal sands and in sands on the updip side of the strand-plain system. Favorable areas are also found along the margins of fluvial systems in the Jackson.

3. The Frio and Catahoula consist of extensive alluvial-plain deposits. Favorable areas for uranium deposits are found along the margins of the paleochannels where favorable structural features and numerous optimum sands are present.

4. The Oakville and Goliad Formations consist of extensive continental deposits of fluvial sandstones. In large areas, these fluvial sandstones are multistoried channel sandstones that form very thick sandstone sequences. Favorable areas are found along the margins of the channel sequences. In the Goliad, favorable areas are also found on the updip margin of strand-plain sandstones where there are several sandstones of optimum thickness.

INTRODUCTION

The Tertiary stratigraphic sequence in the South Texas part of the Gulf Coastal Plain has been the subject of study for many years. In the past, emphasis has been on petroleum exploration rather than on uranium. This report presents the results of a subsurface uranium favorability study of sedimentary strata of late Eocene through Pliocene age that underlies part of the South Texas Coastal Plain. The project began in March 1973 and was concluded in December 1975.

PURPOSE AND SCOPE

The objective of this study was to delineate areas of maximum uranium favorability in Tertiary sediments that underlie part of the South Texas Coastal Plain. With few exceptions, the known uranium ore bodies in South Texas are found in Tertiary sandstone host rocks; thus, major emphasis was placed on delineation of favorable sandstone trends in selected stratigraphic intervals. Although attention was given to sandstones that crop out, most of the findings and conclusions of this report apply to sandstones in the subsurface, down to an arbitrary cut-off depth of 5,000 ft. Because the data analyzed commonly begin below 500 ft, most favorable designations are below depth.

As demand for uranium continues, the subsurface deposits of South Texas will become more important for both conventional and solution mining. This report designates areas within the subsurface judged to be favorable for potential uranium resources.

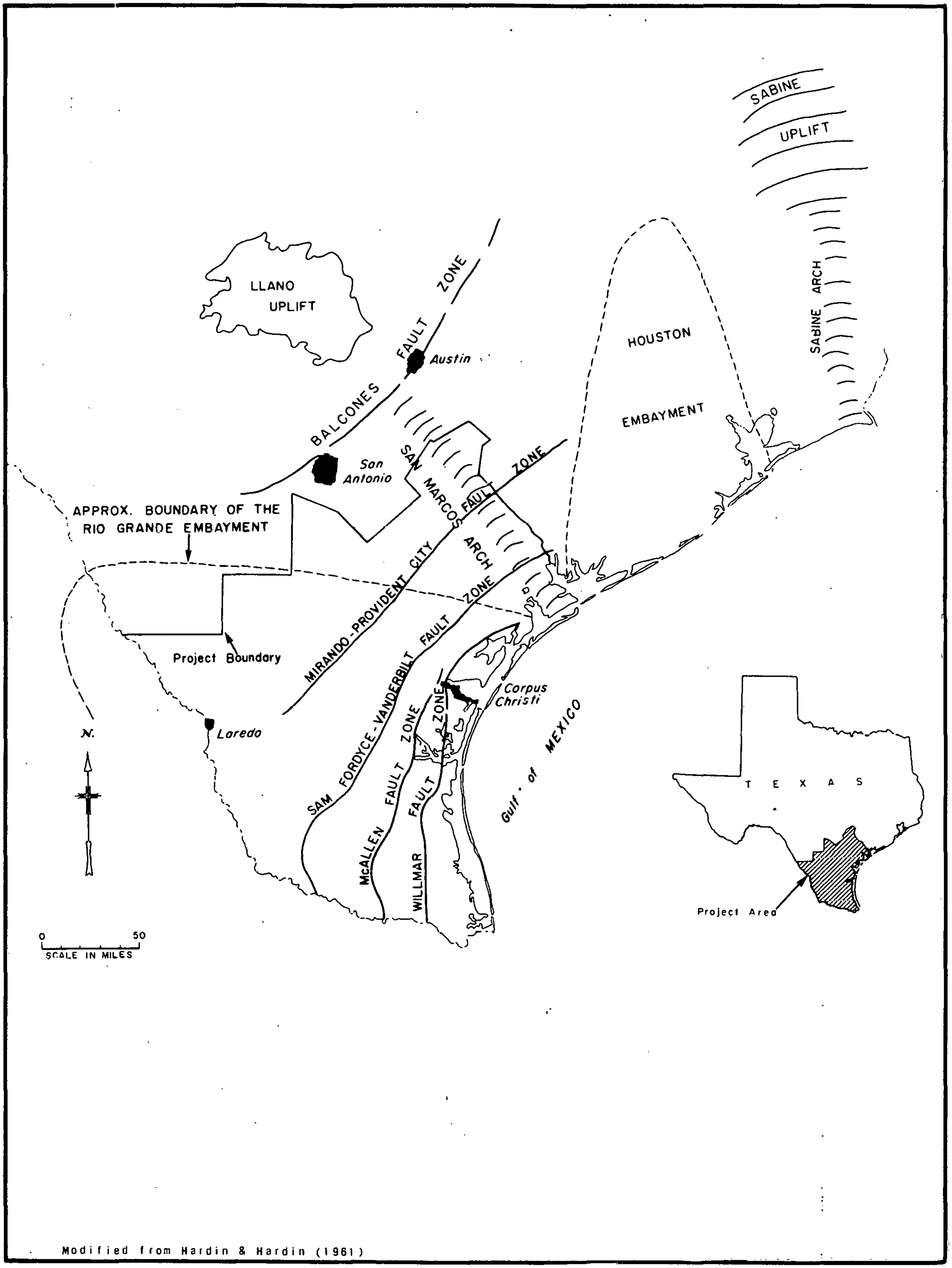
AREA INVESTIGATED

The project area (Fig. 1) is part of the Coastal Plain province of South Texas. It encompasses approximately 29,000 square miles and includes all or parts of Aransas, Atascosa, Bee, Brooks, Calhoun, Cameron, DeWitt, Duval, Goliad, Gonzales, Hidalgo, Jim Hogg, Jim Wells, Karnes, Kenedy, Kleberg, La Salle, Live Oak, McMullen, Nueces, Refugio, San Patricio, Starr, Victoria, Webb, Willacy, and Zapata Counties.

The Rio Grande forms the southern and part of the western boundary of the project area. The Gulf of Mexico marks the eastern limit. The northeastern boundary is an irregular line that extends along the Guadalupe River northwest into Gonzales County. The northwestern boundary extends along the westernmost outcrops of the Yegua Formation in Atascosa, La Salle, and Webb Counties.

GEOLOGIC SETTING

Tertiary sediments of the South Texas Coastal Plain were deposited in a series of wedges that dip and thicken southeastward toward the Gulf of Mexico. These sediments form a band 80 to 190 miles wide that extends from the Rio Grande northward and eastward to Louisiana. Pliocene and



Modified from Hardin & Hardin (1961)

Figure 1 Index map of South Texas Coastal Plain showing project area and major structural features.

younger rocks lie near the surface over much of the project area; the older Tertiary units crop out in a belt along the western edge of the project area (Pl. 1). Within the South Texas part of this outcrop belt, uranium was first discovered and mined in Texas; most production in Texas has come from this area.

The major structural elements in the project area are the Rio Grande Embayment and the San Marcos Arch (Hardin and Hardin, 1961; Fig. 1). The Rio Grande Embayment is a structural depression that underlies the southern two-thirds of the project area. This embayment was the site of 50,000 ft of sediment accumulation during Tertiary time (Hardin, 1962, Fig. 1). The San Marcos Arch is a positive area that marks the approximate northeastern limit of the project. Many of the Tertiary units become progressively thinner northward from the center of the embayment toward the San Marcos Arch.

ACKNOWLEDGMENTS

We extend our appreciation to staff members of the Texas Water Development Board, the Texas Railroad Commission, and the Texas Bureau of Economic Geology for their help and assistance. We especially thank W. L. Fisher, C. G. Groat, and D. G. Bebout of the Texas Bureau of Economic Geology for their advice and assistance.

METHODS

FIELD INVESTIGATIONS

Field work was conducted periodically from November 1974 through May 1975. Several active open-pit mines and widely scattered outcrop localities were visited to obtain samples and to examine facies and ore deposit relationships. For examination and description, 182 samples were collected from outcrops and mines. All samples and descriptions are on file in the Austin Office of Bendix Field Engineering Corporation.

SUBSURFACE METHODS

Stratigraphic and structural interpretations were based primarily on data derived from electric logs of 1,723 petroleum test wells. Of these logs, 727 appear on cross sections depicting stratigraphic correlations. The remaining logs provided fill-in data between cross sections. Test wells used in this study are listed in Appendix A; their locations are shown in Plate 2. All available gamma-ray logs were examined for anomalous radioactivity in the Tertiary formations. The locations of these logs are shown on Plate 3.

STRATIGRAPHIC MAPS AND CROSS SECTIONS

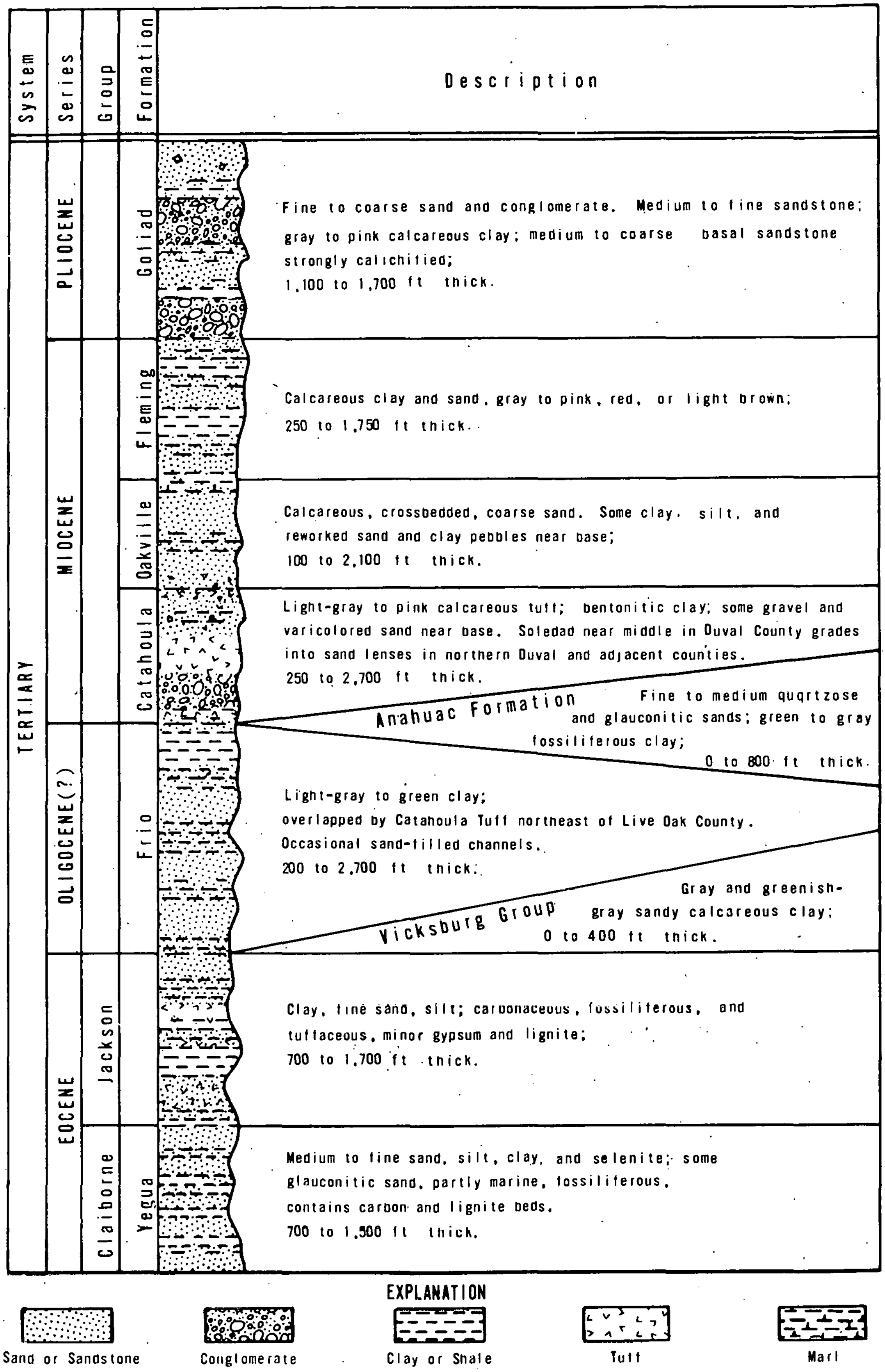
Subsurface correlations are based on a network of 23 intersecting electric-log cross sections (Pls. 5-27). The locations of cross sections and cross-section wells are shown on Plate 4. Thirteen of the cross sections are parallel to regional strike (Pls. 15-27); ten are dip sections (Pls. 5-14). Plates 6, 7, and 9 are revisions of sections prepared by D. F. Sandifer (1969a, 1969b, 1970), a consulting geologist, and Plates 19 and 21 are revisions of those prepared by J. A. Olsen of the U.S. Atomic Energy Commission.

All correlations used in preparation of cross sections and stratigraphic maps are based on electric-log characteristics that delineate rock stratigraphic units; no time relationships are inferred. Guide fossil data were obtained from the Geomap of the Gulf Coast (1974) and are included on the cross sections. Guide fossil horizons, however, were not carried as individual marker horizons but were useful in places as a guide to correlation. There are no persistent marker beds, such as coal, bentonite, or thin limestone, that can be used for correlation throughout the project area. Locally, some beds are distinctive enough to be traced with confidence between closely spaced wells. More commonly, stratigraphic boundaries are indistinct and correlations are interpretative. Sea level is the reference datum upon which all electric logs in the cross sections are aligned in order to show the present structural configurations.

Where possible, correlations were checked with nearby type logs (Kling, 1972), with cross sections prepared by the Corpus Christi Geological Society (1954; Valerius, 1964) and the South Texas Geological Society (1951), with the Geomap of the Gulf Coast (1974), and with reports and bulletins of the Texas Water Development Board (Dale and other, 1957, Pls. 2-3; Anders, 1960, Pls. 2-4; Alexander and White, 1966, Figs. 35-39; Follet and Gabrysch, 1965, Pls. 2-4; Shafer, 1965, Figs. 15-17; Myers and Dale, 1966, Pls. 2-4; Myers and Dale, 1967, Figs. 15-17; Harris, 1970, Pl. 105; Shafer and Baker, 1973, Figs. 19-21; Shafer, 1974, Figs. 5-7; Eargle and others, 1975a, secs. 1-10).

The Tertiary sequence (Fig. 2) along the South Texas Coastal Plain consists principally of sandstone, siltstone, and shale. Of these, sandstone is the most important host rock for uranium ore. Experience indicates that sandstones deposited in certain environments are more favorable to uranium deposition than others. Because the thickness and geometry of sandstones generally reflect the environment of deposition, a series of lithofacies maps were prepared to facilitate analysis of depositional environments. Lithofacies maps were made for the Yegua (Pls. 30-32), Jackson (Pls. 36-38), Frio (Pls. 42-44), Catahoula (Pls. 48-50), Oakville (Pls. 54-56), and Goliad intervals (Pls. 59-61). These maps show total sand thickness (sand isoliths), sandstone/shale ratio, and the number of sands 20 to 50 ft thick (optimum sands) for each of these units.

Structure and isopach maps were prepared for all units except the Anahuac, Vicksburg, and Fleming. Because the Anahuac and Vicksburg units are entirely marine, they are considered to have low potential for uranium. The Fleming is continental but also has low potential because it is predominantly fine grained.



System	Series	Group	Formation	Description
TERTIARY	PLIOCENE		Goliad	Fine to coarse sand and conglomerate. Medium to fine sandstone; gray to pink calcareous clay; medium to coarse basal sandstone strongly calichified; 1,100 to 1,700 ft thick.
	MIOCENE		Fleming	Calcareous clay and sand, gray to pink, red, or light brown; 250 to 1,750 ft thick.
			Oakville	Calcareous, crossbedded, coarse sand. Some clay, silt, and reworked sand and clay pebbles near base; 100 to 2,100 ft thick.
			Catahoula	Light-gray to pink calcareous tuff; bentonitic clay; some gravel and varicolored sand near base. Soledad near middle in Duval County grades into sand lenses in northern Duval and adjacent counties. 250 to 2,700 ft thick.
				Anahuac Formation Fine to medium quqrtzose and glauconitic sands; green to gray fossiliferous clay; 0 to 800 ft thick.
	OLIGOCENE(?)		Frio	Light-gray to green clay; overlapped by Catahoula Tuff northeast of Live Oak County. Occasional sand-filled channels. 200 to 2,700 ft thick.
				Vicksburg Group Gray and greenish-gray sandy calcareous clay; 0 to 400 ft thick.
	EOCENE	Jackson		Clay, fine sand, silt; carbonaceous, fossiliferous, and tuffaceous, minor gypsum and lignite; 700 to 1,700 ft thick.
		Claiborne	Yegua	Medium to fine sand, silt, clay, and selenite; some glauconitic sand, partly marine, fossiliferous, contains carbon and lignite beds. 700 to 1,500 ft thick.

Modified from Eargle and others (1971)

Figure 2 Generalized Stratigraphic Column For the South Texas Gulf Coast

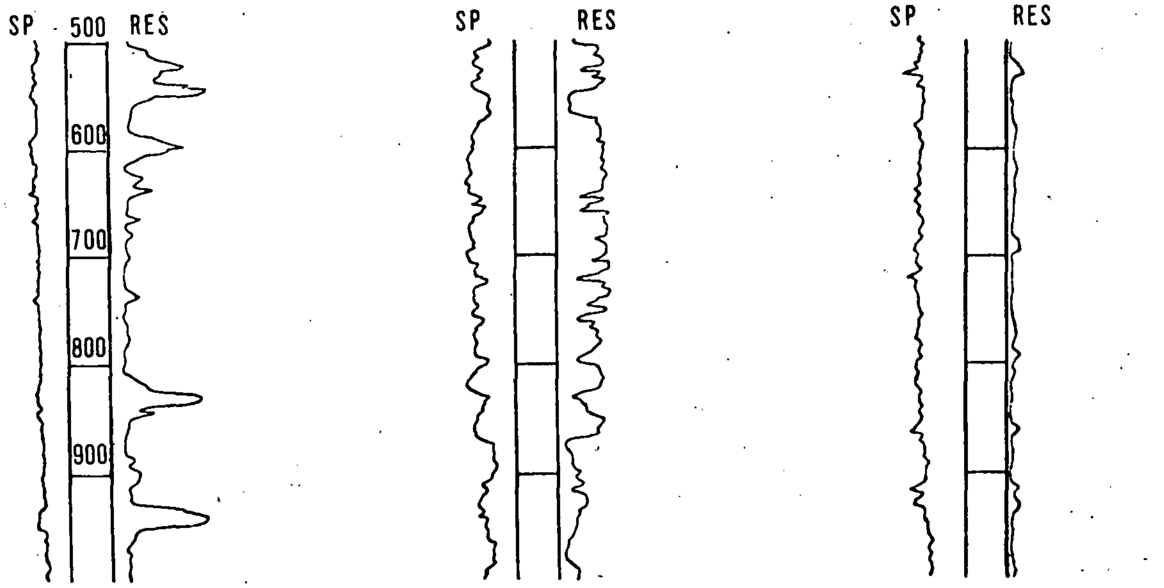
Sands deposited in specific environments within each depositional system have certain unique characteristics. These characteristics influence the SP and resistivity curves on electric logs in ways specific for each environment (Fig. 3). This permits specific depositional environments to be identified and delineated directly on electric logs (Fisher and others, 1969, 1970). Paleogeographic maps were then prepared on the basis of these interpretations and from the lithofacies maps. A paleogeographic map was prepared for each of the Yegua, Jackson, Frio, Catahoula, and Oakville units and for the lower 500 ft of the Goliad (Figs. 4-9). Each map shows the geographic distribution of depositional environments present along the South Texas coast at the time each unit was being deposited.

All of the stratigraphic maps and cross sections made for this report are based on rock stratigraphic units as they appear on electric logs. There are two limits imposed on this data. First, this project was limited to a depth of 5,000 ft. Second, information from the zone of outcrop downward into the shallow subsurface is incomplete because of local erosional truncation or because of the depth at which the logging of the test wells began. Logging of test wells began several hundred feet below the surface of the ground, and thus, the depth of incomplete data is significant. Conclusions for the area within the zone of outcrop and shallow subsurface are based either upon partial data or upon information obtained from other sources, primarily publications. Statements and conclusions pertaining to sediments deeper than 5,000 ft are based on literature sources. Analyses of structure, isopach, lithofacies, and paleogeographic maps integrated with information from the literature provide the basis for the designation of certain areas and stratigraphic horizons that are favorable for uranium resources.

The geologic map (Pl. 1) was prepared by combining data on geologic maps published by the Texas Bureau of Economic Geology (1974a, 1974b, 1975), Geodata International (1974), and Gulf Coast Association of Geological Societies (1972). In some places, the locations of formation contacts on the map were adjusted to tie in with subsurface correlations. Lineaments appearing on LANDSAT imagery and county aerial-photomosaics were added to the map. The purposes of this map are to show patterns of outcrop for the formations covered in this report and to show the locations of lineaments that may represent faults associated with ore deposits.

STRATIGRAPHY

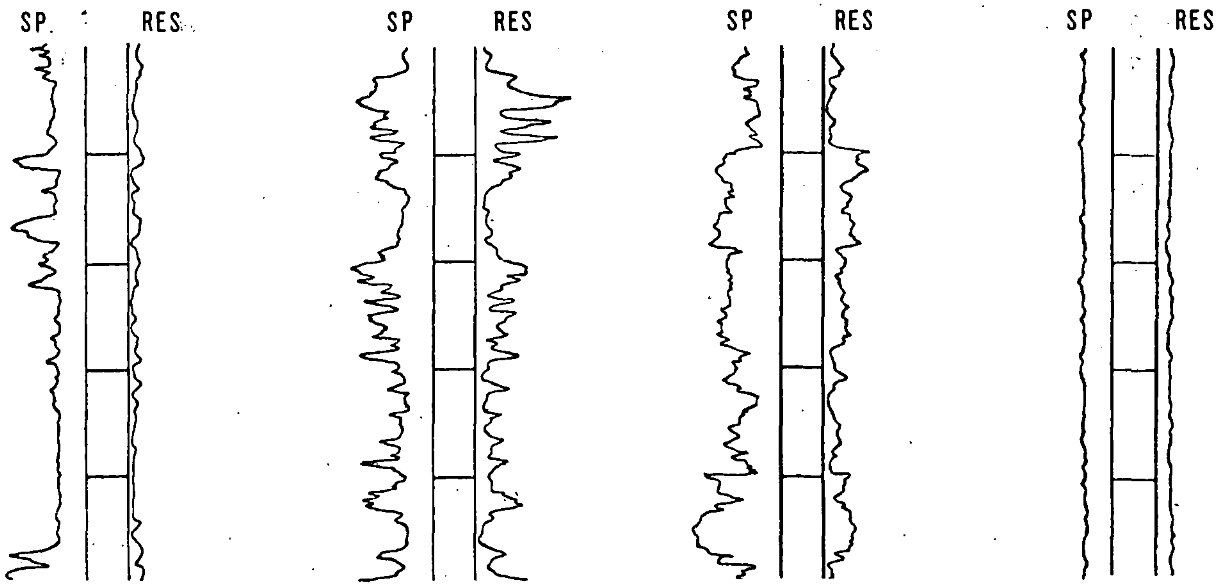
There is no general agreement on the stratigraphic nomenclature of Tertiary sediments along the Texas Gulf Coast; therefore, rock stratigraphic names are used as defined by the U.S. Geological Survey (G. V. Cohee, written commun., 1975). The Tertiary units considered include the following, in ascending order: Yegua Formation, Jackson Group, Vicksburg Group, Frio Clay, Anahuac Formation, Catahoula Tuff, Oakville Sandstone, Fleming Formation, and Goliad Sand (Fig. 2).



Fluvial system: channel and nonchannel

Fluvial system: multistoried channels

Lagoonal system



Strand plain-lagoonal systems

Strand plain-barrier bar systems

Strand plain-barrier bar system: stacked bars

Shelf system

Figure 3. Representative electric-log characteristics of principal depositional systems, South Texas Coastal Plain

Attention is called to the use of Frio Clay and Catahoula Tuff. The Texas Bureau of Economic Geology (W. L. Fisher, personal commun., 1975) considers the Catahoula to be the updip equivalent of the Frio. Thus, in the new Geologic Atlas of Texas (Bureau of Economic Geology, 1974a, 1975), only the Catahoula appears at the surface (Pl. 1, this report). As defined by the U.S. Geological Survey and in the practice of many exploration geologists in South Texas, the Catahoula is stratigraphically younger than the Frio, and both can be recognized in outcrop. In this report, therefore, the Catahoula is mapped as overlying the Frio. Downdip in the subsurface, the Anahuac wedges between them.

The Vicksburg and Anahuac, both marine, and the Fleming Formation are not considered favorable for uranium; however, they are discussed briefly as integral parts of the stratigraphic sequence. The Cook Mountain Formation and older units of the Claiborne Group are likewise excluded from consideration; however, they are included on several cross sections as an aid in correlation.

YEGUA FORMATION

The Yegua Formation is the youngest formation in the Claiborne Group. The Claiborne Group (middle Eocene) in South Texas includes, in ascending order, the Carrizo Sand, Reklaw Formation, Queen City Sand, Weches Formation, Sparta Sand, Cook Mountain Formation, and the Yegua Formation. Of these, only the Yegua was studied in detail.

The Claiborne Group consists of an alternating series of continental and marine beds that represent a succession of transgressions and regressions during middle Eocene time. The Yegua Formation represents the last of these regressions.

The Yegua Formation, as defined by Dumble (1892, p. 148-153) and Deussen (1914, p. 65-67), overlies the Cook Mountain Formation and is overlain by the Jackson Group. The Cook Mountain and most of the Jackson are marine. Dumble and Deussen considered the Yegua to be mostly nonmarine. Their conclusions were based on surface exposures; downdip, in the subsurface, the Yegua becomes increasingly marine.

On electric logs, the top of the Yegua is marked at the top of the massive sandstones, and the base is marked at the bottom of the first sandstone above the thick Cook Mountain shale. Downdip, where the Yegua consists of shelf muds, and updip, where lagoonal muds predominate, the sandstone markers may not be present, and the contacts are difficult to define.

The Yegua crops out in a band that extends from central Gonzales County southwestward through Karnes, Atascosa, McMullen, La Salle, Webb, and Zapata Counties (Pl. 1). The width of outcrop varies from 1 to 17 miles and is widest in Atascosa, La Salle, and Webb Counties.

JACKSON GROUP

The Jackson Group includes all Eocene strata above the Yegua Formation (Sellards and others, 1932, p. 677). The Jackson rests on the Yegua Formation and is overlain by either the Frio Clay or Vicksburg Formation. At Tordilla Hill, Karnes County, the Catahoula rests directly on the Jackson. In the subsurface, the top of the Jackson Group is marked at the top of a 100- to 300-ft-thick sandstone. The base is marked where lowermost Jackson clay overlies marine sands of the Yegua Formation.

The geologic history of the Jackson Group is one of transgressions and regressions (Sellards and others, 1932, p. 689). The lower part of the Jackson was deposited during a major transgression over Yegua beds. One or more regressions mark the middle of the Jackson, and the final withdrawal of the sea marks the end of Jackson deposition.

The Jackson Group has been divided into several formations and members (Eargle, 1972). Many individual sand layers have been informally named by petroleum geologists. In future work, the Jackson should be broken into members and individual sand units to further assess the uranium potential of the group.

The Jackson Group crops out in a belt that arcs southwestward from Gonzales County through Karnes, Atascosa, Live Oak, Duval, McMullen, Webb, Zapata, and Starr Counties. The width of outcrop varies from 4 to 20 miles; it is widest in Webb, Zapata, and Starr Counties (Fig. 5).

VICKSBURG GROUP

The Vicksburg Group is accepted as the lower part of the Gulf Coast Oligocene (Stuckey, 1953, p. 27); however, the name is usually applied either broadly or in the time-rock sense, and as such, it has no real lithologic unity (Murray, 1952, p. 701). In this report, the Vicksburg is treated as a lithologic unit. It appears only in the subsurface and is wedged between the Frio above and the Jackson below.

The Vicksburg consists mostly of gray, slightly calcareous clay with some sandy clay and local lenses of very fine sand (Sellards and others, 1932, p. 702). The lower boundary is selected at the top of the highest Jackson sandstone, and the upper boundary is picked at the top of a sand that is commonly found below the lowest shale sequence in the overlying Frio. This Vicksburg top agrees reasonably well with the top defined by the first appearance of the foram *Textularia warreni* in well cuttings. The sand that marks the top of the Vicksburg is absent in some wells, and in this case, correlation is difficult without fossil data. No attempt was made during this study to subdivide the Vicksburg Group into its formations.

In dip sections (Pls. 6-14), the Vicksburg appears as a wedge that pinches out updip or landward. Seaward and downdip, the Vicksburg wedge thickens to more than 400 ft in the study area and to 2,000 ft in some deep wells near the coast. The Vicksburg is marine in origin (Deussen and Owen, 1939, p. 1618-1619) and does not possess characteristics favorable for uranium deposits. Therefore, it is not treated in detail.

FRIO CLAY

The Frio Clay (Oligocene) has been defined and used in many ways; there is no consensus today as to how the term should be used or restricted (Dumble, 1894, p. 554; Bailey, 1926, p. 45; Sellards and others, 1932, p. 703; Ellisor, 1933, p. 1325; Warren, 1957, p. 222; Boyd and Dyer, 1965, p. 7). In this study, the Frio is defined as the silt and clay that overlie the sandstones that mark the top of the Jackson and Vicksburg Groups and that underlie the basal sandstone of the Anahuac or the tuffs and sandstones of the Catahoula. Because both units are fine grained, the contact with the Catahoula is difficult to define on electric logs.

The Texas Bureau of Economic Geology considers the Frio to be the subsurface equivalent of the Catahoula Tuff (W. L. Fisher, personal commun., 1975); thus, on the Geologic Atlas of Texas only the Catahoula is mapped (Bureau of Economic Geology, 1974a, 1975). Geodata (1974) has followed the Bureau's convention in this matter. Therefore, since neither the Bureau's atlas nor the map from Geodata show the Frio, their Catahoula appears as the Frio-Catahoula on Plate 1 of this report. Thus, the outcrop belt for the Frio occupies approximately the western half of the Frio-Catahoula outcrop pattern on Plate 1. This is a reasonable approximation because the Frio and Catahoula are nearly equal in thickness near the outcrop.

ANAHUAC FORMATION

The Anahuac Formation (upper Oligocene or lower Miocene) is present in Texas only in the subsurface and is informally referred to as the Anahuac wedge. Anahuac sediments consist of sand, sandy clays, and clays. Locally, there are thick lentils of limestone in the form of foraminiferal deposits and coral reefs. The reefs appear to have developed around and over salt domes. The clays are greenish gray or gray, calcareous in part, sandy in some layers, and fossiliferous. Sands are very fine to medium grained and partly glauconitic (Sellards and others, 1932, p. 707).

Updip, the top of the Anahuac is picked at the contact of an Anahuac sandstone below the Catahoula Tuff. Downdip, the top of the Anahuac, marked by the foram Discorbis zone, is shaly and is picked at the base of a massive basal sandstone in the Catahoula. The base of the Anahuac is marked where Anahuac sandstone, containing foram Heterostegina-Marginulina, overlies Frio Clay.

The Anahuac varies along strike from predominantly shale in the southern part of the project area to mostly sandstone in the north (Pls. 6 and 13). Updip to the west, the Anahuac consists mostly of shale and either pinches out or merges with the Catahoula Tuff. The wedge character of the Anahuac is best seen on cross section G-G' (Pl. 11). In the study area the Anahuac ranges in thickness from 0 to 800 ft. Because of its marine nature and because it has no known exposure to ground-water recharge, the Anahuac is considered an unfavorable unit for uranium deposits and is not discussed further.

CATAHOULA TUFF

The Catahoula Tuff (Miocene) in outcrop overlies the Frio Clay and is overlain by the Oakville Sandstone (Sellards and others, 1932, p. 714). In South Texas outcrops, the light-colored Catahoula beds lie upon the green and gray nontuffaceous clay of the Frio. In some places this color distinction is subtle and difficult to discern. In northern Live Oak County, the basal Catahoula is heavily cemented with silica, so that it forms a conspicuous cuesta (the "chalk bluffs") that marks the lower contact. The upper contact of the Catahoula is marked either by a cuesta of brownish-gray calcareous Oakville sandstone or by Oakville clay, which is darker, more calcareous, and less tuffaceous than the underlying Catahoula.

In the subsurface, the top of the Catahoula is marked at the base of the thick Oakville Sandstone. The contact of Catahoula Tuff with the underlying Frio Clay is almost impossible to find on electric logs. Farther downdip where the Catahoula overlies the Anahuac, the base of the Catahoula is marked at the top of the upper Anahuac sandstone or may be marked by basal Catahoula sandstone.

The Catahoula crops out in a belt that curves southwestward through Gonzales, DeWitt, Karnes, Live Oak, McMullen, and Duval Counties, then continues southward through Zapata, Jim Hogg, and Starr Counties (Pl. 1). The width of outcrop ranges from 1 to 16 miles and is widest in Live Oak, Duval, and southern McMullen Counties.

OAKVILLE SANDSTONE

The Oakville Sandstone was first named by Dumble (1894, p. 556) for the exposures along the Colorado River in Fayette County. The formation includes all Miocene strata above the Catahoula Tuff and below the Fleming Formation (Sellards and others, 1932, p. 730).

The Oakville overlies the Catahoula Tuff. In both outcrop and subsurface, the base of the Oakville is marked by either a basal pebble conglomerate that contains abraded Cretaceous fossils or by a coarse-grained sand that overlies the finer grained Catahoula Tuff (Sellards and others, 1932, p. 732). The top is picked where the Oakville Sandstone is overlain by clays of the Fleming Formation. Where either the Fleming or the underlying Catahoula is sandy, the contact is difficult to distinguish on electric logs.

The Oakville crops out continuously in a belt 2 to 13 miles wide across Gonzales, DeWitt, and Karnes Counties (Pl. 1). Outcrops of the Oakville are discontinuous in Live Oak, McMullen, and Duval Counties, where the formation is covered by the younger Fleming Formation or the Goliad Sand. The Oakville is not exposed south of Duval County but is present in the shallow subsurface.

FLEMING FORMATION

The Fleming Formation is sometimes called the Lagarto Clay or the Lagarto Formation. Fleming is the preferred usage of the U.S. Geological Survey (G. V. Cohee, written commun., 1975) and is used in this report.

In outcrop, the base of the Fleming is selected at the base of a yellow-gray, cross-bedded sand which overlies a yellowish, poorly bedded calcareous clay that contains lentils of coarse pebbly sand in the underlying Oakville (Sellards and others, 1932, p. 742). The top of the Fleming is drawn where calcareous silty clays are overlain unconformably by red or orange sands or gravel beds of Pliocene or Pleistocene age. In the subsurface, the lower contact is picked where Fleming Clay overlies thick Oakville Sandstones, and the upper contact is marked at the base of sandstones and conglomerates along the base of the Goliad. Where sandstones are found in the Fleming, contacts are defined with difficulty.

The Fleming crops out in DeWitt, Karnes, Bee, Live Oak, McMullen, and northern Duval Counties (Pl. 1). The width of outcrop is 2 to 19 miles. At places, continuity of the outcrop belt is broken by local extensions of the overlapping Goliad Sand. South of northern Duval County, the Fleming is completely covered by the Goliad and is present only in the subsurface. Thickness of the Fleming ranges from 250 to 1,750 ft, averaging about 1,100 ft.

GOLIAD SAND

The Goliad Sand of Pliocene age is the youngest Tertiary unit studied in this project. The formation was named for exposures of sandstone that overlie the Fleming Clay and that underlie Pleistocene deposits in Goliad County (Sellards and others, 1932, p. 750).

In the subsurface, the lower contact is picked where underlying clays of the Fleming are overlain by sandstones 900 to 1,800 ft thick. Where the Fleming contains sandstone at the top, the contact with the Goliad is obscure. Because of casing, the upper contact of the Goliad is not usually seen on electric logs. Where the upper contact does appear it is at the base of silt and mud deposits of the overlying Lissie Formation (Pleistocene).

Outcrops of Goliad Sand are found in DeWitt, Victoria, Karnes, Goliad, Bee, Live Oak, Jim Wells, Duval, Webb, Brooks, Jim Hogg, Starr, and Hidalgo Counties (Pl. 1). The width of outcrop varies widely because of erosion and the irregular cover of Pleistocene and younger deposits.

STRUCTURE

Faults and salt domes are the structural features important to uranium exploration in South Texas. Details of structural configurations are shown on a series of structure maps prepared for the Yegua Formation (Pl. 28), Jackson Group (Pl. 34), Frio Clay (Pl. 40), Catahoula Tuff (Pl. 46), Oakville Sandstone (Pl. 52), and Goliad Sand (Pl. 58). The top of each unit was used as the structural datum with the exception of Plate 58 for the Goliad. Because data for the top of the Goliad is largely incomplete, structure at the base of the Goliad was mapped instead (Pl. 58). In general, for each stratigraphic unit, regional dip is toward the coast. Dips steepen and structures become more numerous and complex in progressively older and deeper strata.

There are four major strike-oriented fault zones within the project area (Fig. 1). These zones, from northwest to southeast, are Mirando-Provident City, Sam Fordyce-Vanderbilt, McAllen, and Willmar. Displacement within these fault zones ranges locally from a few feet to more than 1,500 ft. The latter is along the Sam Fordyce-Vanderbilt fault zone in Starr County (Pl. 40).

In many places, thickening of sedimentary units on the downthrown side of a fault indicates that faulting and deposition were contemporaneous. Much of the gulfward thickening in the Tertiary of the Coastal Plain is due in part to these contemporaneous growth faults (Bebout and others, 1975, p. 7). Most of these faults were active only during the time of deposition, and unless they were later rejuvenated, they are not covered by younger sediments. The majority of the faults are high-angle normal faults with the downthrown block to the east (Pls. 1, 28, 34, 40, 46, 52, 58, and 59); the fault planes dip seaward on most of them. A few faults are exceptional in that their upthrown blocks are on the southeast side of the fault, toward the coast. These are referred to as up-to-the-coast faults. According to Weeks and Eargle (1963), precipitation of uranium may be controlled by faults that slow the flow of ground water. In several mines, up-to-the-coast faults appear to have done this effectively. Faults may also serve as conduits that allow reductants, such as hydrogen sulfide, to ascend from hydrocarbon-bearing rocks at depth (Eargle and others, 1975b, p. 778).

Few of the many faults in the project area are traceable at the surface. Most have been found by subsurface exploration for petroleum. Only major faults, and small ones mappable within the limits of well control, are shown on the structure maps and cross sections in this report.

The Gulf Coast was a sedimentary basin throughout Cenozoic time. All strata dip gently toward the gulf except where interrupted by faults, flexures, and salt domes. The more significant flexures are gentle, open anticlines, which are mostly associated with major faults (Honea, 1956, p. 52). They are economically significant as traps for oil and gas.

Salt domes are present at several places (Pl. 1) and are thought to be important because of the faults associated with them. Uranium deposits are found in the faulted rocks above Palagana dome in central Duval County. Other salt domes, shown on the Tectonic Map of the Gulf Coast Region (Gulf Coast Association of Geological Societies, 1972) and included on Plate 1, are Pescadito dome in western Webb County, Moca dome in northeast Webb County, Piedras Pintas domes in central Duval County, Gyp Hill in northeastern Brooks County, Alta Verde and Palo Blanco domes in northwestern Brooks County, and Dilworth dome in McMullen County.

LITHOFACIES ANALYSIS

Uranium in South Texas is found chiefly in sandstones deposited in specific depositional environments. Sandstones most favorable are those deposited along the margins of fluvial channels and those deposited in the strand plain marginal to lagoons. The purpose of this part of the report is to identify sandstones with their depositional environments.

The following analysis of facies and depositional environments is based on information from the literature and from a series of isopach and lithofacies maps prepared for this report (Pls. 29-32, 35-38, 41-44, 47-50, 53-56, 59-61). A series of cross sections showing depositional systems in vertical and lateral sequence (Pls. 6, 11, 19, and 20) were prepared by combining data from the lithofacies maps with data interpreted from electric logs. On the basis of data from these sources, paleogeographic maps are presented for the Yegua Formation (Fig. 4), Jackson Group (Fig. 5), Frio Clay (Fig. 6), Catahoula Tuff (Fig. 7), Oakville Sandstone (Fig. 8), and the lower 500 ft of the Goliad Sand (Fig. 9). These maps show the distribution and extent of principal depositional systems which are representative of the time during which each unit was deposited.

LITHOFACIES MAPS

Three types of lithofacies maps were prepared for this project. These maps show (1) the total thickness of sandstone, (2) the ratio of sandstone to shale, and (3) the number of sandstones 20 to 50 ft thick. These maps are based on sandstone data obtained from the electric logs used for subsurface correlation in this study.

Total sand thickness (isolith) maps show the net thickness of sandstone accumulation from place to place within the stratigraphic unit. Thick accumulations of sand, together with their orientations either along strike or parallel to the regional dip, help identify the location of sandy shorelines or fluvial systems. In units that are comparatively fine grained, such as the Frio, the geometry and orientation of small total sand accumulations show better on maps of the sandstone/shale ratio than on the total sand thickness maps.

The third set of lithofacies maps shows the number of individual sandstones 20 to 50 ft thick. These maps are discussed in the section on favorability.

DEPOSITIONAL SYSTEMS

A depositional system is an assemblage of process-related sedimentary facies (Fisher and others, 1969, p. 10). Four depositional systems are present in the subsurface area covered by this report. Each depositional system represents several depositional environments, but all of these are not necessarily present each time the depositional system is recognized. The four depositional systems and examples of environments commonly found within them are as follows (Fisher and Brown, 1972, p. 5-11):

Fluvial System: channel environments (such as channel floor, point bar, longitudinal bar, transverse bar), nonchannel environments (such as levee, crevasse splay, flood plain, swamp, marsh).

Strand Plain-Barrier Bar System: shoreface, beach, offshore bar, dunes, back-barrier, tidal deltas, washover fans.

Lagoon, Bay, and Estuarine Systems: bay-center, bay-margin, bayhead delta, tidal delta, washover fan.

Continental Shelf System: net mud accumulation with occasional sands deposited by storm waves and possibly by turbidity currents or density underflows (for stratigraphic units covered by this report).

These four depositional systems were delineated on electric-log cross sections by analyzing lithofacies maps and the electric logs. Electric-log patterns show that sands and sediments are characteristic of the depositional environments in which they were laid down. Examples of these patterns are given in Figure 3. By comparing electric-log patterns with examples in Figure 3, depositional systems can be delineated on the cross sections as shown on Plates 6, 11, 19, and 20. The paleogeographic maps (Figs. 4-9) are based on these interpretations.

YEGUA FORMATION

In outcrop, the Yegua consists of 50 to 60 percent fine-grained, poorly sorted sandstone. The remainder of the unit is composed of siltstone, sandy shale, and shale with minor lignite and bentonite (Sellards and others, 1932, p. 671). Many of the sandstones are highly cross-bedded. Sandstones are mostly brown, but they weather to gray. The remainder of the formation is chiefly siltstone and shale, which varies in color from dark chocolate brown to gray or greenish gray. The lighter colors are more common toward the top. The shale is usually well laminated. Gypsum and small fragments of carbonaceous (plant) matter are common in outcropping shale.

The Yegua Formation represents a major regression and, as such, consists of continental and marine facies (Renick, 1936, p. 13; Casey and Cantrell, 1941, p. 595). Facies in outcrop represent fluvial channel, flood-plain, lacustrine, and paludal environments (Sellards and others, 1932, p. 671). The cross-bedded sandstones and river channel deposits are separated by fine-grained, flood-plain siltstone and lacustrine shale.

In the subsurface toward the coast, the Yegua is predominantly marine. Analysis of lithofacies maps and facies data derived from electric logs shows that Yegua sandstone in the subsurface was deposited mainly in strand plain-barrier bar environments (Fig. 4).

Thickness of the Yegua in the subsurface varies between 700 and 1,500 ft. Isopachs run closely parallel to the regional strike (Pl. 29). The Yegua tends to thicken downdip slightly, but the isopachs are irregular in many places.

Total sandstone thickness within the Yegua varies from 190 ft in some wells to almost 1,300 ft in others (Pl. 30). The sand isoliths, like the formation isopachs (Pl. 29), parallel the regional strike. The greatest total thickness of sandstone is found as a long linear accumulation that extends northward through Starr, Zapata, and Webb Counties, then northeastward into Gonzales and DeWitt Counties. The shape and location of this concentration of sandstone is similar to that in the strand plain-barrier bar system of the overlying Jackson Group. Dip-oriented channel sands, which cut transversely across the lagoon and barrier-bar trends in the Jackson, are not evident in isoliths on the Yegua total sand thickness map (Pl. 30). These sands are probably present in the Yegua, but they are perhaps smaller and fewer than in the Jackson.

The lithologic composition in the Yegua is indicated by the sandstone/shale ratio map (Pl. 31). Sandstone/shale ratios of 1:1 or higher are found within an area located along the axis of the barrier-bar system. This area of high sand ratios is relatively wide across Zapata, western Starr, and Jim Hogg Counties; narrow across eastern Webb and western Duval counties; but wide again in the northern counties of the project area. Where this area of high sand ratios is widest, it extends into outcrop; where narrow, it is restricted to the subsurface.

Lagoonal sediments lie updip from the strand plain-barrier bar system in Zapata, Webb, and La Salle Counties (Fig. 4). However, these lagoonal sediments do not appear to be so broad and extensive as Fisher found for the overlying Jackson Group (Fisher and others, 1970, Fig. 14).

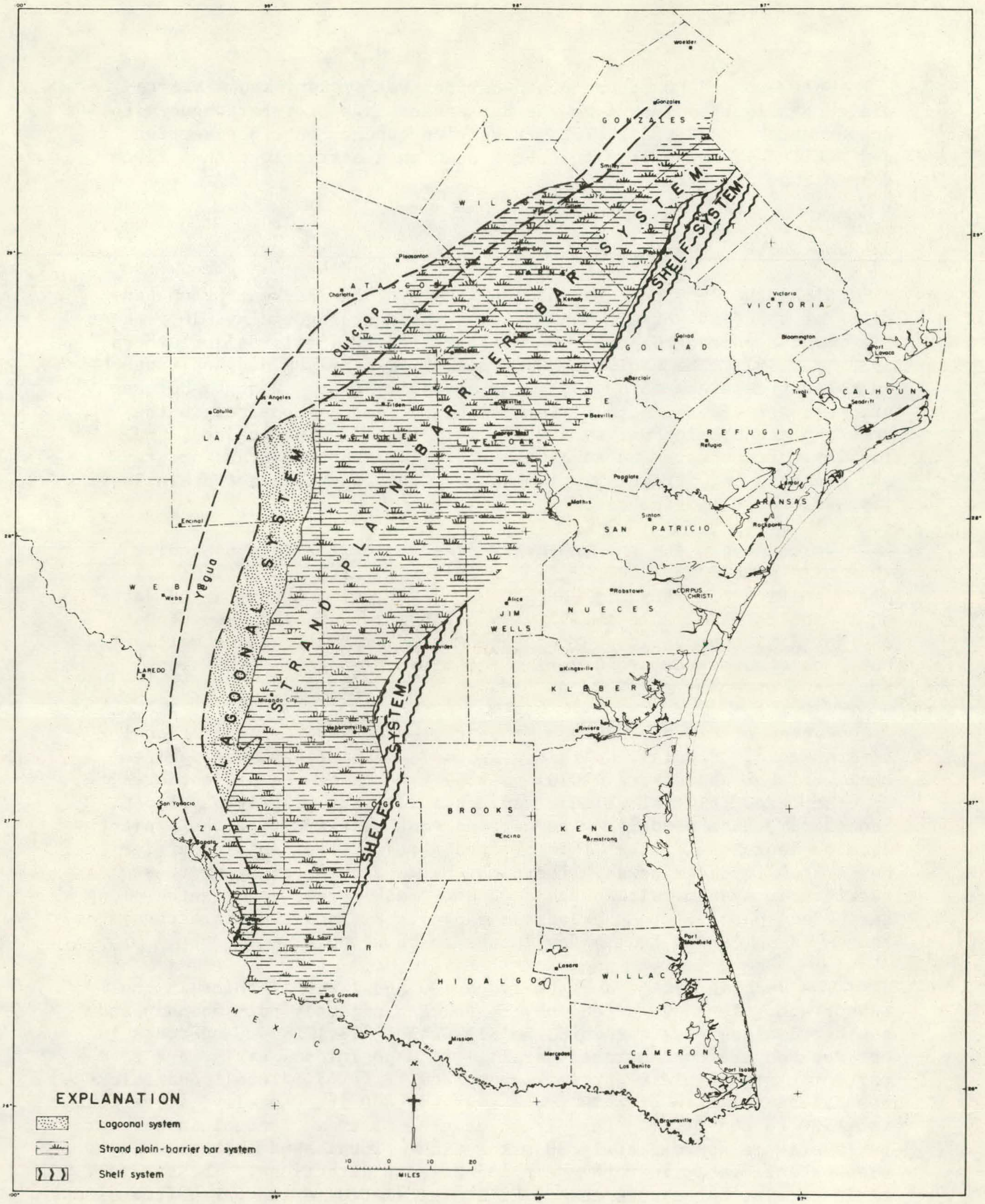


Figure 4. Paleogeographic map showing principal depositional systems in the subsurface, Yegua Formation, South Texas Coastal Plain.

Gulfward of the strand plain-barrier bar system, sands are replaced by finer sediments as the bar sands merge or intertongue with deeper water shelf muds. This transition appears on cross section J-J' (Pl. 14). However, it is best seen on electric logs that reach deeper than 5,000 ft.

JACKSON GROUP

Along the Jackson outcrop, the strata of the Jackson Group consists of about 45 percent sandstone, 40 percent sandy clay, 10 percent clay, and 5 percent bentonite and minor lignite (Sellards and others, 1932, p. 690). The sandstones are medium to fine grained and range in color from cream through various shades of gray. Most sandstones are well stratified in thin, regular beds. Sands deposited in the strand plain-barrier bar system are well sorted, fine grained, and locally tuffaceous. The sandy clays are light brown, drab, or gray and are thin and irregularly laminated. The sandy clays contain leaf impressions in many places.

Volcanic ash and the ash-derived sediments, chiefly bentonite (but also some layers identified as fuller's earth and kaolinite), are significant. They may be the source for the uranium in the Jackson deposits. Volcanic activity in northwestern Mexico, West Texas, and New Mexico probably started during the time of Yegua deposition and became more pronounced during the time of Jackson deposition (Sellards and others, 1932, p. 689).

Facies within the Jackson Group represent several depositional environments: fluvial, deltaic, lagoonal, barrier bar, and marine shelf (Fisher and others, 1970, p. 235). North of the project area, in east Texas, fluvial-deltaic sediments were extensively developed. Sands from these deposits were carried southwestward into the project area by longshore drift. This created a major strand plain-barrier bar system in South Texas. There may be as many as eight of these barrier-bar systems within the Jackson. Each system is oriented along strike and parallel to the Jackson shoreline. Sandstone in each system ranges in thickness from a few inches to about 60 ft.

The Jackson Group ranges between 700 and 1,700 ft thick in the subsurface. It shows a tendency to thicken slightly both downdip and southward along strike toward the Rio Grande (Pl. 35). Sandstones in the Jackson are concentrated parallel to depositional strike and form part of a strand plain-barrier bar system (Pl. 36). Total sand thickness along the axis of this trend averages 400 ft. Locally, it varies from 200 to 600 ft. In the direction of dip, the strand plain-barrier bar system is approximately 30 miles wide. Total sand thickness decreases noticeably in both updip and downdip directions. The strand plain-barrier bar system is primarily restricted to the subsurface except in Starr, southern Zapata, western Karnes, eastern Atascosa, and northeastern Webb Counties.

Downdip from the barrier bar, sands merge or intertongue with shelf muds (Pls. 11-12; Fig. 5). Updip from the sands of the strand plain-barrier bar is a band of lagoonal deposits, mostly muds, that

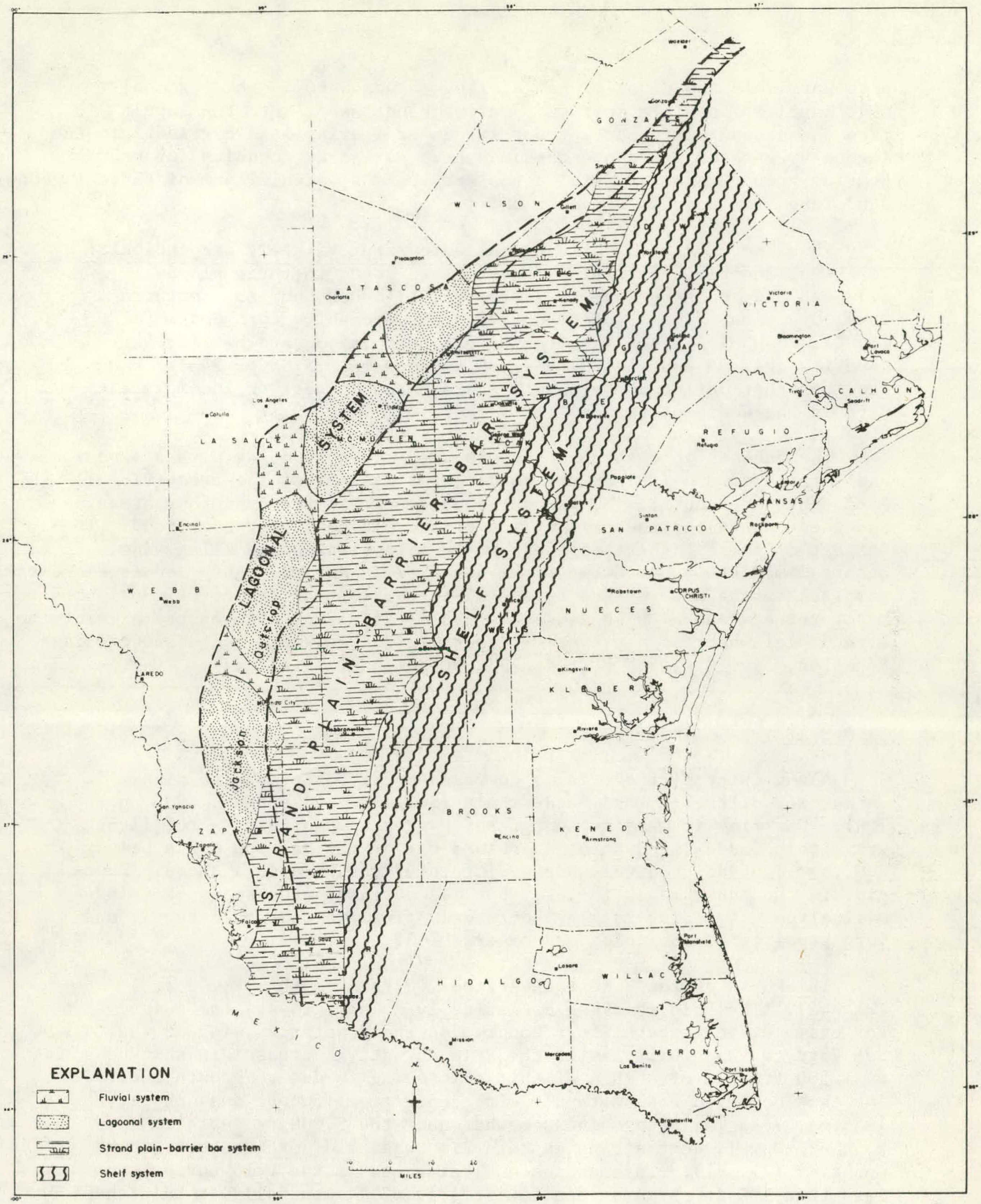


Figure 5. Paleogeographic map showing principal depositional systems in the subsurface, Jackson Group, South Texas Coastal Plain.

also parallels the depositional strike. Sandstones in the lagoonal muds have two possible sources: marine sands swept into the lagoon from the strand plain-barrier bar system or fluvial sand carried into the lagoon by streams. Because they may have served as conduits for uranium-bearing ground water, fluvial sands are the most significant of these lagoonal sandstones for uranium exploration.

Thick accumulations of sands oriented approximately perpendicular to the strand plain-barrier bar system are found in three places: (1) Webb and southern Duval, (2) central Live Oak, and (3) northern Duval Counties. These thick accumulations probably represent local fluvial channel systems that cut across both lagoon and barrier-bar deposits (Pl. 36 and Fig. 5) (Fisher and others, 1970, p. 246). Sand isoliths that define these channels are based in part on incomplete data in the updip portion of the Jackson.

The Jackson in the subsurface is predominantly muddy with a sandstone/shale ratio of 0.4 (29 percent sand) covering most of the area (Pl. 37). Ratios higher than 1:1 (50 percent sandstone) are found in four areas, and these are along the axis of the strand plain-barrier bar trend. The largest of these high-ratio areas is 10 miles long and 3 miles wide. It occurs immediately northwest of Karnes City in Karnes County and is elongated parallel to the axis of the strand plain-barrier bar trend (Pl. 36). The other three areas of high sandstone/shale ratios are also on the axis of the strand plain-barrier bar system. They lie to the south and southwest in McMullen, Live Oak, and northern Jim Hogg Counties (Pl. 37).

FRIO CLAY

Along outcrop, the Frio is composed mostly of clay with minor sandstone, siltstone, and sandy shale (Sellards and others, 1932, p. 706). The clay is massive and greenish-gray in contrast to the light gray, thin-bedded sandy clay and sandstone of the Jackson Group below and the light-colored volcanic sediments of the Catahoula above. Downdip, in the subsurface, the clay becomes more calcareous and contains marine fossils. Silt is gray, extremely fine grained, calcareous, and very gypsiferous (Sellards and others, 1932, p. 706).

Thickness of the Frio ranges from 200 to more than 2,700 ft (Pl. 41). The Frio thickens dramatically downdip toward the coast. For example, in eastern Starr County, on the downthrown side of the Sam Fordyce-Vanderbilt fault, the Frio abruptly increases in thickness by 1,500 ft (Pl. 6). Much of this thickening is due to growth faulting that occurred concomitantly with deposition (Bebout and others, 1975, p. 7). The Frio thins somewhat near the 5,000 ft depth in southern Duval, central and eastern Jim Hogg, and northwestern Brooks Counties (Pl. 41). Total sandstone thickness in the Frio varies from less than 100 ft to more than 600 ft (Pl. 42). Generally, total sandstone thickness increases toward the southern part of the project area where the thickest accumulations are in irregularly shaped areas that are difficult to interpret. Areas of relatively high sandstone/shale ratios in central and southern Duval, central Live Oak, and southern

Jim Hogg Counties are oriented perpendicular to strike (Pl. 43). These areas represent sands deposited in narrow, sinuous bands. Sandstones within these bands are typically thin and laterally discontinuous. These features are indicative of channel sands deposited in the flood plain by meandering streams.

In central and northern Jim Hogg County and in the southeastern tip of Webb County, areas of thick sandstone accumulation are irregularly shaped and apparently randomly distributed. Electric-log characteristics of these sandstones suggest that they are a series of fluvial channel sandstones stacked vertically (Fig. 3).

In eastern Starr County there is a marked increase in total sandstone thickness (Pl. 42). This increase is caused by growth faulting along the Sam Fordyce-Vanderbilt fault zone. It is not indicative of a change in depositional conditions across the fault. The sandstone/shale ratio shows no increase in the amount of sand relative to other sediments on the downthrown side of the fault (Pl. 43). A similar north-south thickening of sands appears in central Starr County. This feature may also be due to fault control.

Within the area covered by this report, the Frio is predominantly mud. In the northern part of the project area (Pl. 43), most of the sandstone/shale ratios are 0.2 (16 percent sand) or less. Ratios in the southern part are more variable but remain relatively low. Two small areas have ratios just slightly greater than 1:1 (50 percent sand); one of these is in southwestern Duval and the other is in southwestern Jim Hogg County. The fine-grained character of sediments indicates that most of the Frio in the project area was deposited in the flood-plain environment bordering channels in the fluvial system (Fig. 6).

CATAHOULA TUFF

The Catahoula in South Texas contains about 82 percent tuffaceous clay, 9 percent sandstone, 3 percent vitric tuff, 5 percent bentonitic clay, and 1 percent conglomerate (McBride and others, 1968, p. 10). North of the McMullen-Duval County line, the Catahoula is predominantly tuffaceous clay and silt. South of this line, channel sands are conspicuous. The major sand buildups were developed in Jim Hogg and southern Duval Counties.

The tuffs are of several types (Bailey, 1926, p. 109), but in general they are massive bedded, fine textured, and light colored. The sandstones are medium to coarse grained, gray or brownish-gray to buffish-gray, cross-bedded quartz sandstones, usually cemented with white opal; but some sands are unconsolidated.

The Catahoula clays are mostly gray or dark brownish-gray. In outcrop they weather to variegated colors. The clay is probably derived from the accumulation and weathering of fine ash.

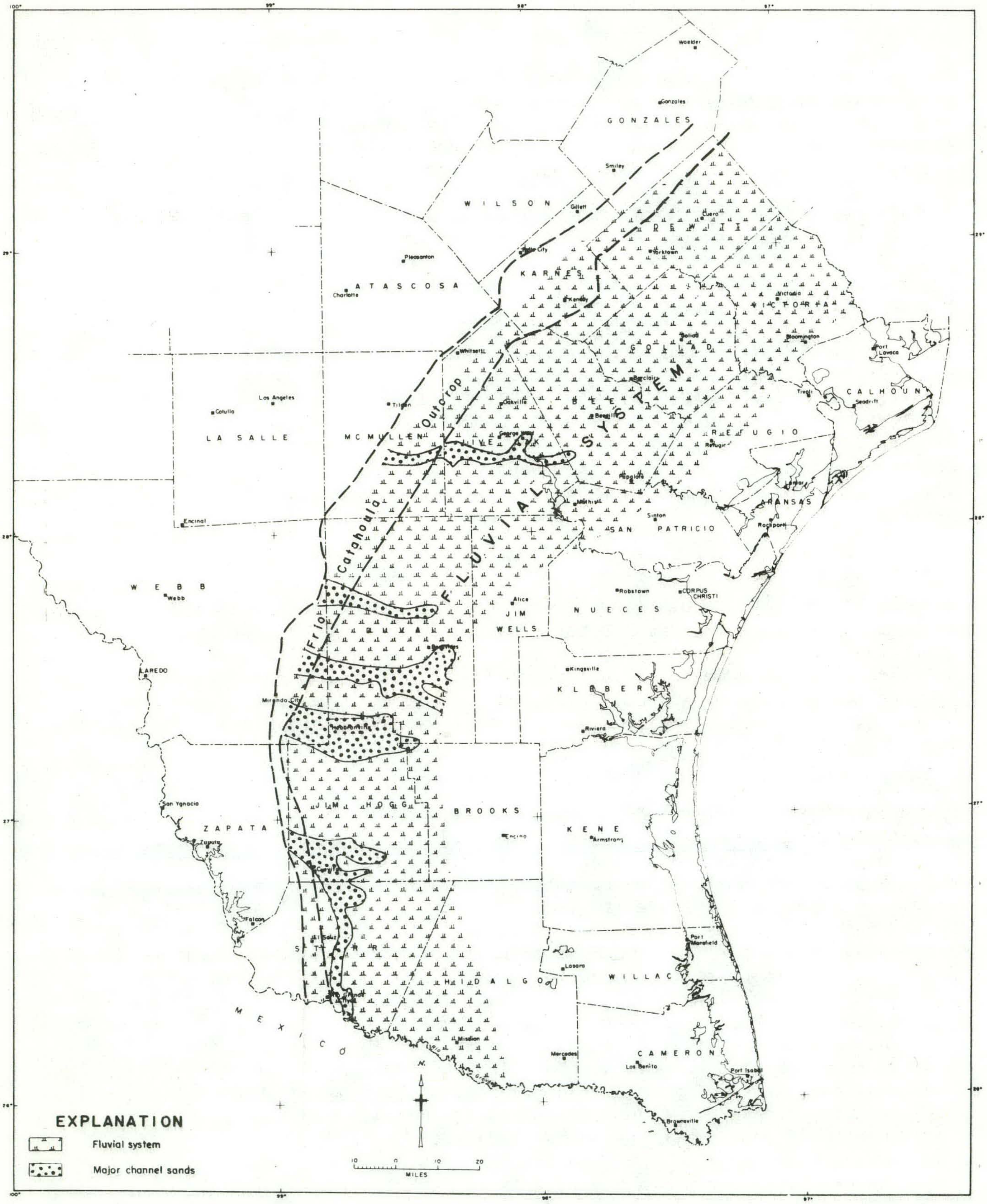


Figure 6. Paleogeographic map showing principal depositional systems in the subsurface, Frio Clay, South Texas Coastal Plain.

Catahoula conglomerates in South Texas are a poorly sorted mixture of dark-colored volcanic and chert pebbles and cobbles set in a matrix of bluish-white opal cement. Some boulders are as large as 2 ft in diameter. Generally, the Catahoula is noncalcareous and unfossiliferous. Shards of volcanic glass are abundant in the Catahoula, rare in the underlying Frio and Jackson, and absent in the overlying Oakville.

Three members are recognized in the Catahoula Tuff of South Texas, although all three may not be present throughout the project area (Sellards and others, 1932, p. 716). At the base is the Fant Member, which consists of about 200 ft of volcanic ash and tuff with some clay. In the middle is the Soledad Conglomerate. This is a series of strata composed of volcanic conglomerate, sandstone, and tuff. The conglomerate is cemented with milky-white opal that forms a series of resistant ridges in McMullen County. The upper member is the Chusa Tuff. The Chusa is an unstratified, unconsolidated, and sometimes marly series of tuff and tuffaceous clay. These three members can be recognized on many of the electric logs, but the Catahoula was not subdivided in this study.

The Catahoula Tuff is a series of continental pyroclastic sediments interbedded with river and stream sediments that merge downdip with marine deposits. Volcanic activity during Catahoula time was a continuation of Jackson volcanism but with much greater intensity. McBride and others (1968) suggested that the volcanic centers were in southwest Texas and adjacent areas of northern Mexico. Some of the fine ash may have been airfall, but the location of the volcanic centers and their distances from the present areas of outcrop are speculative. Scarce brackish-water clams and fossil-plant remains support a continental origin for Catahoula Tuff deposits.

During Catahoula time, sedimentation occurred across a broad coastal plain (Fig. 7). Large volumes of volcanic sediments were carried by wind and stream and were deposited across the plain. Rivers were concentrated in the southern part of the project area where they deposited thick accumulations of sand and gravel (Pl. 48). Other streams and rivers in the northern part of the project area deposited channel-fill sands that can be seen on electric logs (Pls. 11-13). However, the lack of thick total sand accumulation (Pl. 48) and the low sandstone/shale ratios (Pl. 49) suggest that northern rivers were either fewer or smaller than those in the south.

The Catahoula Tuff varies in thickness from north to south. At the northern edge of the project area where sediments thin on the flank of the San Marcos arch, the Catahoula is only 250 ft thick (Pl. 47). Southward into the Rio Grande Embayment, the Catahoula progressively thickens until it reaches a thickness of more than 2,000 ft. None of the other formations covered in this study show such a noticeable increase in thickness within the area of the Rio Grande Embayment as the Catahoula. Apparently, the embayment was actively subsiding during Catahoula time. The greatest subsidence was in the area of southern Duval and northern Jim Hogg and Brooks Counties. Within this area the Catahoula is as much as 2,700 ft thick. As is true for the Tertiary

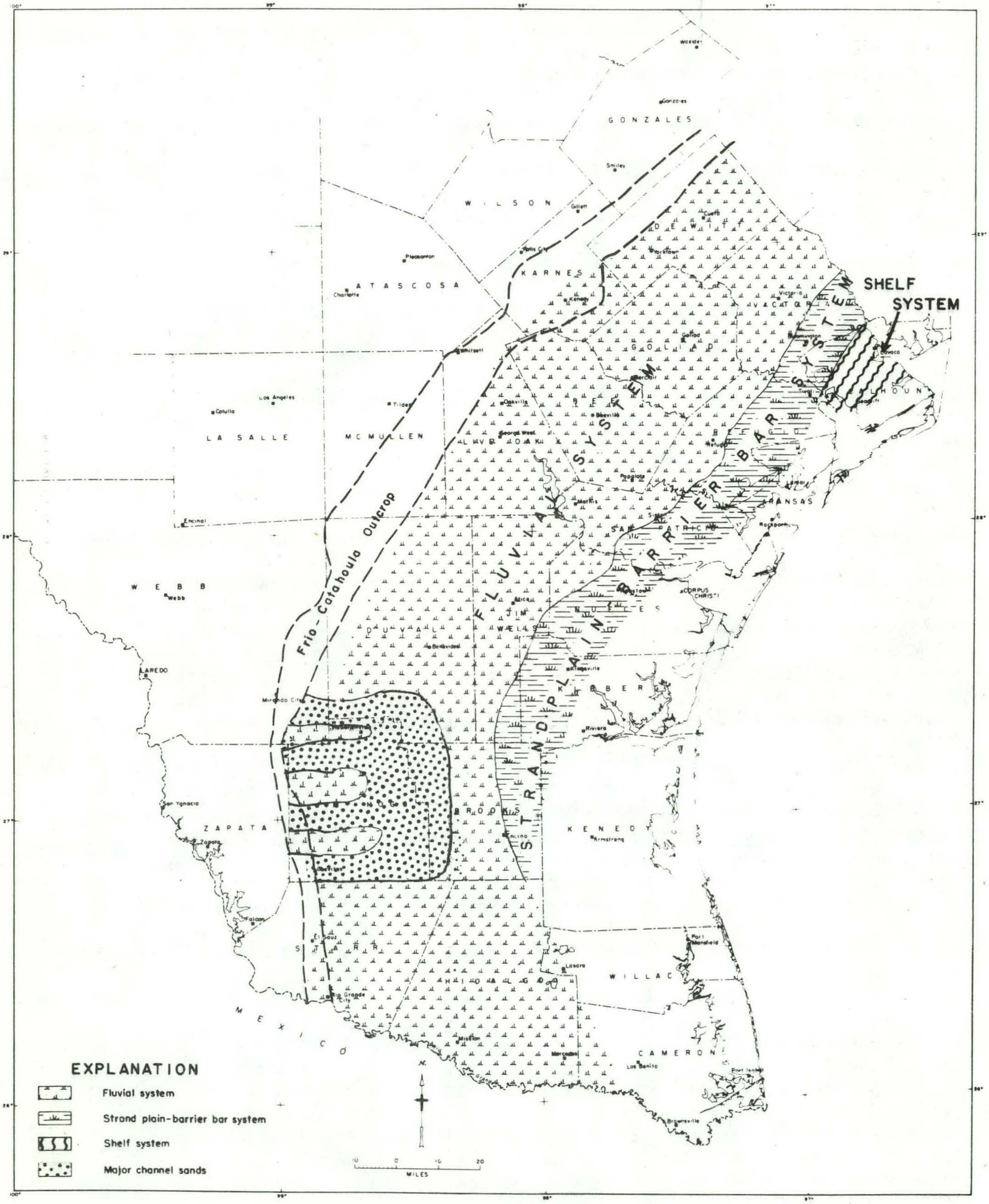


Figure 7. Paleogeographic map showing principal depositional systems in the subsurface. Catahoula Tuff. South Texas Coastal Plain.

sediments in general, the Catahoula also thickens slightly in the downdip direction; but this tendency is overshadowed by the thickening from north to south.

The greatest accumulation of sandstone in the Catahoula Tuff is in the Rio Grande Embayment. In northern Jim Hogg and Brooks Counties, total sandstone thickness exceeds 1,200 ft at several places (Pl. 48). In the remaining area of the embayment, total sandstone accumulation is generally 500 to 1,000 ft.

Along the western edge of the embayment, sand isoliths project abruptly westward in four places. These outline narrow, dip-oriented sand accumulations interpreted as fluvial channel systems along the western edge of the embayment (Fig. 7).

Along the eastern and northeastern edges of the project area is a second thick accumulation of sandstone that forms a long, narrow, strike-oriented, barrier-bar deposit. Total sandstone accumulation along the crest of the barrier-bar system is 400 to 600 ft (Pl. 48). The bar system extends from Kleberg County northeast along the modern coast into Victoria and Calhoun Counties.

The area north of the Rio Grande Embayment and west (updip) of the strand plain-barrier bar consists of fine-grained flood-plain deposits. Throughout this area, total sand thickness rarely exceeds 300 ft.

Sandstone/shale ratios of 1:1 (50 percent sandstone) or higher are found along the barrier-bar system at the northeast edge of the project area (Pl. 49). In the middle part of the system in Kleberg, Nueces, and San Patricio Counties, high ratio areas become smaller and are separated by increasing distances. High sandstone/shale ratios are also located at the south end of the system in Brooks County and at the downdip end of three of the fluvial channel systems in Jim Hogg and southern Webb and Duval Counties. Elsewhere, areas with ratios higher than 1:1 are very small and isolated.

A small area of marine shelf muds is present along cross section I-I' in Calhoun County (Pl. 13). These muds continue southward flanking the strand plain-barrier bar sands on the east, but these muds are either too deep or too far east to show on other cross sections or on Figure 7.

OAKVILLE SANDSTONE

In outcrop, the Oakville consists of about 40 percent sand, 30 percent sandy or bentonitic clay, 20 percent marl, and 10 percent gravel and redeposited Cretaceous fossils (Sellards and others, 1932, p. 734). Sands of the Oakville are mostly light gray, medium grained, intricately and persistently cross-bedded, and friable. Calcite is the most common cement, but opal or chalcedony are locally present. Sandstones cemented with chalcedony are very hard and resemble quartzite. The amount of sand increases along outcrop from northeast to southwest.

Oakville clay is gray or dirty yellow, compact, poorly laminated, calcareous, or marly. In places it contains reworked Cretaceous foraminifera and larger shells. Some Oakville clay contains volcanic ash, derived either from erosion of the older Jackson and Catahoula deposits or, where the ash is very pure, from volcanic activity during Oakville time.

Volcanic ash cemented by chalcedony is found in lentils, pipes, and concretions and resembles chert. It has been suggested that the pipes are volcanic vents filled with tuffaceous sediment that was later cemented with silica. Some of the siliceous deposits may be associated with faults that have allowed the ascent of siliceous waters from depth (Sellards and others, 1932, p. 735).

The Oakville is wholly continental wherever it crops out. Occasionally, fossil remains of land mammals of Miocene age are found in it. In the subsurface near the coast, Oakville strata contains a very rich marine fauna (Sellards and others, 1932, p. 736). Most of the Oakville in the subsurface of the project area is, however, continental. Fluvial facies are more or less continuous along strike (Fig. 8).

Thickness in the Oakville varies from less than 100 ft to more than 2,100 ft (Pl. 53). Generally the Oakville tends to thicken downdip. The thickest part is found in the southern part of the project area in the Rio Grande Embayment.

Total thickness of sandstones in the Oakville varies from less than 100 ft to more than 1,000 ft (Pl. 54). The greatest thicknesses of sandstone are found in two areas that adjoin. The first area, in Brooks County, is perpendicular to the coastline and near the axis of the Rio Grande Embayment. The second area, in Cameron, Willacy, Kenedy, and Kleberg Counties, parallels the coastline. Both accumulations are interpreted as channel sandstone deposits.

Many areas in the Oakville have a high sandstone/shale ratio (Pl. 35). These high ratio areas are irregular in shape and are oriented perpendicular to regional strike. The width of these varies from 10 to 40 miles. Examination of sand maps, electric-log characteristics, and well-cuttings samples indicates that these features are primarily multistoried, coarse-grained fluvial deposits. The greatest development and maximum thickness is in three main areas, one in the north, one in the middle, and one toward the south of the project area.

The channel sands are stacked in massive, multistoried sand bodies commonly as thick as 200 ft. These can be seen best on logs for wells 6433, 6435, 6436, and 6437 on cross section N-N' (Pl. 21). These and similar stacked sand bodies in the Oakville can often be traced horizontally for as far as 8 miles. Samples from well cuttings of these stacked channel sands show that the sands are fine to coarse grained.

Thick, massive fluvial sandstones in the Oakville indicate that sediment-laden rivers flowed across a gently inclined coastal lowland and repeatedly shifted their channels as they deposited great quantities of sand. Rapid deposition of sediment derived from nearby source

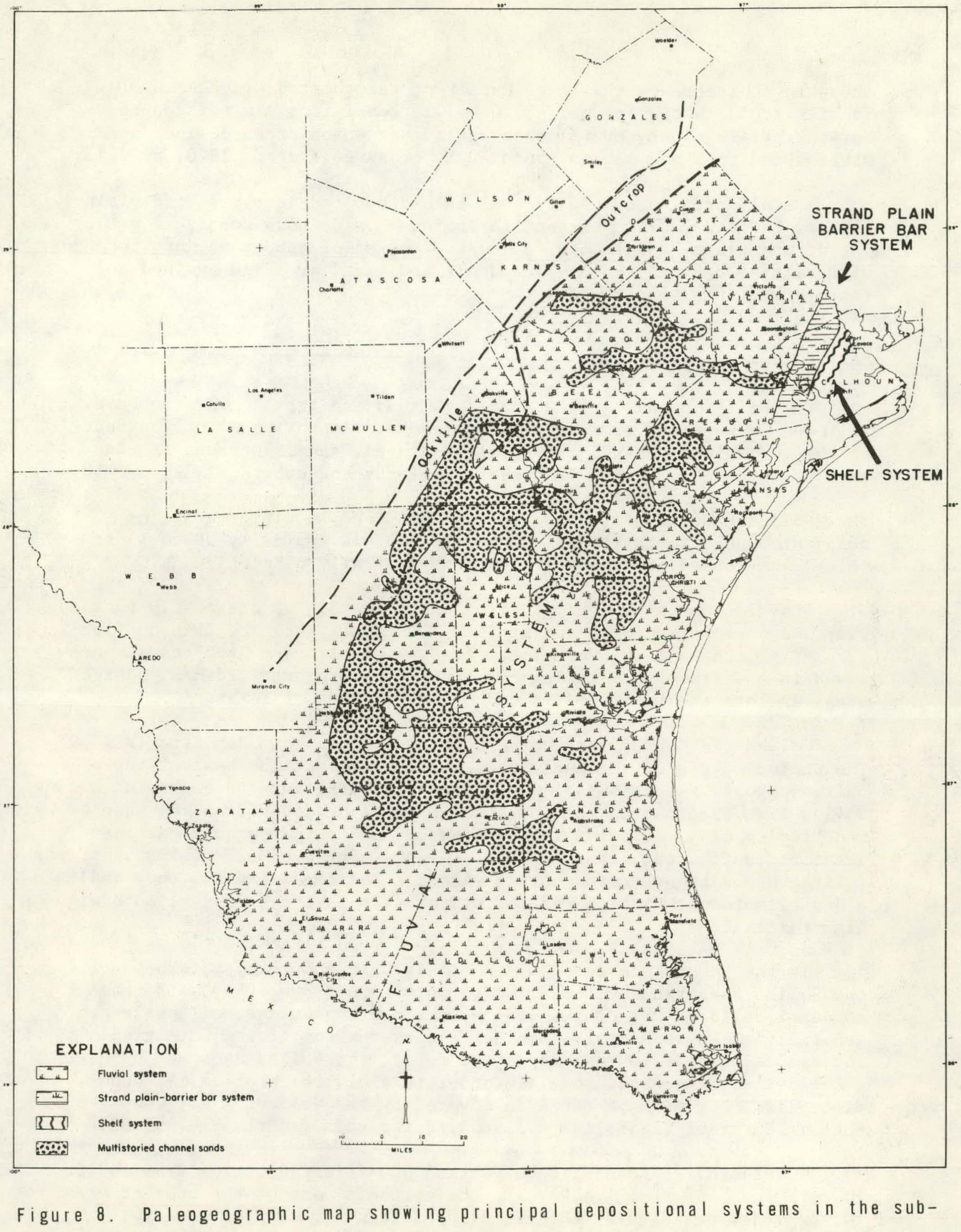


Figure 8. Paleogeographic map showing principal depositional systems in the subsurface, Oakville Sandstone, South Texas Coastal Plain.

areas is indicated by the large number of redeposited Cretaceous fossils found in the formation. Oakville conditions may reflect resurgent uplift along the Balcones fault zone which produced increased stream gradients and was accompanied by erosion (Norton, 1970, p. 21).

A small area underlain by sediments deposited in the strand plain-barrier bar and shelf environments is found in Calhoun County (Fig 8). The strand plain-barrier bar sediments consist of sandstone interbedded with silty rocks and shale. The shelf sediments are fine grained and contain few thin sandstones.

GOLIAD SAND

The Goliad consists of a series of sand and gravel near the base, followed by a series of sand and clay above. Approximately 80 percent of the formation is sand, 5 percent is gravel, and 15 percent is clay matrix and calcium carbonate cement (Sellards and others, 1932, p. 758).

Goliad Sand is whitish or pinkish gray and in places contains abundant black chert grains. Indurated sand is typically 10 to 15 ft thick, lenticular in cross section, and laterally discontinuous.

Gravel beds range in color from white to red but are mostly pinkish gray and are mottled with red spots. The gravel beds are thin and lenticular. Occasionally, vertebrate fossils of Pliocene land mammals are found in the gravel. Lithology of the gravel suggests sediment source areas in both the Llano uplift and Big Bend areas of Texas.

Goliad sediments represent stream and flood-plain deposits (Fig. 9). The coarse nature of the sediments, particularly at the base of the unit, suggests that rainfall and (or) stream gradients were greater during Goliad time than during the previous interval of deposition represented by the Fleming Clay. Some of the calcium carbonate in the unit has been described as caliche deposits (Sellards and others, 1932, p. 759). If the caliche deposits are contemporary with the Goliad sediments, they indicate a dry climate with a high rate of evaporation rather than a climate with high rainfall.

In the subsurface at depths where data is complete, thickness of the Goliad Sand ranges from 1,100 to more than 1,800 ft. Due to the unconsolidated nature of the sediments above the Goliad, oil wells are generally cased to a depth somewhere below the top of the formation. The result is that in most cases the top of the Goliad does not appear on electric logs. Therefore, in order to avoid the problem of incomplete data over much of the area covered by the Goliad, a slice of the bottom 500 ft of the Goliad was studied for this report (Pls. 59-62).

Total sand thickness in the Goliad 500-ft slice varies from 100 ft to more than 450 ft (Pl. 59). In the northern part of the project area, two well-defined fluvial channel systems trend downdip or parallel

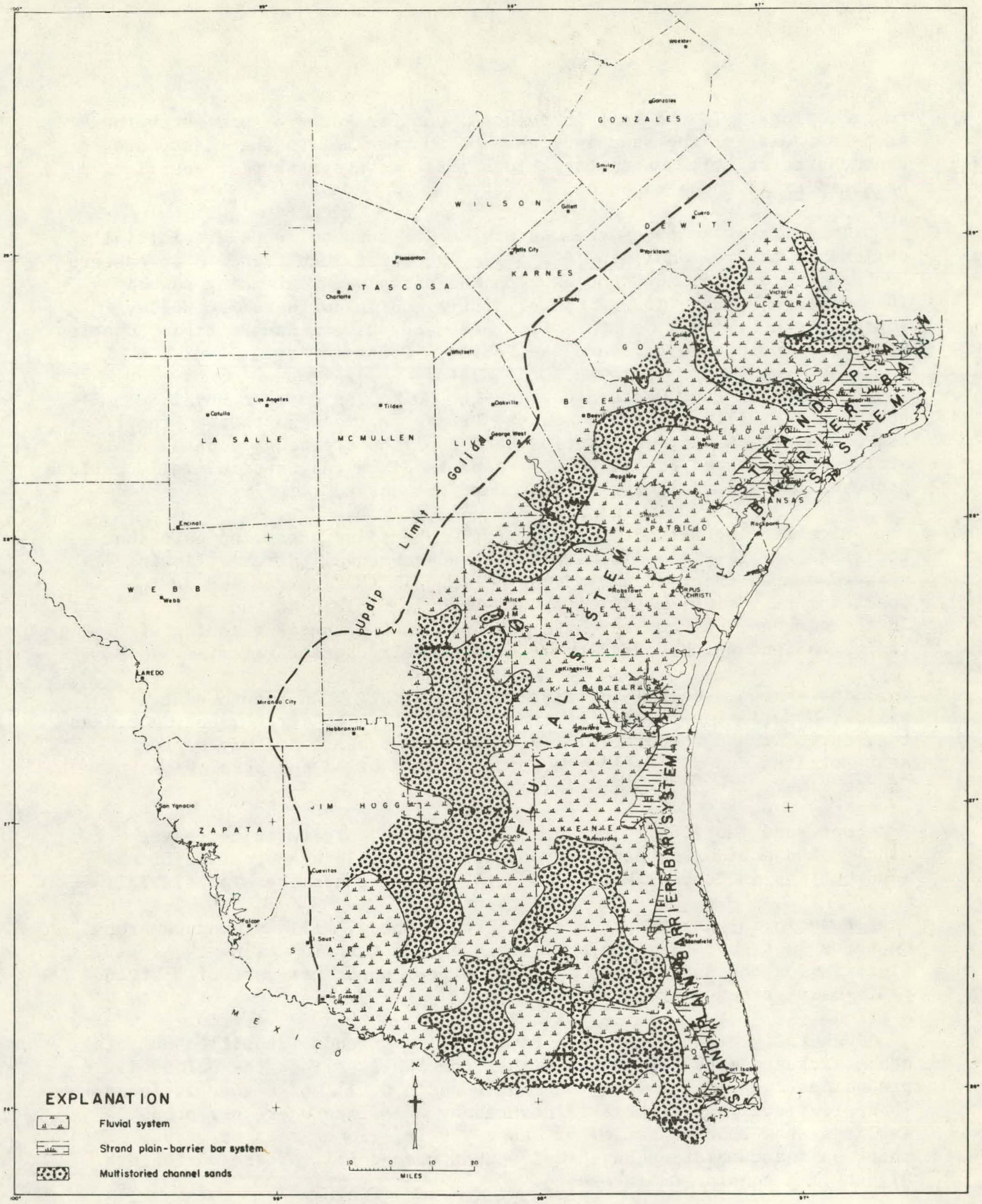


Figure 9. Paleogeographic map showing principal depositional systems in the subsurface, lower 500-ft. slice of the Goliad Sand, South Texas Coastal Plain.

to paleoslope. To the east in Calhoun, eastern Refugio, and northern Aransas Counties, the sand isoliths run subparallel to the coast, and sand characteristics on electric logs indicate a strand plain-barrier bar complex in these counties.

Immediately south of these areas, major sand buildups are initially oblique to the regional dip (Pl. 59). The first such trend is in eastern Bee and eastern Goliad Counties with the distal end extending downdip into western Refugio County. A similar trend in northern Jim Wells, southeastern Live Oak, southeastern Bee, and western San Patricio Counties extends downdip into southern San Patricio County.

Updip along the western edge of the Goliad in eastern Duval, southern Jim Wells, west and central Brooks, extreme northeast Starr, and northwestern Hidalgo Counties sand isoliths are roughly parallel to strike. In central Brooks County, sand isoliths that are initially oblique proceed in the downdip direction toward the coast.

Electric-log patterns in all of the preceding areas indicate that the sands are fluvial, often in a stacked sequence. Streams flowing seaward dumped thick accumulations of sand in these areas and deposited mostly finer material across the flood plain to the east. In these areas, streams may have encountered a marked flattening of their gradient which caused them to drop their coarser material.

In Cameron, central and east-central Hidalgo, and south-central Willacy Counties, net sand isoliths are parallel to strike, but in places they curve around to parallel regional dip. These sands may represent detritus deposited along a former course of an ancestral Rio Grande River.

Net sand isoliths form a horseshoe-shaped pattern in northeast Hidalgo and southwestern Kenedy Counties. They join another major sand buildup in central Willacy County. These sands are also fluvial.

Downdip in eastern parts of Kleberg, Kenedy, Willacy, and Cameron Counties, net sand isoliths are irregular but tend to follow the coast. Electric-log characteristics show that these sands are part of a strand plain-barrier bar system.

Generally, sandstone/shale ratios follow trends identified on total sand thickness maps (Pl. 60). Within the 500-ft slice, the Goliad is predominantly sand. A sandstone/shale ratio of 1:1 or higher is found in approximately half the area covered by the slice where net sand isoliths show thicknesses of at least 250 ft. Some areas of very thick sand accumulation have ratios that exceed 4:1. These ratios are higher than considered favorable.

URANIUM DEPOSITS OF THE SOUTH TEXAS COASTAL PLAIN

SOURCE OF THE URANIUM

Uranium in the Tertiary formations of the South Texas Coastal Plain is believed to be derived from silicic volcanic tuffs and ashes (Eargle and others, 1975b, p. 777). Volcanic sediments are widespread in South Texas. They are particularly important in the Jackson Group (Eocene), Frio Clay (Oligocene?), and Catahoula Tuff (Miocene). Sellards and others (1932, p. 721) noted that the percentage of tuff in the Catahoula generally increases from the Brazos River southward across the project area to the Rio Grande. Along the eastern coast of Texas, the tuff content of the Catahoula decreases, but it probably does not fall below 10 percent even as far east as north-central Louisiana. Volcanic sediments are believed to have originated at volcanic centers in northern Mexico, western Texas, or New Mexico. They were transported to the coast by wind, rivers, and streams. Large angular boulders within the Catahoula, however, suggest that the source for some of the volcanic material may have been within the Coastal Plain itself (Sellards and other, 1932, p. 721).

After deposition of the volcanic ash and tuffs, uranium was leached from these deposits and transported by moderately alkaline ground waters. Precipitation of uranium occurred where the groundwater solution entered a reducing environment. Reducing conditions are encountered where sufficient concentrations of hydrogen and hydrogen sulfide gases are present. These gases are produced by anaerobic bacteria acting on carbonaceous material in the surrounding sediments; thus, the presence of carbonaceous material in the surrounding fine-grained sediments may be critically important. Hydrogen and hydrogen sulfide gas may also rise along faults and may enter overlying host rocks from oil and gas reservoirs below (Fisher and others, 1970, p. 257).

Another source for uranium in South Texas may be the rocks of the Llano uplift in central Texas (Fig. 1). A U.S. Geological Survey airborne survey (Moxham and Eargle, 1957) discovered numerous radioactive anomalies in the Llano area. The Precambrian rocks, especially the pegmatites of the Llano, are known to contain uranium minerals. These rocks are thought to have been first exposed in Pliocene time. Therefore, the Llano uplift may be a secondary source for some of the uranium, especially in the Pliocene sediments of the Goliad Sand.

STRATIGRAPHIC POSITIONS OF URANIUM ORES

Host rocks of the South Texas Coastal Plain are chiefly sands and sandstones with relatively high permeability. These sands either contained ash-derived bentonitic clay and tuffaceous silt or are associated with them. Most of the volcanic material has been diagenetically altered by atmospheric weathering and soil-forming processes indicative of a relatively dry climate (Weeks and Eargle, 1963, p. 12).

Uranium deposits in South Texas are of two types: (1) small near-surface oxidized deposits that are generally out of radioactive equilibrium; or (2) larger, deeper unoxidized deposits more nearly in radioactive equilibrium (Eargle and others, 1975b, p. 770). Unoxidized deposits are higher in grade and are commonly found as ore-roll deposits. Frequently, the unoxidized deposits are found by exploring downdip from near-surface oxidized deposits. Therefore, the presence of oxidized deposits should encourage exploration immediately downdip in the subsurface. Mine locations are shown on Plate 3.

The occurrences of uranium ore are summarized below in stratigraphic sequence. Greater detail on specific mines and mining areas is contained in Eargle and others (1975b).

JACKSON GROUP

Uranium ores in Jackson rocks are found mainly in sandstones of the Whitsett Formation which is the uppermost formation of the Jackson Group. These sands were deposited in a strand plain-barrier bar environment during a regression of the sea.

The oxidized ores are concentrated in a narrow belt that extends from Tordilla Hill to about one-half mile northeast of Deweesville in Karnes County. Here the ores are located in a structural graben between the Falls City and Fashing faults. A similar oxidized ore body is found 3 miles east of Falls City.

These oxidized deposits are in small, lenticular or irregular marine-beach sandstones. The long axes of the sandstones run parallel to strike. The sand bodies consist of fine-grained, light yellowish-gray sands that are well sorted. The sandstones are commonly cross-bedded near the base and contain burrows of the trace fossil Ophiomorpha at the top. These sandstones are enclosed by carbonaceous lagoonal or paludal mudstones or by thin beds of impure lignite.

The unoxidized Jackson ores are located downdip from the Tordilla Hill-Deweesville concentration of oxidized ores. The unoxidized ores are ore-roll deposits in the same marine-beach sand facies as the oxidized ores. Most of the unoxidized ores are also present within the structural graben between the Falls City and Fashing faults, but some of the mines lie just to the southeast beyond the graben (Eargle and others, 1975b, Fig. 2).

The first mines to expose the unoxidized deposits were located a few miles south of Deweesville. The deposits were ore rolls in beach sandstones overlain by lignite, carbonaceous tuff, tuffaceous mudstones, and a layer of white, almost pure ash (Eargle and others, 1975b, p. 773). Other unoxidized ores are in sandy and clayey fluvial deposits that transect the beach sands and in lignite beds that overlie ore rolls in the main ore sands. One unoxidized deposit was found near the oxidized ores but in a stratigraphically lower sand.

The Jackson ore bodies of Karnes County are located near fault zones where seepages of oil and gas have been known to contain hydrogen sulfide. The occurrence of hydrogen sulfide along the fault planes caused the precipitation of uranium in the vicinity of the faults (Eargle and others, 1971, p. 13).

FRIO CLAY

Only one deposit has been mined in the Frio Clay, the Mabel New mine in western Live Oak County. However, radioactive anomalies within the Frio have been found in widely scattered areas as far south as Starr County (McKnight, 1972, p. 101), and a significant deposit is reportedly being developed in the Frio, or its equivalent, in northeastern Mexico (J. A. Olsen, personal commun., 1975).

The ore at the Mabel New mine is oxidized (Eargle and others, 1975b, p. 773). The host rock consists of a fluvial channel sandstone near the Jackson-Frio contact. The sandstone was deposited in a channel cut into a ferruginous, tuffaceous, gypsiferous clay unit. The ore is in irregular masses with podlike bodies scattered along the margins of the channel. The higher grade ore deposits are in soft, ferruginous sandstone between hard, calcite-cemented layers. A few concretionary masses of pyritic sandstone up to 6 ft in diameter contained relatively high-grade ore.

CATAHOULA TUFF

Uranium deposits in the Catahoula are unoxidized ore rolls in sandstones deposited along the lateral margins of fluvial channels. The deposits are found in Duval and southwestern Webb Counties (Eargle and others, 1975b, p. 777). Generally, the ores are associated with faults.

A deposit in Webb County is being developed as a test for solution mining at a depth of about 150 ft. The host rock is a fine-grained, well-sorted, calcareous channel sandstone that contains thin clay beds. The channel sand is 25 to 75 ft thick. The ore is a narrow roll along the margin of the channel sand. A normal fault with displacement of 50 ft is present 1 mile downdip to the east. This fault may have blocked or slowed the flow of subsurface fluids allowing the ore roll to develop.

OAKVILLE SANDSTONE

Uranium ore in the Oakville Sandstone lies along the margins of a major fluvial system in Live Oak County (Eargle and others, 1975b, p. 775). The fluvial system is about 300 ft thick and trends east-southeast parallel to regional dip. The ores, all of them unoxidized, lie north and southwest of the fluvial system.

One of the northern mines, the Kopplin mine, is in a coarse sandstone near the base of the Oakville. The sandstone is overlain by relatively impervious clay. The ore lies updip from a normal fault along which sulfur water is seeping. Sulfur water is also seeping from some of the beds associated with the ore.

The Felder mine, another mine located north of the fluvial trend, is also in the basal part of the Oakville. The mine is just east of a massive 300-ft-thick fluvial channel sandstone. The thick channel sandstone fingers laterally into sandy overbank deposits that later were covered by fine silt and clay. The Felder ore is in one of these lateral sand fingers. The host sandstone is fine to medium grained and is interbedded with clay. The ore is in a large irregular ore roll. Selenium is present near the ore roll, and molybdenum forms a broad halo around the uranium deposit. Hydrogen sulfide gas and oil seep along faults in the area and from some of the rocks in the mine.

Faults have been an important factor in localizing mineralization formation in the Oakville of Live Oak County. The Oakville fault is a normal fault that runs through or near the mines that are north of the fluvial system. An up-to-the-coast fault runs through the deposits that lie south of the fluvial system. Between both faults is a wide graben that extends northeastward through the mining area. A series of smaller faults strike parallel to the larger faults that bound the graben. The northern mines are either cut by these faults or are located within one-half mile of them. The southwestern mines are also close to faults (Eargle and others, 1975b, Fig. 7).

GOLIAD SAND

One commercial deposit in the Goliad Sand is known by the authors. Its location is unusual. The ore is in the caprock above the Palangana salt dome in east-central Duval County. A shaft reached the ore body at a depth of 300 ft, but no commercial ore was produced. Because of the depth of this deposit, there was no radioactivity detected at the surface. The deposit was found on a radioactive log from a petroleum test well (D. L. Norton, personal commun., 1975). This deposit may be unique, but radioactive anomalies in the sediments above other salt domes may indicate similar deposits. Presently, the deposit is being solution mined.

URANIUM FAVORABILITY

FAVORABLE HOST ROCK CRITERIA

Criteria for locating uranium deposits have been discussed in detail by Flawn (1967), Norton (1970), Grutt (1972), Eargle and others (1975b), and Fisher and others (1970). In general, the criteria of these authors are empirical observations which are based on the observed association of known deposits of uranium with certain rock properties and geologic structures. The following criteria are especially applicable to the Tertiary strata in the project area:

1. With few exceptions, uranium in the South Texas Coastal Plain is found in sandstone host rocks of Tertiary age. Therefore, the emphasis of this study is focused primarily on sandstones.

2. Sandstone horizons known to contain commercial deposits of uranium are found in the Jackson Group, Frio Clay, Catahoula Tuff, Oakville Sandstone, and Goliad Sand. These units must be considered optimum for further exploration, especially in facies that have been productive elsewhere in the project area.

3. According to Grutt (1972), favorable stratigraphic intervals are those in which the sandstone/shale ratio is between 1:1 and 4:1. Alternating sandstone and shale establish patterns and rates of ground-water movement. This control of ground-water movement is important because uranium deposits in South Texas sandstones are believed to be formed by the precipitation of uranium ions from ground water. However, the specific ratios of 1:1 and 4:1 may be more applicable to continental sediments of interior basins than to coastal plain and nearshore marine deposits along the Gulf Coast.

4. In South Texas, sandstone layers ranging individually from 10 to 100 ft thick are favorable for uranium mineralization. Sandstones 20 to 50 ft thick are considered optimum (D. L. Norton, personal commun., 1974). Generally, sandstones less than 10 ft thick or more than 100 ft thick are not favorable.

5. Medium to highly permeable sandstones deposited in fluvial, lagoon, and strand plain-barrier bar environments are potential host rocks (Eargle and others, 1975b, p. 778; Fisher and others, 1970, p. 255). These sands, when surrounded by less permeable rocks and when they possess permeable conduits that connect them to surface-water recharge, are optimum targets for exploration. In the fluvial environment, uranium usually is found in sands deposited marginal to the main channel where crevasse splays and point bars are interbedded with finer grained floodplain deposits (Eargle and others, 1975b, p. 778).

6. The presence of lignite or interstitial carbonaceous (plant) matter in potential sandstones or in the surrounding silt and shale is potentially important to uranium mineralization. Anaerobic bacteria acting on organic material produces hydrogen and hydrogen sulfide gases as metabolic by-products. These gases produce chemically reducing conditions in the vicinity of the carbonaceous deposits. Reducing conditions are prerequisite for precipitation of soluble uranium from ground water (Fisher and others, 1970, p. 257). Diagenetic pyrite is another indicator of reducing conditions and is frequently found in sediments in the vicinity of uranium deposits (Grutt, 1972, p. 32).

7. The presence of faults, especially faults with the upthrown block toward the coast is conducive to mineralization because they tend locally to slow the flow of ground water which allows static conditions for the precipitation of uranium (Eargle and others, 1975b, p. 778). Faults may also serve as conduits that allow reductants, such as hydrogen and hydrogen sulfide gas, to ascend from older rocks below. Because faults are commonly associated with salt domes, sandstones occurring above salt domes are favorable.

8. Areas of high radioactive anomalies associated with lithologically favorable sandstones have high potential, especially if the sandstones are not oxidized. If the sandstones are extensively oxidized, the uranium may have been leached.

9. Sandstones that dip less than 5° are favorable. Generally, low angles of dip increase the area of aquifer sandstones exposed to ground-water recharge. Low angles of dip also reduce the migration rate of ground water, thereby preventing reductants and uranium-bearing waters from being flushed through the sands too quickly.

All of the above criteria, with the exception of the presence of carbonaceous matter and pyrite, can be obtained either directly or by interpretation from electric or gamma-ray logs. Parameters used to evaluate subsurface strata for favorability are those that describe the geometry and lithofacies of the potential ore-bearing strata. These parameters include structure, formation thickness, sandstone/shale ratio, total sand thickness, and the number of sands of optimum thickness. These parameters are all mappable properties, and the favorability analysis of each stratigraphic unit in this report is based on maps of these parameters.

One important limitation on subsurface data is the spacing of test wells. Only logs from closely spaced wells provide subsurface information similar in continuity to information from areas of good outcrop. Logs used in this study are from test wells that are, on the average, 3 to 5 miles apart. Detailed study of smaller, more localized areas will require data from more closely spaced test wells.

Several areas of favorable host rock are delineated on favorability maps for each formation analyzed (Pls. 33, 39, 45, 51, 57, and 62). The designated areas are favorable only relative to the other sediments of the same formation; hence, all favorable areas designated in the report are not necessarily equally favorable.

YEGUA FORMATION

To date, uranium has not been found in the Yegua Formation. The Yegua does, however, have many characteristics in common with the Jackson Group, and the Jackson is a major source of uranium in South Texas.

Several areas within the Yegua are designated as favorable (Pl. 33). The largest of these areas extends along strike from southern McMullen County through central Live Oak into northern Bee County. Another similar but smaller area is found northeastward along strike in Karnes County. Both areas have 5-or-more sands of optimum thickness and at many places the number exceeds 10 (Pl. 32). Favorable sandstone/shale ratios are generally present throughout both areas (Pl. 31).

Comparison with the Jackson suggests that favorability in these two areas would be greater if they were located farther updip nearer the lagoon deposits and the present-day ground surface. Both the Yegua Formation and the Jackson Group compose an important strand plain-barrier bar system with a succession of lagoonal and continental facies updip toward the west (Figs. 4 and 5). Most ore deposits in the Jackson are associated with strand plain-barrier bar sands that are adjacent to organic-rich lagoonal and marsh deposits (Fisher and others, 1970, p. 255). Jackson sands in the barrier bar are not favorable because they are so highly permeable that they lack restraints to the movement of reductants and uranium-bearing ground waters. This may also apply to barrier-bar sands of the Yegua.

In western Starr County, there is another favorable area similar to the first two (Pl. 33). This areas has 10-or-more optimum sands and favorable sandstone/shale ratios throughout (Pls. 31 and 32). As in the larger area in the north, this area is elongate parallel to strike and is part of the barrier-bar system.

The area that contains the largest number of optimum sands (sands 20 to 50 ft thick) follows the strand plain-barrier bar trend closely (Pl. 32). Areas of 10-or-more optimum sands are found in a line that extends from southern McMullen and Live Oak Counties northeastward into Karnes County. Smaller areas of 10-or-more optimum sands are found in Zapata and western Starr Counties; these are also elongate parallel to the regional strike. Areas of 5-to-9 favorable sands that enclose areas of 10-or-more favorable sands cover nearly the entire strand plain-barrier bar system. Areas of 5-to-9 favorable sands extend into the outcrop at many places. Comparison of the total sandstone map with the optimum sandstone map (Pls. 30 and 32) shows that, updip from the strand plain-barrier bar system, sands are fewer and thinner than in the strand plain-barrier bar system.

All three of the above-mentioned areas are cut by faults, but only one of these is an up-to-the-coast fault (Pl. 28). This fault is located in central Live Oak County. A graben 3 to 5 miles wide is found on the downthrown side to the west. The presence of this fault and graben increases the favorability of this general area (over the other two in the barrier-bar system).

In northeastern Webb County, there is a fourth area that is favorable (Pl. 33). Two up-to-the-coast faults are located within this area (Pl. 28). The easternmost fault is flanked by a down-to-the-coast fault about 2 miles to the west; an intervening graben lies between these two faults. The second up-to-the-coast fault lies to the west. There is no graben on the updip side. Nevertheless, the movement on this fault may favorably restrict the flow of ground water or form a conduit for reductants. Favorable sandstone/shale ratios are not found in this depositional area (Pl. 31) because it is part of the lagoonal system (Fig. 4). However, the area does contain 5-to-9 optimum sands throughout, and this increases the favorability of the area.

On the basis of both the faults and the number of optimum sands, this area in Webb County may be the most favorable in the Yegua Formation. Furthermore, these sands are on the updip side of the strand plain-barrier bar system close to lagoonal sediments and the carbonaceous matter which they contain.

JACKSON GROUP

Many of the most important mines in South Texas are in sediments of the Jackson Group in western Karnes and eastern Atascosa Counties. The ores are primarily in strand-plain sands interbedded with organic-rich lagoonal and marsh muds that extend westward into outcrop (Fig. 5). The location of these sands in and near the zone of outcrop increases the chances that uranium-bearing ground water may flow through them. Areas within the Jackson which have similar strand plain-barrier bar and lagoonal facies close to outcrop should be considered favorable.

Numerous areas meet the preceding criteria. The first area is in southwestern Starr County (Pl. 39), where favorability is enhanced by a fault across the strand-plain sands. The second area is where Starr, Zapata, and Jim Hogg Counties adjoin. In both of these areas, strand-plain sandstones are just downdip from lagoonal sediments and, at some places, extend to the surface (Fig. 5).

Farther north, there are three more favorable areas: (1) eastern Zapata and southeastern Webb, (2) eastern Webb, and (3) south-central McMullen Counties. In each of these areas, strand plain-barrier bar sands are partially exposed and are associated with lagoonal and marsh deposits that extend to the surface. They are adjacent to sands deposited at the mouth of fluvial channels that may serve as conduits for uranium-bearing ground waters. Normal faults cross all three of these favorable areas. A graben extends across the favorable area in eastern Webb County (Pl. 34). All of the areas have a significant number of sands of optimum thickness.

Three more areas are designated favorable: (1) eastern Webb and southwestern Duval, (2) southwestern McMullen and northwestern Duval, and (3) northeastern McMullen and central Live Oak Counties (Pl. 39). These areas contain fluvial sequences that transect the strike-oriented strand-plain sands. Downdip, these fluvial systems acquire more sands of favorable thickness. Sands in all three of these areas are cut by faults (Pl. 34). However, emphasis is placed on the favorability of the sands that flank the main channel, because most main channel facies are devoid of uranium. The favorability of these flanking fluvial sands increases updip from the strand-plain trend because of the increase in surrounding lagoonal and marsh muds, which may act as reductants. Contributing to the favorability of the area in northern McMullen County is a radioactive anomaly from a petroleum test well (Pl. 3).

FRIO CLAY

The only uranium that has been mined to date in the Frio is at the Mable New mine in western Live Oak County, where the host rock is sandstone.

deposited marginal to a fluvial channel. Areas within the Frio where fluvial channel systems can be located should be considered favorable. However, it must be emphasized that sandstones deposited marginal to the main channel sands are the exploration targets because sands in the main channels are usually devoid of mineralization (Fisher and others, 1970, p. 255).

In the northern part of the project area, sandstones of optimum thickness are scarce in the Frio, with the exception of one area of 10-or-more optimum sands (Pl. 44). The number of optimum sands in the Frio is highest in the south where 5-to-9 optimum sands cover part of the project area. Ten-or-more optimum sands are present in small, randomly distributed areas in the south.

The northernmost favorable area in the Frio is in central Live Oak County (Pl. 45). The area encloses a fluvial system that follows courses similar to the present-day Nueces, Atascosa, and Frio Rivers in that region. Sandstones of this fluvial system extend westward into outcrop where they are exposed to ground-water recharge that may carry dissolved uranium. Downdip along the eastern side of this favorable area there is an area of 5-or-more sands of optimum thickness; several normal faults cross this area (Pl. 40). Immediately northwest and adjacent to the fluvial sandstones is an up-to-the-coast fault with a graben on the west side. Because these structures are considered favorable, they are incorporated in the favorable area even though the greatest development of optimum sandstones is south of them.

A similar favorable area is spread over most of Jim Hogg, southeastern Webb, central and southwestern Duval, and west-central Jim Wells Counties. This area contains 5-or-more sands of optimum thickness throughout, and patchy areas of 10-or-more optimum sands are present at several places. Faults transect this area but are more numerous in northern Jim Hogg and east-central Duval Counties. In addition, three of the seven radioactive anomalies from petroleum test wells in the Frio lie close to this favorable area. These three wells are in north-central Duval County (Pl. 3).

Sandstone geometry in this large area is generally oriented parallel to dip, which indicates that these sands were deposited in fluvial channels (Pl. 42). Sandstones in north and central Jim Hogg County are an exception in that they are more evenly distributed and are not confined to easily delineated fluvial systems. Electric log characteristics indicate that the sands are nevertheless fluvial (Pl. 7).

A third favorable area is a long narrow strip of 5-or-more optimum sands that extends southward from the previous area into Starr County. This area is parallel both to present-day rivers and to regional strike in Starr County. Rivers in this area today, as well as those in Frio time, aligned north-south, probably because they are controlled by either the regional strike, which is north-south, or by north-south striking faults.

The preceding three areas are favorable relative only to other sediments in the Frio. It would be wrong to assume that all favorable areas designated in this report are equally favorable. Because of the relatively small number of favorable sands in the Frio, it is generally less favorable than the Jackson, Catahoula, Oakville, or lower part of the Goliad.

CATAHOULA TUFF

The number of optimum sands in the Catahoula Tuff is very small throughout most of the northern half of the project area (Pl. 50). A few areas contain 5-to-9 optimum sandstones, but these areas are a small fraction of the northern half of the project area. These sandstones probably represent relatively small fluvial systems. Since mines in the Catahoula are found in sandstones deposited along the margins of fluvial channels, areas that contain fluvial systems are favorable.

In the southern (Rio Grande Embayment) part of the project area, 5-or-more optimum sandstones are found across most of the area of the embayment with 10-or-more optimum sandstones in a large area covering southern Duval, eastern Jim Hogg, and western Brooks Counties. This area of 10-or-more optimum sandstones is just downdip from the major fluvial system that enters the embayment from the west (Fig. 7).

This entire area of 10-or-more optimum sandstones is considered favorable (Pl. 50). Not only are there a large number of optimum sandstones, but these sandstones are in a position to be reached by uranium-bearing ground waters flowing downdip through sandstone aquifers from the fluvial systems to the west. Favorable sandstone/shale ratios are found within the area of 10-or-more optimum sands in northwestern Brooks County (Pl. 50). An up-to-the-coast fault in southeast Jim Hogg County (Pl. 46) improves the favorability of this small region within the larger area of favorability.

This favorable area also includes the fluvial systems that enter from the west (Fig. 7). As stated above, the main channel sandstones are not as favorable as the sandstones deposited laterally to the main channel.

OAKVILLE SANDSTONE

Uranium deposits in the Oakville Sandstone have been found in sandstones deposited along the margins of major fluvial channel systems. In the mining area of Live Oak County, faults have been an important factor in localizing the mineralization.

Favorable sandstone/shale ratios of 1:1 to 4:1 appear to be more applicable as a criterion of favorability in the Oakville than in the Yegua, Jackson, Frio, or Catahoula (Pl. 55). The favorability of 1:1 to 4:1 ratios is applicable to the intermontane basins of the interior of the continent where sedimentation is dominated by fluvial deposition. If this criterion were heavily relied upon for units beneath the Oakville, many areas within these units, which are considered favorable on the basis of other criteria, would be disqualified. These ratios seem to be applicable to the Oakville because of the similarity of the Oakville to uranium-producing strata of Wyoming and the Colorado Plateau.

Generally, areas that contain a significant number of sands of optimum thickness are on the coastward or downdip part of the Oakville (Pl. 56). The largest area of 10-or-more optimum sands is found in southern Kenedy, central and western Willacy, western Cameron, and eastern Hidalgo Counties. In this area, both the entire formation and the total accumulation of sandstones are thickest. The areas that contain a large number of optimum sands are generally large and irregular in shape. Areas of optimum sandstone in the northern part of the project area appear to have no relationship to total sandstone thickness (Pl. 54) or to high sandstone/shale ratios (Pl. 55). However, in the southern part of the project area, significant numbers of optimum sands are found in the same areas that contain high sandstone/shale ratios and total sandstone thickness.

Favorable areas in the Oakville were delineated on the basis of (1) proximity to major fluvial systems, (2) favorable sandstone/shale ratios of 1:1 to 4:1, (3) significant numbers of sandstones of optimum thickness, and (4) faulting near or within the area.

On the basis of the above criteria, favorable areas are shown on Plate 57 and are listed as follows: (1) east-central Goliad and northwest Refugio; (2) central Live Oak and south-central Bee; (3) south and central Refugio; (4) east-central San Patricio; (5) north-central Nueces; (6) north and east Jim Wells; (7) southeast Duval, southern Jim Wells, southwest Kleberg, and north and central Brooks; (8) eastern Jim Hogg; (9) southeast Brooks, northeast Hidalgo, and west-central Kenedy; and (10) northern Kenedy Counties.

Two radioactive anomalies have been identified in Oakville sediments (Pl. 3). These are located in test wells just downdip from the favorable area in north-central Nueces County (Pl. 57).

GOLIAD SAND

To date, only one uranium deposit is known by the authors in the Goliad. This deposit is unusual because it is found in the caprock above a salt dome, the Palangana salt dome in east-central Duval County. A radioactive anomaly in the Goliad is known from a test well in southern Victoria County. This well is near the favorable area in central Calhoun County (Pl. 3).

The Goliad is similar to the Oakville in that it is primarily fluvial in nature and the channel sands are often stacked. Therefore, as in the Oakville, sandstones deposited along the margins of major fluvial systems are prime targets for exploration.

Another similarity is that, as in the Oakville, sandstone/shale ratios of 1:1 to 4:1 are considered useful as a criterion of favorability in the fluvial portion of the unit (Pl. 62). In the marine or marginal marine part of the Goliad, ratios of 1:1 to 4:1 are not considered useful as a favorability criterion.

Areas that contain a significant number of sands of optimum thickness are randomly distributed and are elongate, somewhat spherical, or irregular in shape (Pl. 61). These areas do not necessarily coincide with areas where total sand thickness is greatest (Pl. 59) or where sandstone/shale ratios are high (Pl. 60). This is because many of the sands in the lower part of the Goliad are thicker than 50 ft, which disqualifies them from being considered optimum. The largest area of 5-or-more optimum sands is an elongate area parallel to the coast in central Kenedy and central Willacy Counties. There are no areas of 10-or-more optimum sands within the bottom 500-ft slice of the Goliad because the slice represents less than half of the formation.

Favorable areas in the updip fluvial portion of the Goliad have been designated on the basis of (1) proximity to major fluvial systems, (2) favorable sandstone/shale ratios of 1:1 to 4:1, (3) significant numbers of sandstones of optimum thickness, and (4) faulting near or within the area. On the basis of these criteria, favorable areas (Pl. 64) are as follows: (1) northwest Victoria; (2) western Refugio, eastern Bee, and the extreme southern tip of Goliad; (3) northeastern Jim Wells; (4) central Jim Wells; (5) south-central Brooks; (7) northwest Kenedy; (7) eastern Hidalgo; and (8) eastern Hidalgo, northwest Cameron, and southwestern Willacy Counties.

Downdip, where the Goliad becomes primarily strand plain-barrier bar sands, a different set of favorability criteria applies. Considered favorable are (1) areas updip from the strand plain-barrier bar, where a significant number of optimum sands are encountered and (2) areas with faults. On plate 62, these areas near the coast may be joined with favorable areas in the fluvial sequence. On the basis of the latter set of criteria, favorable areas are found in (1) central Calhoun, (2) northern Aransas, and (3) central Kenedy, central Willacy, and north-central Cameron Counties.

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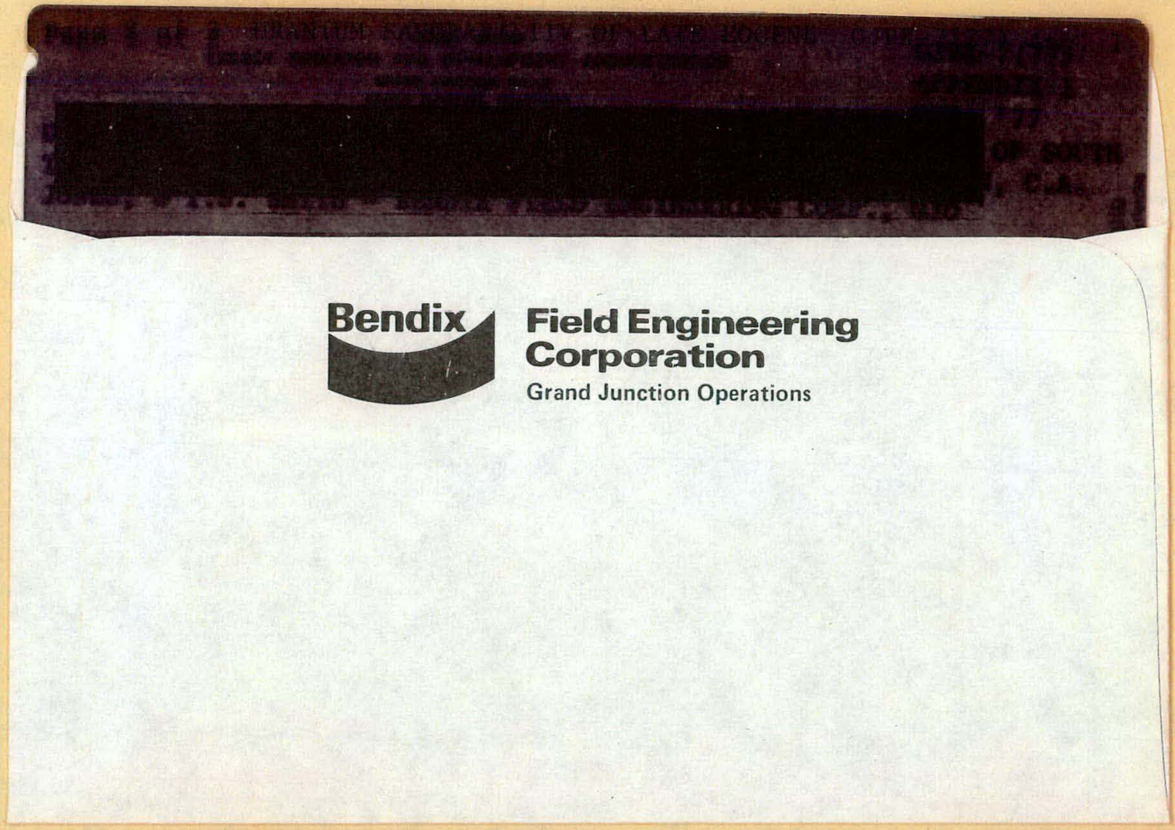
APPENDIX A

LOCATIONS OF TEST WELLS

(Appendix A, pages 50 through 113, on microfiche in back pocket.)



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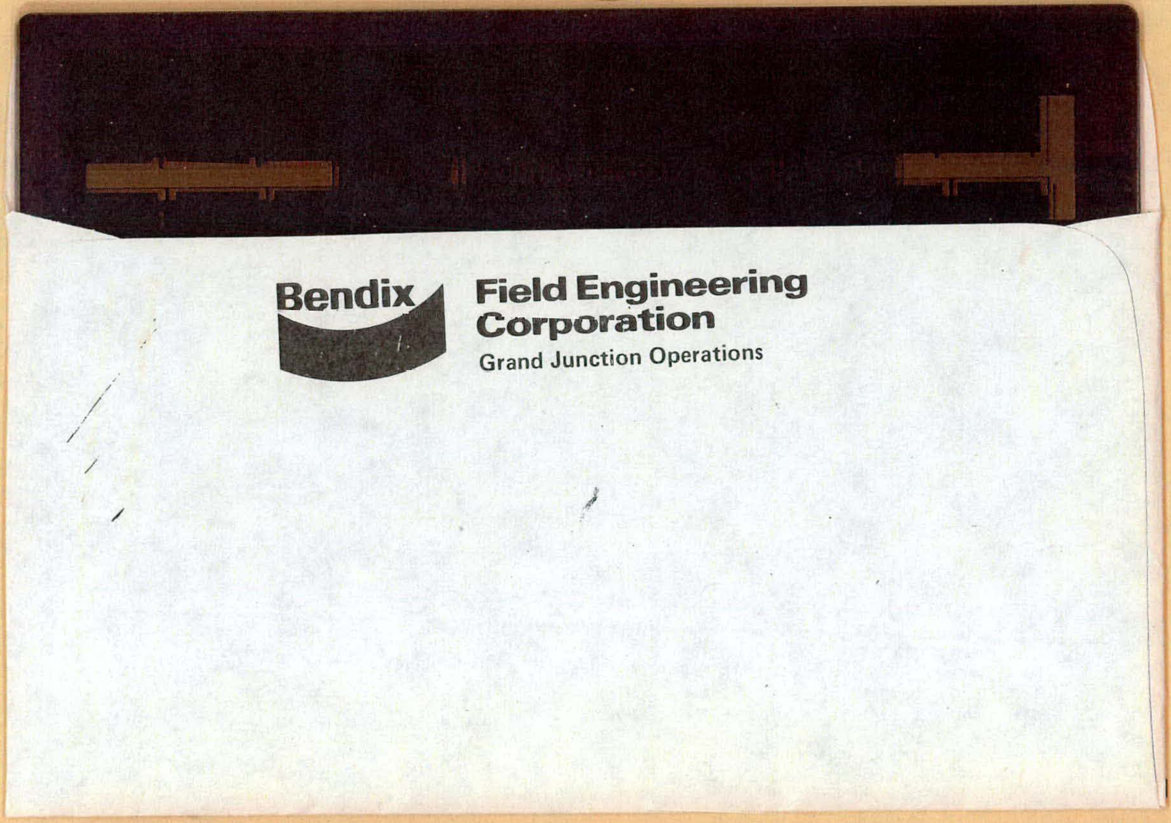
APPENDIX



PLATES