MIOCENE DEPOSITIONAL SYSTEMS AND HYDROCARBON RESOURCES: THE TEXAS COASTAL PLAIN

by

Jules R. DuBar

assisted by

Elizabeth M. Andrews, Katherine Hubby,
and David C. Noe

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78712

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ABSTRACT

The Miocene Major Stratigraphic Unit (MSU) of the Texas Coastal Plain is an off-lapping sedimentary sequence deposited over the continental platform constructed by Late Oligocene Frio progradation. These Miocene deposits have yielded nearly 3 billion bbl of oil and 7 trillion ft^3 of gas. Correlations with mammalian and foraminifer zones indicate that the Miocene MSU and its updip equivalents, the Oakville and Lagarto Formations (Fleming Group), range in age from Early to Late Medial Miocene (22.5 to 12 m.y.a.). Downdip, the upper Heterostegina and Discorbis Zones of the Anahuac shale wedge are included as a part of the Miocene MSU.

Regional subsurface study indicates division of the Miocene MSU into six principal depositional systems: the Cypress fluvial system and San Jacinto delta system, developed in the Houston Embayment; the Moulton streamplain and Indianola barrier-strandplain-lagoon system across the San Marcos Arch; and the Santa Cruz fluvial system and Rosita delta system located in the Rio Grande Embayment. Integration of regional studies of depositional systems, their facies suites, structural styles, and character of produced hydrocarbons permitted delineation of 10 hydrocarbon production-exploration plays. The play forms the basic analytical unit in characterization of hydrocarbon production histories, predictions of future discoveries, and the placement of potential resources in a geographic-stratigraphic context.

The Miocene MSU lacks entirely, or contains only negligible volumes of thermally mature source rocks. Thus, all Miocene MSU hydrocarbons are exotic, having been derived either by upward migration from older formations, or by lateral, updip migration from offshore marine Miocene units. Based on three historical evaluation methods employed in this study, the Miocene MSU contains between 250 and 1360 million boe of undiscovered, conventionally producible hydrocarbons.

INTRODUCTION

General Statement

The onshore Miocene Major Stratigraphic Unit (MSU) of the Texas Coastal Plain (pl. 1) is an extensive aggradational-progradational wedge of interfingering fluvial, deltaic and marine sediments. This wedge, which averages 121 km (75 mi) in width, and which reaches a maxium thickness of more than 2286 m (7500 ft), has produced more than 4 billion boe of hydrocarbons making it a significant Gulf Coast reservoir. Throughout this report, natural gas is converted to barrel-of-oil (boe) equivalents on an approximate Btu basis of 1 bbl = 6 Mcf.

A long history of exploration and production has combined to make the Miocene MSU a mature exploration target which probably has yielded approximately 70 percent of its recoverable hydrocarbon reserves. Even so, the remaining fraction of undiscovered petroleum is an important natural resource. Relatively shallow drilling depths of 610 to 3658 m (2000 to 12,000 ft), the variety of potential structural and stratigraphic traps, and the potential of multiple pay zones add to the attractiveness of this regional play.

Objectives

The objectives of this report are (1) to compile a geologic base necessary for a hydrocarbon resource assessment of the productive onshore Miocene MSU of the Texas Gulf Coastal Plain, (2) to integrate the geologic framework analyses, historical finding rates and reservoir/source facies volumetrics as a basis for definition and quantitative resource evaluation of exploration production plays, and (3) to assess the potential undiscovered hydrocarbons of the Miocene MSU. The play, which is the integral subdivision of production in this study, is a moderately homogeneous segment of the MSU that is delineated on the basis of its characteristic structural, depositional and production parameters.

Methodology

Component steps in this study are (1) regional delineation, subdivision and stratigraphic analysis of the Miocene MSU, (2) completion of an inventory of known hydrocarbon distribution, (3) compilation and interpretation of the Miocene MSU geologic framework, (4) delineation and quantitative evaluation of exploration plays, and (5) determination of hydrocarbon production history and probable undiscovered recoverable reserves.

A grid of 24 dip and 2 strike sections (fig. 1) modified from those of Dodge and Posey (1981) served as a base for stratigraphic and regional delineation of the Miocene MSU. Supplementary control was derived from several hundred infill logs. To stratigraphically characterize the genetic subdivisions of the Miocene MSU, correlations were made using conventional outcrop and subsurface terminology. The data base for the hydrocarbon inventory was derived largely from annual reports of the Railroad Commission of Texas and bulletins of the American Association of Petroleum Geologists. The resultant inventory provides information on reservoirs of all Miocene MSU fields (Appendix) that have produced more than 1 million bbl of liquid equivalent hydrocarbons and includes year of discovery, number of producing wells, depth, thickness and hydrocarbon gravity of producing zones, cumulative production of oil, condensate, casing head gas, and non-associated gas, and calculated reserves of hydrocarbons.

Geologic framework studies included preparation of regional isopach, structure and sand distribution maps, and delineation of depositional systems and their component facies. Also investigated were factors controlling reservoir and potential source rock quality.

Exploration plays serve to place into a geographic context an integrated picture of geologic controls and hydrocarbon production for the Miocene MSU.

Resource assessment was related to ten exploration plays. For each play, limiting factors and variables such as drilling density, depth range, reservoir character and structural style were evaluated. Historical finding rates and volumetric extrapolations were used to calculate ranges of possible undiscovered hydrocarbons. Geologically defined plays, such as employed in this study, should serve as an effective approach to an accurate and functional method of hydrocarbon resource evaluation and should assist in identification and evaluation of potential areas for future exploration.

STRATIGRAPHY

General Statement

The stratigraphic position of the Miocene MSU and its component operational units A and B is depicted and related to the Late Cenozoic stratigraphic framework of the Texas Coastal Plain in figures 2 and 3.

The Miocene MSU, as employed in this report, is essentially a stratigraphic equivalent of the Miocene Fleming Group as defined by Plummer (1932). Operational Unit A correlates closely with the Oakville Formation, and Operational Unit B is

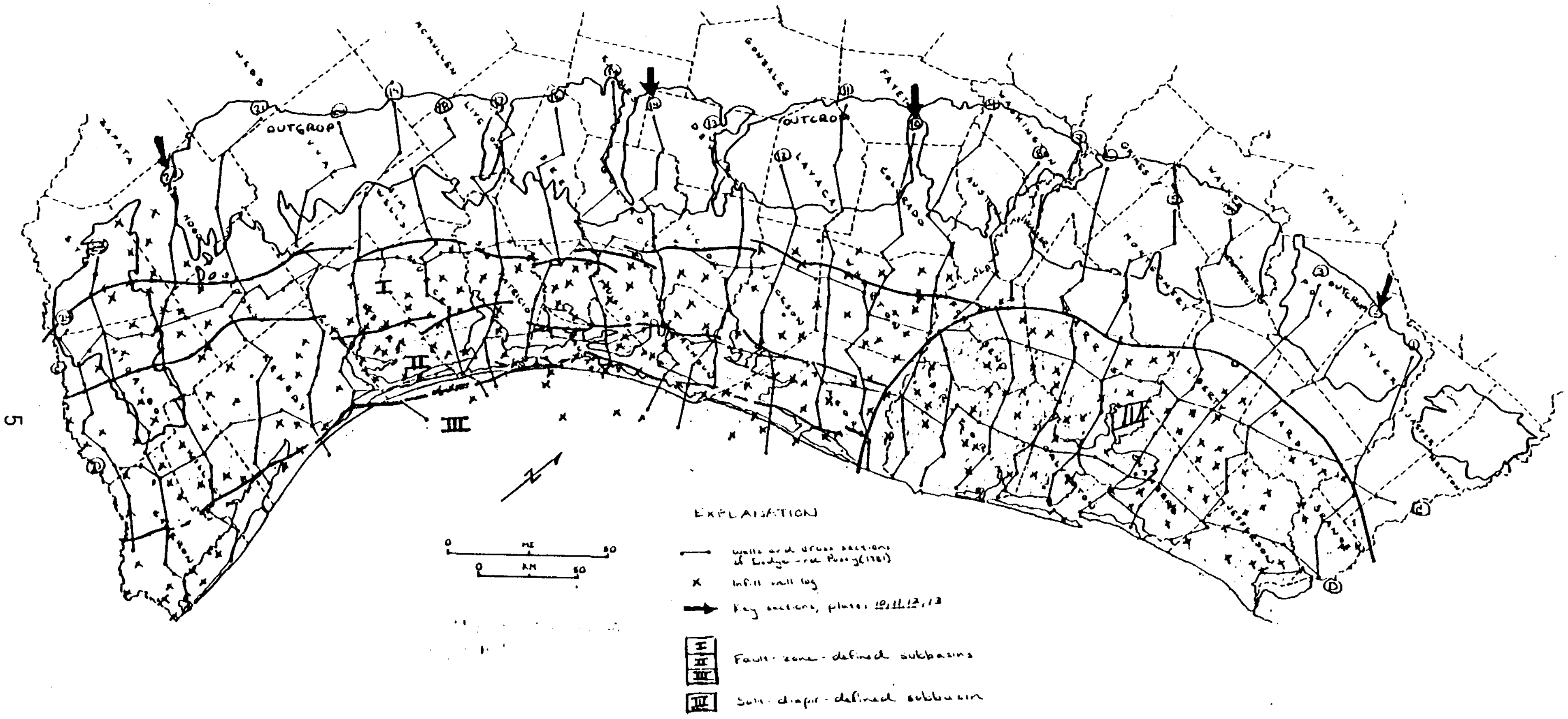


Figure 1. Regional correlation sections and depositional sub-basins.

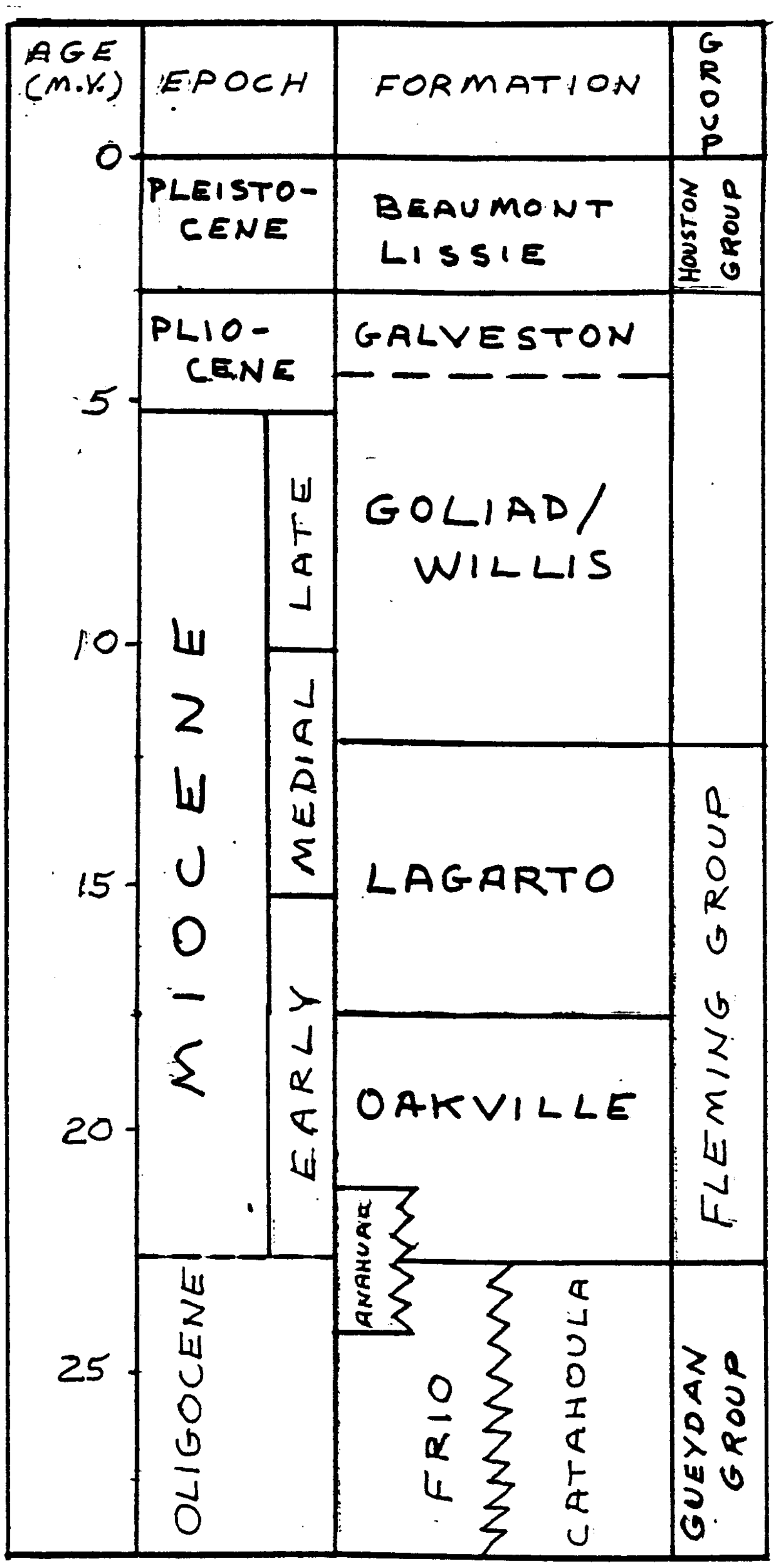


Figure 2. Formal Late Cenozoic lithostratigraphic units; Texas Coastal Plain.

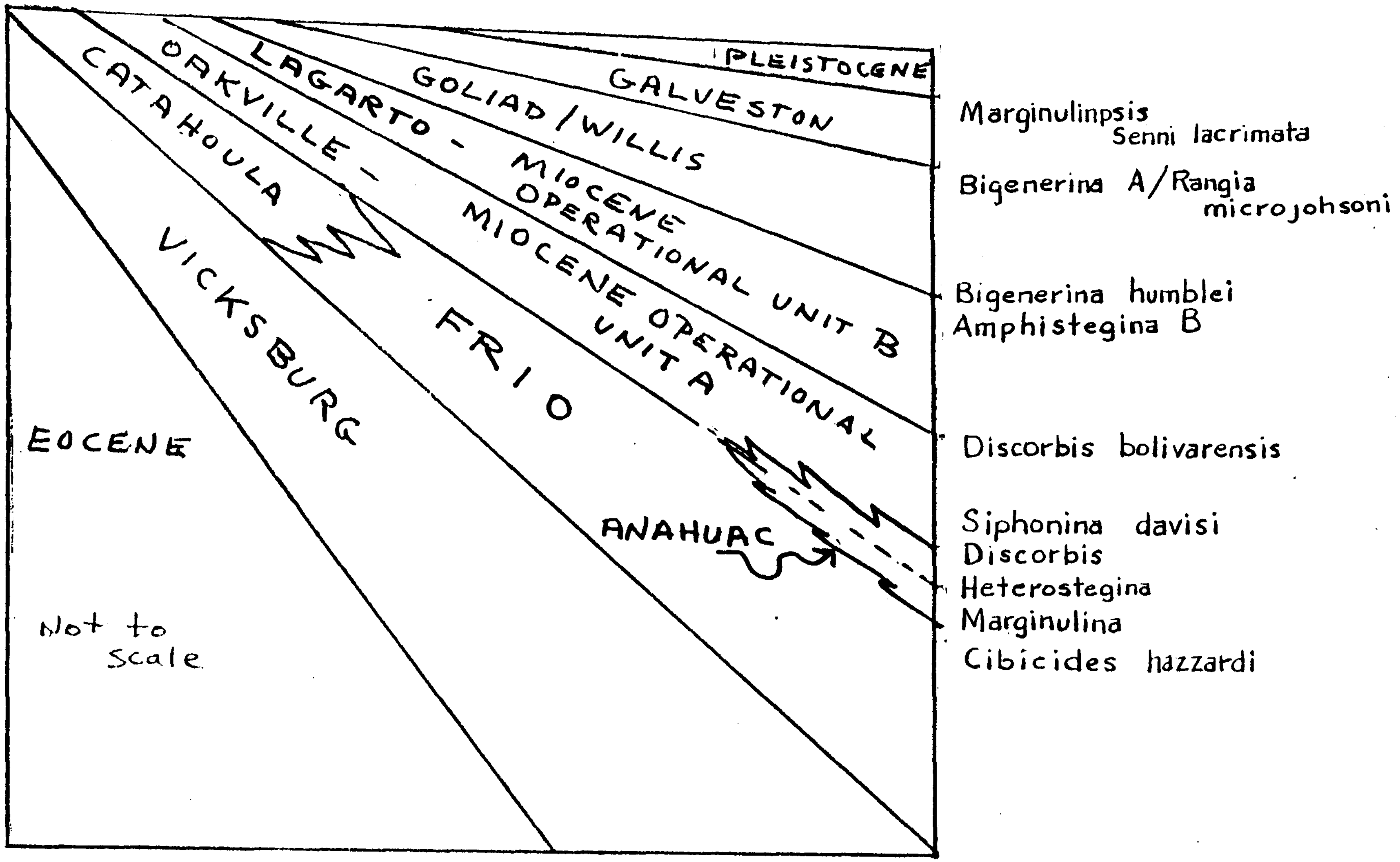


Figure 3. Generalized dip-section showing stratigraphic relationships of Miocene MSU Operational Unit A and B; Texas Coastal Plain.

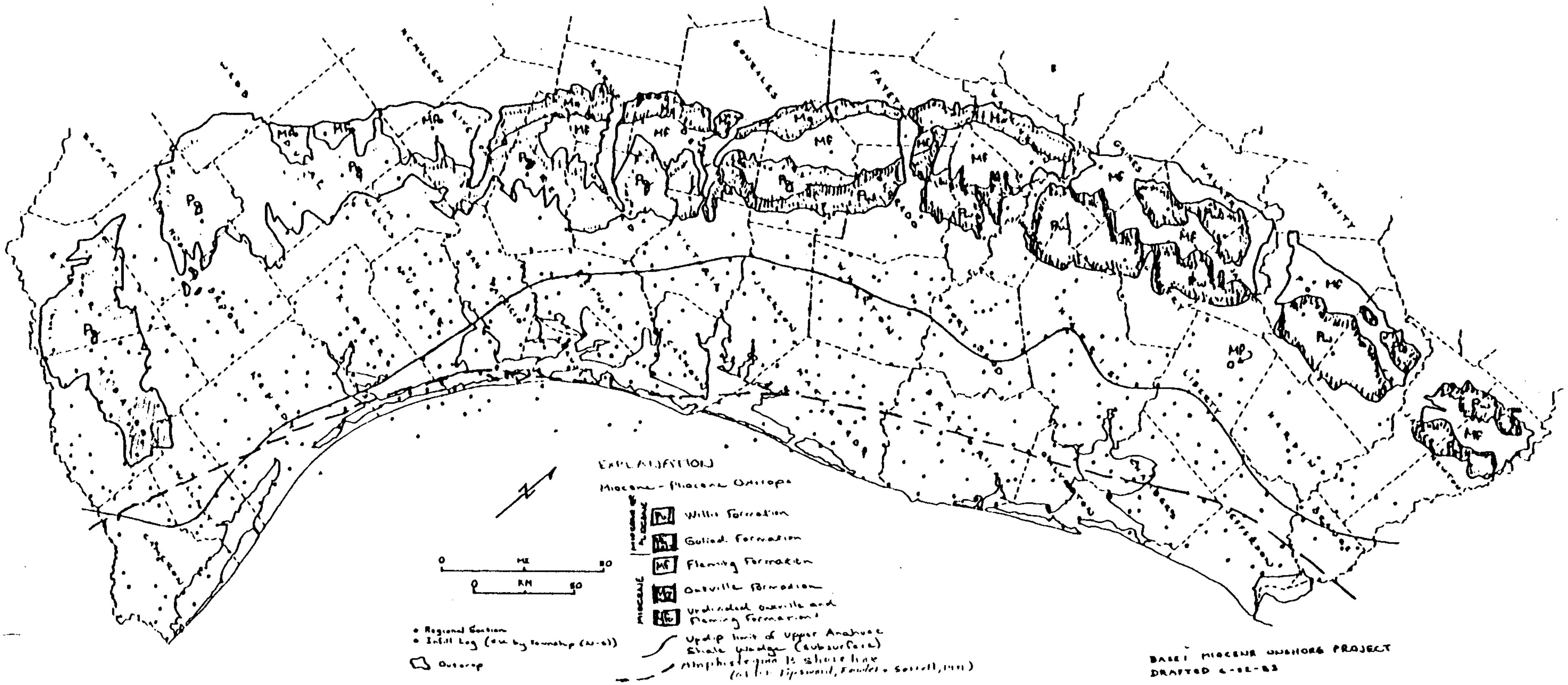


Figure 4. Miocene-Pliocene outcrops; updip limit upper Anahuac shale wedge, and Amphistegina B shoreline.

approximately equivalent to the Lagarto Formation. Together the outcropping Oakville and Lagarto Formations are conventionally considered to record the total time-span of the Miocene Epoch (Rainwater, 1966; Tipsword, 1963; Wilmarth, 1957). Evidence developed as a product of this investigation indicates that the post-Lagarto Goliad and Willis Formations, assigned to the Pliocene Epoch by the U.S. Geological Survey (Wilmarth, 1957), are at least in part Miocene in age.

Delineation of the Miocene MSU was based primarily on electric log interpretations. In the shallow subsurface log-determined contacts were carefully projected to the outcrop (fig. 4), and these correlated with conventional stratigraphic subdivisions. In the deeper subsurface correlations were related to laterally extensive and distinctive progradational sand bodies, transgressive shale units, and to available paleontologic control. Downdip basal Miocene sands grade into and interfinger with the Discorbis and upper Heterostegina Zones of the widespread, transgressive Anahuac mudstone wedge. The top of the Miocene MSU coincides updip with the base of thick sands of the overlying Goliad/Willis depositional sequence. Downdip the upper boundary is placed at the top of a progradational sequence superjacent to the Amphistegina B transgressive shale (fig. 3). Division of the Miocene MSU into two operational units (A and B) was based, in large part, on carefully correlated log patterns, and a generally upward-fining trend indicated in strike-oriented stratigraphic cross-sections. Paleontologic control downdip appears to place the boundary between Operational Units A and B near the upper occurrence of *Discorbis bolivarensis* and thus approximately at the contact of the Golbigerinatella insueta and Golbigerinita dissimilis planktonic foraminifer zones.

In an effort to place the Miocene MSU and its operational units in a modern stratigraphic context, a correlation chart (fig. 5) was prepared. This chart relates the Texas Late Cenozoic lithostratigraphic units to Texas' land mammal zones, the standard North American land mammal stages, to an interhemispherical planktonic foraminifer zonation, to the northwest Gulf of Mexico benthonic foraminifer zones, to a geochronometric scale, and to the European stages.

The correlation chart is largely an interpretative summarization of published, and unpublished sources. The most pertinent of these sources, listed by category, are: geochronometric scale (Berggren and Van Couvering, 1974; MacFadden and Webb, 1982), planktonic foraminifer zonation (Beard and others, 1976; Beard, Sangree and Smith, 1982; Kennett and Srinivasan, 1983; Lamb, personal communication, 1983; Lamb and Beard, 1972; Stainforth and others, 1975; and Van Couvering and Berggren, 1977), benthonic foraminifer zonation (Ellisor, 1940, 1944; Lamb, personal communication, 1983; Rainwater, 1966; and Tipsword, 1963), molluscan zones (Dall, 1913; Ellisor, 1936; Fisk, 1940; Gardner, 1940; Harris, 1895; and Stenzel and Turner, 1944), and mammalian zonation (MacFadden and Webb, 1982; Patton, 1969; Quinn, 1955; and Wilson, 1956).

Anahuac Formation

The Anahuac Formation was named in 1944 by the Houston members of the American Association of Petroleum Geologists' Geologic Names and Correlation Committee (Houston Geological Society, 1954 a-c). The formation had been referred to for the previous 28 years as the "Middle Oligocene," or by its three paleontological zones, the Discorbis, the Heterostegina, and the Marginulina (Applin and others, 1925).

Ellisor (1944) defined and described the Anahuac Formation. She designated the Anahuac Oil Field, five miles east of the town of Anahuac, Chambers County, Texas, as the type locality; and she selected for description and type section, sample interval -5890 to -6984 ft in the HORC Middleton #1 discovery well.

Ellisor described the Anahuac as follows:

> The Anahuac at the type locality in the Humble Oil and Refining Company's Middleton #1 consists of dark, greenish-gray, slightly micaceous calcareous shale with very fine partings of sand. Lenses of sand and calcareous sand are interlaminated with shale.
>
> The electrical log shows a well defined lithologic pattern of shale with sand lenses between two essentially sandy units.

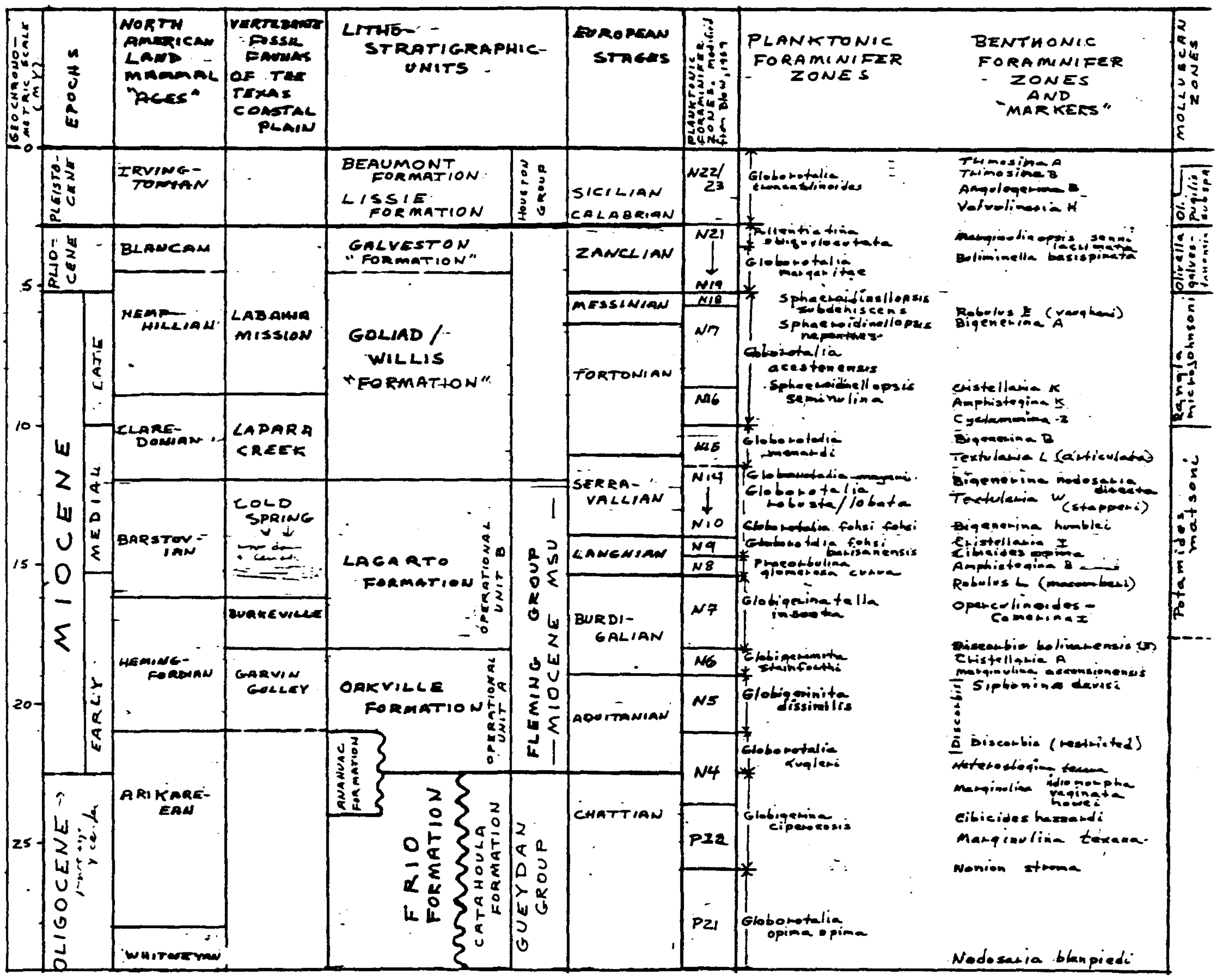


Figure 5. Estimated calibration and correlation of Texas Late Cenozoic biostratigraphic and lithostratigraphic units and paleontological markers.

> The Formation is divided into three faunal units, the Discorbis, the Heterostegina, and the Marginulina zones. Because the Discorbis zone is very sandy in some areas the contact with the Fleming is difficult to determine on the electrical log. Also in the basal Fleming downdip, brackish-water and lignitic shale lenses are interlaminated with the sands. In these shale lenses are oysters, ostracodes, *Rotalia beccarii*, *Discorbis subauracana* var. *dissona*, reworked Cretaceous material and here and there one or two species of the Discorbis zone. Some paleontologists include these beds in the Discorbis zone.
>
> Around some of the salt domes, as already stated, the facies of the Heterostegina zone is a reef limestone. In some areas, the Heterostegina zone is principally sand. The Marginulina zone is predominantly shale with lenses of sand.

Cushman (1918 and 1921) identified Anahuac *Heteostegina* specimens as *H. antillea*, a species characteristic of the Middle Oligocene West Indian Antigua Formation. When Howe (1933) placed the Anahuac and Catahoula Formations of Louisiana in the Miocene, the controversy concerning the age of the Anahuac was initiated. Gravell and Hanna (1937) assigned the names *H. texana* and *H. israelskyi* to the forms previously named *Heterostegina antillea* by Cushman, however, these authors, on the basis of associated species of *Lepidocyclina*, assigned a Late Oligocene age to the Heterostegina Zone. The observation made by Gravell and Hanna in 1937 that the age of the Anahuac could not be resolved until general agreement was reached concerning placement of the Oligocene-Miocene boundary remains equally true today.

It is apparent that Ellisor initially defined the Anahuac Formation properly as a lithostratigraphic unit, that is, a unit defined on the basis of lithic characteristics and stratigraphic position (North American Commission on Stratigraphic Nomenclature, 1983). Subsequently Ellisor, in her reference to three foraminifer-based subdivisions of Anahuac sediments, tacitly cast these deposits in the role of a biostratigraphic entity constrained explicitly, therefore by paleontologically-defined bounds. Boundaries of biozones and lithic units can, of course, coincide, at least locally, where biotic and lithic character are strongly, and more-or-less equally controlled by the same set of primary environmental parameters. This situation seems to apply to the typical Anahuac mudstone facies and the apparently concomitant Marginulina, Heterostegina, and Discorbis Interval Zones found beneath the lower Texas Coastal Plain. Updip, however, the typical Anahuac facies grades to sand-dominant units best referred to the Frio or the lower Miocene Unit A of this study. These sandy facies commonly retain the characteristic "Anahuac" zonal fossils.

In this study the author has attempted to restrict application of the name Anahuac to Late Oligocene/Early Miocene shelfal mudstones representing the Heterostegina and Discorbis Interval Zones. The interpreted stratigraphic relationship of the Anahuac mudstone wedge and the Frio and "Oakville" (Unit A) sand facies in a part of south Texas is illustrated in figure 6.

Maximum Anahuac transgression coincides with deposition of sediments of the Heterostegina Interval Zone, and was in response to a regional climatic warming trend. During this episode orbitoid foraminifers moved into the Gulf from the Caribbean, and coral reefs formed on the flanks of salt domes as far north as Houston, Texas (Ellisor, 1926). Deposits of the succeeding Discorbis Interval Zone record a lesser transgressive-regressive cycle (Holcomb, 1964).

Fleming Group

The term Fleming Group (Plummer, 1932) is adopted in this report to include strata of the Oakville, Lagarto and Fleming Formations, as well as the subsurface Miocene Major Stratigraphic Unit (MSU) and its operational units A and B.

Oakville Formation

The name Oakville was applied by Dumble (1894) to "Miocene" grits, coarse sandstone, and clay exposed along the Nueces River at Oakville, Live Oak County, Texas (Wilmarth, 1957). As defined by Dumble, the Oakville included all strata between the Frio Clay and the overlying Pliocene deposits. It was Dumble's opinion that this sequence correlated with the lower half of Kenedy's Fleming Beds of east

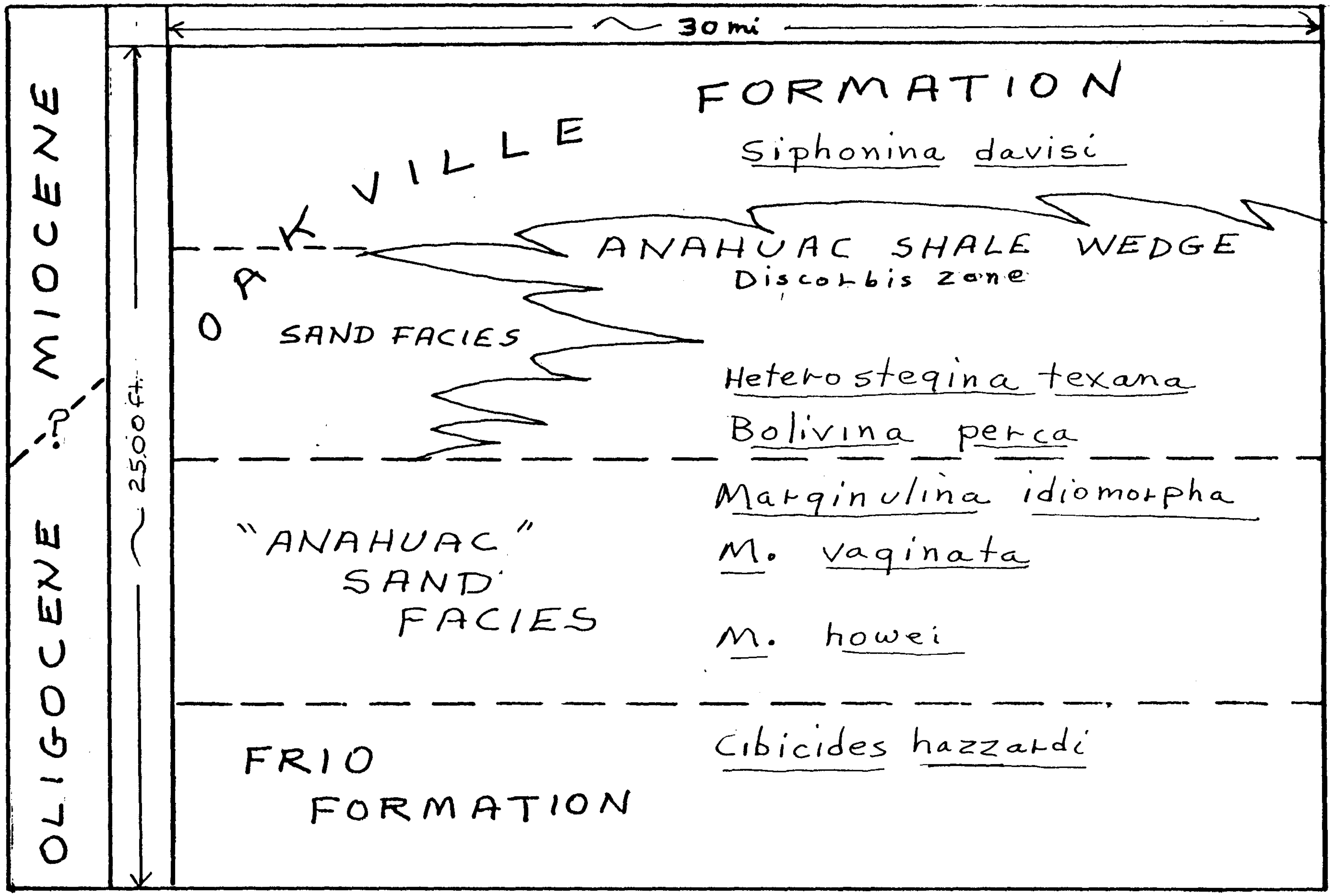


Figure 6. Stratigraphic relationship of the Oakville, Anahuac, and Frio Formations, Kenedy County, Texas.

Texas. Bailey (1926) included the basal Oakville beds of Dumble in his Gueydan Formation (=Catahoula Formation), and Plummer (1932) redefined the type Oakville to include all Miocene strata above the Catahoula and below the Lagarto Formation. Plummer's definition of the Oakville Formation is currently employed by the USGS. The vertebrate fossil assemblage (fig. 7, and table 1) of the Oakville Formation is called the Garvin Gully Fauna for Garvin Gully, 4 km (2.5 mi) north of Navasota, Grimes County, Texas (Wilson, 1956). Quinn (1955) placed this fauna in the Arikareean North American Land Mammal Stage (NALMS) and considered it slightly older than the Early Miocene Thomas Farms Fauna of Florida. Patton (1969), based on a re-study of Texas Neogene mammals, reassigned the Garvin Gully Fauna to the Hemingfordian NALMS. Currently the Early Hemingfordian Stage is included in the Early Miocene (Berggren and Van Couvering, 1974; and MacFadden and Webb, 1982) stratigraphically below the Burkeville Fauna of the Lagarto Formation.

Based on the paleontological evidence the Oakville Formation and Operational Unit A are considered in this report to represent a geochronometric age of 18 to 21 my (fig. 5).

Downdip approximate marine equivalents of the Oakville Formation included in Operational Unit A of this study appear to encompass, from the base upward, the upper Globorotalia kugleri, Globigerinita dissimilis and Globigerinita stainforthi Planktonic Foraminifer Zones (fig. 5). These planktonic zones in turn coincide, approximately, with the stratigraphic interval between the upper Heterostegina zone below to the Discorbis bolivarensis benthonic foraminifer datum above.

Fleming Formation

Kenedy used the name "Fleming beds" for exposures of clays, sands, and sandy clays best represented near the railroad station at Fleming in Tyler County, Texas. The sequence as mapped by Kenedy (1892) in northern Tyler and Polk Counties included all deposits above the Jackson and below the Pleistocene (Weeks, 1945),

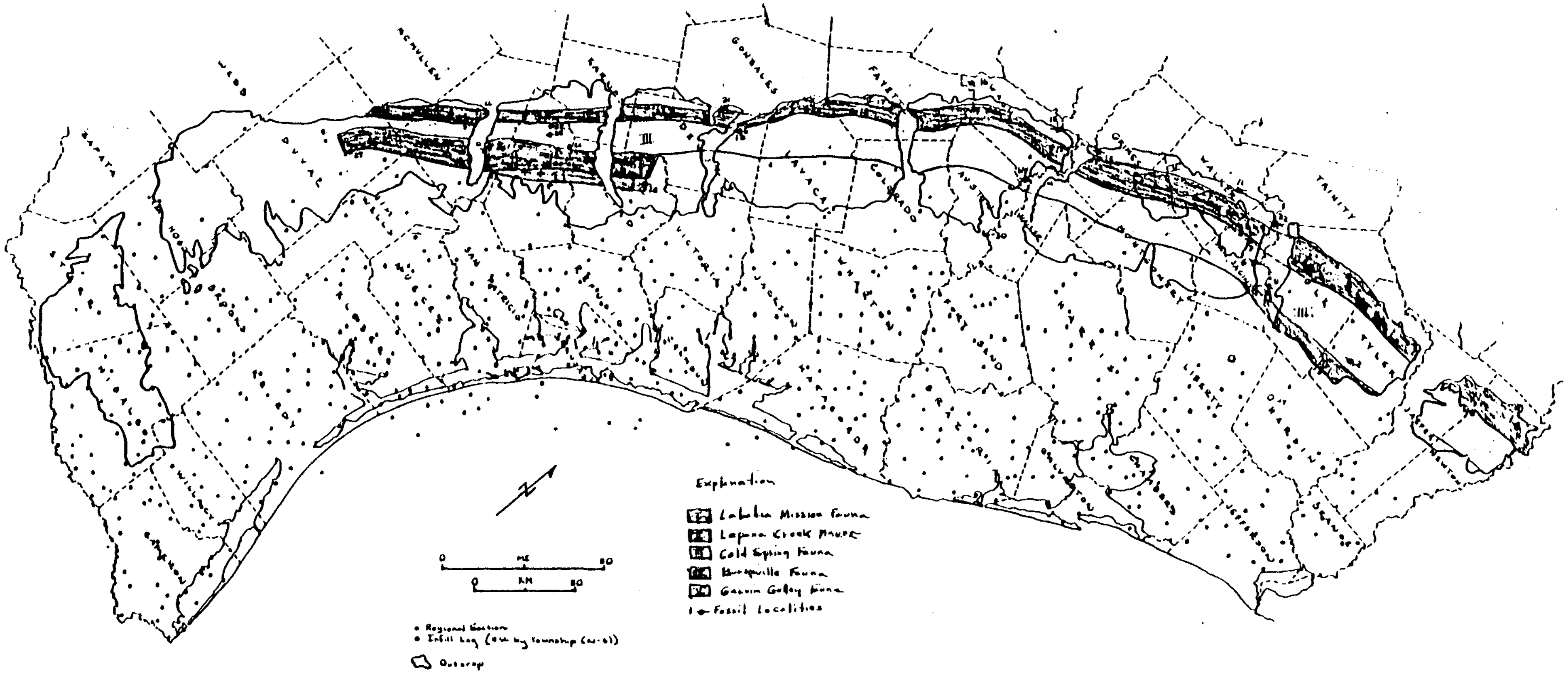


Figure 7. Areal distribution of Miocene-Pliocene mammalian faunas.

Table 1. Key to vertebrate fossil localities depicted on figure 7.

Map no.	UTBEG no.	County	Location
1	31160	Newton	Near Burkeville
2	31087	Tyler	Near Town Bluff
3	31057	Polk	Near Moscow
4	31183	Polk	Near Goodrich
5	31200	Polk	Near Goodrich
6	31219	San Jacinto	Near Cold Spring
7	31191	San Jacinto	Near Cold Spring
8	31243	San Jacinto	Near Point Blank
9	31190	San Jacinto	Near Point Blank
10	31242	San Jacinto	Near Point Blank
11	30873	Walker	Aiken Hill
12	40071	Grimes	Near Navasota
13	40070	Grimes	Sommers Pit
14	31272	Washington	Near Chappell Hill
15	40067	Washington	Hidalgo Bluff
16	40068	Washington	Near Carmine
17	31259	Fayette	Near LaGrange
18	31278	Fayette	Near Amandsville
19	31273	Lavaca	Near Shiner
20	31262	De Witt	Near Concrete
21	30896	Bee	Near Berclair
22	31132	Bee	Near Normanna
23	31080	Bee	Near Berclair
24	31170	Bee	Near Normanna
25	30936	Live Oak	Near George West
26	30904	Live Oak	Near George West
27	31089	Duval	Palangana Dome
28	30895	Goliad	Goliad State Park
29		Hardin	Saratoga field
30	40539	Austin	S. F. Austin State Park
31	40193	De Witt	Near Hochheim
32	40224	San Jacinto	Near Point Blank
33	40262	Gonzales	Near Shiner

thus including, as presently defined, the Catahoula and Willis Formations. Kenedy first published a description of the section near Fleming, now regarded as the type section for the Fleming Formation, in 1903 (Hayes and Kenedy).

Lagarto Formation

The name Lagarto was applied by Dumble (1894) to a calcareous clay bed exposed above his Lapara Sand unit on Lagarto Creek, Live Oak County, Texas (Wilmarth, 1957). Plummer (1932) noted that a thick clay deposit, stratigraphically positionedbetween the Oakville Formation below, and Dumble's Lapara Sand above, had become known to most geologists as the Lagarto Clay. To clarify the resultant stratigraphic confusion, Plummer restricted the name Lagarto to the clay immediately below the Lapara Sand of Dumble, and designated as the type locality for the emended Lagarto Formation, outcrops on the Brenham-Houston highway west of the Brazos River in Washington County, Texas. Subsequently Dumble's Lapara Sand and Lagarto Creek clay beds (the original Lagarto Clay) were assigned as members of the Goliad Formation.

Two stratigraphically distinct vertebrate faunas occur in the Lagarto Formation (fig. 5). The lower of these is termed the Burkeville Fauna (Table 1) and the upper, the Cold Spring Fauna (Wilson, 1956). The Cold Spring Fauna, named for Cold Spring, near Navasota, Grimes County, is placed in the middle Barstovian NALMS (Patton, 1969) and is thus of Late Early Miocene to Early Medial Miocene age. Recently MacFadden and Skinner (1981) reported the earliest (approximately 15 my) occurrence of a hipparion horse from an apparent Cold Spring assemblage near the Trinity River in San Jacinto County.

The Burkeville Fauna is named for Burkeville, Newton County, Texas (Wilson, 1956). Deposits of the Lagarto Formation (=Upper Fleming Formation) at this locality are of particular stratigraphic importance because they contain both terrestrial mammals and brackish-water invertebrate fossils permitting correlation of outcrops with subsurface marine equivalents. Important studies of the Burkeville beds include those of Dall (1913), Hesse (1942), Stenzel, Turner and Hesse (1944), and Floyd, Miller and Berry (1958).

Presence of the gastropod Potamides matsoni Dall establishes correlation of the Burkeville beds with the subsurface Potamides matsoni Zone of Ellisor (1936) and with the Caster Creek Member of the Louisiana Fleming Formation (Fisk, 1940).

The Burkeville vertebrate fauna is correlated with the late Hemingfordian (Patton, 1969) and is thus of Late Early Miocene age.

Downdip marine facies of Operational Unit B, approximately equivalent to the outcropping Lagarto Formation, lie between the Discorbis Bolivarensis benthonic foraminifer datum below and the Bigenerina humblei benthonic foraminifer datum above (fig. 2).

Goliad Formation

Howeth and Martyn (1932) used the name "Goliad Sandstone Formation" for Pliocene beds exposed along the San Antonio River in Goliad County, Texas. The U.S. Geological Survey (Wilmarth, 1957) adopted the name "Goliad Sand" to include all Pliocene beds below the Lissie Formation (Pleistocene) and above the Lagarto Clay as restricted by Plummer (1932). The outcrop belt (fig. 4), as mapped by Barnes (1968 to 1976) extends from Stark and Hidalgo Counties in southwest Texas into Lavaca County where Goliad and Willis outcrops occur in close proximity. In current usage the Goliad Formation is subdivided into three members which, in ascending stratigraphic order, are the Lapara Sand, Lagarto Creek, and Labahia (Plummer, 1932).

Most Goliad vertebrate fossils originated from the Lapara Member (Wilson, 1956) and this assemblage was referred to as the Lapara Creek Fauna by Quinn (1955). The Lapara Creek Fauna (figs. 5 and 7) is correlated with the Clarendonian

NALMS (Quinn, 1955, and Patton, 1969) and is thus Late Medial to Early Late Miocene (12 to 9 mya) in age. Stratigraphic downdip projection of the lower Goliad-Willis sequence during the present study, and by Solis (1981) indicates that marine facies of this interval coincide, at least in part, with the Globoratalia menardi Planktonic Foraminifer Zone (Late Medial Miocene).

No vertebrate fossils are known from the Lagarto Creek Member; however, a sparse assemblage from the Labahia Member has been assigned to the Hemphillian North American Mammal Stage which originally was considered to be of Pliocene age (Wilson, 1956; Patton, 1969). More recently it has been shown that the Hemphillian is of Late Miocene to Early Pliocene age (Berggren and Van Couvering, 1974; and MacFadden and Webb, 1982); thus it appears that the Labahia Member probably straddles the Miocene/Pliocene boundary. The stratigraphically intermediate Lagarto Clay Member, bracketed by Late Miocene deposits above, and Late Medial Miocene deposits below, must logically be assigned to the Late Miocene. From available evidence, therefore, it seems apparent that the Goliad Formation ranges in age from Late Medial Miocene to possibly Early Pliocene. The precise stratigraphic relationship of marine equivalents of the Labahia Member to the Galveston Formation has not been determined.

Doering (1935) noted that a close relationship existed between the Willis and Goliad Formations. Plummer (1932) considered both units to be of the same age, but thought that the Willis was, in part, slightly younger than the Goliad. He also pointed out that where the two units occur together in the same area they are difficult to differentiate. The stratigraphic position of both the Willis and Goliad Formations between basal Pleistocene units above and the Lagarto Formation below strongly suggests that they represent facies of a single contemporaneous stratigraphic unit of Late Miocene to Pliocene age (fig. 5).

Willis Formation

The name Willis (fig. 2) was employed by Doering (1935) for sands and gravelly ands of probable Pliocene age exposed near the town of Willis, Montgomery County, Texas. Doering (1956) reassigned these deposits to the Citronelle Formation which he then considered to be of early Pleistocene age. The Willis sands of Doering were included by Plummer (1932) in his Citronelle Group and considered by him to be of Pliocene age, but slightly younger than most of the Goliad Formation. Willis deposits of the type area in Montgomery County are classified as lower Pleistocene by Barnes (1968) and shown by him to stratigraphically lie between the Pleistocene Bentley Formation above and the Fleming Formation.

Fossils are apparently unknown from Willis sediments; however, for reasons explained in the above discussion for the Goliad Formation, it appears logical to consider the Willis Formation an essentially contemporaneous eastern facies of the Goliad, and thus to be of Late Medial Miocene to at least Early Pliocene age.

Galveston Formation

The designation "Galveston Formation" (fig. 2) has been applied by the author (DuBar and others, 1980) to a brackish-water to marine sequence of fossiliferous fine sand and clay mapped along the coast of the northwestern Gulf from South Marsh Island, Louisiana, to Mexico. The type section for these deposits is the -1320 to -3030 ft sample interval of the Humble Oil and Refining Company #1 Ostermeyer well located on Galveston Island approximately 10 km (6 mi) southwest of the city of Galveston. In the type area the Galveston is unconformably overlain by the Early Pleistocene "Williana Formation" and rests unconformably on sediments included in the Late Miocene Rangia microjohnsoni Zone. This interval coincides closely with the Evangeline Aquifer of Baker (1978). Fossils representative of the interval were first reported by G. D. Harris (1895), who mistakenly assigned the lower part of the interval to the Miocene. Study of the contained molluscan assemblages demonstrates that the Galveston Formation correlates with the Pliocene Jackson Bluff and Tamiami Groups of Florida (DuBar and others, in press). To determine the stratigraphic relationship of the Galveston deposits with their outcropping equivalents, a dip-oriented stratigraphic section based on electric logs and well samples was prepared. This section demonstrates that the Galveston interval correlates with the upper Willis Formation as mapped by Barnes (1968b) in Montgomery County, 48 km (30 mi) northwest of Houston. This evidence supports the view that the upper part of the Willis and probably the Labahia Member of the Goliad Formation are of Pliocene age.

GEOLOGIC FRAMEWORK

The Miocene MSU was deposited upon the continental platform constructed by the earlier Frio progradation. This style of sedimentation differs from that of the Frio for which the depocenter was located along the Texas coast. Miocene depocenters (fig. 8) progressively shifted eastward so that the Early Miocene depocenter lay off southwestern Louisiana and later depocenters off southeastern Louisiana (Rainwater, 1966).

The three major structural provinces of the Texas Coastal Plain are, from northwest to southeast, the Houston Embayment, the San Marcos Platform and the Rio Grande Embayment (pl. 1). These broadly defined provinces, with their respective structural styles, have importantly influenced the character of Miocene deposition. In the Rio Grande Embayment and across the San Marcos Platform salt and salt-related structures are rare or absent. In this province growth fault belts and associated anticlines, clay ridges and clay diapirs are the major structures (Bishop, 1978 and Bruce, 1973). In the Houston Embayment salt diapirism and associated faulting, and salt withdrawal basins are most characteristic (Bebout and others, 1978, Bruce, 1973 and Jackson, 1982).

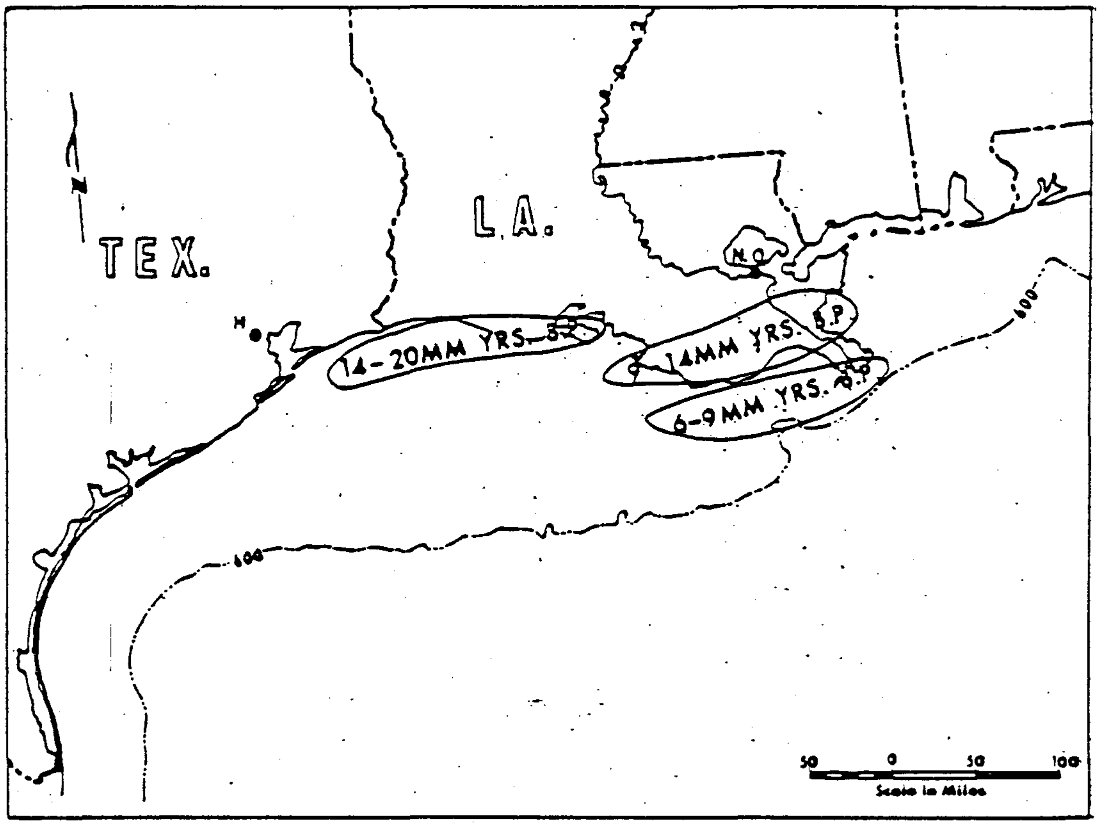


Figure 8. Principal Miocene depocenters based on isopach maps constructed from subsurface well control. (After H. O. Woodbury and others, 1973).

Three fault-defined subbasins are recognized in the Rio Grande and San Marcos structural provinces (fig. 1). The updip subbasin is characterized by faulting related to the Vicksburg Flexure (Gregory, 1966). These faults generally have Miocene displacements of less than 122 m (400 ft) affecting only strata of the lower Miocene Unit A. Growth faults of the Frio Flexure characterize subbasin II. Unit A strata are displaced up to 305 m (1,000 ft) by some of these faults, whereas faulting of Unit B strata is less common and displacements are usually less than 91 m (300 ft). Subbasin III, the updip margin of which extends along the lower Texas Coastal Plain, is dominated by the Miocene fault belt. Faults of this trend dislocate the entire Miocene MSU and downdip they contribute to a dramatic section expansion. These subbasins do not extend as clearly defined entities into the salt dome province of the Houston Embayment.

DEPOSITIONAL SYSTEMS

General Statement

The Miocene MSU was subdivided into six regionally distinct but geologically integrated depositional systems (pl. 8). Differentiation of these systems was based on analysis of net sand, sand percent and facies maps and the vertical distribution of log facies as represented by key log dip sections (pls. 10 to 13). Procedures adopted to recognize and delineate these genetic units followed the approach of Fisher and McGowen (1967) and Galloway, Hobday and Magara (1982). Facies relationsips across the depositional systems are depicted in four key stratigraphic dip sections (pls. 10 through 12) and two regional facies maps (pls. 7 and 8).

Two extensive progradational bodies, designated the San Jacinto and Rosita Systems, occur centered in the Houston and Rio Grande embayments respectively (pl. 9). The San Jacinto delta system is characterized by relatively small, coalescing wave-influenced and wave-dominated delta lobes (pls. 7, 8, 10 and 11) fed by mixed-load streams of the adjacent Cypress fluvial system which carried fine to coarse sands, silts and clay (Spradlin, 1980). Much of the sand contributed to this system, as mapped in east Texas, appears to have been transported along strike from deltaic counterparts in adjacent Louisiana. Delta lobes of the northeastern part of the Rosita delta system were similar to those of the San Jacinto delta system but were fed by bed-load and mixed-load streams of the Santa Cruz fluvial system. To the southwest ancestral counterparts of the Rio Grande River constructed larger and more clearly vertically stacked deltaic lobes.

Located between the two structurally-controlled fluvial-deltaic complexes was an area across the San Marcos Platform termed the Moulton Streamplain and the adjacent shoreward-located Indianola barrier-strandplain-bay system. Streams of the Moulton Streamplain were small, commonly ephemeral, and, for the most part, transported fine sands and muds. Small delta lobes prograded into the adjacent lagoons, which developed behind a Gulfward line of barriers and strandplain systems. Sands of the barrier and strandplain were derived primarily from strike-transported sands of adjacent depocenters; however, it is probable that wave-reworking of the small bayhead deltas provided a minor secondary sand source.

Cypress Fluvial System

The Cypress Fluvial System lies northeast of the Moulton Streamplain. This area is more than 298 km (185 mi) wide, and extends in subsurface beneath the Miocene Texas Coastal Plain 64 to 80 km (40 to 50 mi). Sand isolith, sand percent and facies maps (pls. 3 through 8) indicate the contemporaneous existence of four main mixed-load fluvial channel systems. These are, (from west to east) the Burton, Penn, Polk, and Tyler Axes (pl. 9). These axes enter the coastal plain in Washington, Grimes, Polk and Tyler Counties respectively. Although it is apparent that channel shifting was commonplace the axes of the four systems remained generally constant throughout deposition of the Miocene MSU. As pointed out by Spradlin (1980) the downdip decrease in sinuosity of sand isolith patterns, and the decrease in thin sands in the floodplain facies indicate presence of well-developed levees along major channels.

The channel-fill/floodplain complex which represents the Burton axis is approximately 64 km (40 mi) wide. Along the axis sand distribution is characterized by several dip-oriented moderately sinuous dendritic sand belts generally 3 to 8 km (2 to 5 mi) wide. The system enters the Miocene Coastal Plain in Washington County and merges with the San Jacinto Delta System near the Ft. Bend-Brazoria County line, and thus follows closely the present course of the Brazos River. Sand content in updip channel-fill facies reaches 60 to 70 percent, however, downdip the range is typically 30 to 50 percent. Net sand thickness for channel-fill deposits ranges from 61 to 152 m (200 to 500 ft) for both Units A and B. Sand content for floodplain facies is typically 20 to 30 percent and net sand thickness is 30 to 91 m (100 to 300 ft). Channel-fill sand units up to 15 m (50 ft) occur vertically stacked and amalgamated.

Miocene MSU sands at the outcrop along the Burton Axis are calcilithic with greatest percentage of carbonates and coarse sand in Unit A (Ragsdale, 1960).

That part of the Tyler Axis which occupies the easternmost section of the Cypress Fluvial System is approximately 153 km (95 mi) wide, however, an additional segment of the system occurs in adjacent Louisiana. The system is located in parts of San Jacinto, Polk, Tyler, Jasper, Newton, Liberty, and Hardin Counties. Sand isolith belts are 3 to 10 km (2 to 6 mi) wide, and represent various courses of the Miocene ancestral Neches and Sabine Rivers. Similar to the Penn Axis, multiple dip-oriented sand belts of the Tyler Axis are moderately sinuous, forming dendritic patterns updip and basinward bifurcating belts downdip.

Sand content of channel-fill isoliths commonly is 40 to 60 percent, and sand content for floodplain facies is 25 to 50 percent in Unit A and 30 to 40 percent in Unit B. Net sand thicknesses for channel-fill isoliths are 152 to 213 m (500 to 700 ft) for both Unit A and Unit B. Channel-fill sand units are most typically 6 to 12 m (20 to 40 ft) thick, however, some sand units, especially updip facies, reach 30 m (100 ft) or more in thickness. Commonly several cycles of channel-fill occupy the same drainage course producing vertically stacked and amalgamated sequences. Sand content of floodplain facies is 25 to 50 percent for Unit A and 30 to 40 percent for Unit B. Flood basin net sand thickness ranges from 30 to 152 m (100 to 500 ft) for Unit A and 61 to 152 m (200 to 500 ft) for Unit B.

Although rivers of this axis delivered a substantial sediment load to the adjacent Gulf, deltas were strongly wave-dominated and basinward progradation of the Miocene fluvial system during deposition of Unit B in this area was only 16 km (10 mi) or less.

The Penn Axis (pl. 9), the largest and most complex component of the Cypress Fluvial System is approximately 105 km (65 mi) wide and represents various positions of the San Jacinto and Trinity Rivers. Multiple dip-oriented sand isoliths are moderately sinuous, are arranged dendritically updip, and form basinward bifurcating belts downdip.

Major sand belts are generally 5 to 16 km (3 to 10 mi) wide, however, a maximum width of approximately 24 km (15 mi) is attained at the conjunction of several isoliths in north-central Harris County. Sand content for channel-fill trends ranges upward to 80 percent in updip facies, whereas in downdip facies a range of 20 to 40 percent is characteristic. Net sand thickness is 91 to 152 m (300 to 500 ft) in Unit A and 91 to 274 m (300 to 900 ft) in Unit B. Sand content for floodplain facies is typically 20 to 40 percent, and net sand thickness ranges from 30 to 152 m (100 to 500 ft). Numerous thin sandstone units incorporated in the floodplain facies represent tributary channel-fill deposits, and crevasse and splay facies. Sand units of major channels, commonly 12 to 18 m (40 to 60 ft) thick, occur in vertically stacked and commonly amalgamated sequences. As observed by Galloway and others (1982), the intermediate sand content, restriction of sand to laterally isolated belts and internal features of these sand isoliths suggest deposition by flashy, coarse-mixed-load to distal bed-load rivers.

Rivers of the Burton Axis, similar to those of the Penn Axis, built small coalescing deltas where they discharged into the Gulf. In this manner the Penn and Burton systems prograded Gulfward more than 32 km (20 mi) during deposition of the Miocene Operational Unit B.

Dominant structures of the Cypress Fluvial System are growth faults and numerous salt diapirs, with associated radial faults, and salt withdrawal basins. The system coincides in large part with Play VIII (pl. 14), the most prolific hydrocarbon producing region of the Texas Coastal Plain.

Moulton Streamplain System

In the middle of the Texas Miocene Coastal Plain, between the Cypress and Santa Cruz Fluvial Systems, is an area 121 to 161 km (75 to 100 mi) wide designated the Moulton Steamplain by Galloway, Henry and Smith (1982). This mudrich area contains several relatively thin and narrow dip-oriented sand tracts. Net sand thickness in these tracts ranges from 30 m (100 ft) at outcrop to 152 m (500 ft) downdip. Sand content is greatest (50 to 60 percent) updip in the outcrop and shallow subsurface. Net sand thickness for floodplain areas is 30 to 92 m (100 to 300 ft) for Unit A and 61 to 122 m (200 to 400 ft) for unit B. Sand content in this facies is characteristically 20 to 30 percent for both units.

The sand-rich trends encased in finer-grained sediment indicate that deposition in this part of the Coastal Plain was characterized by small, ephemeral, primarily mixed-load streams subject to flooding (Galloway, Henry, and Smith, 1982).

Following the Early Miocene transgression the Moulton Streamplain was advanced Gulfward across the Vicksburg Flexure by construction of coalescing bayhead deltas, and subsequent fluvial progradation. Later, during depositon of Unit B, the strandplain system was prograded an additional 16 to 32 km (10 to 20 mi) Gulfward overriding bayhead delta and lagoonal facies of Unit A.

Galloway, Henry, and Smith (1982) described outcropping fluvial sands of the Moulton streamplain as moderate to well-sorted, coarse to very fine sand, and sparse granule conglomerate and pebbly sand which occur as lenticular channel-fill units ranging from 10 to 25 ft (3-7 m). Well logs show that in subsurface most of the sand bodies are less than 9 m (30 ft) thick, that they are commonly vertically stacked, but rarely amalgamated. Intercalated floodplain sediments between channel-fill units range up to 61 m (200 ft) thick. Interbedded with both channel-fill and floodplain sediments are numerous thin (less than 10 ft) sandstone bodies which represent crevasse and splay facies and small tributary channel-fills.

The gently coastward dipping sediments of the Moulton Streamplain are crossed by numerous growth faults associated with the Vicksburg and Frio Flexures. Numerous hydrocarbon fields of plays VI and VII (pl. 14) produce from these sediments.

Santa Cruz Fluvial System

The Santa Cruz Fluvial System is at least 306 km (190 mi) wide and it extends in subsurface beneath the Texas Coastal Plain a maximum distance of approximately 97 km (50 mi). It is traversed by three major fluvial complexes. These are, from south to north, the Hebbronville Axis, George West Axis, and the New Davey Axis (pl. 9). Each of the axes was delineated and named by Galloway, Henry, and Smith (1982).

The Hebbronville, largest of the three drainage systems, is the Miocene representative of the modern Rio Grande. Within Texas, the Hebbronville channel-fill complex is more than 129 km (80 mi) wide, and a part of this system extends for an undetermined distance into Mexico. Along the axis, sand distribution is characterized by multiple dip-oriented, slightly sinuous, anastomosing, basinward bifurcating belts most commonly 5 to 11 km (3 to 7 mi) wide. Isolith trends for Unit A display a generally southeastward orientation whereas those of Unit B possess a stronger eastward orientation.

Sand content for major channel-fill trends is 40 to 80 percent and 10 to 40 percent for floodplain facies. Net sand thickness ranges from 91 to 305 m (300 to 1000 ft) for both units A and B. Individual channel sand units are generally 6 to 15 m (20 to 50 ft) thick and commonly occur vertically stacked and amalgamated.

The George West Axis constitutes the locus of a major river on the Texas Coastal Plain which appears to represent deposition of an ancestral Neches River. Galloway, Henry, and Smith (1982) suggested that the George West and Hebbronville axes are elements of an ancestral, single large, extrabasinal river system (Rio Grande) and that the George West axis shifted southward during the early Miocene. Based on study of sand isolith and sand percent maps (pls. 3 through 6) the George West and Hebbronville axes appear to have maintained their relative positions and identities throughout deposition of the Miocene MSU.

The George West Axis is physically similar to the Hebbronville Axis; however, it is somewhat less extensive, possesses fewer major dip-oriented sand trends, and the system probably delivered less sediment to the Gulf than the Hebbronville System.

Width of George West sand belts is 3 to 10 km (2 to 6 mi) for Unit A and 3 to 16 km (2 to 10 mi) for Unit B. Sand content of major sand isoliths is 40 to 60 percent, and net sand thickness is 61 to 213 m (200 to 700 ft) for Unit A and 122 to 213 m (400 to 700 ft) for Unit B. Sand unit thickness most commonly falls in the range of 6 to 15 m (20 to 50 ft) with unit-thickness more than 23 m (75 ft) relatively rare. Vertical stacking and amalgamation of these units is most common in updip facies. Floodplain facies most commonly contain 30 to 40 percent sand, and 30 to 107 m (100 to 350 ft) net sand thicknesses.

As pointed out by Galloway, Henry, and Smith (1982) the George West and most likely the Hebbronville systems were characterized by bed-load streams.

The New Davey Fluvial Axis was described by Galloway, Henry, and Smith (1982) as a major Oakville River. The system, which is much smaller, and less complex than the Hebbronville and George West Systems (pl. 9) has been shown in this study to be better developed in Unit A than Unit B. The principal sand belts are located in parts of Karnes, De Witt, Goliad, Refugio, Victoria, and Calhoun Counties. The major dendritically arranged sand belts generally are 3 to 8 km (2 to 5 mi) wide. Sand content of major channel-fill trends ranges from 40 to 60 percent, and sand isolith thickness is 61 to 213 m (200 to 700 ft) for Unit A and 122 to 213 m (400 to 700 ft) for Unit B. Average sand content for floodplain facies is 30 to 40 percent and isolith thickness is 30 to 107 m (100 to 350 ft) for Unit A and 61 to 107 m (200 to 350 ft) for Unit B. Approximately 40 percent of the channel-fill sand units are 6 to 15 m (20 to 50 ft) thick, and approximately 15 percent are thicker than 15 m (50 ft). Commonly, especially in updip facies, these sands occur vertically stacked in sequences 61 m (200 ft) or more in thickness. Intercalated and encasing facies include floodplain mudstones and thin crevasse splay facies.

Dominant structures of the Santa Cruz Fluvial System are growth faults of the Vicksburg and Frio Flexures. Primary hydrocarbon production is associated with downdip parts of the George West and New Davey Axes.

San Jacinto Delta System

The San Jacinto Delta System extends 322 km (200 mi) along strike from Matagorda County into Newton County, and for an undetermined distance into western Louisiana. Most typical and extensive onshore delta development is centered in Chambers, Jefferson and Orange Counties; the offshore, most distal parts of the delta were not mapped as they are not included within the bounds of this study. The boundary with the Indianola Barrier/Strandplain/Lagoon System is gradational through a coastwise distance of at least 48 km (30 mi). The updip boundary with the Cypress Fluvial System shifted during deposition of Miocene MSU through a zone up to 48 km (30 mi) wide in response to transgressive and regressive marine fluctuations.

Shifting distributaries of the Cypress Fluvial System constructed multiple coalescing delta lobes into the adjacent Gulf. These deltas, subjected to strong destructive wave energy probably developed geometrically arcuate morphology as illustrated by Fisher and others (1969).

Updip proximal deltaic sectors include an intricate complex of vertically and laterally interfingering and overlapping facies, including marsh-lagoon, distributary mouth bar, and various backbarrier sand facies. Such sequences reach a thickness of 366 m (1200 ft) and display variable sand content ranging from 30 to 50 percent. Galloway, Henry, and Smith (1982) pointed out that these facies are difficult to distinguish except on the basis of their position relative to equivalent seaward facies, and to some degree to the extent of strike continuity of some backbarrier facies. Proximal deltaic deposits occur in a significantly narrower belt than those of Unit A.

Gulfward blocky, strike-oriented deltaic sandstones are interpreted as destructional bar and strandplain facies developed most representatively during transgressions. The facies is the product of strong wave and longshore current modification of contemporaneously prograding updip, arcuate deltas. Much of the sand of this facies appears to have been transported westward from contemporaneous delta lobes developed in western Louisiana. Thickness of the vertically stacked, blocky sand sequences ranges up to 396 m (1300 ft). Galloway and others (1982) in explanation of similar thick sequences of the Frio Houston Delta suggested that they are, in part, the product of transgressive reworking, and subsequent aggradation of strandplain and destructional bar sands.

Delta front and prodelta/shelf facies are most characteristic of the lower, downdip part of Unit A, but also occur as thin wedges interbedded with destructional barrier and strandplain sequences in Unit B, and Upper Unit B (pls. 7 and 8).

Prodelta and shelf facies form vertically continuous sequences of mudstone which cannot be accurately separated on log characteristics alone. The lower, thicker parts of such sequences are properly included in the Discorbis and upper Heterostegina Zones of the Anahuac Formation and overlying mudstones are classified as prodeltaic facies. The mudstone wedge gradually thickens basinward, but where crossing major growth faults thickness increase is commonly dramatic. Delta-front facies are characterized by upward coarsening sequences that are generally less than 91 m (300 ft) thick.

Dominant structures are regional growth faults, salt diapirs, and associated sediment uplift and faulting. Contemporaneous fault displacement and initiation of new faults served to accentuate the strike-orientation of the deltaic sand bodies.

Major hydrocarbon accumulation, dominantly oil, is primarily structurally trapped with stratigraphic traps relegated to a secondary role. Traps occur on both upthrown and downthrown sides of growth faults and in association with salt-produced structures. Thick, porous and permeable sands of the distal delta do not serve as major reservoirs because they lack effective impermeable seals.

Indianola Barrier/Strandplain/Lagoon System

The San Jacinto Delta System grades southwestward into the Indianola Barrier/Strandplain/Lagoon System. The latter system extends from southwestern Brazoria County to northeastern Nueces County, a distance of approximately 209 km (130 mi). The System thus coincides with the updip, sand-poor, contemporary Moulton Streamplain and it lies immediately basinward of the Frio Greta/Carancahua Barrier/ Strandplain System of Galloway and others (1982). The Indianola System shifted basinward more than 40 miles during deposition of the Miocene MSU, however, vertical upbuilding of sands was the dominant depositional pattern. The massive barrier/ strandplain sands, attaining a thickness in excess of 305 m (1000 ft) in Unit A and 610 m (2000 ft) in Unit B form an arcuate belt which curves seaward as it crosses the San Marcos Platform. In Unit A these elongate sands overlie up to 274 m (900 ft) of progradational delta front sediments, and more than 609 m (2000 ft) of shelf and slope mudrocks. Along the basinward margin of the barrier/strandplain trend these sands are interbedded with wedges of delta front, shelf and barrier front facies. Along the updip margin of this trend these sands grade into and interfinger with a variety of backbarrier, lagoonal, and fluvio-deltaic sediments. The array of backbarrier facies, in turn, grade into and interfinger with fluvial-channel and floodplain/marsh facies.

The core of the thick sand trend is composed of elongated, vertically stacked sand units up to 46 m (150 ft) thick. Sequences of these vertically stacked blocky sand units with total thickness up to 305 m (1000 ft) are judged to represent aggradational barrier deposits. The barrier trend of Unit A is oriented essentially parallel to the present shoreline (pl. 7), and the Miocene depositional strike. Unit B barriers form a wider, more complex trend with a north-south orientation somewhat oblique to the Miocene depositional strike. The dominant barrier/strandplain sand source was provided by southwestward long-shore drift of wave-destroyed deltas of the Penn and Burton stream systems. Streams of the Moulton Streamplain delivered only comparatively minor quantities of sediment to the lagoon system which lay landward of the barrier system. Sand content for the barrier/ strandplain complex ranges from 30 to 60 percent, and net sands are 900 to 1500 feet thick for Unit A and 305 to 701 m (1000 to 2300 ft) for Unit B.

Mudstone and interbedded thin sandstone units, which lie landward of the barrier/strandplain trend, are interpreted as complementary lagoon deposits. This belt of lagoonal deposits, 24 to 48 km (15 to 30 miles) in width, extends through northern Matagorda, southern Jackson, southern Victoria, most of Calhoun, southern Refugio, southern San Patricio, eastern Nueces and most of Aransas Counties (pls. 7 and 8). Solis (1980) recognized a Fleming lagoonal system in much the same area, Walton and Smith (1967) comment that, "Coastal lagoons (marginal marine sediments) are extensive in the central portion of the area mapped but tend to disappear to the north and south."

The mudstone-dominated lagoon system ranges in thickness to more than 914 m (3000 ft). Intercalated sand units are typically 1.5 to 3 m (5 to 10 ft) thick, however, landward sheet-like sand bodies, interpreted as distributary mouth bar sands, are typically more than 30 m (100 ft) in thickness.

Throughout time of deposition of the Miocene MSU streams of the Moulton Streamplain prograded small bay-head deltas into the lagoon and, in places, nearly bisected the lagoon. Persistence of the lagoons through time is testimony to the fact that local subsidence at least kept pace with sediment influx.

Dominant structural control was growth faulting which tended to augment the strike-parallel sand-body orientation. During deposition of Unit A the landward boundary of the lagoonal system was the basinward front of the Vicksburg Flexure, and during deposition of unit B this boundary was established by the Frio Flexure. Younger, downdip faults are located on, and parallel to the barrier/strandplain trend.

Hydrocarbon production from sediments of the Indianola Barrier/Strandplain/Lagoon System, mainly gas, is structurally trapped by growth faults and related anticlines. Stratigraphic traps and reservoirs include fore-barrier and delta front facies.

Rosita Delta System

The Rosita Delta System extends 330 km (205 mi) along strike from Refugio County, Texas, and for an unmapped additional distance into adjacent Mexico. In southwest Texas the delta sequence has a maximum mapped dip-oriented width of 105 km (65 mi) and a recorded thickness of more than 1829 m (6000 ft). Offshore segments were not included in this study. Northward along strike the system grades into the Indianola Barrier-Strandplain-Lagoon System. A northward shift in the bounday between those two systems following deposition of Unit A correlates with a corresponding shift of the New Davey fluvial axis. The updip boundary with the Santa Cruz Fluvial System shifted through a zone up to 80 km (50 mi) wide partly in response to transgressive and regressive fluctuations, but also in part to variations in major stream courses of the Santa Cruz Fluvial System.

The southwestern segment of the delta system is largely the product of the migrating channels of the Hebbronville fluvial axis. Northward, streams of the George West and New Davey axes constructed smaller, coalescing delta lobes similar to those of the San Jacinto System. Configuration and sand-body patterns indicate that these deltas were wave-modified to strongly wave-dominated and that wave-eroded sands were dispersed southwestward by littoral drift.

Adjacent to the Santa Cruz Fluvial System proximal deltaic deposits form a coastwise elongate belt up to 48 km (30 mi) wide. This depositional complex is composed of a variety of interfingering overlapping and vertically stacked facies including delta plain, upward-fining channel sands, splay-channel fill, blocky laterally persistent channel-mouth bars, and to the northeast, lagoonal mudstones and relatively thin sand units which formed in association with shifting and temporary barrier sand bodies. Mixed aggradational and progradational log patterns are characteristic for this facies suite. Sand content along this belt is most commonly 20 to 40 percent, but ranges upward to 80 percent in parts of Hidalgo, Willacy, and Cameron Counties. Net sand also increases to the southwest; the thickness reaches 518 m (1700 ft) in Unit A and 701 m (2300 ft) in Unit B.

Gulfward deltaic deposits are characteristically thick, strike-oriented destructional bar, barrier and strandplain sand bodies displaying blocky to serrate, or funnel-shaped log responses. Combined characteristics of these sediments suggest a high-energy system involving strong wave activity, storm-induced currents and well-established littoral drift systems. Sand units 15 to 30 m (50 to 100 ft) thick occur vertically stacked and commonly amalgamated, or separated only by thin mudstone units. Sand content in this facies reaches 80 percent in the southwest, but elsewhere is typically 30 to 50 percent. Net sand thickness is greatest in Cameron County where maxima of 518 m (1700 ft) and 640 m (2100 ft) are recorded for Units A and B respectively. This trend is reversed for the Unit B sequence in extreme southwestern Cameron County where both sand percent and net sand decrease in a Gulfward direction. Here, and elsewhere along the lateral extent of the system, the strike-oriented sand-bodies of Unit A overlie 91 to 152 m (300 to 500 ft) of progradational, generally upward coarsening delta front deposits. Delta-front sand units, including splay sands, thin fringe sands, and distributary mouth bars are usually less than 15 m (50 ft) thick and occur vertically stacked with shelf mudstone interbeds up to 30 m (100 ft) or more thick. These delta-front facies rest, in downdip areas, on a thick sequence of shelf mudstone much of which represents the Anahuac Formation. Downdip Unit B destructional bar and strandplain sands are usually interbedded with relatively thin (less than 91 m, 300 ft) delta front and shelf facies wedges.

The maximum Anahuac transgressive episode triggered by regional, or perhaps worldwide, climatic warming, and represented by sediments of the Heterostegina Interval Zone, initiated Miocene marine deposition along the entire Texas coast. Concurrent progradation of the Rosita Delta System more effectively neutralized the effect of this transgression than elsewhere along the coast, with the result that, except in Cameron County, Anahuac shelf mudstones do not extend more than 8 to 24 km (5 to 15 mi) inland of the present coast line.

Dominant structures are growth faults and associated rollover anticlines. Thick, stacked, strike-oriented porous sands have not served as good hydrocarbon reservoirs due to lack of effectively impermeable seals. Faulted sequences of delta front facies composed of thinner sands and thicker interbedded mudstones provide potentially excellent reservoirs.

HYDROCARBON PRODUCTION

General Statement

The Miocene MSU has produced nearly 3.0 billion bbl of oil and 7 trillion cubic feet of gas for a total of more than 4 billion boe of hydrocarbons. Included in this total are hydrocarbons from fields discovered and developed during the early part of the century as well as fields discovered, especially in downdip coastal areas, during the past decade. Collectively Miocene MSU hydrocarbon production includes 30 counties, and 250 fields in shallow nearshore waters (pl. 14).

The hydrocarbon data base employed in this study was derived from fields containing more than 1 million boe (Appendix). It is estimated that these fields contain 95 percent of the known reserves of the Miocene MSU. This estimate is consistent with the general observation that in other basins of the world most hydrocarbons are produced from the large pools. It seems probable that errors introduced by deleting smaller fields are less important than those introduced by the incomplete records of early production for the largest, most prolific fields.

Geology of Hydrocarbon Plays

Each of the 10 Miocene MSU plays is characterized by a unique combination of structural style, sedimentary facies suites, and hydrocarbon production. Thus,

Table 2. Geologic exploration attributes of Miocene MSU plays.

Play	Productive System(s)	Structural Style	Exploration Maturity	Frontiers	Limiting Factors
I	Rosita Delta System	Growth fault and deep shale ridge	Immature	(1) Deep anticlinal trends (2) OCS	(1) Migration efficiency (2) Lack of adequate reservoir seals (3) Lack of source rocks
II	Santa Cruz Fluvial System, Rosita Delta System	(1) Growth fault and deep shale ridge	Immature	Combination stratigraphic fault traps in fluvio-deltaic transition zone	(1) Lack of indigenous source rocks
III	Santa Cruz Fluvial System	Vicksburg Flexure and deep shale ridge	Mature	None	(1) Thin, shallow section (2) Lack of source rocks
IV	Santa Cruz Fluvial System, Rosita Fluvial System	Growth fault, deep shale ridge and shale diapir	Supermature	OCS	(1) Well density
V	Indianola Barrier-Strandplain-Bay System	Growth fault, shale diapir and minor salt diapirism	Mature	Downdip faulted stratigraphic traps	(1) Widespread poor reservoir quality updip
VI	Indianola Barrier-Strandplain-Bay System, Moulton Streamplain	Vicksburg flexure shale diapir and minor salt diapir	Supermature	Downdip faulted delta-front facies	(1) Well density
VII	Moulton Streamplain	Inherited, low amplitude folds and faults	Mature	None	(1) Well density (2) Thin, shallow section
VIII	Cypress Fluvial Cypress, San Jacinto Delta System	Salt diapirism and associated faulting	Mature	Downdip faulted delta-front facies	(1) Drilling density
IX	Cypress Fluvial System	Inherited low amplitude folds and faulting, and minor salt diapirism	Mature	None	(1) Thin, shallow section (2) Lack of major structures (3) Remoteness from source rocks
X	San Jacinto Delta System	Growth fault and salt diapirism	Supermature	Downdip faulted delta-front facies	(1) Well density

Table 3. Quantitative geologic attributes of Miocene MSU plays.

		Rock Volume					Structure			
Play	Area (mi^2)	Rock volume (mi3)	Sandstone (mi3)	Mudstone (mi3)	Percent sandstone	Percent mudstone	Miles of major faulting	Number of salt diapirs	Number of mapped closures	Average well density (wells/mi^2)**
I	2,501	2,960	1,158	1,802	39.1	60.9	143	0	65	0.03
II	3,546	2,640	1,192	1,448	45.3	54.7	191	2	113+	0.11
III	4,199	1,366	554	812	40.6	59.4	209	0	21+	1.13
IV	2,373	1,731	672	1,059	38.8	61.2	194	0	27	3.01
V	4,075	3,518	1,342	2,176	38.1	61.9	364	1	66	1.24
VI	2,891	1,623	522	1,101	32.6	67.4	345	1	74	1.85
VII	2,915	1,077	408	669	33.8	66.2	148	1	29+	1.49
VIII	6,953	4,481	1,801	2,680	42.0	58.0	352	58	102	1.22
IX	3,080	1,012	478	534	47.2	52.8	minimal	6	not mapped	0.93
X	3,321	3,167	1,568	1,599	49.5	50.5	76	19	42	1.50
Totals	35,864	23,575	9,695	13,880	--	--	2022+	88	539+	--

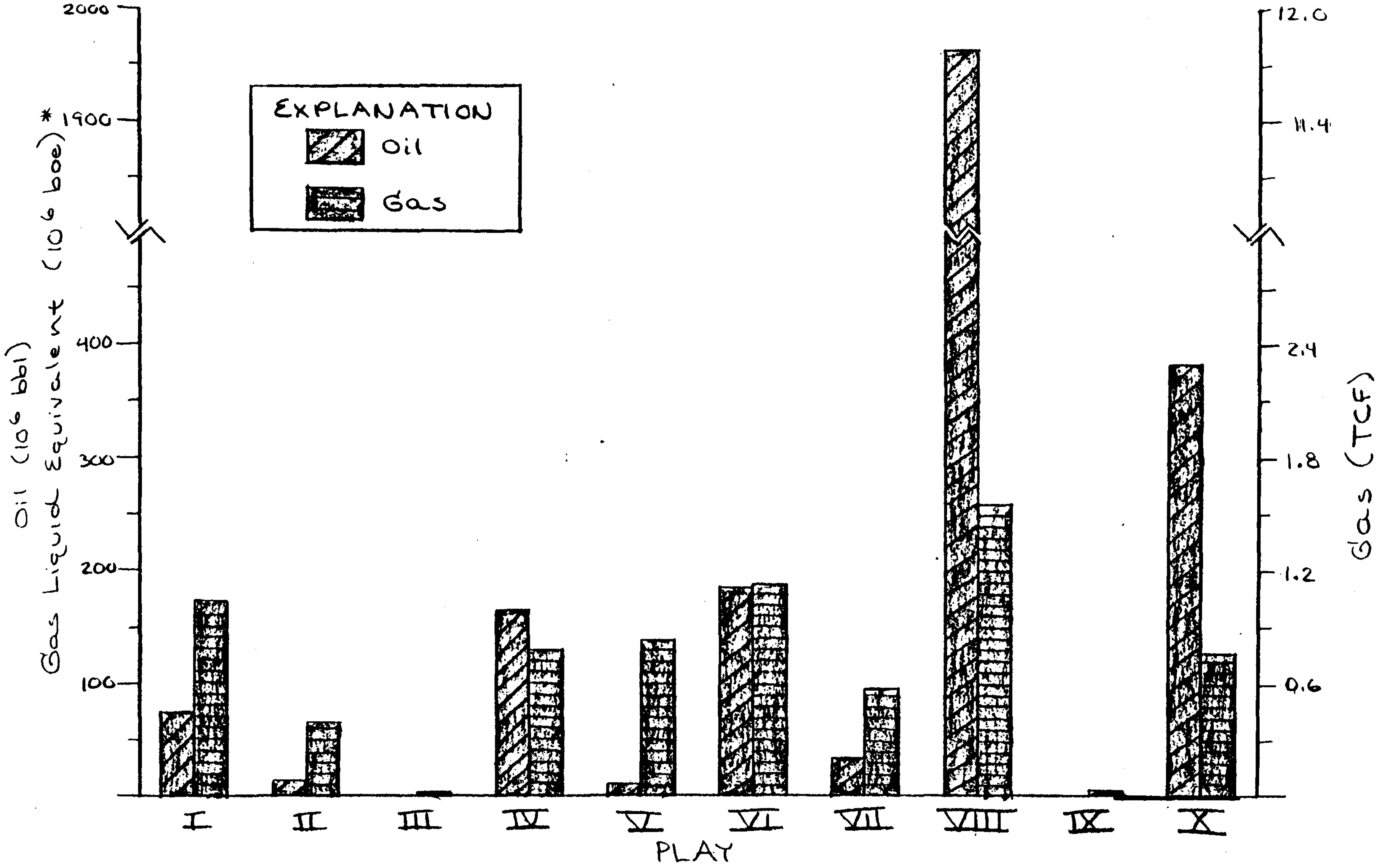
** $<0.5/mi^2$ = immature; $0.5\text{-}1.5/mi^2$ = mature; $>1.5/mi^2$ = supermature

Table 4. Summary of General Characteristics, and Analytical and Computed Data, Miocene Crude Oils of Texas.
(After Coleman and others, 1978)

GENERAL CHARACTERISTICS								VOLUME PERCENT					CORRELATION INDEX		CHARACTERISTICS OF RESIDUUM	
Item (Coleman's numbers in parentheses)	Sample	Gravity API	Color	Sulfur Weight %	Nitrogen Weight %	Viscosity, Saybolt, at 100°F, seconds	Carbon Residue, Conradson, weight %	Fractions 1-3 (light gasoline)	Fractions 4-7 (naphtha)	Fractions 8-12 (kerosene and gas, oil)	Fractions 13-15 (lubricating oil)	Residuum	Average of fraction 4 - 7	Average of fraction 13 - 15	% on light gasoline-free basis	Specific Gravity $60/60^{\circ}$F
1 (436)	69,089	44.7	Green	0.11	0.004	30	0.03	9.3	38.6	35.9	9.6	5.0	29	31	11	0.932
2 (455)	62,063	25.7	BB	0.18	0.05	100	1.4	--	2.3	42.6	25.6	28.3	--	49	29	0.949
3 (487)	63,146	21.0	BB	0.317	0.071	598	2.9	--	--	27.6	13.6	58.8	--	53	--	0.948
4 (490)	55,055	32.3	Green	0.15	0.033	45	0.5	2.1	17.6	47.0	16.9	16.3	32	47	20	0.934
5 (514)	55,056	35.0	BG	0.13	--	42	0.8	5.0	17.1	41.3	18.7	17.7	29	42	23	0.936
6 (532)	55,057	27.8	BG	0.26	0.48	79	1.4	0.9	9.2	44.5	24.2	21.0	37	51	23	0.961
7 (533)	76,037	32.8	BG	0.07	0.007	49	0.9	--	--	62.2	21.3	15.9	--	--	16	0.914
8 (536)	55,039	31.1	Green	0.35	0.037	41	0.7	2.6	30.8	33.3	15.3	17.5	29	67	26	0.956
9 (538)	56,088	15.4	BB	0.46	0.097	2,000	3.6	--	0.4	25.9	28.3	44.4	--	74	--	0.996
10 (666)	52,084	23.8	BB	0.25	--	140	1.5	--	1.4	40.1	24.3	33.5	--	50	34	0.945
11 (667)	63,139	24.9	GB	0.20	0.040	126	1.2	--	2.5	40.9	21.2	34.8	--	--	36	0.941

Key to items listed in Table 4.

Item	Field	County	Depth (ft)
1 (436)	Big Creek	Ft. Bend	3,851
2 (455)	Clear Lake	Jefferson	4,436 - 4,444
3 (487)	Esperson Dome	Liberty	2,644 - 2,660
4 (490)	Fennett	Jefferson	2,989 - 2,920
5 (514)	Goose Creek	Harris	2,284 - 2,380
6 (532)	High Island	Galveston	4,482 - 4,509
7 (533)	Hoskin Mound	Brazoria	5,900
8 (536)	Hull	Liberty	1,651 - 1,705
9 (538)	Humble	Harris	905 - 975
10 (666)	Thompson	Ft. Bend	3,478 - 3,510
11 (677)	Thompson South	Ft. Bend	4,334 - 4,340



* Calculated energy equivalent in bbl of oil (6 Mcf = 1 boe)

Figure 9. Cumulative production of oil and gas for each of the 10 Miocene MSU plays.

such a subdivision of the Miocene MSU sedimentary prism permits systematic and meaningful evaluation of the relationships between hydrocarbon occurrence and geologic control. Geologic exploration attributes for each play are summarized in tables 2 and 3; crude oil analyses are presented in table 4. Cumulative production of oil and gas by play is shown on figure 9.

Play I

Play I (pl. 14) is a gas-prone division which lies within a distal part of the Rosita Delta System. The play, which has been sparsely explored, has a drilling density of only 0.03 well/mile^2 (table 3). Dominant facies include thick strandplain and destructional barrier sands and thinner delta front sand facies.

Sandstone percentages of 40 to 70 characterize much of the play, and net sand values range to 518 m (1700 ft) in each of the delineated operational units. Thick, porous stacked sands (6-15 per 305 m, 1000 ft) are abundant but due to lack of effective shale seals may not constitute high-quality reservoirs. Thinner delta front sands, intercalated with relatively thick shales are potentially excellent reservoirs. Downdip mudrocks, in part Miocene and in part of Frio age, are potential hydrocarbon source rocks, however, according to Galloway and others (1982), the hydrocarbon source quality of the Frio mudrocks is poor.

Major structures are growth faults with associated roll-over anticlines and deep shale ridges. The top of the Miocene MSU lies between -762 to -1067 m (-2500 and -3500 ft), and total thickness of the unit is approximately 1219 to 2286 m (4000 to 7500 ft). Greatest sediment thickness occurs in southern Cameron County.

Play II

Play II is a poorly explored gas-prone division with few fields and a drilling density of only 0.11 wells/mi^2 (pl. 14 and table 3). The play corresponds to a downdip section of the Santa Cruz fluvial system, and proximal delta facies of the Rosita delta system (pl. 9). Potential reservoir facies include thick, elongated, strandplain sands, distributary mouth bars, and channel-fill sands. Potential for stratigraphic traps is especially high in the transitional zone between deltaic and fluvial systems, where interfingering of sand and shale units should be at a maximum for the play.

Sand percentages are generally 30 to 50 percent, but range to 70 percent in predominantly deltaic environments. Net sand values for each operational unit are most commonly 152 to 274 m (500 to 900 ft) but reach 518 to 701 m (1700 to 2300 ft) where associated with major growth faults. Mudrocks comprise slightly more than 50 percent of total play volume but are thermally immature, therefore hydrocarbon sources are confined to downdip, offshore Miocene mudrocks, or to underlying older units.

Dominant structures are growth faults, deep-seated anticlinal ridges. Hydrocarbons should be associated with faulting, anticlinal rollovers, and stratigraphic traps. Top of the Miocene MSU occurs between -305 and -610 m (-1000 and -2000 ft) and thickness of the unit ranges from 762 to 1676 m (2500 to 5500 ft).

Play III

Play III, a large, gas-prone division (pl. 14), extends along the entire updip breadth of the Santa Cruz fluvial system. The play is characterized by minor gas production (fig. 9), and by a drilling density of 1.13 wells/mi^2 (table 3). Miocene mudstones of this play are thermally immature, and underlying Frio mudstones (Galloway and others, 1982) have undergone inadequate thermal maturation for oil generation.

Sand percentages for each operational unit are variable, ranging from 10 to 50 percent for floodplains and 50 to 80 percent for dip-oriented fluvial sand belts. Net sand values for each operational unit are 30 to 91 m (100 to 300 ft) for floodplains, whereas major fluvial sands range from 91 to 213 m (300 to 700 ft).

Stacked and amalgamated channel-fill sands encased in finer floodplain sediments constitute the primary reservoir rocks.

The Vicksburg Flexure extends across Play III, however, fault displacement of Miocene sediments along the flexure seems minimal and basically confined to Operational Unit A. Two salt diapirs occur in Brooks County. The top of Miocene MSU occurs between -152 and -305 m (-500 and -1000 ft), and thickness of the unit is 457 to 610 m (1500 to 2000 ft).

Play IV

Play IV is a heavily explored oil-prone play (table 2) which also has produced significant quantities of gas. It corresponds to a downdip part of the Santa Cruz fluvial system and the northwestern part of the Rosita delta system.

Potential reservoir facies are similar to those described for Play II. The transitional area between updip fluvial and downdip deltaic systems is relatively broad (16 to 24 m, 10 to 15 mi) and was the site of considerable fluvial progradation during deposition of Operational Unit B. It is in this intermediate zone, where growth faults of the Frio Flexure are common, and where the Anahuac shale wedge is absent, that hydrocarbon production is concentrated. It appears that the ultimate hydrocarbon source is from the underlying Frio, or older units.

Traps are rollover anticlines, growth faults with closure on the upthrown block, and sandstone pinchouts.

Top of the Miocene MSU occurs at -457 to -762 m (-1500 to -2500 ft), and total thickness of the unit ranges from 762 to 1829 m (2500 to 6000 ft).

Play V

Play V is a gas-prone province that coincides with the downdip part of the Indianola Barrier-Strandplain-Lagoon System. It is a maturely explored play with a drilling density of 1.24 wells/mi^2 (table 3).

Dominant facies include thick barrier and strandplain strike-oriented sands behind which lie a variety of backbarrier-lagoon sand and mudstone deposits. Backbarrier sands, such as washover fan facies, which pinch out into bay mudstones provide excellent stratigraphic traps (Geehan, Grimes, and Swanson, 1983). Thicker barrier and strandplain bodies may be relatively unproductive because they commonly lack effective seals.

Generally, bay facies are characterized by 15 to 30 percent sand content, and sand units are thin. Barrier and strandplain facies are characterized by 50 to 75 percent sand. Net sands along barrier trends range to 640 m (2100 ft) in Operational Unit B and 396 m (1300 ft) in Operational Unit A as compared to 91 to 274 m (300 to 900 ft) for backbarrier counterparts.

Growth faults and associated anticlinal folding are the chief structural traps. As pointed out by McCarthy (1970), displacements along faults in coastal Calhoun and Matagorda Counties cause gentle anticlinal closures which trap gas. Source of the hydrocarbons of this play are presumably both offshore, downdip Miocene mudstone, and underlying Frio, and possibly older units. Top of the Miocene MUS occurs at -610 to -1371 m (-2000 to -4500 ft), and total thickness is 1219 to 1676 m (4000 to 5500 ft).

Play VI

Play VI, a significant producer of both gas and oil (fig. 9), has a well density of 1.84 wells/mi^2. The play extends across the downdip section of the Moulton Streamplain, includes a part of the Santa Cruz fluvial system, and incorporates a narrow, updip strip of the Indianola Barrier-Strandplain Lagoon system.

Reservoir facies include relatively thin, but stacked channel-fill sands, which occur interconnected with permeable sheet and splay facies. These systems are encased in generally thick impermeable floodplain mudstones. Bay deposits, largely confined to Operational Unit A, are characterized by thin sand units interbedded with thicker mudstones, low sand percentages (15 to 25 percent), and low hydrocarbon production.

Growth faults of the Vicksburg Flexure are the dominant structures of the play. Five shale diapirs are mapped in Jackson and Calhoun Counties (Bishop, 1977).

Contained hydrocarbons are not indigenous to the play sediments. The thin updip edge of the Anahuac Shale underlies much of the play, but apparently because of heavy faulting did not prevent migration of Frio and possibly older hydrocarbons updip into Miocene reservoirs.

Top of the Miocene lies at -305 to -610 m (-1000 to -2000 ft), and thickness of the unit is 610 to 1219 m (2000 to 4000 ft).

Play VII

Play VII is gas-prone with limited oil production (fig. 9). The play, which extends across the updip part of the Moulton Streamplain, has a supermature drilling density of 1.85 wells/mi^2 (table 3).

Reservoir facies are similar to those described for Play VI, however, in Play VII major sand belts are thicker and broader. Sand percentages reach 65 to 70 percent in these belts and net sands range from 30 to 183 m (100 to 600 ft) for each operational unit. Sand content in the broad floodplain areas is generally 25 to 40 percent.

Major growth faults are primarily confined to the downdip part of the play. Updip from the faulted zone, the Anahuac shale wedge is absent, and thus there is no apparent obstruction to upward migration of Frio and older unit hydrocarbons into Miocene reservoir facies. Top of the Miocene MSU lies at -157 to -457 m (-500 to -1500 ft), and total Miocene MSU thickness is 152 to 762 m (1500 to 2500 ft).

Play VIII extends across the downdip one-half of the Cypress fluvial system, and into the San Jacinto delta system (pl. 9). This play, the most prolific producer of Miocene oil and gas, has a well density of $1.22/mi^2$ (table 3). Reservoir facies include multistoried channel-fill sands, high-porosity, wave-reworked deltaic sands, and the delta front sands of Operational Unit A. The Anahuac shale wedge underlies the entire play. Fluvial facies are most extensive in Operational Unit B, where channel-fill facies are broader and thicker than in the lower unit. Likewise barrier and strandplain facies of Unit B are thicker and more extensive than those of Unit A.

Dominant structures are growth faults and numerous salt diapirs with associated sediment uplift, Heterostegina coral reefs (Cantrell, 1959; Ellisor, 1926), and faulting.

Top of the Miocene MSU occurs between depths of -305 to -1372 m (-1000 to -4500 ft), and total thickness (pl. 2) of the unit ranges from 762 to 1372 m (2500 to 4500 ft).

Play IX

Play IX is an unimportant gas producer which extends across the breadth of the Cypress Fluvial system. Drilling density is 0.93 $wells/mi^2$, primarily as a product of exploration for deeper targets (table 3).

Major structures are absent within the play therefore hydrocarbons are most likely to be stratigraphically trapped. The lack of major structures and thermally mature source rocks combine to make the play unattractive for Miocene hydrocarbon exploration. Top of the Miocene MSU lies at -152 to -305 m (-500 to -1000 ft) and total thickness of the unit ranges from 457 to 610 m (1500 to 2000 ft).

Play X

Play X, confined to the San Jacinto delta system, has produced relatively large quantities of oil and gas (fig. 9). Drilling density for the play is 1.50 $wells/mi^2$ (table 3).

The proportion of sandstone is high, amounting to 49 percent (table 3). Reservoir facies include thick, stacked progradational and aggradational destructional barrier and strandplain units and thinner progradational delta front sands. Miocene mudstones of the play are probably all thermally immature, however, thermally mature source rocks do occur in the underlying Frio and in the offshore Miocene. Traps include faulted anticlines above deep salt diapirs (Rieter, 1959) and growth faults. Stratigraphic traps are most characteristic of the delta front facies.

The top of the Miocene MSU lies between -762 to -1219 m (-2500 and -4000 ft) and total thickness ranges from 1219 to 1829 m (4000 to 6000 ft).

EVALUATION OF REMAINING RESOURCE POTENTIAL

Miocene MSU Source Rock Quality

Resource evaluation methods involving contemporaneous source rock quality do not have application to the Miocene MSU. Available evidence strongly supports the view that the Texas onshore Miocene MSU lacks entirely, or contains a negligible volume of thermally mature hydrocarbon source rocks. Dow (1978) defined a source bed as:

> ...a unit of rock that has generated and expelled oil or gas, in sufficient quantity to form commercial accumulations. Must meet minimum criteria of organic richness, kerogen type and thermal maturity.

On the basis of vitrinite reflectance (R_o) values, a technique commonly applied to assess the petroleum maturation level, Dow (1978) delineated the probable oil-generating interval (0.6 to 1.35 percent R_o) in the Louisiana Gulf Coast (fig. 10). He concluded that Louisiana Gulf Coast hydrocarbon production, including that of the Miocene, is from thermally immature progradational facies, which overlie older thermally mature slope and rise facies. Young and others

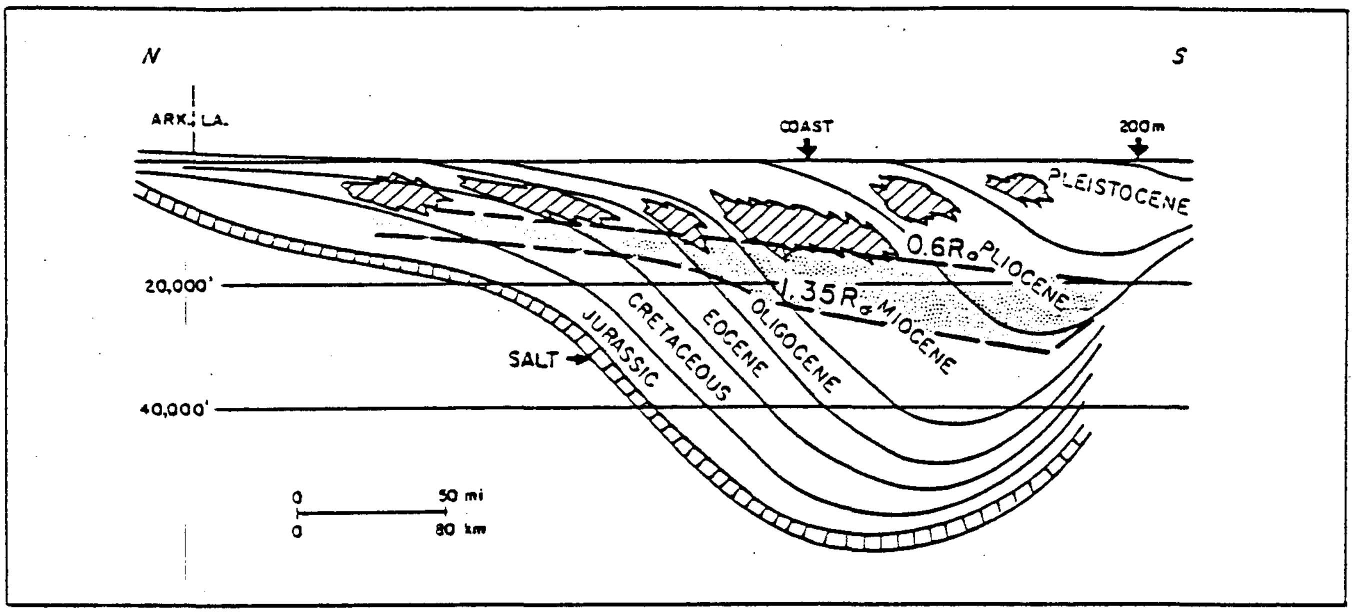


Figure 10. Cross-section of the Louisiana Gulf Coast Basin showing distribution of productive intervals for oil and most probable oil generation zone. (After Dow, 1978).

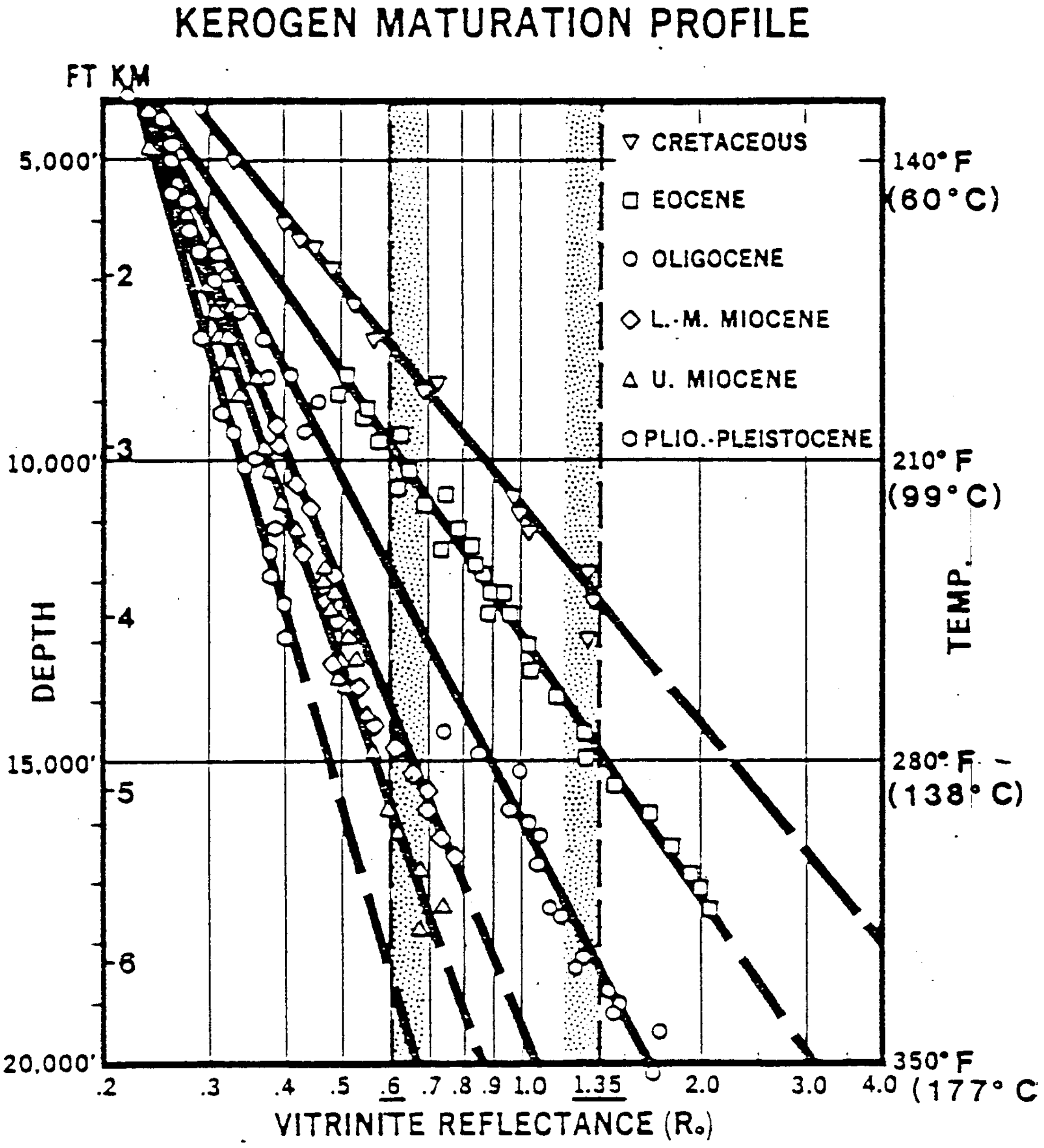


Figure 11. Composite maturation profiles of two representative wells in age-defined Gulf Coast producing trend. (After Dow, 1978).

(1977) demonstrated that offshore Gulf Coast oils average 8.7 m.y. older than their reservoirs. This, if true, suggests that most oil of the Texas Miocene MSU originated from rocks of the Vicksburg Stage.

Dow presented composite profiles of vitrinite reflectance for the Cretaceous through Plio-Pleistocene in the Louisiana Gulf Coast. According to this plot (fig. 11) the temperature which corresponds to the minimum requirements for inception of oil-generation (0.6 R_o) is approximately 290°F for the upper Miocene, and 265°F for the lower/middle Miocene. This stated temperature range occurs in Louisiana at depths of 12,000 to 13,500 feet. Virtually none of the onshore Texas Miocene MSU deposits occur where the temperature reaches or exceeds 265°F. It may be noted that even through hydrocarbon generation can begin early in the thermal history of a sedimentary sequence, commercial quantities probably are not expelled from the source rocks until the principal phase of generation is attained (Dow, 1978; Momper, 1978; and Ronov, 1958).

Both in the Rio Grande and Houston Embayment areas the Miocene deltaic sediment accumulation rate was only 152 to 213 m (500 to 700 ft/m.y.). The relatively low Miocene rate is partly the product of the sediment-spreading effect of persistent wave-reworking, and massive coast-wise sediment transport. In such high-energy environments the organic material would have been intensively degraded. Degradation can seriously impair by hydrogen reduction, the generating capability, and can revise upward the minimum quantity of organic material needed for hydrocarbon expulsion (Momper, 1978; Ibach, 1982).

The only detailed source of organic geochemical data for the Texas Miocene MSU is that presented by Brown (1979) for the DOE/GCO Pleasant Bayou nos. 1 and 2 wells in Brazoria County. In both of these wells the Miocene lies above the oil-maturation interval where down-hole temperature exceeds 235°F and vitrinite reflectances are at least 0.5 R_o. Brown concluded that, with the exception of an anomalous, very thin interval near 2137 m (7000 ft), the entire evaluated section,

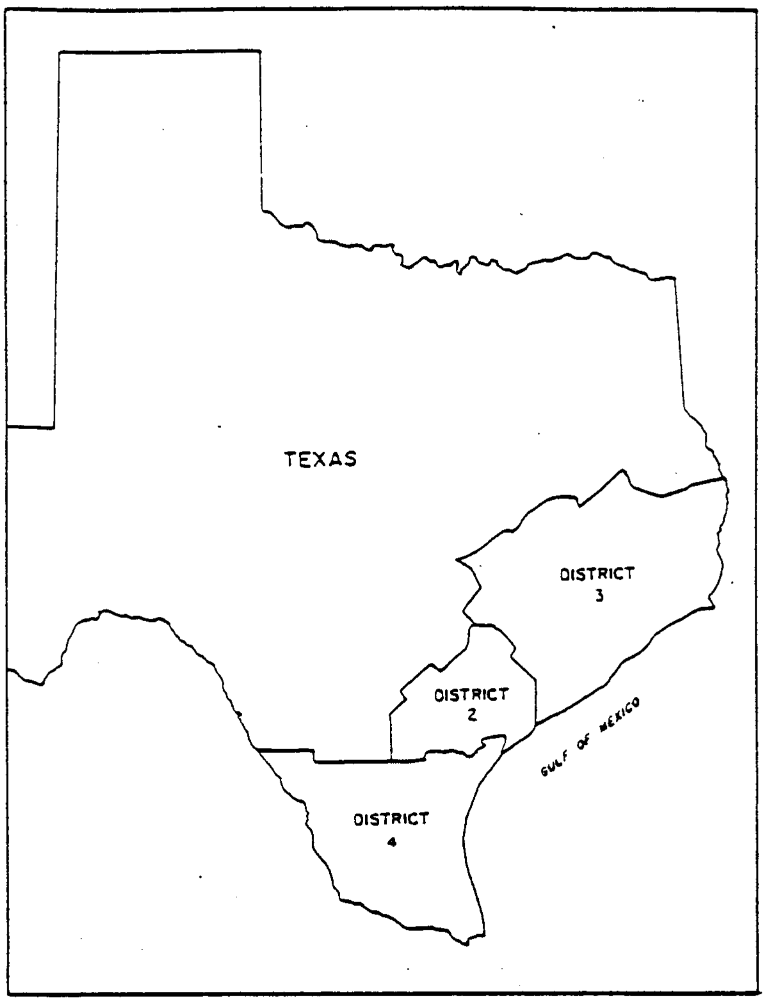


Figure 12. Location and boundaries of Railroad Commission of Texas (RRC) Districts 2, 3, and 4.

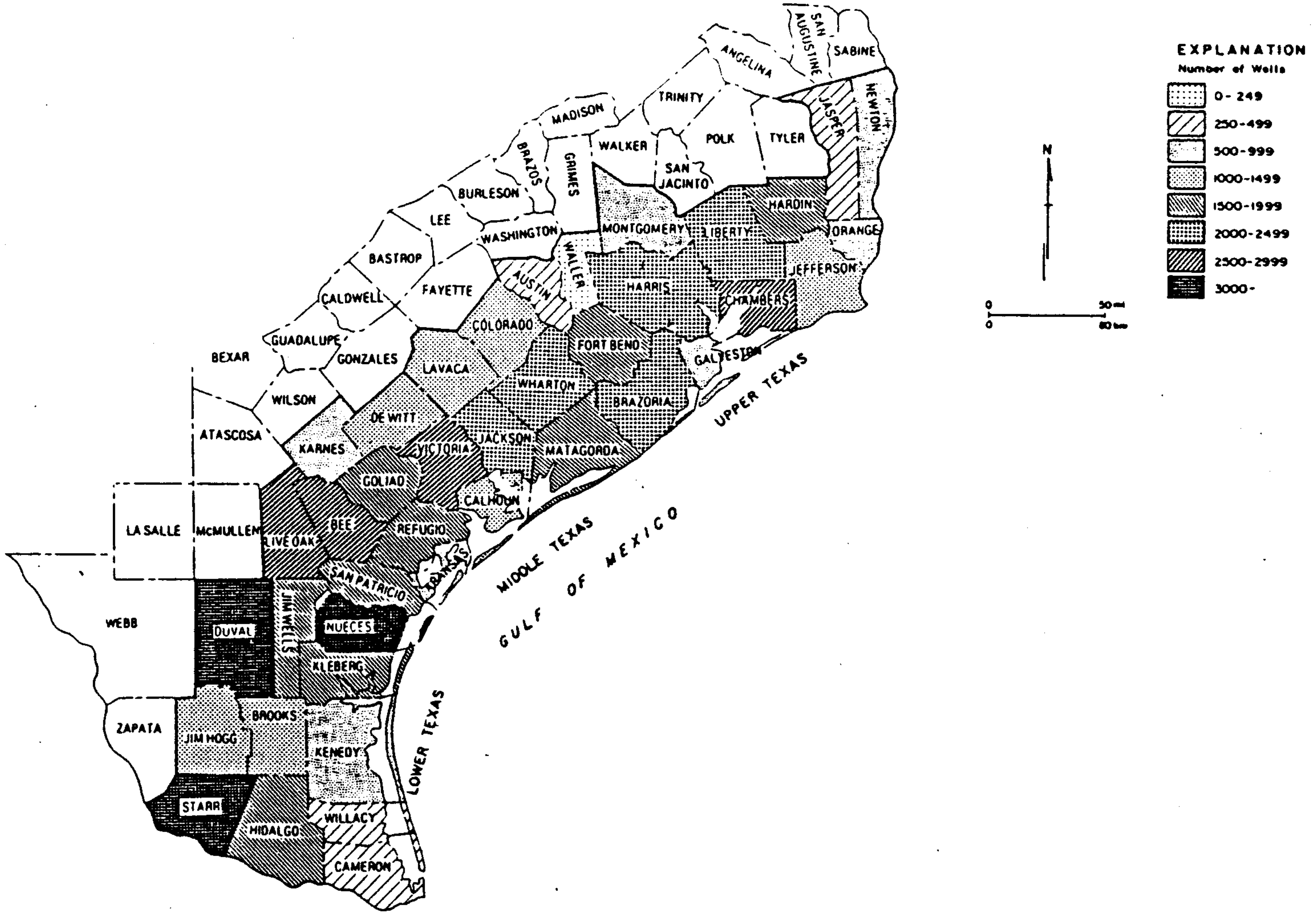


Figure 13. Total number of wells drilled in each county of RRC Districts 2, 3, and 4.

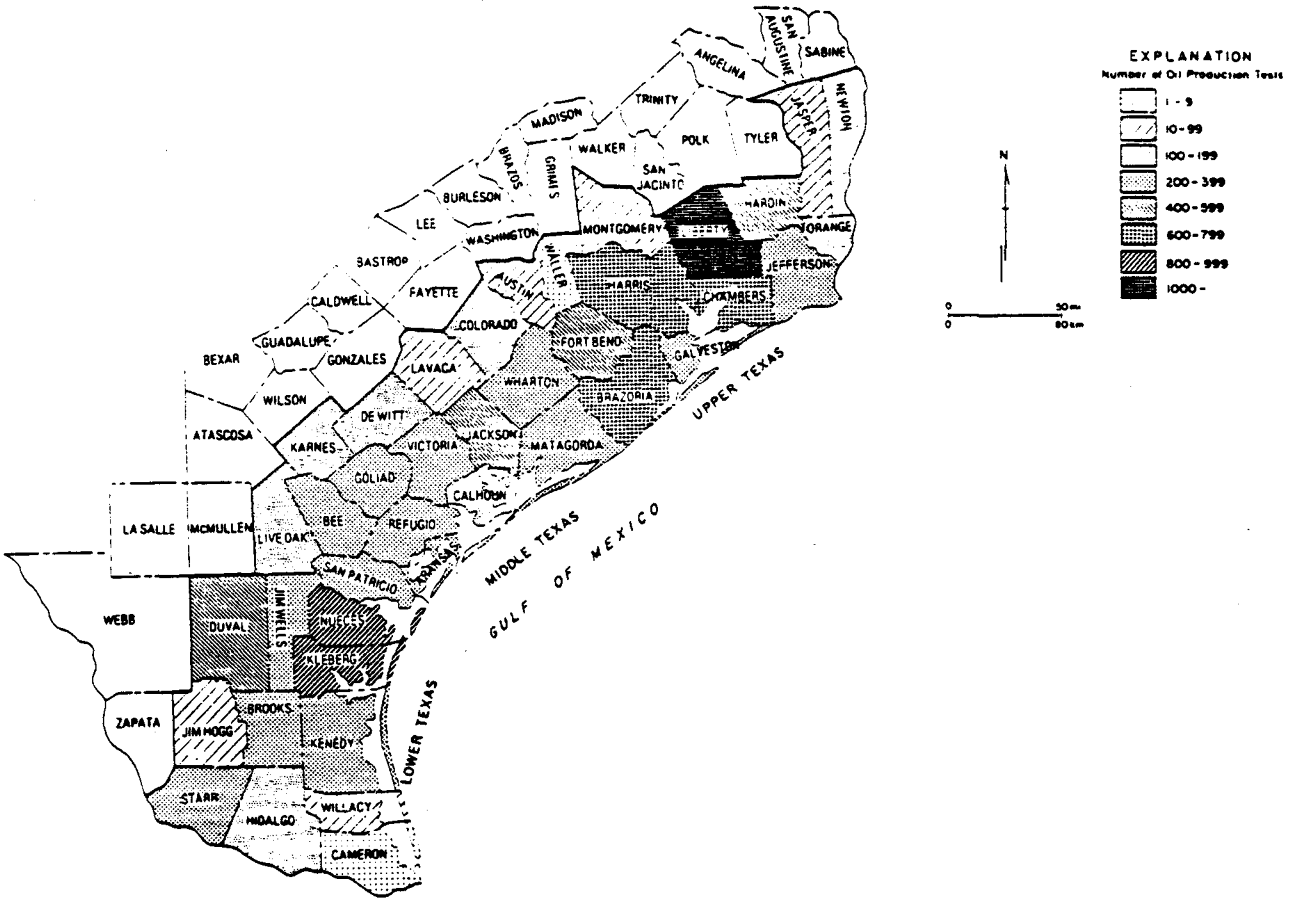


Figure 14. Total number of oil tests in each county of RRC Districts 2, 3, and 4.

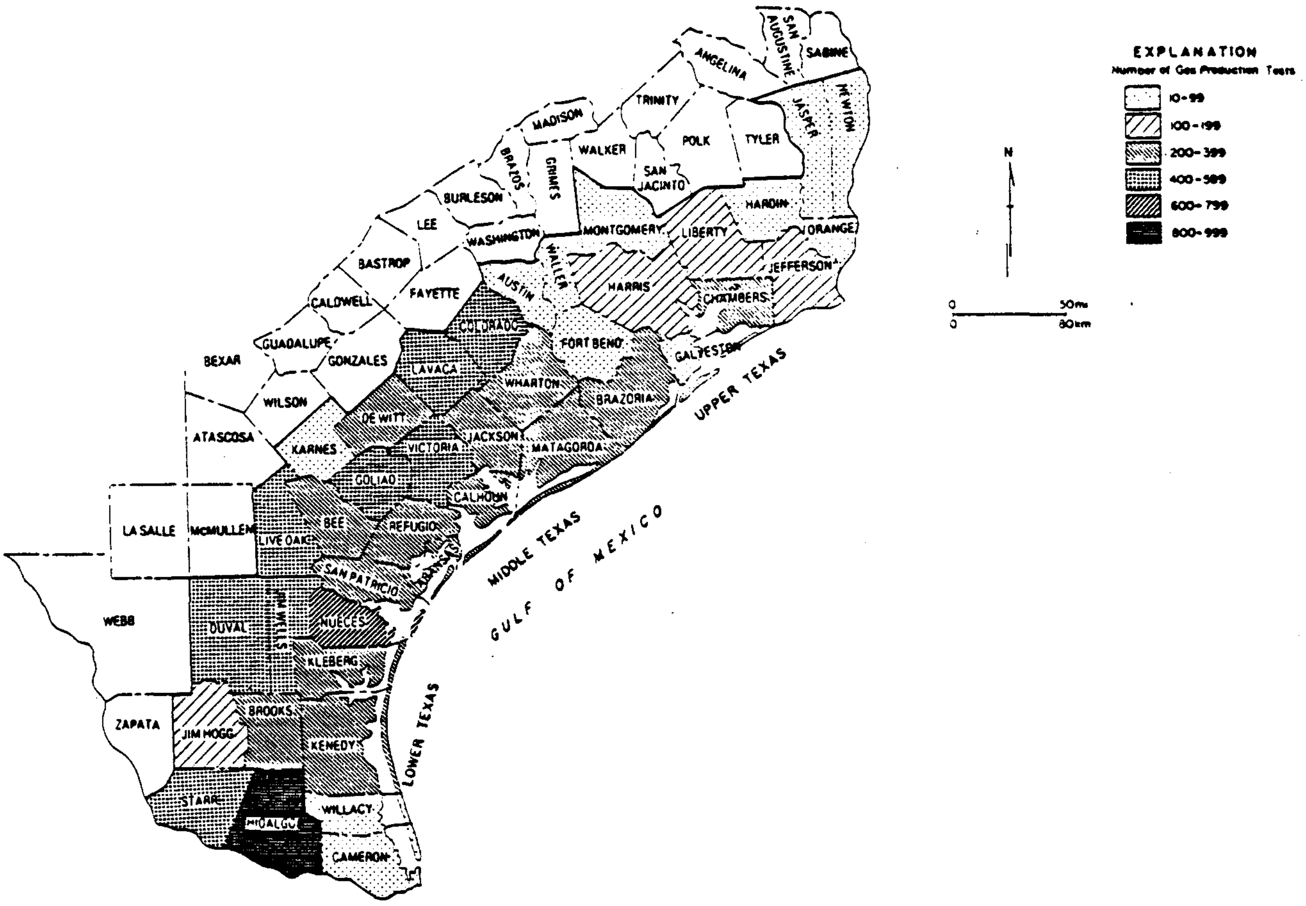


Figure 15. Total number of gas tests in each county of RRC Districts 2, 3, and 4.

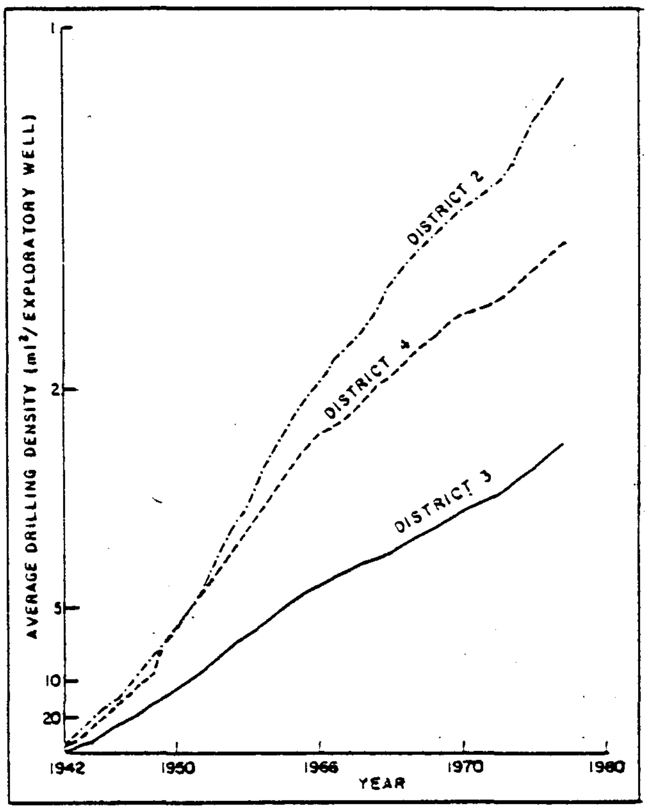


Figure 16. Historical changes of drilling density (mi^2 per exploratory well) for RRC Districts 2, 3, and 4. (After H. O. Woodbury and others, 1973).

including the Frio, is thermally immature, and that it has no significant potential for generating producible quantities of either liquid or gaseous hydrocarbons.

Evaluation Methods

In this study three historical approaches, discussed in detail by Galloway and others (1982), were employed to evaluate ultimate discovered and undiscovered hydrocarbons of the Texas Miocene MSU. These methods, briefly described below, were used to evaluate both the Texas Railroad Commission Districts 2, 3 and 4, and the ten (fig. 12) delineated exploration plays. Figures 13, 14 and 15 show the areal distribution of the total numbers of wells and of oil and gas production tests in the study area. Change in average density for each district is shown in figure 16.

The first evaluation method plots discovery rate against the cumulative number of exploratory wells. This method defines the limit of the number of exploratory wells to be drilled in an area (i.e., 1 well/mi^2). On this basis it is possible to estimate the ultimate number of wells to be drilled in an area. A disadvantage to the method is that fluctuations in economic conditions are not considered.

The second method plots amounts of discovered oil and gas per footage drilled by exploratory wells each year against cumulative footage of exploratory wells (Davis, 1958; Zapp, 1961 and 1962). This method, in addition to limiting drilling density, considers economic factors. As concluded by White and Gehman (1979) extrapolations have the advantage of being tied directly to the realities of experience.

Comparative Results

Estimates of remaining hydrocarbons using the three described evaluation methods, are summarized for Texas Railroad Commission Districts in tables 5 through 11, and for the 10 plays in table 12 through 19.

Table 5. Statistical summary of recoverable oil, million bbl (cumulative-well-number method). (Modified from Galloway, Hobday and Magara, 1982)

Location		* Oil discovery before 1942	** Oil discovery 1942-1977	Total oil discovery by 1977		Oil to be discovered up to a drill density of 0.5 mi^2/well		Total recoverable	
Dist. 2	All formations	1,884	662	2,546		50		2,596	
(11,000 mi^2)	Miocene (% of above)			183	(7.2)	4	(7.2)	187	(7.2)
Dist. 3	All formations	6,663	907	7,570		410		7,980	
(30,000 mi^2)	Miocene (% of above)			2,393	(31.6)	130	(31.6)	2,522	(31.6)
Dist. 4	All formations	2,078	979	3,057		169		3,226	
(21,000 mi^2)	Miocene (% of above)			261	(8.5)	14	(8.5)	275	(8.5)
Dist. 2, 3, 4	All formations	10,625	2,548	13,173		629		13,802	
Total	Miocene (% of above)			2,837	(21.5)	148	(23.5)	2,984	(21.6)

* Source: API, 1978
** Source: AAPG (1943-1978)

Table 6. Statistical summary of recoverable gas, bcf (cumulative-well-number method).
(Modified from Galloway, Hobday and Magara, 1982)

Location		Gas discovery before 1942	Gas discovery 1942-1977	Total gas discovery by 1977	Gas to be discovered up to a drill density of 0.5 mi^2/well	Total recoverable
Dist. 2	All formations	12,206	12,857	25,063	3,159	28,222
(11,000 mi^2)	Miocene (% of above)			1,057 (4.2)	133 (4.2)	1,190 (4.2)
Dist. 3	All formations	30,564	22,640	53,204	93,750	146,954
(30,000 mi^2)	Miocene (% of above)			3,744 (7.0)	6,563 (7.0)	10,307 (7.0)
Dist. 4	All formations	22,839	26,543	49,382	9,051	58,433
(21,000 mi^2)	Miocene (% of above)			2,275 (4.6)	416 (4.6)	2,691 (4.6)
Dist. 2, 3, 4	All formations	65,609	62,040	127,649	105,960	233,609
Total	Miocene (% of above)			7,076 (5.5)	7,112 (6.7)	14,188 (6.1)
Miocene liquid equivalent				1,179 million bbl	1,185 million bbl	2,364 million bbl

Bcf (0.16667 $\frac{\text{mill bbl}}{\text{Bcf}}$) = million bbl

Table 7. Statistical summary of recoverable oil, million bbl (cumulative-footage method). (Modified from Galloway, Hobday and Magara, 1982)

Location		Oil discovery before 1942	Oil discovery 1942-1977	Total oil discovery by 1977		Oil to be discovered up to exploratory footage of 15,000 ft/mi^2		Total recoverable	
Dist. 2	All formations	1,884	662	2,546		83		2,629	
(11,000 mi^2)	Miocene (% of above)			183	(7.2)	6	(7.2)	189	(7.2)
Dist. 3	All formations	6,663	907	7,570		553		8,123	
(30,000 mi^2)	Miocene (% of above)			2,393	(31.6)	175	(31.6)	2,568	(31.6)
Dist. 4	All formations	2,078	979	3,057		265		3,322	
(21,000 mi^2)	Miocene (% of above)			261	(8.5)	23	(8.5)	284	(8.5)
Dist. 2, 3, 4	All formations	10,625	2,548	13,173		901		14,074	
Total	Miocene (% of above)			2,837	(21.5)	204	(22.6)	3,041	(21.6)

Table 8. Statistical summary of recoverable gas, bcf (cumulative-footage method). (Modified from Galloway, Hobday and Magara, 1982)

Location		Gas discovery before 1942	Gas discovery 1942-1977	Total gas discovery by 1977	Gas to be discovered up to exploratory footage of 15,000 ft/mi^2	Total recoverable
Dist. 2	All formations	12,206	12,857	25,063	4,618	29,681
(11,000 mi^2)	Miocene (% of above)			1,057 (4.2)	194 (4.2)	1,251 (4.2)
Dist. 3	All formations	30,564	22,640	53,204	103,927	157,131
(30,000 mi^2)	Miocene (% of above)			3,744 (7.0)	7,275 (7.0)	11,019 (7.0)
Dist. 4	All formations	22,839	26,543	49,382	15,116	64,498
(21,000 mi^2)	Miocene (% of above)			2,275 (4.6)	695 (4.6)	2,970 (4.6)
Dist. 2, 3, 4	All formations	65,609	62,040	127,649	123,661	251,310
Total	Miocene (% of above)			7,076 (5.5)	8,164 (6.6)	15,240 (6.0)
Miocene liquid equivalent				1,179 million bbl	1,361 million bbl	2,540 million bbl

$$\text{Bcf}\ (0.16667\ \frac{\text{mill bbl}}{\text{Bcf}}) = \text{million bbl}$$

Table 9. Statistical summary of recoverable oil, million bbl (discovery-versus-time method). (Modified from Galloway, Hobday and Magara, 1982)

Location		Total oil discovery by 1977		Oil to be discovered		Total recoverable	
Dist. 2	All formations	2,546		482		3,028	
	Miocene (% of above)	183	(7.2)	35	(7.2)	218	(7.2)
Dist. 3	All formations	7,570		1,172		8,742	
	Miocene (% of above)	2,393	(31.6)	370	(31.6)	2,763	(31.6)
Dist. 4	All formations	3,057		573		3,630	
	Miocene (% of above)	261	(8.5)	49	(8.5)	310	(8.5)
Dist. 2, 3, 4	All formations	13,173		2,227		15,400	
Total	Miocene (% of above)	2,837	(21.5)	454	(20.4)	3,291	(21.4)

Table 10. Statistical summary of recoverable gas, bcf (discovery-versus-time method). (Modified from Galloway, Hobday and Magara, 1982)

Location		Total gas discovery		Gas to be discovered		Total recoverable	
Dist. 2	All formations	25,063		4,727		29,790	
	Miocene (% of above)	1,057	(4.2)	199	(4.2)	1,256	(4.2)
Dist. 3	All formations	53,204		6,550		59,754	
	Miocene (% of above)	3,744	(7.0)	459	(7.0)	4,203	(7.0)
Dist. 4	All formations	49,382		18,720		68,102	
	Miocene (% of above)	2,275	(4.6)	861	(4.6)	3,136	(4.6)
Dist. 2, 3, 4	All formations	127,649		29,997		157,646	
Total	Miocene (% of above	7,076	(5.5)	1,519	(5.1)	8,595	(5.5)
	Miocene liquid equivalent	1,179 million bbl		253 million bbl		1,432 million bbl	

$$\text{Bcf}\ (0.16667\ \frac{\text{mill bbl}}{\text{Bcf}}) = \text{million bbl}$$

Table 11. Summary of estimates of future discoveries, Miocene MSU, derived from historical projections. (Modified from Galloway, Hobday and Magara, 1982)

	Cumulative well number	Cumulative footage	Discovery time
Oil (million bbl)			
Dist. 2	4	6	35
Dist. 3	130	175	370
Dist. 4	14	23	49
Total	148	204	454
Gas (bcf)			
Dist. 2	133	194	199
Dist. 3	6,563	7,275	459
Dist. 4	416	695	861
Total	7,112	8,164	1,519
Liquid equivalent	1,185 million boe	1,361 million boe	253 million boe

Estimates of remaining oil for the Texas Railroad Commission districts are highest with the discovery-time method, next highest with the cumulative-footage method, and lowest with the cumulative well method. The amount estimated by the first method is a possible maximum, that by the second method a probable amount, and that by the third a possible minimum. The highest estimate for remaining gas is by the cumulative-footage method in Districts 3 and 4, and by the discovery-time method for District 2. The lowest estimate for all districts is by the cumulative-well number method.

The estimated amounts of remaining gas projected by the cumulative-footage and cumulative well methods for District 3 are probably due to recent improved gas discovery rates for that district. Such projections into the future of high discovery rates could be inaccurate and misleading. It seems probable that for District 3 the discovery-time method provides a more realistic estimate of remaining gas.

The estimates of remaining oil for each play are highest with the discovery-time method, and lowest with the cumulative well-number method. Estimates of remaining gas are notably high by the cumulative-footage and the cumulative-well methods for plays 6 through 10. The area of these six plays approximately coincides with that of the Texas Railroad Commission District 3 and, therefore, the explanation for the optimistic estimate is the same as for that district.

CONCLUSIONS

Integration of regional studies of the Miocene MSU depositional systems and structural character with a comprehensive compilation of contained hydrocarbons has permitted differentiation of 10 distinct hydrocarbon-producing plays. Each play is characterized by a unique combination of facies suites, structural and stratigraphic traps, reservior characteristics, and hydrocarbon production histories.

Table 12. Recoverable oil (10^6 bbl) in Miocene MSU plays.
(Cumulative-well-number method)

	Total Discovery by 1977	% of Dist. Total	Oil to be discovered up to drill density of 0.5 mi^2/well	Total recoverable oil
Dist. 2 (All Miocene)	182.88	(100%)	4.00	186.88
Play III*	0.00	--	0.00	0.00
Play V*	4.83	2.6	0.10	4.93
Play VI*	148.68	81.3	3.25	151.93
Play VII*	29.37	16.1	0.65	30.02
Dist. 3 (All Miocene)	2,293.30	(100%)	130.00	2,522.30
Play V*	6.56	0.3	0.39	6.95
Play VI*	32.92	1.4	1.82	34.74
Play VII*	7.62	0.3	0.39	8.01
Play VIII	1,936.17	82.0	106.60	2,069.77
Play IX	<0.01	--	0.00	<0.01
Play X	383.02	16.0	20.80	403.82
Dist. 4 (All Miocene)	260.94	(100%)	14.00	274.94
Play I	75.25	28.8	4.03	79.28
Play II	12.51	4.8	0.67	13.18
Play III*	0.30	0.1	0.01	0.31
Play IV	167.22	64.1	8.97	176.19
Play V*	0.49	0.2	0.03	0.52
Play VI*	7.67	3.0	0.42	8.09

* Partial total where Plays overlap RR Districts

Table 13. Recoverable gas (bcf) in Miocene MSU plays.
(Cumulative-well-number method)

	Total Discovery by 1977	% of Dist. Total	Gas to be discovered up to drill density of 0.5 mi^2/well	Total recoverable gas
Dist. 2 (All Miocene)	1,057.00	(100%)	133.00	1,190.00
Play III*	8.34	0.8	1.06	9.40
Play V*	93.87	8.9	11.84	105.71
Play VI*	828.96	78.4	104.27	933.23
Play VII*	125.83	11.9	15.83	141.66
Dist. 3 (All Miocene)	3,743.89	(100%)	6,563.00	10,306.89
Play V*	675.23	18.0	1,181.34	1,856.57
Play VI*	271.09	7.2	472.54	743.63
Play VII*	452.76	12.1	794.12	1,246.88
Play VIII	1,560.67	41.7	2,736.77	4,297.44
Play IX	25.04	0.7	45.94	70.98
Play X	759.10	20.3	1,332.29	2,091.39
Dist. 4 (All Miocene)	2,274.93	(100%)	416.00	2,690.93
Play I	1,001.09	44.0	183.04	1,184.13
Play II	388.86	17.0	71.14	460.00
Play III*	17.71	0.8	3.32	21.03
Play IV	781.58	34.4	143.10	924.68
Play V*	62.43	2.7	11.23	73.66
Play VI*	23.26	1.0	4.16	27.43

* Partial total where plays overlap RR Districts

Table 14. Recoverable oil (10^6 bbl) in Miocene MSU plays.
(Cumulative-footage method)

	Total Discovery by 1977	% of Dist. Total	Oil to be discovered up to exploratory footage of 15,000 ft/mi^2	Total recoverable oil
Dist. 2 (All Miocene)	182.88	(100%)	6.00	188.88
Play III*	0.00	--	0.00	0.00
Play V*	4.83	2.6	0.15	4.98
Play VI*	148.68	81.3	4.88	153.56
Play VII*	29.37	16.1	0.97	30.34
Dist. 3 (All Miocene)	2,293.30	(100%)	175.00	2,568.30
Play V*	6.56	0.3	0.53	7.09
Play VI*	32.92	1.4	2.45	35.37
Play VII*	7.62	0.3	0.53	8.15
Play VIII	1,963.17	82.0	143.50	2,106.67
Play IX	<0.01	--	0.00	<0.01
Play X	383.02	16.0	28.00	411.02
Dist. 4 (All Miocene)	260.94	(100%)	23.00	283.94
Play I	75.25	28.8	6.62	79.37
Play II	12.51	4.8	1.10	13.61
Play III*	0.30	0.1	0.02	0.32
Play IV	167.22	64.1	14.74	181.96
Play V*	0.49	0.2	0.05	0.54
Play VI*	7.67	3.0	0.69	8.36

* Partial total where Plays overlap RR Districts

Table 15. Recoverable gas (bcf) in Miocene MSU plays.
(Cumulative-footage method)

	Total Discovery by 1977	% of Dist. Total	Gas to be discovered up to exploratory footage of 15,000 ft/mi^2	Total recoverable gas
Dist. 2 (All Miocene)	1,057.00	(100%)	194.00	1,251.00
Play III*	8.34	0.8	1.55	9.89
Play V*	93.87	8.9	17.27	111.14
Play VI*	828.96	78.4	152.10	981.06
Play VII*	125.83	11.9	23.08	148.91
Dist. 3 (All Miocene)	3,743.89	(100%)	7,275.00	11,018.89
Play V*	675.23	18.0	1,309.50	1,984.73
Play VI*	271.09	7.2	523.80	794.89
Play VII*	452.76	12.1	880.27	1,333.03
Play VIII	1,560.67	41.7	3,033.67	4,594.34
Play IX	25.04	0.7	50.93	75.97
Play X	759.10	20.3	1,476.83	2,235.93
Dist. 4 (All Miocene)	2,274.93	(100%)	695.00	2,969.93
Play I	1,001.09	44.0	305.80	1,306.89
Play II	388.86	17.1	118.85	507.71
Play III*	17.71	0.8	5.56	23.27
Play IV	781.58	34.4	239.08	1,020.66
Play V*	62.43	2.7	18.76	81.19
Play VI*	23.26	1.0	6.95	30.21

* Partial total where plays overlap RR Districts

Table 16. Recoverable oil (10^6 bbl) in Miocene MSU plays. (Discovery-versus-time method)

	Total Discovery by 1977	% of Dist. Total	Oil to be discovered	Total recoverable oil
Dist. 2 (All Miocene)	182.88	(100%)	35.00	217.88
Play III*	0.00	--	0.00	0.00
Play V*	4.83	2.6	0.91	5.74
Play VI*	148.68	81.3	28.46	177.14
Play VII*	29.37	16.1	5.63	35.00
Dist. 3 (All Miocene)	2,293.30	(100%)	370.00	2,763.30
Play V*	6.56	0.3	1.11	7.67
Play VI*	32.92	1.4	5.18	38.10
Play VII*	7.62	0.3	1.11	8.73
Play VIII	1,963.17	82.0	303.40	2,266.57
Play IX	<0.01	--	0.00	<0.01
Play X	383.02	16.0	59.20	442.22
Dist. 4 (All Miocene)	260.94	(100%)	49.00	309.94
Play I	75.25	28.8	14.11	86.86
Play II	12.51	4.8	2.35	14.86
Play III*	0.30	0.1	0.05	0.35
Play IV	167.22	64.1	31.41	198.63
Play V*	0.49	0.2	0.10	0.59
Play VI*	7.67	3.0	1.47	9.14

* Partial total where plays overlap RR Districts

Table 17. Recoverable gas (bcf) in Miocene MSU plays.
(Discovery-versus-time method)

	Total Discovery by 1977	**% of Dist. Total**	**Gas to be discovered**	**Total recoverable gas**
Dist. 2 (All Miocene)	1,057.00	(100%)	199.00	1,256.00
Play III*	8.34	0.8	1.59	9.93
Play V*	93.87	8.9	17.71	111.58
Play VI*	828.96	78.4	156.02	984.98
Play VII*	125.83	11.9	23.68	149.51
Dist. 3 (All Miocene)	3,743.89	(100%)	459.00	4,202.89
Play V*	675.23	18.0	82.62	757.85
Play VI*	271.09	7.2	33.05	304.14
Play VII*	452.76	12.1	55.54	508.30
Play VIII	1,560.67	41.7	191.40	1,752.07
Play IX	25.04	0.7	3.21	28.25
Play X	759.10	20.3	93.18	852.28
Dist. 4 (All Miocene)	2,274.93	(100%)	861.00	3,135.93
Play I	1,001.09	44.0	378.84	1,379.93
Play II	388.86	17.1	147.23	536.09
Play III*	17.71	0.8	6.89	24.60
Play IV	781.58	34.4	296.18	1,077.76
Play V*	62.43	2.7	23.25	85.68
Play VI*	23.26	1.0	8.61	31.87

* Partial total where Plays overlap RR Districts

Table 18. Summary of estimates of future discoveries, Miocene plays, derived from historical projections.

	Cumulative well number	Cumulative footage	Discovery-vs.-time
Oil (million bbl)			
Play I	4.03	6.62	14.11
Play II	0.67	1.10	2.35
Play III	0.01	0.02	0.05
Play IV	8.97	14.74	31.41
Play V	0.52	0.73	2.12
Play VI	5.49	8.02	35.11
Play VII	1.04	1.50	6.74
Play VIII	106.60	143.50	303.40
Play IX	0.00	0.00	0.00
Play X	20.80	28.00	59.20
Total	148.13	204.23	454.49
Gas (Bcf)			
Play I	183.04	305.80	378.84
Play II	71.14	118.85	147.23
Play III	4.38	7.11	8.48
Play IV	143.10	239.08	296.18
Play V	1,204.41	1,345.53	123.58
Play VI	580.97	682.85	197.68
Play VII	809.95	903.35	79.22
Play VIII	2,736.77	3,033.67	191.40
Play IX	45.94	50.93	3.21
Play X	1,332.29	1,476.83	93.18
Total	7,111.99	8,164.00	1,519.00
Liquid equivalent (million boe)	1,185.33	1,360.67	253.17

Table 19. Hydrocarbon inventory for Miocene MSU plays.

Play	Cumulative Production				Average $\frac{\text{boe gas}}{\text{bbl oil}}$
	Oil (10^6 bbl)	Gas (10^3 MMcf)	Gas liquid equivalent (10^6 boe)*	Total hydrocarbons (10^6 boe)	
Play I	75	1,001	167	242	2.2
Play II	13	389	65	78	5.0
Play III	0	26	4	4	N/A
Play IV	167	782	130	297	0.8
Play V	12	832	139	151	11.6
Play VI	189	1,123	187	376	1.0
Play VII	35	578	96	131	2.7
Play VIII	1,963	1,561	260	2,223	0.1
Play IX	0	25	4	4	N/A
Play X	383	759	127	510	0.3
Total	2,837	7,076	1,179	4,016	0.4

*Calculated energy equivalent in bbl of oil (6 Mcf = 1 boe)

Table 20. Field size distribution by play; Miocene MSU.

Play	Total number of fields	Number of fields with cumulative production (1977) of:		
		1-15 million boe	15-100 million boe	> 100 million boe
I	13	11	1	1
II	8	7	1	0
III	2	2	0	0
IV	26	19	7	0
V	25	22	3	0
VI	30	24	5	1
VII	24	22	2	0
VIII	43	16	20	7
IX	3	3	0	0
X	27	17	9	1
Totals	201	143	48	10

Table 21. Fields with >100 million boe production; Miocene MSU.

Map number	Field	Cumulative (1977) production* (million boe)
152	Thompson	447.23
127	Hastings	295.03
66	Willamar	169.26
107	Tom O'Connor	152.50
178	Humble	147.38
182	Webster	146.99
176	Goose Creek	140.21
134	West Columbia	133.83
203	Spindletop	106.43
210	Hull	102.32

*Many of these fields also produce from other horizons. Only Miocene production is shown.

The Miocene MSU has produced approximately 2.8 billion bbl of oil, and 7 trillion ft^3 of gas in existing fields of 1 million boe or larger. On an energy equivalency basis the Miocene has produced 2.5 times as much oil as gas. Total Miocene production is approximately 25 percent that reported for the Frio MSU (Galloway and others, 1982). That hydrocarbons are not uniformly distributed throughout the Miocene MSU is demonstrated by the observation that 67 percent of the total production has been derived fom two plays (#8 and #10).

Fields of Play I are characteristically gas producers, and future discoveries in the area likewise will be predominately gas-dominated. One field, the Willamar, in Hidalgo County, has produced 99.8 percent of all the oil, 56.4 percent of the gas, and 75 percent of the total hydrocarbon of the play. The low drilling density for the play, 0.03 $wells/mi^2$, suggests that further exploration should yield many more small fields and perhaps several large fields. Source of hydrocarbons in the strata of this play presumably is from underlying Frio or older strata; however, lateral updip migration from offshore Miocene mudstones cannot be discounted. Thick, elongate strandplain sand bodies probably have poor reservoir potential due to the lack of effective seals. Seaward of these deposits thinner delta front sands encased in relatively thick shelf mudstones should provide excellent hydrocarbon reservoirs.

Play II has been a moderate producer of gas and relatively minor quantities of oil. The play includes nine fields with cumulative production exceeding 1×10^6 boe, has been a moderate producer of both oil and gas. Although the area has a supermature well density of $3.01/mi^2$, significant future production should derive from infill wells and possibly from downdip coastally located delta-front sands associated with growth-faulting. It seems probable that gas will dominate future discoveries, especially in coastal areas.

Play V has been, and probably will remain a predominantly gas-producing province. Drilling density has reached the stage of maturity and 28 fields each have cumulative production in excess of 1 x 10^6 boe. Infill wells should provide continued production, and new fields may be discovered downdip, especially where backbarrier washover facies occur associated with growth faulting and rollover anticlines. Additional small fields might be discovered in the transitional belt between the updip fluvial, and downdip deltaic systems.

Play VI has produced relatively large and approximately equal amounts of oil and gas (fig. 9). The play includes one field, the Tom O'Connor, which has produced more than 150 x 10^6 boe, six fields with 15 x 10^6 boe, and 30 with 1 x 10^6 boe each. Well density for the play is high (1.85 wells/mi^2) and prospects for new large fields seem very slight. Infill wells and future small field discoveries should provide continued significant production.

Play VII has been a moderate producer of gas and of minor amounts of oil. The play, which has a drilling density of 1.49 wells/mi^2, includes 24 fields with of more than 1 x 10^6 boe each, and 2 fields with cumulative production of more than 15 x 10^6 boe each. Eighty-two percent of all the oil of the play has been produced from four fields (#82 Cordele, #83 Cordele S/SE, #108 Colletto Creek, and #149 Moore's Orchard). It seems probable that future discoveries in this play will be predominately gas. It is unlikely that many, if any, additional large fields will be discovered, but new, small fields and additional infill wells should provide significant reserves in the future.

Play VIII has produced 70 percent of the total Miocene MSU oil and 22 percent of the total gas. The play includes 7 fields (table 21) each with cumulative production of more than 100 x 10^6 boe. The giant fields account for 69 percent of the oil, 57 percent of the gas, and 67 percent of the cumulative play production. Hydrocarbon traps occur arranged vertically around salt domes, and most such traps have been discovered. Most new oil and gas will be discovered by infill wells with the best possibility for new fields confined to downdip coastal areas. Production from future discoveries should continue to be overwhelmingly oil.

Play IX, with a well density of 0.93 wells/mi^2, has three gas fields with cumulative production each of more than 1 x 10^6 boe. Lack of major structures, thinness of the sedimentary section, and remoteness from high-quality source rocks combine to indicate that only minor quantities of hydrocarbons, primarily gas, remain to be discovered in this play.

Play X has produced large quantities of oil and important amounts of gas (table 19). The play includes 10 fields with cumulative production in excess of 15 x 10^6 boe and one with production in excess of 100 x 10^6 boe (Spindletop-/, #203). The latter field and two others (#163 and #237) have accounted for 64 percent of the oil production and two fields (#186 and #190) have produced 43 percent of the gas for this play. It is probable that all the major fields have been discovered. Best prospects would appear to be deeper offshore delta front reservoirs. Based on the three historical evaluation methods employed in this study (table 18) the Miocene MSU contains between 250 and 1360 million boe of undiscovered, conventionally producible hydrocarbons. These figures represent an extrapolation of current trends that have prevailed for many years. Prediction of new major discoveries that could significantly alter the projected figures is essentially impossible (Ryan, 1973). From the evidence reviewed above such new discoveries are most probable in Play I and offshore areas of Plays VIII and X. Search for new sources of hydrocarbons in the maturely explored Miocene MSU should follow the recommendations of Halbouty (1980).

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APPENDIX

APPENDIX

MIOCENE FIELD INVENTORY BY RAILROAD DISTRICT AND COUNTY

District	County	Number	Field
4	Aransas	1	Fulton Beach
		2	Halfmoon Reef
	Brooks	3	Alta Mesa
		3.5	Carl Peters
	Cameron	4	Boory
		5	Holly Beach
		6	Luttes
		7	Padre Island
		8	Parks Farm
		9	Port Isabel W
		10	San Martin
		11	Three Islands E
		12	Vista Del Mar
	Duval	13	Sejita E
	Hidalgo	14	Hidalgo W
	Kenedy	15	Cabazos
		16	Monte Pasture
		17	Murdock Pass
		18	Murdock Pass W
		19	Penascal
		21	Potrero Lopena S
		22	Rita
		23	San Jose

District	County	Number	Field
4	Kenedy	24	Sarita
		25	Stillman
4	Kleberg	26	Chevron
		27	Alazan
		28	Alazan N
		29	Hinojosa
		30	Kingsville
		32	Lobo
	Nueces	33	Agua Dulce
		34	Baldwin
		35	Clara Driscoll
		36	Cody
		37	Corpus Christi
		38	Flour Bluff
		39	London/London Gin
		40	Luby
		41	McGregor
		42	Minnie Bock
		43	Nueces Bay
		44	Petronilla
		45	Ramada
		46	Saxet
		47	Turdey Creek
		48	Viola
		48.5	Chapman Ranch

District	County	Number	Field
4	San Patricio	49	Odem
		50	Plymouth
		51	Portilla
		52	Reymet
		53	Sinton N
		54	Sinton W
		55	Taft
		56	Taft W
		57	White Point
	Willacy	58	Arroyo Colorado
		59	Chess
		60	Harena
		61	King Ranch W
		62	La Sara
		63	Paso Real
		64	Raymondsville
		66	Willamar
2	Bee	67	Blanconia
	Calhoun	68	Heyser
		69	Jay Welder
		70	Matagorda Bay
		71	Playa
		72	Powderhorn E
		73	Powderhorn W/SE

District	County	Number	Field
2	Calhoun	74	Saluria
		75	Sherman Offshore
		76	Six-Sixty
		77	Steamboat Pass
	Goliad	78	Clip
	Jackson	80	Carmichael
		81	Collier
		82	Cordele
		83	Cordele S/SE
		84	Cordele W
		85	Francitas
		86	Granado
		87	Hornberger
		88	Mayo
		89	Morales
		90	Navidad
		91	West Ranch
	Lavaca	92	Borchers
		93	Hope
		94	Morales N
		95	Speaks
	Refugio	96	Bonnie View
		97	Fagan
		98	Greta
		99	Huff
		100	La Rosa

District	County	Number	Field
2	Refugio	101	Lake Pasture
		102	Lake Pasture W
		103	Refugio Heard
		104	Refugio New
		105	Refugio Old
		106	Refugio-Fox
		107	Tom O'Connor
	Victoria	108	Coletto Creek
		109	Coletto Creek S/SW
		110	Cologne
		111	Garcitas Creek
		112	Kay Creek
		113	McFaddin
		114	McFaddin N
		115	Nursery S
		116	Pridham Lake
		117	Salem
		118	Telferner
		119	Victoria
3	Brazoria	121	Bastrop Bay
		122	BR Blk 386-5
		123	Cowtrap
		124	Damon Mound
		125	Danbury Dome/Danbury
		126	Freeport

District	County	Number	Field
3	Brazoria	127	Hastings
		128	Hoskins Mound
		129	Manvel
		130	Nash Dome
		131	Pledger
		132	Rattlesnake Mound
		133	Stratton Ridge
		134	West Columbia
	Chambers	136	Anahuac
		137	Barber's Hill
		138	Cedar Point
		139	Lost Lake
		140	Red Fish Reef
		141	Winnie N
	Colorado	142	Eaton
		143	Garwood
		144	Krueger
		145	Mustang Creek
		146	Eagle View
	Fort Bend	147	Big Creek
		148	Blue Ridge
		149	Moore's Orchard
		150	Needville
		151	Sugarland
		152	Thompson

District	County	Number	Field
3	Galveston	153	Blk.176-5
		155	Caplen
		156	Crystal Beach
		160	Galveston Bay W
		161	Gs. Blk. 310-L
		162	Galveston Island
		162.5	Gs. Blk. 102-L
		163	High Island
		164	Hitchcock
		165	Lafittes Gold
		166	Point Bolivar N
		167	Shipwreck
		168	Teichman Point
	Hardin	169	Batson Old
		170	Saratoga
		171	Sour Lake
		171.5	Arriola
	Harris	172	Clear Lake
		173	Clinton
		174	Deckers Prairie S
		175	Dyersdale
		176	Goose Creek
		177	Houston S
		178	Humble
		179	Olcott

District	County	Number	Field
3	Harris	180	Pierce Junction
		181	Tomball
		182	Webster
	(High Island)	183	H. I. Blk. 10L
		184	Blk. 14L
		185	Blk. 19S
		186	Blk. 24L
		187	Blks. 30, 30L
		188	Blk. 52m
		189	Blk. 129
		190	Blk. 140L
3	Jefferson	192	Amella
		193	Beaumont
		194	Beaumont W
		195	Big Hill
		196	Clam Lake
		197	Fannett
		199	La Belle
		200	Lovells Lake
		201	McFaddin Ranch
		202	Sabine Pass
		203	Spindletop
		204	Stowell
		204.5	McFaddin Beach

District	County	Number	Field
3	Liberty	205	Dayton N
		206	Esperson Dome
		207	Hankamer
		209	Hankamer SE
		210	Hull
		211	Liberty S
		212	Moss Bluff
	Matagorda	213	Blk. 368-L
		214	Blk. 369-L
		216	Br. Blk. 405
		217	Br. Blk. 440
		218	Br. Blk. 445
		219	Br. Blk. 446
		220	Br. Blk. 519-S
		221	Collegeport
		222	Colorado Delta
		223	Cove
		224	El Gordo
		226	Kain
		227	Markham
		228	Matagorda Bay
		229	Oliver Pt.
		230	Oyster Lake
		231	Oyster Lake W
		232	Rusty
		233	Sargent S

District	County	Number	Field
3	(Matagorda)	234	Blk. 485-L
		235	Blk. 582-S
	Montgomery	236	Conroe
	Orange	237	Orange
		238	Port Neches
	Wharton	239	Blue Basin
		240	Boling
		241	Duffy
		242	Hillie
		244	Hutchins
		245	Lane City
		246	Lissie
		247	Louise
		248	Louise N
		249	Magnet Withers
		250	New Taiton
		251	Popp
		252	Prasifka
		253	Spanish Camp
		254	Trans-Tex
		255	Hungerford