UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

# Geologic Framework, Petroleum Potential, Petroleum-resource Estimates, Mineral and Geothermal Resources, Geologic Hazards, and Deep-water Drilling Technology of the Maritime Boundary Region in the Gulf of Mexico

Edited

By

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not constitute endorsement by the USGS.

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Contents

Contents continued



## Illustrations

Illustrations continued

Illustrations continued

Illustrations continued

## Tables

# GEOLOGIC FRAMEWORK, PETROLEUM POTENTIAL, PETROLEUM-RESOURCE ESTIMATES, MINERAL AND GEOTHERMAL RESOURCES, GEOLOGIC HAZARDS, AND DEEP-WATER DRILLING TECHNOLOGY OF THE MARITIME BOUNDARY REGION IN THE GULF OF MEXICO

## Summary


This report presents the detailed findings of a study by the U.S. Geological Survey on the oil and gas potential of a designated assessment area in the Gulf of Mexico (fig. 1). Information available on this region is sufficient for us to gain an understanding of its oil and gas resource potential. The principal conclusions from analysis of these data are:

1. Favorable geological conditions exist for the occurrence of crude oil and natural gas resources in the designated area of study;
2. Estimates of undiscovered in-place resources range from 2.24 billion to 21.99 billion barrels of oil (BBO) and from 5.48 trillion to 44.40 trillion cubic feet (TCF) of gas;
3. Exploration and exploitation of these deep-water estimated resources are expected to become feasible in the future.

The designated study area is divided into six individual assessment areas on the basis of their geologic characteristics. The total designated area of assessment comprises approximately 58,940 $mi^2$ (152,660 $km^2$) and contains a total measurable sediment volume of 188,140 $mi^3$ (784,170 $km^3$). Water depths in the study area range from a minimum of 98 ft (30 m) on the continental shelf off the Rio Grande, to a maximum of about 12,270 ft (3,740 m) in the deep abyssal plain of the west-central Gulf; more than 75 percent of the study area lies in water depths exceeding 10,000 ft (3,049 m).

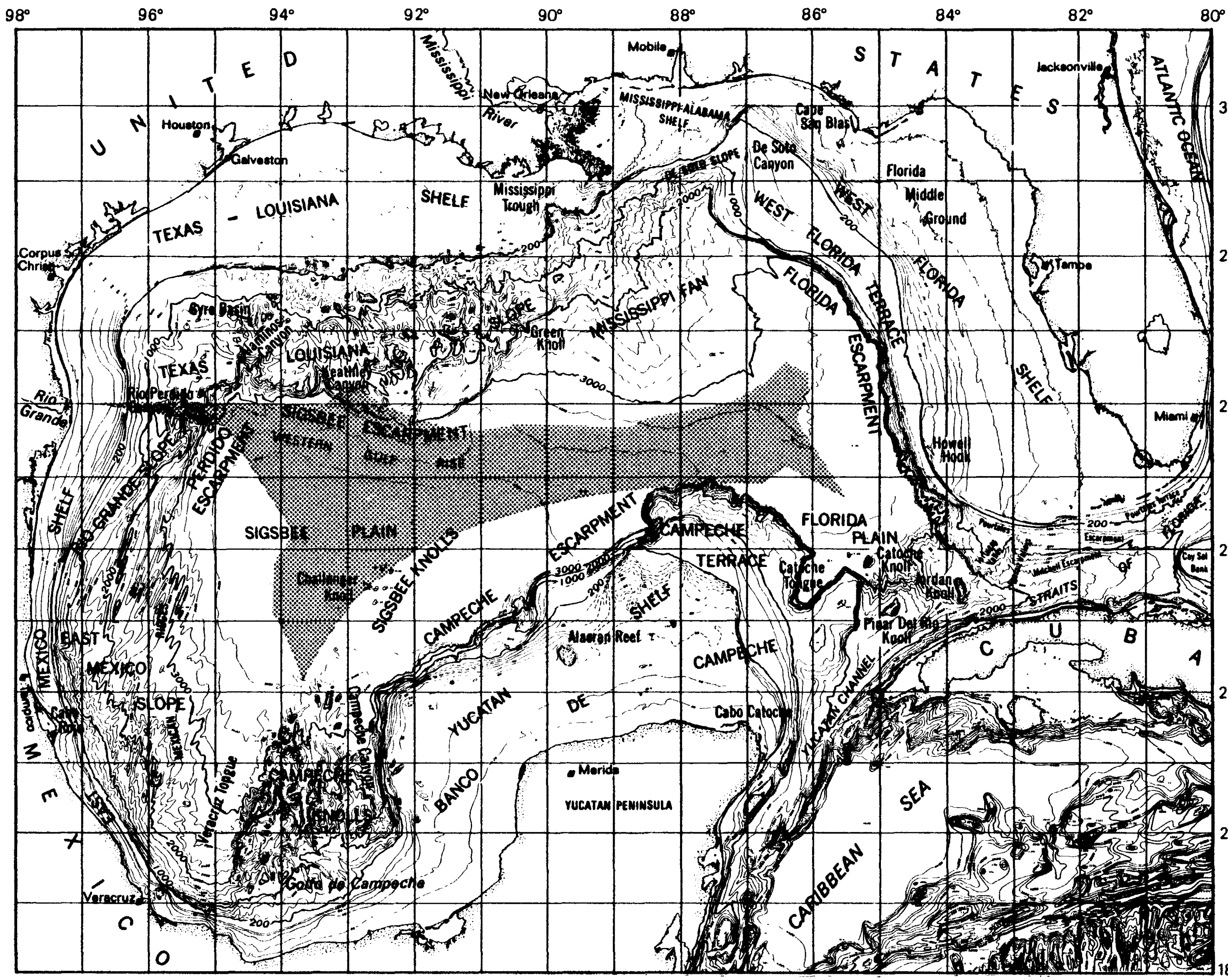


Figure 1.—Map showing Gulf of Mexico Maritime Boundary region, physiographic provinces, and subordinate topographic features. Contour intervals: 20m in water depths less than 200m; 200-m interval in water depths greater than 200m. From Martin and Bouma (1978). The entire assessment area is shaded.

The study focused on factors critical to the generation, migration and entrapment of hydrocarbons, such as: structural and stratigraphic traps, source beds and thermal maturation, reservoir rocks and seals, and timing of hydrocarbon migration relative to formation of traps.

The oil and gas potential of the six assessment areas in the Maritime Boundary region of the Gulf of Mexico was analyzed by using all publicly available geophysical data recorded in the region, supplemented by a limited amount of geological data obtained from drilling within and adjacent to the area of study. Geophysical data included approximately 8,350 nautical miles (nmi) (15,448 km) of seismic-reflection profiles ranging from shallow-penetration recordings to deep-penetration, common-depth-point (CDP) multichannel profiles. Geological information relative to lithology and stratigraphic age of the upper few thousands of feet of strata were derived 1) from two Deep Sea Drilling Project (DSDP) sites in the study area, 2) from 10 shallow industry drill holes within the perimeter of the area of investigation, 3) from projections from as many as 10 deep stratigraphic tests drilled adjacent to the study area, and 4) from many bottom core samples collected by academic institutions at widespread localities in the deep-water areas of the Gulf of Mexico.

Evaluation of the petroleum potential and estimates of petroleum resources are related only to undiscovered in-place crude oil and natural gas, not recoverable amounts. We do not speculate on what part of the estimated in-place resources in the six assessment areas might be ultimately recoverable because not enough is known at present about petroleum-reservoir properties, economics, and the technology needed to develop these deep-water areas.

Geologic hazards that may affect drilling, production, and pipeline transportation in the study area include soil movements, active faults, shallow high-pressure gas accumulations, and possibly earthquakes. The risks presented by these hazards, except earthquakes, are fairly well documented from the experience of more than three decades of drilling operations on the Continental Shelf off Texas and Louisiana. The magnitude and probability of hazard risk in the assessment areas cannot be inferred or predicted at this time.

At present, only a small part of one assessment area, which is in relatively shallow water, could be exploited by use of current drilling and production technology. For the remainder of the study area, however, exploration and production technology is not presently available to exploit any of the estimated petroleum resources in deep water. We expect that by the year 2000, the methods and equipment required for drilling and producing in water as deep as 10,000 ft (3,049 m) will be available.

# INTRODUCTION

By

Richard B. Powers

In the relatively short span of some 30 years, drilling and production of oil and gas in offshore regions of the United States have progressed from very shallow waters to deeper water on the Outer Continental Shelf, which extends from shore to water 656 ft (0 to 200 m) deep. Some fields are presently being developed in water depths as great as 1,025 ft (312 m), beyond the shelf edge, in the Gulf of Mexico. Exploration for future sources of hydrocarbons will be attempted in even deeper water.

Considerable attention has been focused recently by Hedberg (1979, 1980) on the petroleum potential of the deep-water region in the Gulf of Mexico, most particularly in the deep abyssal plain (figs. 1, 2), where water depths reach a maximum of 12,270 ft (3,740 m). In response to this rapidly increasing interest in deep-water exploration for petroleum, the U.S. Geological Survey initiated a comprehensive study within a designated region in the Gulf of Mexico, for the express purpose of defining the existing geology and assessing the undiscovered in-place resources of this deep-water region.

## Scope of the Study

The study encompasses an area of the Gulf of Mexico where jurisdiction over natural resources by adjacent coastal countries has not yet been established. This Maritime Boundary region is the designated area of investigation of this report (fig. 1).

The need for information on possible energy resources in the deep-water region of the Gulf of Mexico is evident and is not expected to diminish in the immediate future. This report, as its title implies, mainly concerns the petroleum potential and the geology related to its determination, of six assessment areas in the Maritime Boundary region of the Gulf of Mexico. The term, "petroleum potential" includes the evaluation and assessment of conventional undiscovered in-place oil and gas resources. The main objective of the work was to bring together as much publicly available information as possible that would bear on evaluation and assessment of petroleum resources. Fortunately, there existed a considerable amount of data that could be assembled to enable us to gain a good understanding of the oil and gas potential of this broad region.

## Topical Discussions

Important main topics in the report that apply directly to oil- and gas-resource assessment include detailed discussions of the physiography of the study area, regional geology of the Gulf of Mexico, geology and geophysics of the six assessment areas, and petroleum geology and evaluation of the petroleum potential in these same areas. A comprehensive review and an analysis of the factors identified in these discussions as being significant to petroleum generation, migration, and entrapment were used in estimating volumes of undiscovered in-place oil and gas resources in each of the six assessment areas. No estimates of hydrocarbon resources in the deep-water area of the Gulf of Mexico are known to have been published prior to this present assessment.

Included within the broad scope of this report are topical discussions of other, non-energy mineral resources and energy resources of a geothermal origin. An assessment of potential geologic hazards that may affect future exploration in deep waters is also discussed. The final topic of investigation explores the technology presently available for offshore drilling and production and the technology that may be feasible for deeper water drilling in the near future.

We wish to acknowledge the following members of the U.S. Geological Survey (USGS) for their assistance in assessing the petroleum potential of the Gulf of Mexico: Anny Coury, Abdul Khan, Edward Scott, David Cooke, and Roger Corbeille. We thank Price McDonald and Ray H. Wallace, both also of the USGS, for their technical contributions. Our special thanks go to Mahlon Ball and Gordon Dolton for their substantial contribution in many areas of the study, and for their thoughtful and constructive review of the manuscript.

PHYSIOGRAPHY OF THE GULF OF
MEXICO MARITIME BOUNDARY REGION

By

Ray G. Martin and Richard Q. Foote

## Introduction

The Gulf of Mexico Maritime Boundary region covers the seabed of the central Gulf of Mexico from a point 12 mi (19 km) offshore the mouth of the Rio Grande in the west to the abyssal Gulf basin between the Florida and Campeche Escarpments in the east (fig. 1). The area includes parts of the continental shelf, slope, and rise and the abyssal plain and submarine fan regions of the northwest and central Gulf of Mexico. Specific physiographic provinces and features present within the boundary region include the Rio Grande Shelf and Slope, the Perdido Escarpment, the Texas-Louisiana Slope, the Sigsbee Escarpment, the Western Gulf Rise, the Sigsbee Plain, the Sigsbee Knolls, the Campeche Escarpment, and the lower Mississippi Fan (fig. 2). The study area lies within a perimeter discussed by Hedberg (1979, 1980) and contains a total of 58,940 $mi^2$ (152,660 $km^2$). Water depths within the region under study range from a minimum of 98 ft (30 m) on the continental shelf off the southern tip of Texas to a maximum of 12,270 ft (3,740 m) in the abyssal plain southwest of the Sigsbee Knolls in the west-central Gulf. More than 75 percent of the Maritime Boundary region lies in water depths greater than 10,000 ft (3,049 m).

## Regional Physiographic Setting

The Gulf of Mexico is composed of two geomorphic provinces--a continental margin and a deep seabed or ocean-basin floor (Martin and Bouma, 1978). The continental margin consists of the emergent coastal plain and the submergent continental shelf and slope (fig. 3). The continental shelf and slope together are called the continental terrace.

The continental shelf is the submerged shoulder of the continental platform and represents the subaqueous extension of the coastal plain from the coastline to a pronounced increase in sea-floor gradient which generally occurs in water depths of 328 to 656 ft (100 to 200 m). The surface of the continental shelf in the western Gulf of Mexico has a gentle dip of less than $1^{\circ}$; the width ranges from about 45 nmi (83 km) at the Rio Grande to more than 120 nmi (222 km) offshore western Louisiana and eastern Texas.

The continental slope is a region of gently to steeply sloping sea floor that extends from the shelf edge to the upper limit of the continental rise, or locally to the abyssal plain. The continental slope is usually thought to end at that point where gradient decreases below a ratio of 1:40. The continental slope in the northwestern Gulf consists of two parts, the upper slope (dipping $1-2^{\circ}$) (which is characterized by a hummocky topography) and a relatively steep lower slope that breaks off abruptly in water depths of 9,184 to 11,152 ft (2,800 to 3,400 m). The median water depth of the base of the continental slope in the Gulf of Mexico is about 9,184 ft (2,800 m) according to Emery and Uchupi (1972). The structural grain and topography

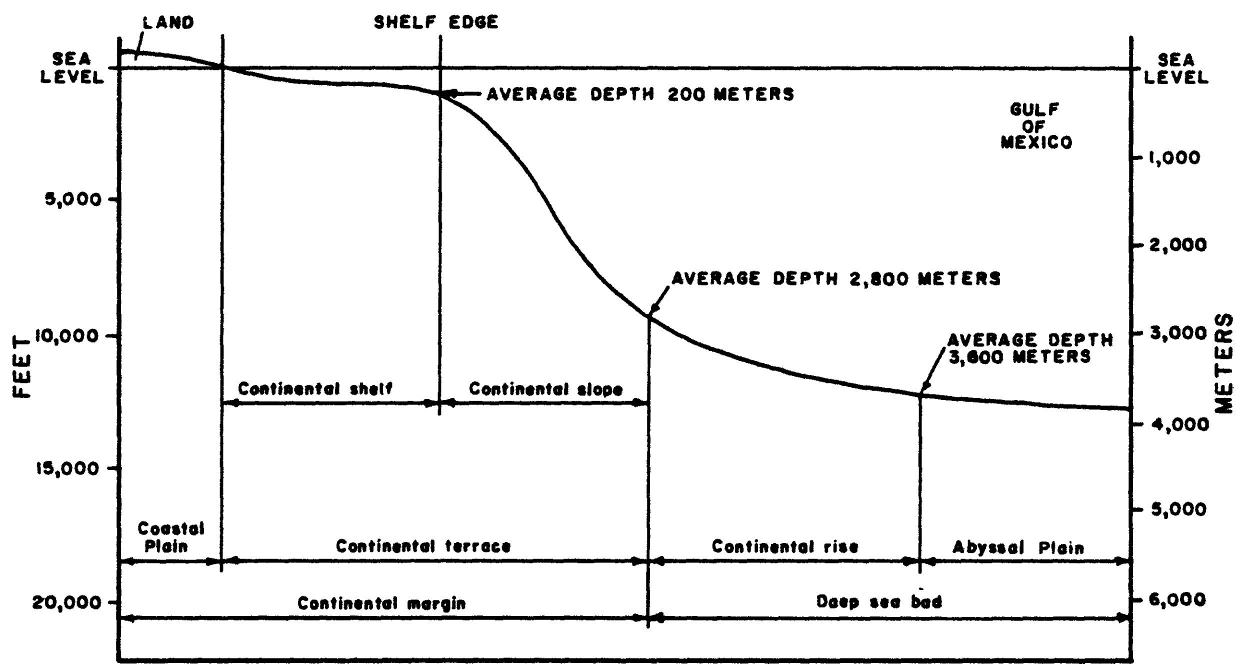


Figure 3.—Diagrammatic profile across the continental margin and deep ocean floor.

of the continental slope are controlled primarily by salt tectonics, and the hummocky or hilly nature of the slope is due to diapiric salt structures. The transition from continental shelf to continental slope in the northwest Gulf of Mexico is significant in terms of potential geologic hazards because of differences in sea-floor stability.

Commonly, continental terraces contain a thick sequence of young sedimentary rocks that were deposited in the same terrace environment in which they are now found. Terraces reflect a seaward growth of the continents (Emery, 1968). Sediment traps, formed by dams created by fault blocks, reefs, or mud or salt intrusions, play an important part in the accumulation of sediments on some terraces, such as those in the Gulf of Mexico.

The deep seabed, or ocean-basin floor, includes the continental rise and abyssal plain provinces. The continental rise is the gently sloping surface that extends from the toe of the slope to the abyssal plain. Its seaward boundary is indefinite and is sometimes defined to be where the slope becomes less than 1:1,000. The continental rise is a depositional feature composed of sediments that were transported from the continents by bottom currents, gravitational creep, and turbid flow down submarine canyons. The abyssal plain is a deep seabed area in water depths generally more than 11,000 ft (3,354 m). The plain is essentially flat, having a gradient of less than 1:8000, and is the surface of a thick sequence of sediment deposited in a deep-ocean environment.

## Physiography of the Boundary Region

The pertinent physiographic subprovinces (fig. 2) within and adjacent to the study region are described from west to east.

### Rio Grande Shelf

The part of the Gulf of Mexico continental shelf within and adjacent to the westernmost part of the study area is called the Rio Grande Shelf in this report. The Rio Grande Shelf (fig. 2) is adjacent to southern Texas and northeastern Mexico and is the surface of a moderately thick accumulation of deltaic sediments delivered to the area by the Rio Grande during Pleistocene time (fig. 4). The Rio Grande Shelf occupies a geographic position whch is transitional between the broad continental shelf off Texas and Louisiana to the north and the relatively narrow shelf off eastern Mexico to the south. The seaward bulging of bathymetric contours that mark the outer edge of the shelf reflects the progradational effect of Pleistocene deposition. The shelf is 40 nautical miles (74 km) wide, and within the study area, lies in water depths that range from about 98 ft (30 m) to 328 ft (100 m). The outer edge of the shelf province is marked by a pronounced steepening of the sea floor in water depths of 328 to 656 ft (100 to 200 m). The surface of the shelf generally is smooth but locally is marked by subdued topographical features relict from times of glacially lowered sea level and by small fault scarps that express the relatively mild tectonism caused by gravity that affects this region.

## MAJOR GEOCHRONOLOGIC AND CHRONOSTRATIGRAPHIC UNITS

| Subdivisions in use by the U. S. Geological Survey (and their map symbols) | | | | | Age estimates[1] of boundaries in million years (m.y.) | |
|---|---|---|---|---|---|---|
| Phanerozoic Eon or Eonothem | Cenozoic Era or Erathem (Cz) | Quaternary Period or System (Q) | | Holocene Epoch or Series | 0.010 | |
| | | | | Pleistocene Epoch or Series | 2 | (1.7-2.2) |
| | | Tertiary Period or System (T) | Neogene Subperiod or Subsystem (N) | Pliocene Epoch or Series | 5 | (4.9-5.3) |
| | | | | Miocene Epoch or Series | 24 | (23-26) |
| | | | Paleogene Subperiod or Subsystem (Pε) | Oligocene Epoch or Series | 38 | (34-38) |
| | | | | Eocene Epoch or Series | 55 | (54-56) |
| | | | | Paleocene Epoch or Series | 63 | (63-66) |
| | Mesozoic Era or Erathem (Mz) | Cretaceous Period or System (K) | | Late Cretaceous Epoch or Upper Cretaceous Series | 96 | (95-97) |
| | | | | Early Cretaceous Epoch or Lower Cretaceous Series | 138 | (135-141) |
| | | Jurassic Period or System (J) | | | 205 | (200-215) |
| | | Triassic Period or System (TR) | | | ~240 | |
| | Paleozoic Era or Erathem (Pz) | Permian Period or System (P) | | | 290 | (290-305) |
| | | Carboniferous Periods or Systems (C) | Pennsylvanian Period or System (IP) | | ~330 | |
| | | | Mississippian Period or System (M) | | 360 | (360-365) |
| | | Devonian Period or System (D) | | | 410 | (405-415) |
| | | Silurian Period or System (S) | | | 435 | (435-440) |
| | | Ordovician Period or System (O) | | | 500 | (495-510) |
| | | Cambrian Period or System (€) | | | ~ 570[2] | |
| Proterozoic Eon or Eonothem (P) | Proterozoic Z (Z)[3] | | | | 800 | |
| | Proterozoic Y (Y)[3] | | | | 1,600 | |
| | Proterozoic X (X)[3] | | | | 2,500 | |
| Archean Eon or Eonothem (A) | | | | Oldest known rocks in U. S. | 3,600 | |

[1] Ranges reflect uncertainties of isotopic and biostratigraphic age assignments. Age of boundaries not closely bracketed by existing data shown by ~ Decay constants and isotope ratios employed are cited in Steiger and Jager (1977).

[2] Rocks older than 570 m.y. also called Precambrian (p€), a time term without specific rank

[3] Time terms without specific rank.

Geologic Names Committee, 1980 edition

**Figure 4.—Major stratigraphic and geologic time divisions used by the U.S. Geological Survey in 1980.**

## Rio Grande Slope

The base of the Perdido Escarpment, at 9,184 ft (2,800 m), forms the foot of the Rio Grande Slope (fig. 2). The average water depth in the Rio Grande Slope province is about 4,920 ft (1,500 m). The topography of the upper slope, in water depths ranging from 656 to 3,936 ft (200 to 1,200 m), depicts a smooth, gently sloping sea floor marked locally by small features of low relief formed by slumping, faulting, and variations in depositional patterns. The middle and lower slope region, on the other hand, is marked by moderately rugged topography consisting of broad, steeply flanked hillocks and perched basins which surficially express the presence of underlying salt massifs, and narrow basins and troughs that contain thick sections of clastic sediment. Along the lower part of the slope, the sea floor grades steeply basinward to form the face of the Perdido Escarpment.

## Texas-Louisiana Slope

The north-central part of the Maritime Boundary region lies within the Texas-Louisiana Slope (fig. 2). Water depths range from about 6,396 ft (1,950 m) to about 9,840 ft (3,000 m) along the base of the Sigsbee Escarpment, which forms the foot of the slope. The sea floor generally is smooth and has slopes less than 8 percent. Minor irregularities in topography result from downslope sediment creep, from minor amounts of mass-movement on steeper slopes, and from erosion by deep marine currents and turbidity flows.

In general, the Texas-Louisiana Slope is a region of complex hillocks, closed basins, and submarine canyons formed by diapiric intrusion and uplift as a result of differential sediment loads on thick deposits of salt. The overall profile of the Texas-Louisiana Slope is steplike, consisting of moderate upper and lower slope gradients and a plateau-like middle slope region. The average gradient of the slope generally is less than $1^{\circ}$, but slopes in excess of $12^{\circ}$ are common on the flanks of numerous hillocks.

The Sigsbee Escarpment forms the foot of the slope from Alaminos Canyon in the west to the Mississippi Fan (fig. 2). The escarpment is little more than a minor steepening of sea-floor gradient between the middle slope plateau and the continental rise. The escarpment is the expression of a complexly lobate frontal edge of thinly covered sheetlike masses of salt that were extruded basinward over relatively young strata.

Mississippi Fan

The Mississippi Fan is a broad sedimentary apron that transcends both bathyal and abyssal water depths and is the result of large accumulations of sediment transported to the Gulf of Mexico by the ancestral Mississippi River, mainly since early Pleistocene time. The apex of the fan lies on the upper continental slope near the Mississippi Delta, from which point it spreads radially downslope abutting the Florida, Campeche, and Sigsbee Escarpments and grades almost imperceptibly into the near-horizontal sea floors of the Sigsbee and Florida Plains to the west and south (fig. 2). The fan is divided into upper and lower regions on the basis of major changes in sea-floor gradient and overall topographic character that occur generally in water depths of 9,184 ft (2,800 m); the eastern one-third of the study area lies within the lower Mississippi Fan region. The lower fan is a broad area of low gradient, 6 ft/mi, (1.83 m/km) and almost featureless topography. Water depths within the study area range from about 10,000 ft (3,049 m) to as much as 11,808 ft (3,600 m), and average approximately 10,988 ft (3,350 m).

## Western Gulf Rise

The continental rise of the central Gulf of Mexico extends basinward from the bases of the Sigsbee and Perdido Escarpments (fig. 2) into water depths of approximately 12,000 ft (3,658 m). The rise is a broad expanse of gently sloping sea floor that separates the continental slope from the abyssal plain and extends counterclockwise from the western margin of the Mississippi Fan into the western and southwestern regions of the deep Gulf of Mexico basin. The rise has a gradient of less than 12 ft/mi (6 m/km) and merges with the near-horizontal floor of the Sigsbee Plain. The rise is the surface of a thick wedge of strata that thins and dips basinward from the continental slope to a gradual merger with relatively thin near-horizontal strata which underlie the abyssal Gulf floor. Common topographic irregularities on the rise include depositional aprons at the mouths of submarine canyons along the Sigsbee Escarpment, linear mounds that express differential sedimentation across the shallow crests of anticlinal structures east of the Perdido Escarpment, and numerous broad areas near the base of the slope characterized by moderately roughened sea floor resulting from mass sediment movement and turbidity scour.

## Sigsbee Plain

The Sigsbee Plain is the abyssal floor of the Gulf of Mexico (fig. 2) and occupies the west-central part of the basin at a maximum depth of 12,270 ft (3,740 m). The plain is essentially flat having a gradient of less than 1:8000. The surface of the abyssal sea floor is the top of a well-stratified section of horizontally layered turbidites and interbedded pelagic muds that range in age from Pliocene to Holocene. These layers onlap and grade into deposits of the Western Gulf Rise and the Mississippi Fan, and abut the Campeche Escarpment. The only features that interrupt the smooth topography of the plain are the Sigsbee Knolls. The knolls are the surface expressions of but a few of the large salt diapirs that intrude and uplift many thousands of feet of abyssal strata along a narrow belt that parallels the southern edge of the study area northwest of the Campeche Escarpment.

## Campeche Escarpment

Near lat 25° N and long 87° 35′ W, the southern edge of the Maritime Boundary region passes across the foot of the Campeche Escarpment (fig. 2), which outlines the exposed perimeter of the broad Yucatan carbonate platform. The escarpment is the product of Early Cretaceous reef building and upward growth of the platform through the slow accumulation of shallow-water carbonate sediment in pace with regional subsidence. The escarpment is moderately steep and descends generally through water depths of 3,280 to 10,496 ft (1,000 to 3,200 m). The face of the escarpment forms a smooth concave profile which passes beneath abyssal sediments and outlines the surface of buried carbonate strata that compose the foundation of the Yucatan platform.

# REGIONAL GEOLOGY OF THE GULF OF MEXICO

by

Ray G. Martin

## Introduction

The Gulf of Mexico is a relatively small ocean basin covering an area of more than 579,000 $mi^2$ (1.5 million $km^2$). The basin is almost completely surrounded by landmasses and opens to the Atlantic Ocean and Caribbean Sea through two narrow passages, the Straits of Florida and the Yucatan Channel (fig. 1). The central deep-water region of the Gulf is underlain by dense oceanic basement rocks (fig. 5), which are depressed substantially below the levels of equivalent crustal layers in normal ocean basins (Ewing and others, 1960, 1962; Menard, 1967; Martin and Case, 1975). Thinned, moderately dense basement forms the foundation beneath the continental slopes and large parts of the continental shelf areas representing a crustal transition between the thin basaltic basement in the center of the basin and thick granitic type basement that floors the emergent margins and parts of the continental shelves (fig. 6; Hales and others, 1970; Worzel and Watkins, 1973; Martin and Case, 1975). In contrast to ocean basins, such as the Caribbean Sea basin, whose margins have been either created or highly modified by convergent plate-tectonic processes, the Gulf basin appears to have drifted passively with North America, gaining its present form from a combination of basin rifting, sedimentary, and intrabasin tectonic processes.

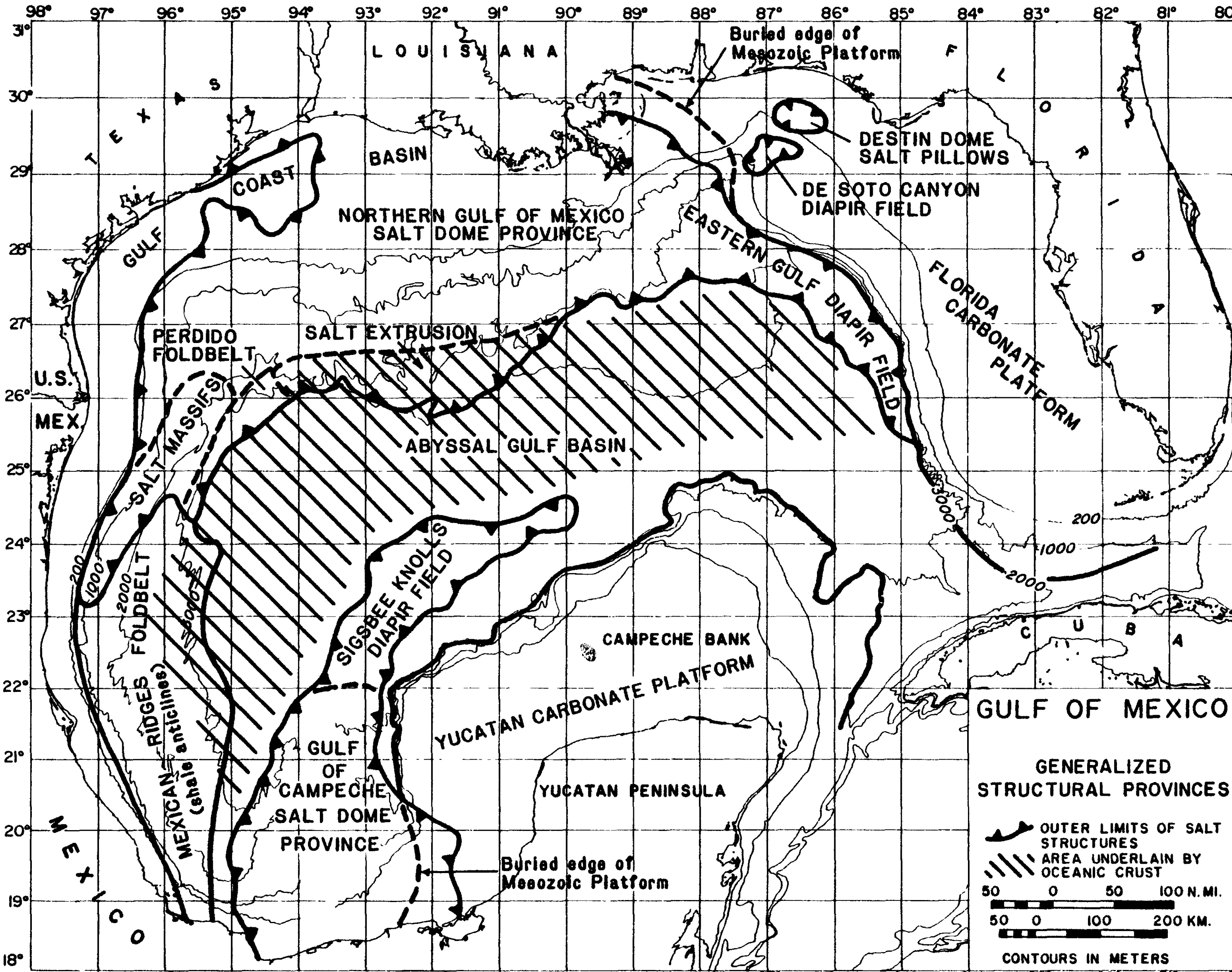


Figure 5.--Map of Gulf of Mexico region showing generalized structural provinces. Distribution of salt from Martin (1980a); extent of oceanic crust from Buffler and others (1980).

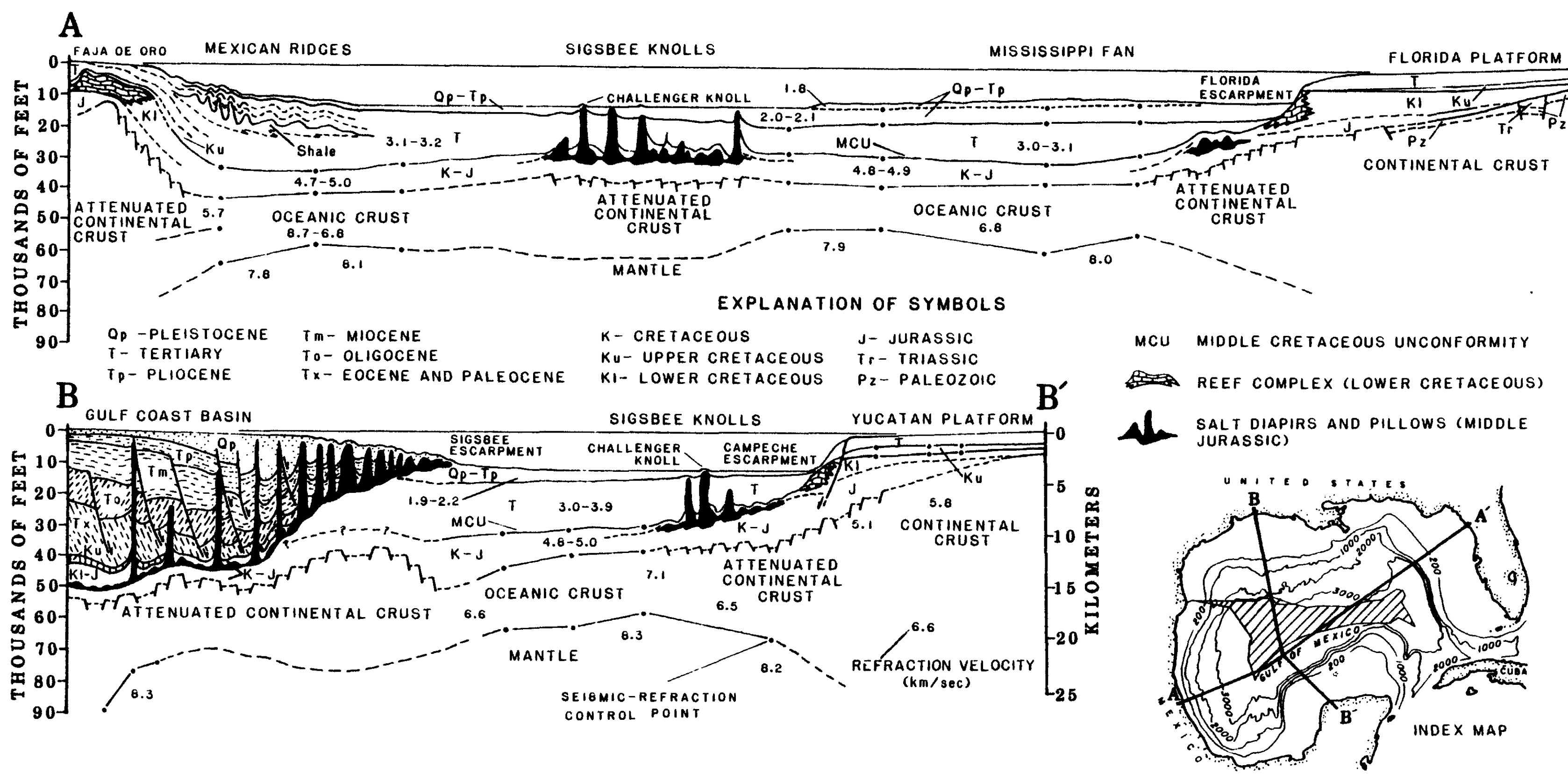


Figure 6.--Diagrammatic crustal sections A-A′ and B-B′ across continental margin and deep ocean basin regions of the Gulf of Mexico. Based on (1) published cross-sections (Lehner, 1969; Dorman and others, 1972; Antoine and others, 1974; Martin and Case, 1975; Martin, 1978); (2) interpretation of seismic-reflection profiles; (3) seismic-refraction data (Cram, 1961; Ewing and others, 1962; Antoine and Ewing, 1963; Hales and others, 1970; Dorman and others, 1972; Buffler and others, [in press]); and (4) drill-hole information from Florida, Yucatan, and Faja de Oro (Maher and Applin, 1968; Lopez Ramos, 1975; Viniegra O. and Castillo-Tejéro, 1970).

## Origin and Early Evolution

The age and early evolution of the Gulf of Mexico are not well known, but subsurface geologic information from deep drilling and from outcrop studies in the peripheral coastal plains and on the continental shelves suggests that the basin is relatively young. At the close of the Paleozoic era and during the earliest Mesozoic time (fig. 4), the present Gulf basin appears to have been an emergent region periodically invaded by shallow epicontinental seas. During this period, the Earth was beginning to undergo the latest in a cycle of worldwide tectonic processes that would ultimately lead to the present distribution of continental landmasses and ocean basins. At one time, early in the Mesozoic Era, much of North America was part of a supercontinent, earlier in geologic history having been welded together with South America, Africa, Antarctica, India, and the European continent. Geologic evidence in the emergent margins of the Gulf basin suggests that the region began to be affected by tensional crustal extension during the Triassic as Africa and South America began to drift southeasterly away from North America. This early stage of continental pulling apart produced widespread rifting along eastern North America and into the Gulf region. This episode of rifting formed complex systems of graben basins, which were quickly filled by sands and muds in a primarily subaerial environment. Separation of the North American, South American, and Central American continental plates continued through the Triassic and Jurassic, establishing by the beginning of the Cretaceous the basic configuration of the Gulf basin, which has since been modified principally by sedimentary, rather than tectonic, processes.

During this extensional phase, the Gulf of Mexico region underwent remarkable changes both at the surface and within the crustal foundation. The divergent drift of the continental masses, imperceptibly slow, stretched the deep crustal layers beneath the basin into thinner and thinner proportions. During this process, the basement was subject to fracturing and injection of dense molten rock into the fissures. As this complex process proceeded, the crust was slowly attenuated by rifting and intrusion with attendant change from low-density continental basement having a thickness of 15.5-21.7 mi (25-35 km) to intermediate-density, moderately thick 6.2-9.4 mi (10-15 km) transitional crust (Ewing and others, 1960, 1962; Hales and others, 1970; Worzel and Watkins, 1973). Owing both to crustal thinning and complex phase changes related to pressure and temperature gradients in the deep crust and upper mantle (Martin and Case, 1975), the Gulf of Mexico region began to subside and become subject to thick accumulation of sediment from surrounding landmasses. Initial subsidence due to rifting and crustal attenuation combined with subsequent sediment load have caused maximum subsidence of about 30,000 ft (9,146 m) since mid-Jurassic time in the central Gulf basin and as much as 50,000 ft (15,244 m) in major depocenters along the northern Gulf margin (fig. 6).

In the early stages of the evolution of the Gulf basin, thick deposits of sands and muds were deposited subaerially in complex graben systems formed by rifting and divergent drift of continental plates. By mid-Jurassic time and perhaps earlier, shallow seas began to invade the region periodically. For long periods of time, these shallow bodies of seawater were restricted from circulation with open-ocean waters, and large amounts of salt precipitated across a wide area of the region as the seawaters were evaporated. These restricted-circulation conditions prevailed over the northern, central, and southwestern Gulf regions into late Jurassic time, producing accumulations of salt that locally amounted to as much as 10,000 to 15,000 ft (3,049 to 4,573 m) thick before flowage into the numerous pillows, massifs, and diapiric stocks that today dominate the structural fabric of much of the Gulf basin (fig. 5). Whether these vast deposits of salt accumulated in one broad basin, subsequently separated during the Late Jurassic by active sea-floor spreading (Buffler and others, 1980, [in press]; Dickinson and Coney, 1980; Walper, 1980), or whether they were deposited in complex graben systems in essentially their present geographic positions in the northern and southwestern Gulf margins and central basin, is unknown. Crustal layers beneath the deep Gulf floor between the present salt-dome provinces have physical properties similar to those of oceanic basement formed by sea-floor spreading (fig. 6). Oceanic crust emplaced between Jurassic salt basins that were rifted apart would imply a thin section of Mesozoic rocks beneath the Cenozoic fill of the deep Gulf basin. A relatively thin section of Mesozoic strata above oceanic crust is shown by refraction data used in the construction of cross sections A-A′ and B-B′ (fig. 6). On the other hand, thicker deposits of pre-middle Cretaceous strata are indicated in areas of attenuated continental crust (fig. 6), thus suggesting the presence of older Mesozoic and possibly Paleozoic strata in these areas.

## Mesozoic and Cenozoic Depositional History

Following the last major cycle of evaporitic deposition early in Late Jurassic time, the Gulf of Mexico region was flooded by open seas. Depositional environments quickly changed from evaporitic and continental to shallow and perhaps locally, deep marine. Terrigenous sands and muds initially were deposited across the basin, and eventually they were overlain by predominantly carbonate accumulations as subsidence slowed and the supply of terrigeneous clastic material waned. A carbonate depositional regime prevailed into the Early Cretaceous, during which time, broad carbonate banks composed of limestones, dolomites, and interbedded anhydrites were constructed around the periphery of the basin (fig. 7). Carbonate muds accumulated in the deeper water areas between these broad banks. The seaward edges of these shallow banks were sites of reef building and detrital carbonate accumulation. As reef construction and sedimentation kept pace with regional subsidence, the banks were continually built upward as their foundations sank. Because only meager amounts of sediment were being supplied to the deeper regions of the basin at this time, sediment accumulation there was extremely low in comparison to that on the shallow bank margins. The net effect was the formation of thick, steeply fronted carbonate platforms around the periphery of the basin that grade abruptly seaward into a relatively thin sequence of time-equivalent deep-water strata. The present-day Florida and Campeche Escarpments in the eastern and southern Gulf for the most part expose these Early Cretaceous platforms.

In mid-Cretaceous time, a profound increase in the subsidence rate and sea level affected the carbonate depositional environment throughout the Gulf region. As the Late Cretaceous seas expanded over the region, shallow-water carbonate environments transgressed landward from the outer margins of the banks. Increased subsidence in the Gulf region was accompanied by an increase in land-derived sediment supply, which quickly overwhelmed carbonate environments in the northern and western regions of the basin (fig. 7). Carbonate deposition persisted, however, on the Florida and Yucatan platforms in the eastern and southern Gulf.

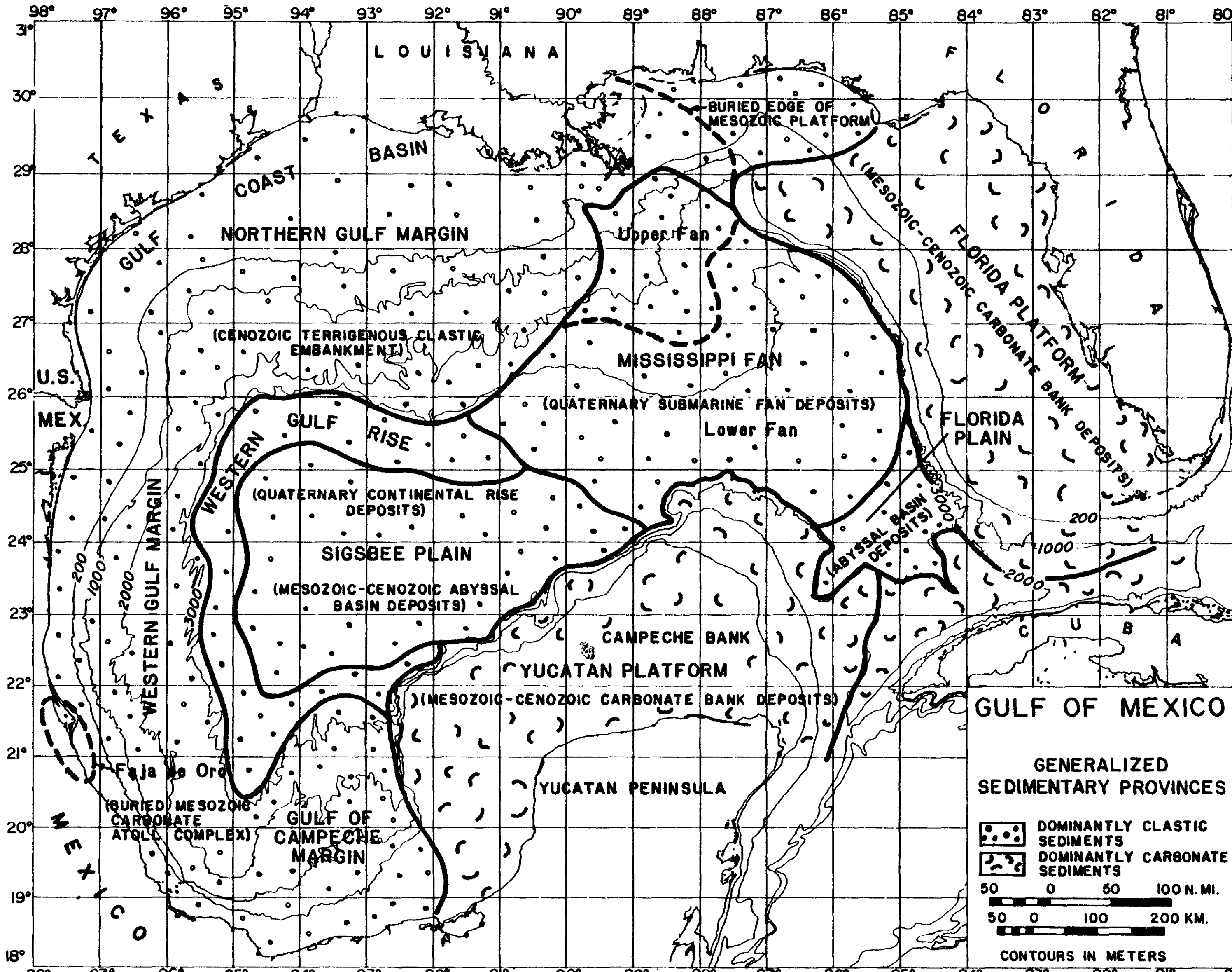


Figure 7.--Map of Gulf of Mexico region showing generalized sedimentary provinces.

General uplift of the North American continent during latest Cretaceous and early Tertiary times was related to the tectonic formation of the Rocky Mountains in the Western United States and Canada and the Sierra Madre and Chiapas ranges in Mexico; this general uplift produced voluminous amounts of clastic sediment that were delivered to the northern, western, and southwestern Gulf regions (fig. 7) throughout the Tertiary period. These tectonic events in the southern and western periphery of the Gulf basin apparently induced erosion that removed substantial amounts of Upper Cretaceous strata from the rock record. Following this episode, large volumes of land-derived sands and muds were deposited in successively younger wedges of offlapping strata as the basin subsided relatively rapidly (fig. 6). The supply of sediment was generally out of phase with load-induced subsidence so that multiple transgressions and regressions of depositional environments are characteristic of the Tertiary sequence in the northern and western Gulf margins. Sediment supplies during the Tertiary and later in Quaternary time overwhelmed the general rate of subsidence, causing the margins to be prograded as much as 240 mi (384 km) from the edges of Cretaceous carbonate banks around the northern and western rim of the basin to the present position of the continental slopes off Texas, Louisiana, and eastern Mexico.

Almost without interruption, the voluminous infilling of the Gulf basin during Tertiary time was followed by sediment influx of similar proportions due to the profound effects of continental glaciers that advanced and retreated across North America during the Pleistocene. Sea level rose and fell in concert with climatic conditions that controlled the retreats and advances of the glacial sheets. Pleistocene sediments accumulated mainly along the outer shelf and upper slope regions of the northern margin, and on the continental slope and deep basin floor in the east-central Gulf where the topography expresses the apronlike shape of the Mississippi Fan (fig. 7). Thick accumulations of Pleistocene strata extend southeastward to the topographically high approaches to the Straits of Florida and southwestward from the fan into the Sigsbee Plain.

In contrast to the profound infilling by voluminous clastic deposition in the northern and western margins of the basin during Cenozoic time, very little clastic debris reached the platform regions of the eastern and southern Gulf. Consequently, the carbonate environments that had prevailed on these banks during the Mesozoic, for the most part, persisted throughout Tertiary and Quaternary times. Land-derived clastic sediments from source areas north and northwest of the Florida platform were deposited as minor components of Tertiary carbonate environments as far south as the middle shelf region. In the absence of significant supplies of sands and muds from highlands to the south and southwest, Tertiary and Quaternary strata across the Yucatan platform likewise represent continued accumulation of shallow-shelf limestones and carbonate detritus that prevailed earlier in Mesozoic time.

## Structural Framework

The continental margins and deep ocean basin regions of the Gulf of Mexico, in spite of much subsidence, are, for the most part, stable areas in which simple tectonism caused by gravity has played a major role in contemporaneous and post-depositional deformation. Mesozoic and Cenozoic strata in the Gulf basin have been deformed principally by uplift, folding, and faulting associated with plastic flowage of Jurassic salt deposits and masses of underconsolidated Tertiary shale. Cenozoic strata in the northern and western margins of the Gulf, from the Mississippi Delta region southwestward into the Bay of Campeche, are offset by a complex network of normal faults that formed in response to depositional loading along successive shelf edges during Tertiary and Quaternary times. Sedimentary loading of thick deposits of Jurassic salt in the northern margin from the Mississippi Delta region to northeastern Mexico, in the southwestern margin in the Bay of Campeche, and in the deep basin north of the Yucatan platform caused the formation of extensive fields of salt diapirs, which have pierced many thousands of feet of overlying strata (fig. 5). Similarly, loading of water-saturated muds that were rapidly deposited and buried in the western margin from southern Texas to the Bay of Campeche caused plastic flowage that buckled overlying strata to form a complex and extensive system of linear anticlines and synclines (figs. 5 and 6). Mesozoic and Cenozoic strata in the deep basin regions of the Western Gulf Rise, Sigsbee Plain, and lower Mississippi Fan have been only mildly deformed as a result of regional crustal warping and adjustments due to differential sedimentation and compaction; the stratigraphic sequence mainly is affected by normal faults of minor displacement and by broad wrinkles having a few tens to a few hundreds of feet (three to thirty m) of relief. In the massive carbonate platforms of the eastern and southern Gulf, deformation has resulted largely from broad regional uplift and crustal warping.

These structural features are contained within the young sedimentary prism of the Gulf of Mexico, and although generally related to crustal subsidence, are not direct products of major crustal events. Structural deformation of the sedimentary prism resulting from dynamic earth processes appears only to affect a small part of southernmost Bay of Campeche where Mesozoic and Cenozoic strata have been thrust and sheared and intruded by volcanic rocks in response to major tectonic episodes in Late Cretaceous and relatively recent Tertiary times.

GEOLOGY AND GEOPHYSICS OF THE MARITIME BOUNDARY ASSESSMENT AREAS

by

Ray G. Martin and Richard Q. Foote

## Introduction

The Gulf of Mexico Maritime Boundary region is divided into six assessment areas on the basis of distinctive structural and stratigraphic characteristics (fig. 8). The boundary region is primarily situated within the deep-water area of the Gulf of Mexico and includes small parts of the northern and western continental margin. The Rio Grande Margin area traverses the Rio Grande Shelf and Slope in water depths from 98 ft (30 m) to 9,184 ft (2,800 m). The Perdido Foldbelt area lies at the foot of the Rio Grande Slope in the northwestern part of the deep Gulf of Mexico in water depths of about 10,000 ft (3,049 m). The Sigsbee Escarpment area lies at the foot of the Texas-Louisiana Slope in the north-central part of the study area; average water depth is about 8,200 ft (2,500 m). The Sigsbee Knolls area lies in the south-central Gulf and includes two small areas of abyssal sea floor, generally about 12,000 ft (3,658 m) deep, underlain by large salt domes that are outliers of the Sigsbee Knolls diapir field to the south (fig. 5). The Campeche Escarpment area is just north of the Campeche Escarpment in the eastern region of the study area, where water depths average about 11,152 ft (3,400 m). The remainder of the Maritime Boundary region is referred to as the Abyssal Gulf Basin area. The area encompasses parts of the lower Mississippi Fan, the Western Gulf Rise, and the Sigsbee Plain regions, and it is underlain by thick, relatively undeformed deposits of Cenozoic age which unconformably overlie moderately deformed strata of Mesozoic age.

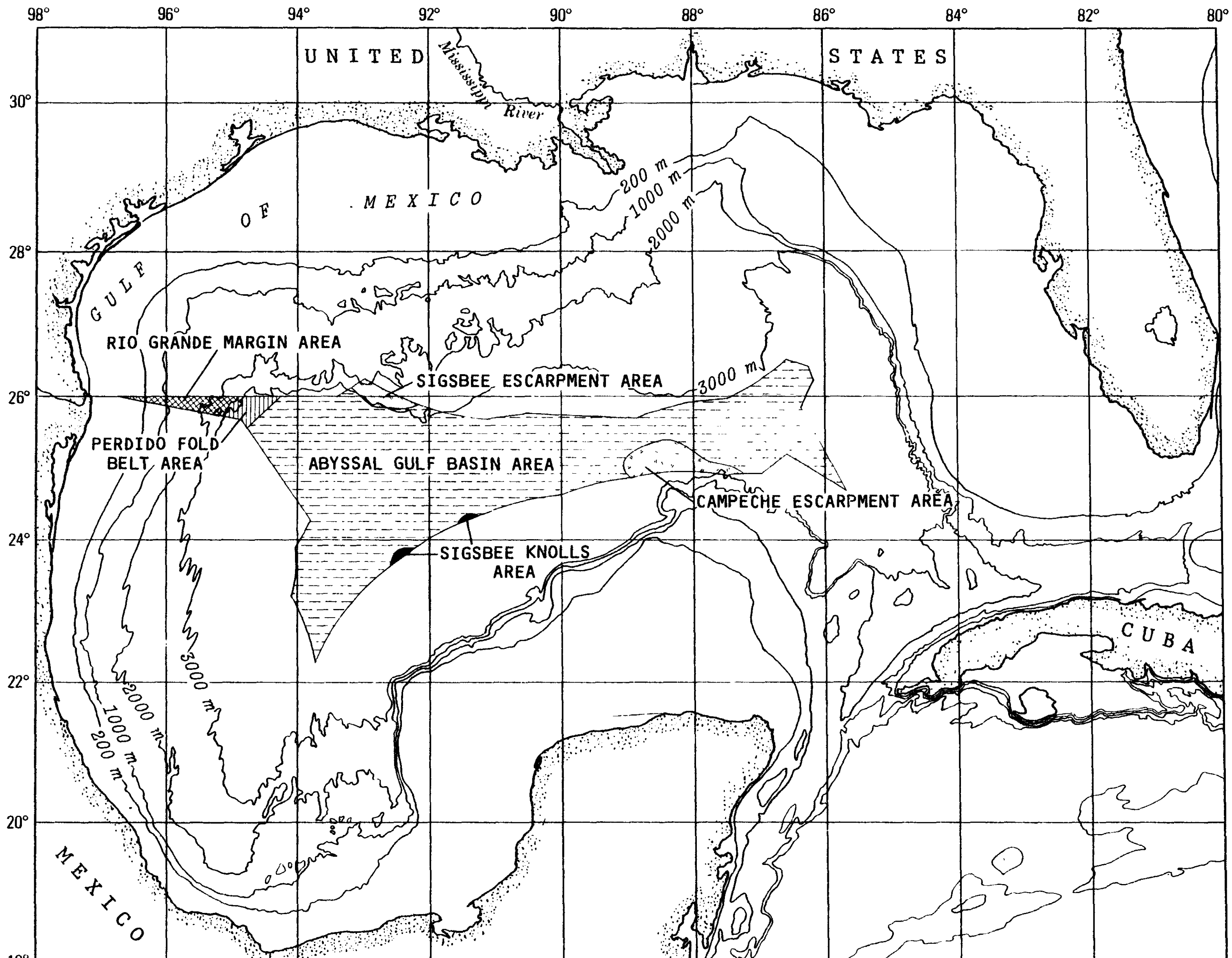


Figure 8.--Map showing individual resource assessment areas in the Gulf of Mexico Maritime Boundary region.

## Geophysical Data

Geological and geophysical descriptions of the assessment areas are primarily based on seismic-reflection geophysical data recorded in the Gulf of Mexico basin by Government agencies and a host of academic institutions during the last 20 years (fig. 9). These data are supplemented by geological information from deep wells and shallow stratigraphic test holes drilled by industry and by the Deep Sea Drilling Project (DSDP) since the mid-1960's (fig. 10). In addition, data from seismic-refraction studies (fig. 11) of the deep basin during the 1950's and 1960's (M. Ewing and others, 1955; J. Ewing and others, 1960, 1962; Antoine and Ewing, 1963) and from modern ocean-bottom seismometers (Ibrahim and others, 1980; Buffler and others, in press) proved invaluable in defining thicknesses and depths of the deep crust and the older stratigraphic sequences.

More than 8,350 nmi (15,448 km) of seismic-reflection data (table 1) were available for this study (fig. 9). Approximately 1,600 nmi (2,960 km) of these data consist of high-technology multichannel profiles recorded and computer processed by the University of Texas Marine Science Institute (UTMSI) for Government- and industry-funded studies of the deep basin. An additional 1,200 nmi (2,219 km) of data consist of deep-penetration single-channel sparker profiles recorded jointly by the U.S. Geological Survey (USGS) and the U.S. Naval Oceanographic Office (USNAVOCEANO) in a basin-wide exploration of the Gulf of Mexico. The balance of seismic-reflection coverage, approximately 5,550 nmi (10,269 km), is low-energy, shallow-penetration data recorded in the region during scientific surveys sponsored by the Government and by the academic sector. Findings and conclusions relative to the geological aspects of assessment areas within the Maritime Boundary region are largely based on the UTMSI and USGS-USNAVOCEANO data, which are of better quality and have

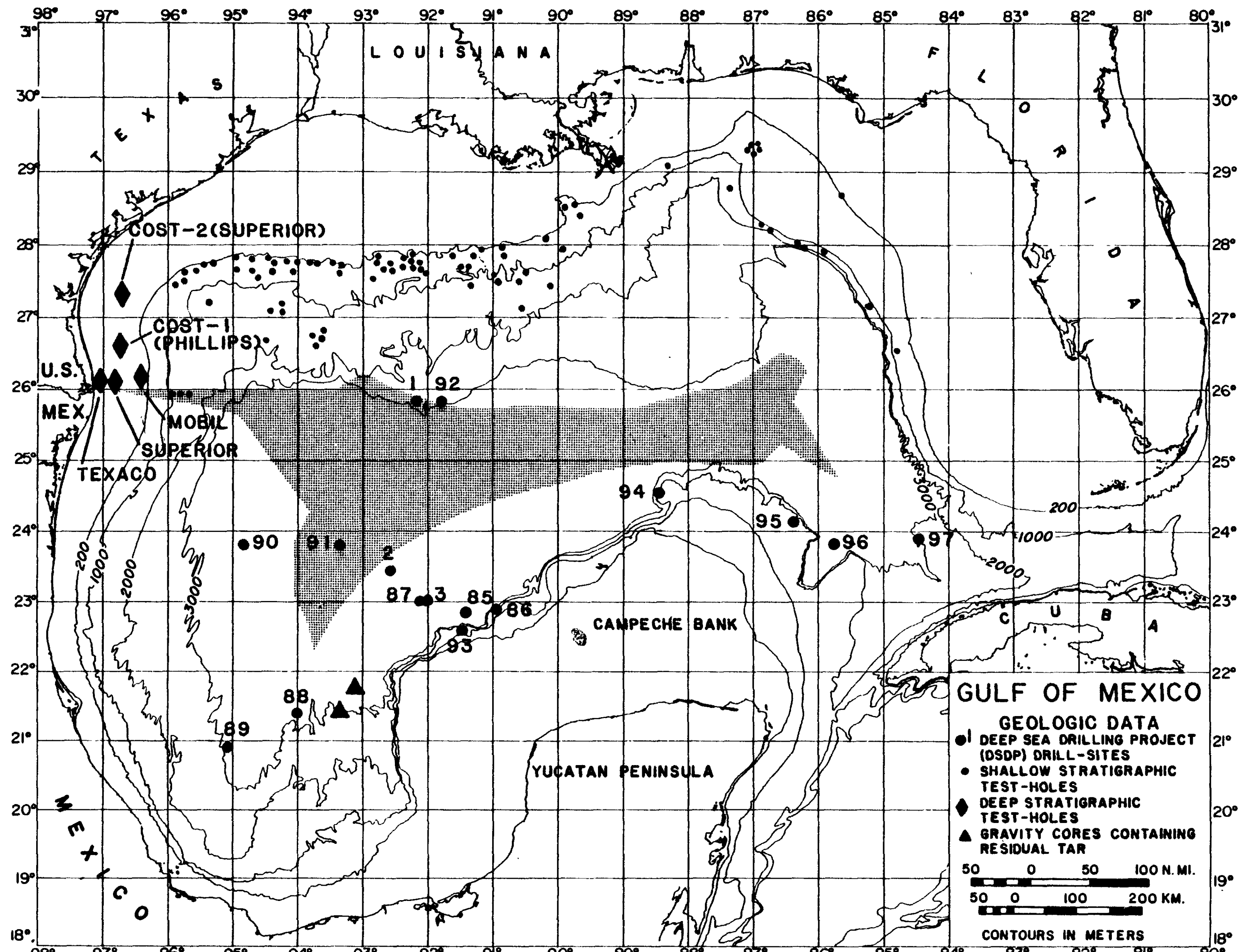


Figure 10.--Map of Gulf of Mexico region showing locations of shallow and deep stratigraphic drill holes and selected bottom samples. The total assessment area is shaded.

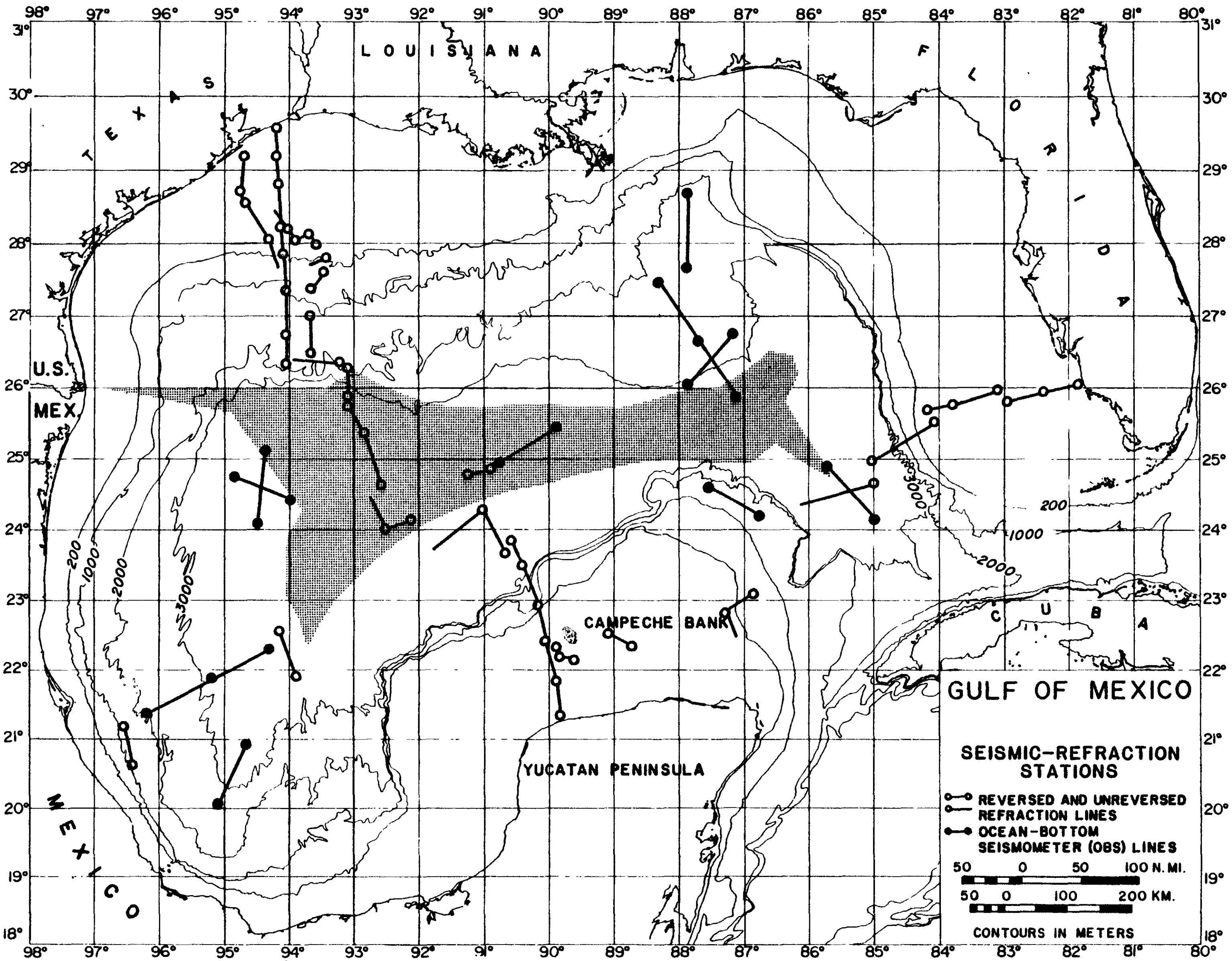


Figure 11.--Map of Gulf of Mexico region showing seismic-refraction profile coverage.

Table 1.--*Distribution of seismic-reflection profile coverage in assessment areas in the Gulf of Mexico.*

| Assessment area | Multichannel[1] | | Deep Reflection[2] Single-channel | | Shallow Reflection Single-channel[3] | | Totals | |
|---|---|---|---|---|---|---|---|---|
| | nmi | km | nmi | km | nmi | km | nmi | km |
| Rio Grande Margin------------ | 21 | 39 | 115 | 213 | 310 | 574 | 446 | 826 |
| Sigsbee Escarpment-------- | 0 | 0 | 38 | 70 | 113 | 209 | 151 | 279 |
| Perdido Foldbelt---------- | 4 | 7 | 38 | 70 | 114 | 211 | 156 | 288 |
| Sigsbee Knolls------------ | 20 | 37 | 0 | 0 | 10 | 19 | 30 | 56 |
| Campeche Escarpment Area--- | 207 | 383 | 32 | 59 | 190 | 352 | 429 | 794 |
| Abyssal Gulf Basin------------- | 1,348 | 2,494 | 977 | 1,807 | 4,813 | 8,904 | 7,138 | 13,205 |
| Totals | 1,600 | 2,960 | 1,200 | 2,219 | 5,550 | 10,269 | 8,350 | 15,448 |

[1]University of Texas Marine Science Institute at Galveston; mainly 12-fold CDP stack.

[2]USNS Kane 160,000 joule sparker; U.S. Geological Survey and U.S. Naval Oceanographic Office, 1969.

[3]Low-power air-gun and sparker profiles by U.S. Naval Oceanographic Office, Texas A&M University, Lamont-Doherty Geological Observatory, and Woods Hole Oceanographic Institution.

deeper penetration than the other data. Seismic-reflection data of lesser quality, however, were particularly useful in mapping areas of complex geology such as in the Rio Grande Slope, Perdido Foldbelt, Sigsbee Escarpment, and Sigsbee Knolls regions.[1]

Except in areas near drill-hole control, where geological aspects of the sequence are known to the depth of drilling, stratigraphic age and lithologic interpretations in the following discussions represent projections and assumptions drawn from a variety of information and inference available from the offshore Gulf basin and around its emergent margins. Stratigraphic interpretations, particularly for the Mesozoic sequence, then must be considered, at best, as approximations predicated on extensive research rather than factually based conclusions.

## Geology of Assessment Areas

Descriptions of the six resource assessment areas within the Gulf of Mexico Maritime Boundary region (fig. 8) are arranged to provide a foundation of information that subsequent sections build on and reference. The Abyssal Gulf Basin is the largest area in the boundary region and is underlain by strata representing the full range of geologic units present in other assessment areas and is, therefore, discussed first. The Perdido Foldbelt area, the Sigsbee Knolls area, and the region of seabed north of the Campeche Escarpment are described in subsequent sections because of geological aspects that set them apart from the remainder of the deep Gulf. Descriptions of the continental margin regions within the study area (Rio Grande Margin and Sigsbee Escarpment areas) conclude the discussion. Table 2 summarizes water

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[1] See Appendix I for discussions of geophysical techniques.

Table 2.--*Areal size, sediment volume, and water depth range of the assessment areas in the Gulf of Mexico.*

| Assessment Area | Area | | Sediment Volume | | Water Depth | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Minimum | | Maximum | |
| | Miles$^2$ | Km$^2$ | Miles$^3$ | Km$^3$ | Feet | Meters | Feet | Meters |
| a. Rio Grande Margin-------- | 1,130 | 2,930 | 3,040* | 12,670* | 98 | 30 | 9,184 | 2,800 |
| b. Perdido Foldbelt--------- | 760 | 1,970 | 2,700** | 11,250** | 9,184 | 2,800 | 11,152 | 3,400 |
| c. Sigsbee Escarpment------- | 760 | 1,970 | 2,770*** | 11,550*** | 6,396 | 1,950 | 9,840 | 3,000 |
| d. Sigsbee Knolls----------- | 230 | 600 | 380** | 1,580** | 11,470 | 3,497 | 12,218 | 3,725 |
| e. Campeche Escarpment------ | 2,140 | 5,540 | 3,970** | 16,550** | 9,512 | 2,900 | 11,480 | 3,500 |
| f. Abyssal Gulf Basin------- | 53,920 | 139,650 | 175,280** | 730,570** | 9,922 | 3,025 | 12,270 | 3,740 |
| Totals | 58,940 | 152,660 | 188,140 | 784,170 | | | | |

*Based on an estimated total thickness of Mesozoic and Cenozoic strata beneath the continental shelf and upper slope of 26,240 ft (8,000 m) and calculated average thickness of sediment above salt in the middle and lower slope of 11,152 ft (3,400 m).

**Based on measured thickness of strata above middle Cretaceous unconformity; poor data quality and meager velocity information below horizon precluded thickness computation for pre-middle Cretaceous strata above basement.

***Based on measured thickness above extruded salt layer and thickness of post-middle Cretaceous strata below extruded salt.

depths, areas, and sediment volumes of the assessment areas. Figure 12 shows locations of seismic sections used as illustrations in the following sections.

Abyssal Gulf Basin Area

The abyssal Gulf of Mexico encompasses all the geomorphic provinces that lie basinward of the continental slopes, generally beneath water depths of more than 9,184 ft (2,800 m). Although they are within the Abyssal Gulf Basin area, the Perdido Foldbelt, Sigsbee Knolls, and Campeche Escarpment areas have distinctive geological aspects that dictate that they be discussed separately. Water depths in the Abyssal Gulf Basin area range from a minimum of 9,922 ft (3,025 m) to a maximum of 12,270 ft (3,740 m). The sea floor ranges from essentially flat in the Sigsbee Plain to gentle gradients of less than 1:800 on the Western Gulf Rise.

The deep-water region of the Gulf is floored by a relatively thin (16,000 to 20,000 ft (4,800 to 6,100 m)) basement (fig. 6) having physical properties similar to those of the crust beneath major ocean basins (M. Ewing and others, 1955; J. Ewing and others, 1960, 1962; Menard, 1967; Martin and Case, 1975). The oceanic basement overlies relatively shallow mantle at depths of about 55,000 ft (16,768 m) below sea level under the Sigsbee Plain (Ewing and others, 1960; 1962). Both basement and mantle surfaces lie 15,000 to 20,000 ft (4,573 to 6,098 m) lower than in typical ocean basins, thus reflecting the effect of substantial sediment load (Menard, 1967; Martin and Case, 1975). Seismic-refraction recordings using ocean-bottom seismometers (Ibrahim and others, 1980; Buffler and others, in press) indicate similar basement thicknesses and mantle depths beneath the easternmost part of the Abyssal Gulf Basin area. Sediment thickness ranges from about 13,000 ft (4,000 m) near the Campeche Escarpment to more than 30,000 ft (9,150 m) near the Sigsbee

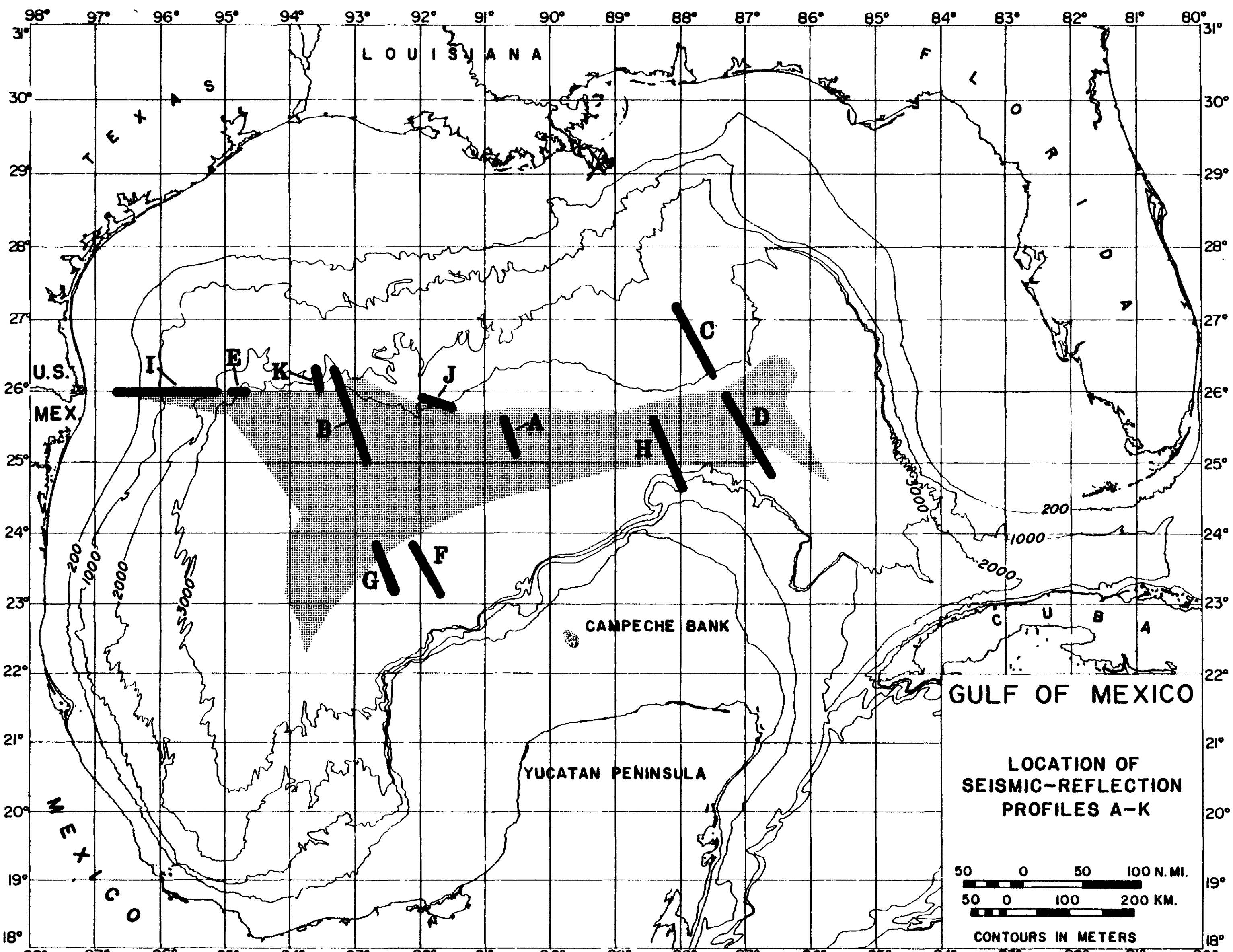


Figure 12.--Map of Gulf of Mexico region showing locations of seismic-reflection profiles A through K (figs. 13 and 16 through 23).

Escarpment (fig. 6). These thicknesses contrast with an average thickness of about 8,200 ft (2,500 m) for sedimentary and interbedded volcanic rocks found in typical oceanic provinces (Raitt, 1963). Seismic-reflection data across the deep Gulf suggest a threefold division of the stratigraphic sequence overlying basement. The division is based on changes in gross seismic aspects of the sequence that take place at prominent seismic-reflection horizons which can be followed easily in the data network throughout the deep basin (fig. 13).

The surface of the oldest sequence is defined by a pronounced reflection of high amplitude, which appears to truncate underlying strata in the section seaward of the Florida and Yucatan carbonate platforms and lies generally conformal to underlying beds elsewhere. The reflector also appears to conform smoothly with buried and exposed faces of the Florida and Campeche Escarpments where rocks of early Cretaceous age have been recovered with gravity corers and dredge hauls (Bryant and others, 1969). Seismic-reflection data recorded through DSDP Site 97 in the deep seabed of the southeastern Gulf (fig. 10) suggest that this horizon is equivalent to a major unconformity that separates limestones and calcareous mudstones of middle Cretaceous age (early Cenomanian) from deep-water chalks of early Tertiary (Eocene) age. The gap in the rock record at Site 97 spans some 40 to 50 million years. The reflector possibly is equivalent to horizons in the Atlantic Ocean and Caribbean Sea. In the Gulf of Mexico, this prominent reflector essentially represents the boundary between Mesozoic and Cenozoic strata.

Seismic-reflection data in the deep basin were not sufficient to make calculations of the thickness of pre-middle Cretaceous strata suitable for isopachous contouring. Seismic-refraction data giving depths to crystalline

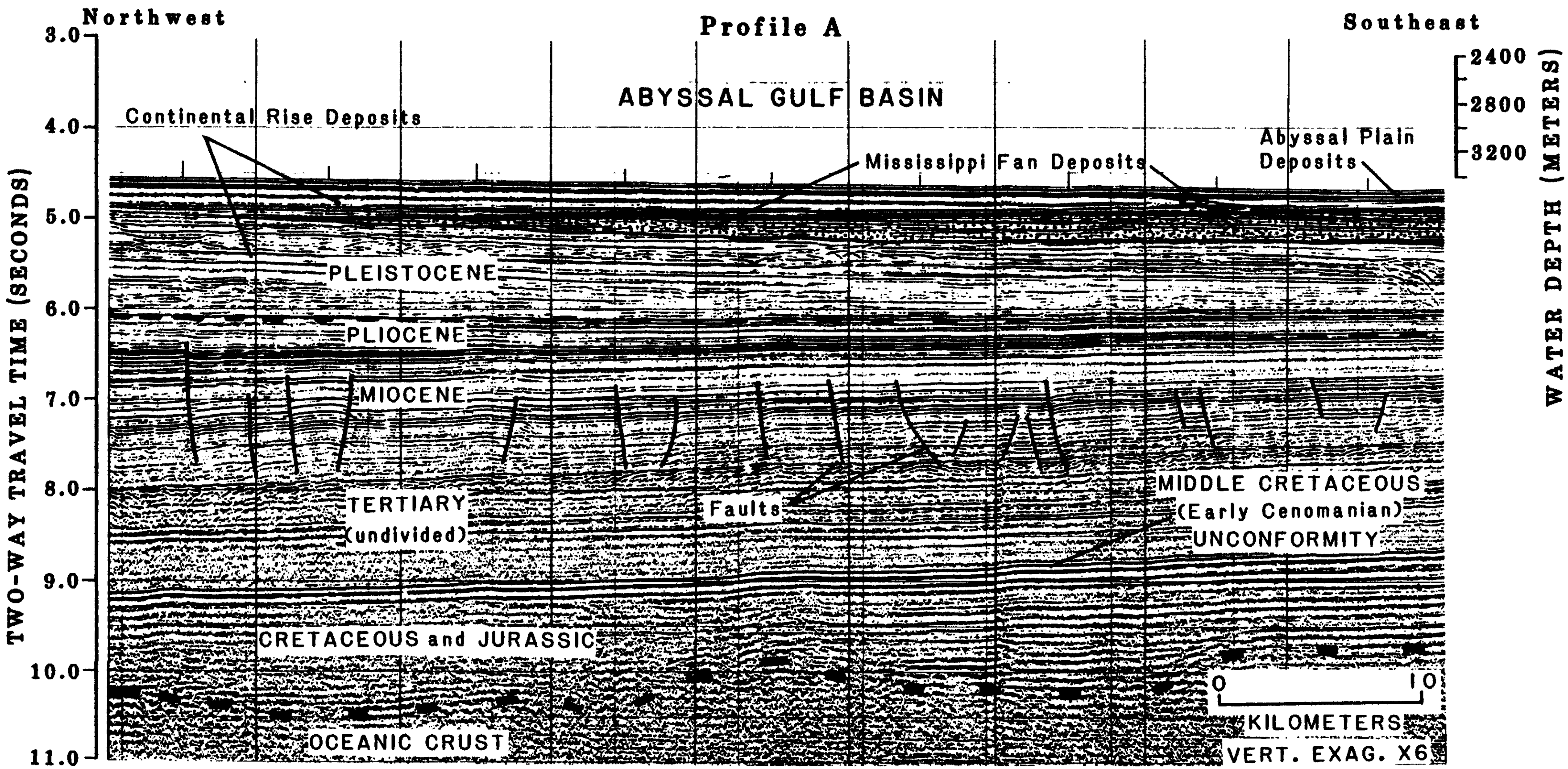


Figure 13.--Multichannel Common-Depth-Point (CDP) profile A in Abyssal Gulf Basin showing seismic-stratigraphic characteristics and typical structural anomalies (faults and low-relief folds) in the Mesozoic-Cenozoic sequence. Location of profile A is shown in figure 12.

basement rocks similarly were not sufficient to map structural contours on the basement surface. Data were more than sufficient to map the thickness of post-middle Cretaceous strata (fig. 14) and the surficial configuration of the middle Cretaceous unconformity (fig. 15).

The older sequence of rocks below the middle Cretaceous unconformity is composed of rift and post-rift deposits which grade upward from continental clastic and interbedded volcanic deposits to shallow and deep marine clastic and carbonate deposits. The presence of pre-rift strata in the deep Gulf cannot be confirmed. Geological and geophysical data presently available from the deep basin cannot be used to assign ages to strata older than those deposited in late Mesozoic time. Seismic-refraction data (fig. 14) in the basin indicate that the late Mesozoic and older sequence ranges from 8,200 to 11,152 ft (2,500 to 3,400 m) in thickness beneath the Sigsbee Plain and is as much as 15,432 ft (4,400 m) thick beneath the Western Gulf Rise; the section beneath the eastern part of the assessment area ranges from 5,904 to 13,776 ft (1,800 to 4,200 m) in thickness. The lower part of the sequence is generally faulted throughout the deep basin province; deformation in the upper part of the sequence is primarily the result of differential sedimentation and compaction over paleo-relief features.

Post-middle Cretaceous strata (middle and upper sequences discussed below) range in thickness from 7,020 ft (2,750 m) in the southeasternmost part of the boundary region to as much as 24,600 ft (7,500 m) near the Sigsbee Escarpment (fig. 14). Average post-middle Cretaceous sediment thickness is about 18,532 ft (5,650 m).

The middle sequence of deep basin sediment ranges from early Tertiary (Paleocene?) to Miocene in age. The sequence is bounded by the middle Cretaceous unconformity at the base and at the top by a pronounced transition

 (Page 44 is figure 14)
(Page 45 is figure 15)

from well-stratified deposits of late Miocene age to discontinuously bedded units of Pliocene age and younger (fig. 13). Seismic-reflection data suggest a general uniformity of depositional character in the sequence throughout the basin. Stratification is generally parallel to subparallel except where the sequence onlaps older strata at the bases of the Campeche and Florida Escarpments and on flanks of salt diapirs in the Sigsbee Knolls region. Paleogene, or pre-Miocene deposits are generally less well stratified than Miocene units and consist of widely distributed units of discontinuously bedded material bounded by continuous, relatively high amplitude reflections. The general seismic character of the Paleogene section suggests the preponderance of fine-grained silts and clays containing only minor amounts of sand. Well-stratified units in the Paleogene section, as well as thin sequences represented by prominent reflections that extend over broad areas of the basin, probably signify depositional stages and events when appreciable amounts of sand were delivered to the basin floor. Miocene deposits are well stratified throughout the basin and are presumed to consist generally of alternating layers of sand and shale. DSDP drill holes in the western part of the basin (fig. 10) penetrated significant quantities of sand in beds of late and middle Miocene age. Miocene and older Tertiary strata generally thin from west to east across the basin with proportional decreases in average grain-size and number of sand horizons. Within the Abyssal Gulf Basin area, Miocene and older Tertiary strata range in thickness from about 18,368 ft (5,600 m) southwest of the Sigsbee Knolls to about 15,908 ft (4,850 m) at the Sigsbee Escarpment, and to less than 7,462 ft (2,275 m) in the lower Mississippi Fan region of the southeastern Gulf. Faults of a few feet to a few tens of feet (few meters to a few tens of meters) of displacement are present throughout the sequence in the deep basin, as are broad archings, or wrinkles, of relatively low relief. These features most probably result from crustal warping and differential compaction.

Pliocene and Pleistocene strata compose the upper sequence of the deep basin and represent a profound change in the general depositional character as a result of huge sediment volumes that were delivered to the Gulf from glaciated regions in the continental interior. The section is composed of coalesced sedimentary aprons built seaward from the mouths of submarine canyons in the Western Gulf Rise, submarine channel and "over-bank" deposits that form the upper Mississippi Fan and lower fan apron in the eastern Gulf, and nearly horizontally stratified turbidite layers that cover the Sigsbee Plain.

In the Western Gulf Rise, the Pliocene-Pleistocene sequence thins and dips southward and younger beds successively overstep older strata to form a complex series of wedges (fig. 16). The internal composition and structure of the continental rise sequence is characterized by many zones of unstratified material interpreted as debris-flow deposits that originated on the adjacent continental slope. The sequence merges with and, in part, is onlapped by near-horizontal strata of the Sigsbee Plain. Pliocene-Pleistocene deposits in the continental rise are as much as 6,462 ft (1,970 m) thick along the Sigsbee Escarpment and thin to about 3,444 ft (1,050 m) at the edge of the Sigsbee Plain.

In the eastern Gulf, the Pliocene-Pleistocene sequence is characterized by relatively complex internal stratigraphy in the upper Mississippi Fan to relatively uniform bedding in the lower fan between the Florida and Campeche Escarpments (fig. 17). The sequence ranges from 4,920 to 6,888 ft (1,500 to 2,100 m) in thickness and thins gradually toward the Florida Plain to the

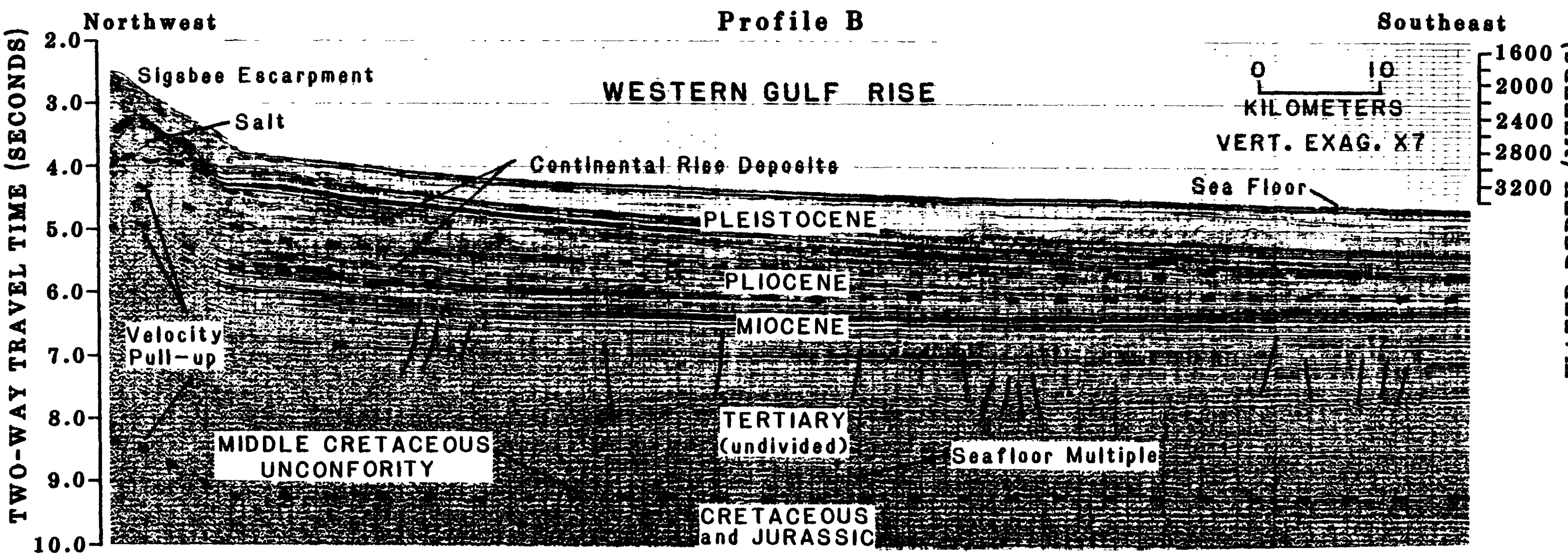


Figure 16.--Multichannel CDP profile B across the Western Gulf Rise and Sigsbee Escarpment provinces showing seismic-stratigraphic characteristics of complexly bedded continental rise wedges. Seismically transparent unit immediately beneath sea floor likely is composed of fine-grained debris-flow and pelagic clay deposits. Stratification in underlying continental rise deposits suggests the presence of sandy turbidite beds; disruption of bedding near the Sigsbee Escarpment is due to slumping. The location of profile B is shown in figure 12.

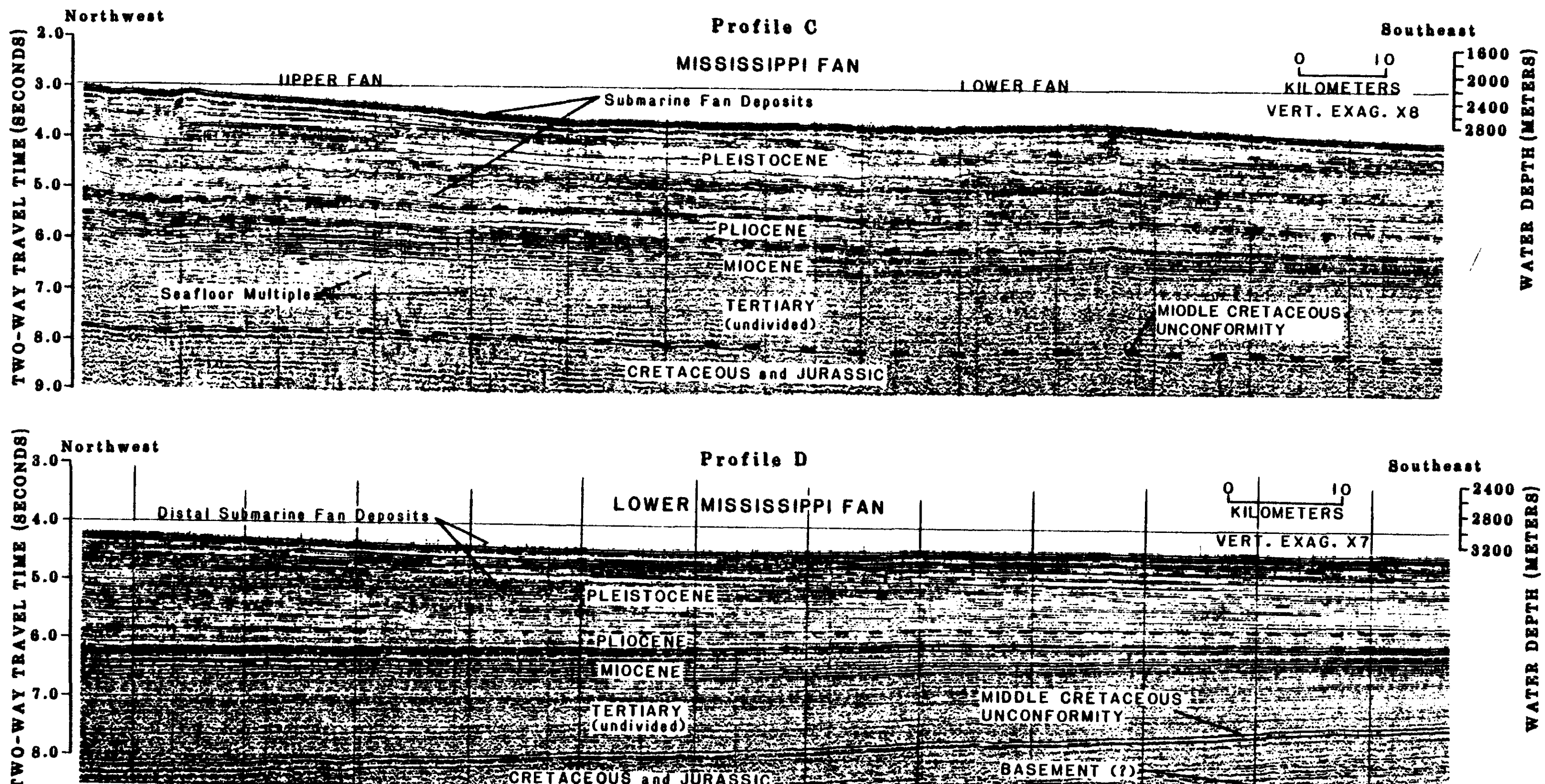


Figure 17.--Multichannel CDP profiles C and D in upper and lower Mississippi Fan regions of the eastern Gulf of Mexico. Complex bedding in upper part of fan grades southward into more normally stratified deposits. Note minor faulting and low-relief warps in Miocene and older strata, and the general thinning of the entire stratigraphic section to the southeast. Locations of profiles C and D are shown in figure 12.

southeast and toward the Sigsbee Plain to the southwest. The sequence is seismically well stratified toward the southeast, but toward the west, it contains diffuse zones indicative of fine-grained debris-flow deposits. Reflection characteristics suggest a preponderance of fine-grained silts and clays with few sands in the western sector of the lower fan, and a greater likelihood of turbidite sand horizons interbedded with silts and clays in the southeast.

The Pliocene-Pleistocene section of the Sigsbee Plain is characterized by a generally uniform sequence of nearly horizontally layered distal turbidite deposits (fig. 13). The section thins appreciably from a maximum of about 4,920 ft (1,500 m) at the edge of the lower Mississippi Fan to less than 1,181 ft (360 m) near the southwestern perimeter of the assessment area. Although the sequence is well stratified, especially in the upper few hundred feet, DSDP drilling in the plain shows only minor quantities of turbidite sand in the section. Except for onlaps around flanks of thinly covered and topographically expressed salt domes, and minor faulting over the crests of more deeply buried structures in the Sigsbee Knolls region, the Pliocene-Pleistocene sequence in the Sigsbee Plain is essentially devoid of structures favorable for hydrocarbon entrapment.

## Perdido Foldbelt Area

The Perdido foldbelt is a system of mostly buried anticlines which lie beneath the Western Gulf Rise and generally parallel the trend of the Perdido Escarpment northeasterly into the Alaminos Canyon and lower Texas-Louisiana Slope (figs. 15, 18). The anticlines are composed of well-layered strata generally as young as early Miocene, that were folded over a core of mobile material, perhaps a thin layer of salt. The limbs of the folds are

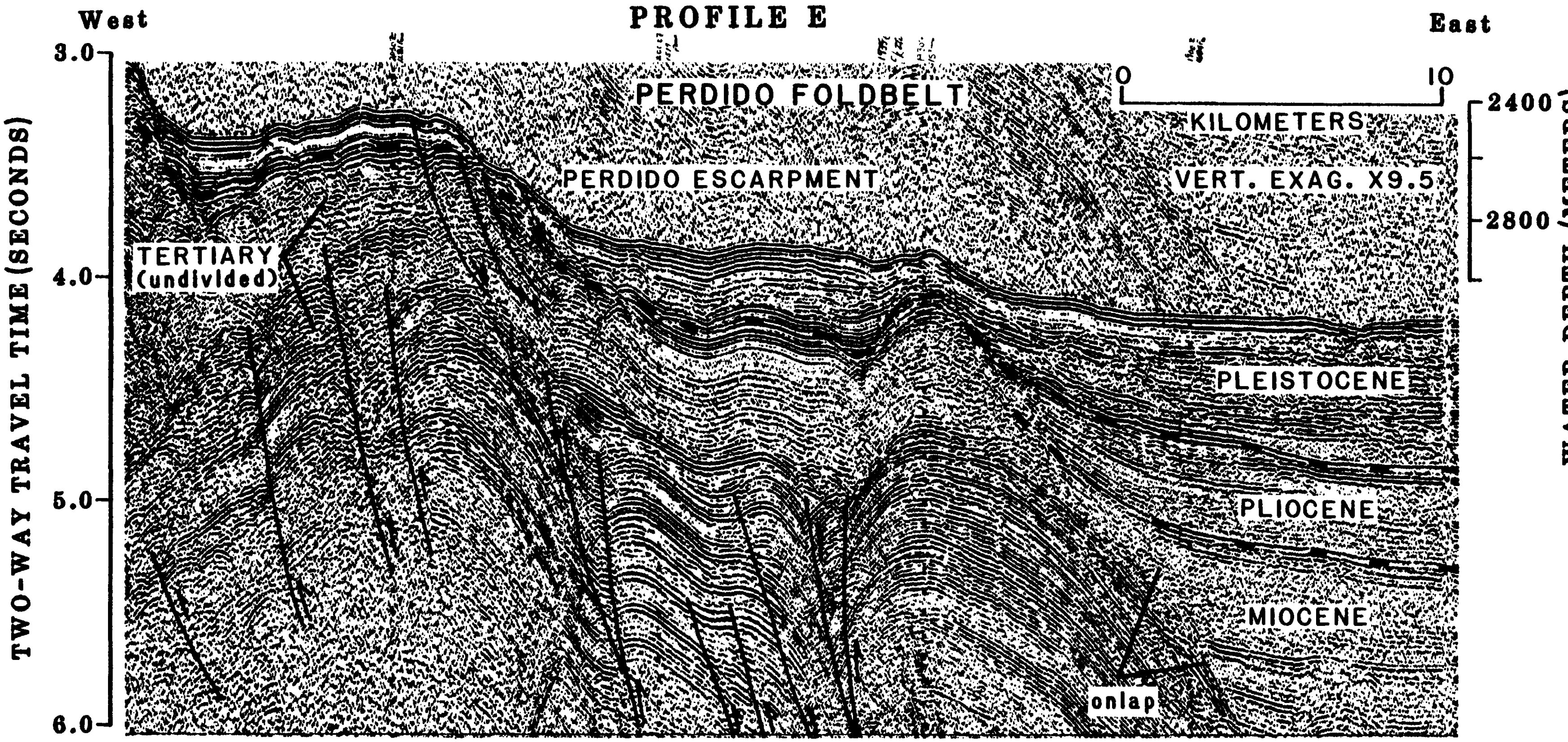


Figure 18.--Single-channel sparker profile E across part of the Perdido foldbelt in the extreme northwest sector of the abyssal Gulf basin. Well-layered section of folded strata is probably of middle Miocene age and older. Beds of upper Miocene age and younger onlap flank of fold in right part of section; Pliocene strata thin appreciably over crest of fold and may not be present in the Tertiary section to the west. Pattern of faulting is more complex than shown, and several alternative interpretations are possible. Folded Cretaceous strata and pillowed Jurassic salt lie several tenths of a second below base of profile. Location of profile E is shown in figure 12.

asymmetrical, and the steeper flanks are landward. Miocene and younger strata onlap the gently dipping seaward limbs. Landward, or northwesterly limbs, on many of the anticlines are reverse faulted so that older beds lie over younger layers. Both the asymmetry and evidence of reverse faulting suggest anticlinal formation by compressional force oriented northwest against the foot of the continental margin. The origin of such compression and its direction of orientation are not understood. Sudden (in a geological time frame) landward tilt of the basement and overlying strata in early Miocene time conceivably could have induced a thin deeply buried layer of stratiform salt to mobilize and flow into anticlinal waveforms, concurrently folding and thrusting the overlying sedimentary sequence. Some evidence of rejuvenated or recurrent movements are suggested by folding of strata as young as Pleistocene and by topographic expression on the sea floor. Recurrent movements would be expected if folding is related to salt mobility.

Individual structures can be traced for as much as 85 nmi (157 km), but most average about 30 nmi (56 km) in length. Maximum flank-to-flank widths range from 1.5 to 3.5 nmi (2.8 to 6.5 km) and generally average about 3.0 nmi (5.6 km) at maximum breadth. Measurements from seismic-reflection profiles suggest that as much as 12,005 ft (3,660 m) of Cretaceous and Tertiary strata is folded and, in turn, covered by an additional 3,936 ft (1,200 m) of Tertiary and Quaternary sediments. Sediment thicknesses between structures range generally from 16,006 to 20,992 ft (4,880 to 6,400 m). The stratigraphic sequence present in the Perdido Foldbelt ranges in age from Late Jurassic to Holocene, and the thickest sediment unit is of Tertiary age. Most of the section was deposited in a continental rise or abyssal plain environment and can be expected to consist mainly of fine-grained pelagic muds and interbedded turbidite deposits. For the most part, Miocene and older strata are seismically well layered, suggesting a sequence of alternating changes in grain size, possibly turbidite sands, silts, and fine-grained muds. Thick units of discontinuously bedded sediments bounded by relatively thin well-layered sequences generally dominate the seismic character of upper Miocene, Pliocene, and Pleistocene deposits. Except in areas near mouths of major submarine canyons, the younger Quaternary sequence is likely to consist predominantly of fine-grained pelagic muds containing uncommon stringers of turbidite sand.

### Sigsbee Knolls Area

The Sigsbee Knolls (Ewing and others, 1958; Nowlin and others, 1965; Ewing and Antoine, 1966) are surface expressions of large diapiric salt stocks that lie within a relatively narrow belt along the southern boundary of the study area in the central Gulf of Mexico (figs. 8, 15 and 19). The field of diapiric structures is about 40 nmi (74 km) wide and extends along a northeasterly trend for more than 200 nmi (370 km). Fourteen major structures are grouped in the heart of the diapir field near lat 23°30′N and long 92°30′W; five of these form broad mounds on the otherwise flat floor of the Sigsbee Plain. Isolated outlier structures include five domes to the northeast and two to the southwest of the main cluster. Three of the larger diapirs lie within the assessment area (fig. 15). A narrow zone of isolated salt diapirs and low-relief pillow structures connects the diapir field with salt structures in the Golfo de Campeche Slope to the southwest.

Structural sizes of salt diapirs in the Sigsbee Plain range from about 5 to 15 nmi (9 to 28 km) in width; maximum diameter of the average dome is about 10 nmi (19 km). All structures are deeply rooted to a mother salt layer at the general depth of about 24,928 ft (7,600 m) below sea level, or about 12,628 ft (3,850 m) below the floor of the plain.

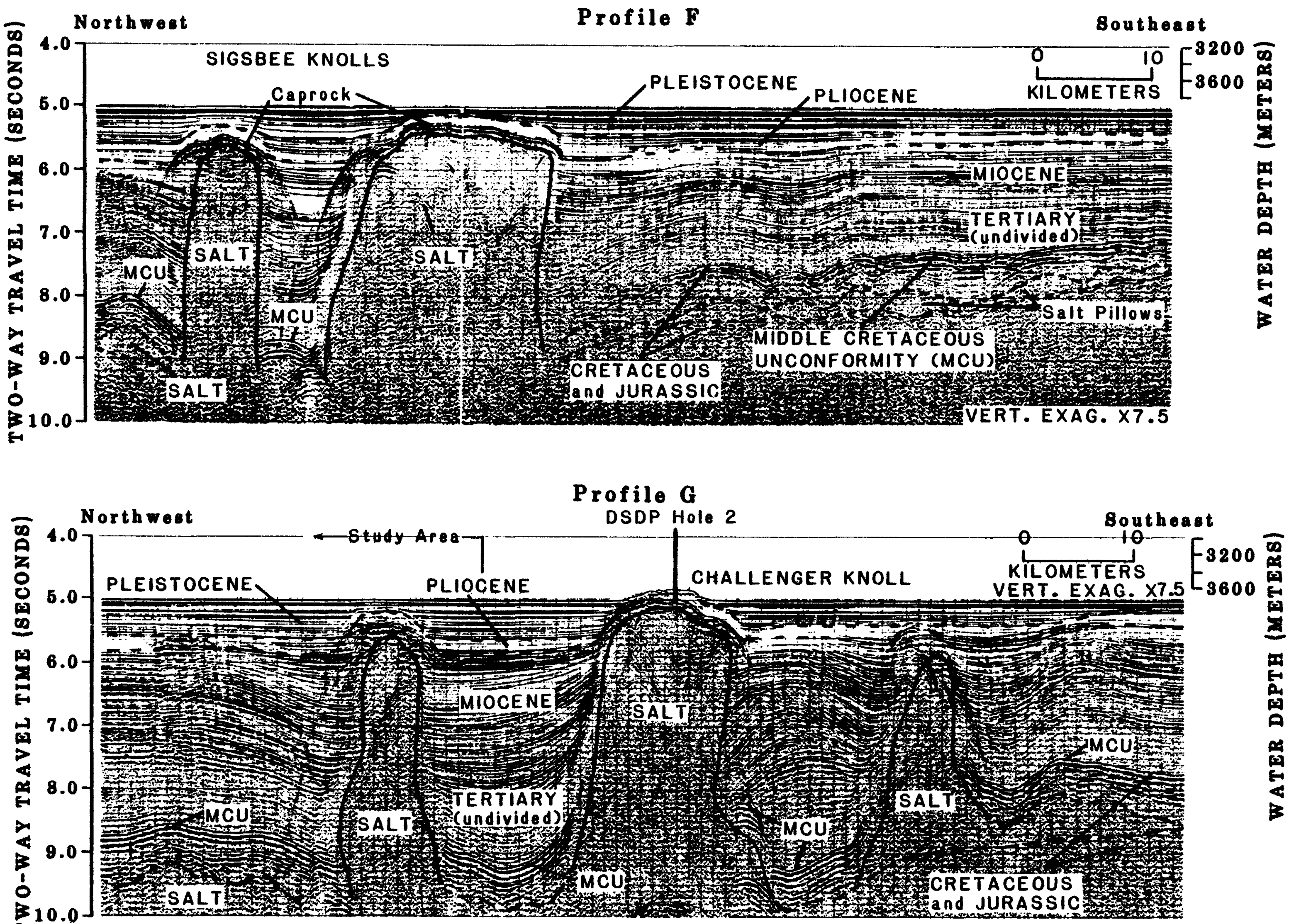


Figure 19.--Multichannel CDP profiles F and G across the Sigsbee Knolls diapir field in the south-central Gulf of Mexico showing deeply-rooted diapiric salt stocks and nondiapiric salt pillows. Note deformation styles in Cenozoic and Mesozoic strata on flanks of salt stocks and over deep-seated salt pillows. Distortions in Tertiary beds near left edge of sections are due to closely spaced faults. The locations of profiles F and G are shown in figure 12.

Mingled with major salt diapirs, and distributed generally throughout the Sigsbee Knolls diapir field, are many pillowlike structures that arch overlying strata of considerable thickness. These structures are deeply buried, and many are small in areal extent (figs. 15 and 19). Although seismic characteristics indicative of salt are indistinct in many of the seismic data across these features, they are considered to be composed of salt because their level of occurrence corresponds to an interval of seismic velocity normally attributed to salt deposits.

The stratiform salt unit that has been deformed into nondiapiric salt pillows and massive diapiric stocks in the Sigsbee Knolls region is present in a broad area of the abyssal plain generally from the northern edge of the diapir field to near the base of the Campeche Escarpment. Ladd and others (1976) named the unit "Challenger Salt" because it is the mother salt to which the Challenger Knoll salt stock is rooted (fig. 19); Challenger Knoll derives its name from the drilling vessel *Glomar Challenger* which successfully cored into caprock on the knoll at DSDP Site 2 (fig. 10). Between the outer belt of diapiric salt stocks and the base of the Campeche Escarpment, seismic-reflection data show the base of the Challenger Salt as a generally smooth, northwesterly dipping surface conformal with presalt strata (fig. 19). The seismic characteristics of the salt unit consist of incoherent reflections and diffractions. The Challenger Salt pinches out just seaward of the base of the Campeche Escarpment and thickens to as much as 8,200 ft (2,500 m) at the southern edge of the diapir field. Because of the large amounts of salt withdrawn from the Challenger unit and emplaced into diapiric stocks, accurate measurements of prediapiric salt thicknesses are not possible, but reasonable estimates may range from 10,000 to 13,000 ft (3,049 to 3,963 m). Seismic data reveal no comparable unit north and west of the Sigsbee Knolls, thus suggesting that the seaward edge of the Challenger salt basin is subcoincident with the northern and western periphery of the diapir province. The surface of the Challenger Salt layer generally has been deformed into broad waveforms of relatively low relief indicating flowage in response to sediment load and general seaward tilt of the section during basin subsidence. Deformation in overlying strata as a result of salt flowage ranges from minor warping, arching, and faulting to significant vertical uplift and downwarping in response to major thickening and thinning of the salt layer. In areas of thickest salt accumulation, likely in complex fault-bounded basins, the effect of sediments sinking deep into the salt induced the salt to rise intrusively through the overlying strata.

Post-Challenger Salt strata within the Sigsbee Knolls region and within the assessment area range in age from late Jurassic to Holocene and consist predominantly of Jurassic and Cretaceous carbonate rocks unconformably overlain by generally well bedded deep-basin pelagic muds and turbidite sands of mainly Tertiary age (fig. 19). Near-horizontal stratified deposits of Pliocene and Pleistocene age cap the section lying locally in unconformal contact with upper Miocene beds and onlapping shallow crests of diapiric structures. Strata of Miocene age and older are severely upwarped in a halo around individual piercement structures generally for a distance of about 2 nmi (3.7 km) away from the structure. Uplift of sedimentary layers on domal flanks amounts to as much as 6,000 ft (1,829 m) of displacement. Because vertical growth of the salt structures has been contemporaneous with sediment accumulation since probably early in Tertiary time, much of the Tertiary section on domal flanks is composed of structurally elevated onlaps and pinchouts that are highly conducive for hydrocarbon entrapment. Thicknesses of post-salt strata in the province range from only a few hundred feet on domal crests to 18,000 ft (5,488 m) or more in interdomal depressions. Interdomal strata range from relatively undeformed to broadly arched, folded, and faulted units; the deformation has resulted from lateral compression exerted by growth in adjacent diapirs and from uplift over nondiapiric salt pillows. Some of the more pronounced pillowing has uplifted as much as 6,000 ft (1,829 m) of overlying strata.

Campeche Escarpment Area

The assessment area off the northernmost face of the Campeche Escarpment (fig. 11, 8) is floored by strata of high seismic velocity that appear equivalent in age and lithology to Mesozoic rocks that compose the Yucatan carbonate platform (fig. 20). Seismic velocities and general character suggest that the section is composed of limestones and may include reef deposits and forereef talus deposits. The section appears to be block faulted into horst and graben structures that were subject to truncation by erosion and to depositional infilling. The section may represent an early stage of shallow-bank carbonate accumulation that ended during climax of basinal rifting in Late Jurassic-Early Cretaceous time. If so, the section is likely to consist principally of Jurassic strata which, to the south, form the foundation for Lower Cretaceous shallow-water carbonate accumulations in the Yucatan platform. The older section is covered by Lower Cretaceous forereef talus deposits and carbonate detritus shed from the adjacent bank and mixed with deep-water carbonate and pelagic muds. The surface of the section is outlined by the prominent mid-Cretaceous seismic horizon, which locally truncates underlying strata and elsewhere lies conformably above them. Pre-middle Cretaceous strata in this region may be as much as 10,000 ft (3,049 m) thick and are covered by Tertiary and Quaternary basin-fill ranging from 6,000

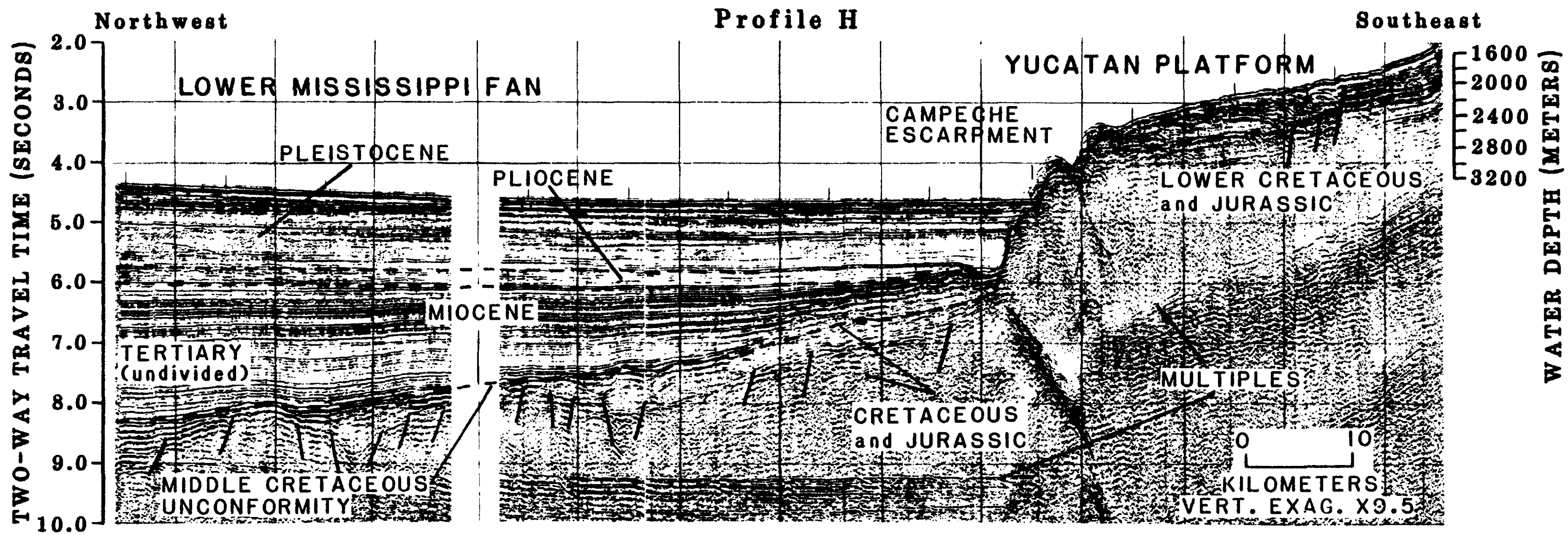


Figure 20.--Multichannel CDP profile H across the Yucatan Platform and Mississippi Fan provinces in the Campeche Escarpment assessment area showing faulted carbonate rocks of Mesozoic age beneath onlapping Tertiary pelagic and turbidite deposits and Quaternary submarine fan-strata. Reef-complex deposits may be present in Lower Cretaceous strata along the buried face of the Campeche Escarpment. Southeasterly sloping reflections below escarpment are from arrivals of wide-angle reflections off face of escarpment to the west of the ship's track. The location of profile H is shown on figure 12.

to 18,000 ft (1,829 to 5,488 m) in thickness (fig. 14). The proto-Yucatan platform sequence extends approximately 30 nmi (56 km) northwest of the Campeche Escarpment over an area about 40 nmi (74 km) wide, and appears to be onlapped by well-stratified Mesozoic beds which conformably overlie the mid-Cretaceous horizon.

Tertiary strata of Miocene age and older onlap the mid-Cretaceous surface from near the outer edges of the buried platform sequence to the buried face of the Campeche Escarpment (fig. 20). The mid-Cretaceous to Miocene sequence ranges in thickness from about 2,000 ft (610 m) at the abrupt contact with the Campeche Escarpment to more than 8,000 ft (2,439 m) at the outer edge of buried platform strata. The Tertiary sequence is generally well bedded, especially in deposits thought to be of middle and late Miocene age. Near the Campeche Escarpment smooth parallel to subparallel stratification in the sequence is disrupted by local thickening and thinning over what appear to be deposits of forebank debris. The section is locally offset by faults having only a few feet of throw. Broad warpings are associated with differential compaction over paleorelief deposits.

Pliocene and Pleistocene strata conformably overlie the Miocene and older sequence and sharply abut the face of the Campeche Escarpment. Late Tertiary and Quaternary deposits range in thickness from 600 to 4,000 ft (183 to 1,220 m) at the escarpment to more than 5,900 ft (1,799 m) above the perimeter of the buried Mesozoic bank. The young sequence is characterized by a thick section of generally discontinuous reflection events and transparent zones. Infrequent continuous reflections divide the section, which is capped by a veneer of well-bedded late Pleistocene strata. The overall character suggests a predominance of fine-grained muds and clays that are not likely to contain appreciable quantities of sand. The more pronounced, continuous reflections that characterize the upper 1,000 to 1,500 ft (305 to 457 m) of section suggest the presence of interbedded sands and muds. Most strata in the sequence are acoustically typical of deposits in the lower Mississippi Fan, where appreciable quantities of sands were supplied by turbidity flows of catastrophic magnitude.

## Rio Grande Margin Area

The continental shelf and upper continental slope regions off south Texas and northeast Mexico are called the Rio Grande Margin assessment area (fig. 8) and are composed of thick sections of Mesozoic and Cenozoic strata that are pierced by isolated stocks of diapiric salt and uplifted over broad anticlinal features composed of underconsolidated Tertiary shale (fig. 21). Normal faults, mainly down-to-the-basin faults, offset late Tertiary and Quaternary strata in the shelf and uppermost slope. The stratigraphic sequence consists primarily of shales with interbedded sands that were deposited in outer shelf and continental slope environments. A minor amount of algal and detrital carbonate matter is present in the younger part of the section (Berryhill and Trippet, 1980a). Drilling on the inner shelf region adjacent to the study area (fig. 10) has penetrated strata as old as Oligocene, and drilling on the outer shelf has penetrated strata as old as Miocene. Virtually no data are available relative to lithology and depositional environments for the sequence older than late Oligocene. The older Tertiary sequence consists predominantly of shale deposited in a slope or deep-water environment. Mesozoic rocks that floor the section are likely to consist of deep-water carbonate and clastic muds which grade downward into older shallow-water limestones and continental deposits. Mesozoic and Cenozoic strata in the shelf and upper slope are estimated to be as much as 26,240 ft (8,000 m) thick (fig. 14, table 2).


Figure 21.--Single-channel sparker profile I across continental shelf and slope in Rio Grande Margin assessment area showing variation of structural deformation in Tertiary and Quaternary strata from movement of underconsolidated shale and diapiric intrusion by narrow salt plugs and broad salt massifs. The location of profile I is shown in figure 12.

The lower continental slope in water depths of about 3,280 to 9,184 ft (1,000 to 2,800 m) is underlain by very broad salt massifs that crest as high as within a few hundred feet (61 m) of the sea floor (figs. 15, 21). Although generally irregular in outline, the structures are formed along northeasterly trends roughly parallel to the strike of the slope. The broad structures are separated by large basins and troughs filled by thick accumulations of sediment. The salt massifs have fairly broad crests and steep flanks, which appear to plunge abruptly for many thousands of feet. Basinal sediment accumulations within the study area may be as much as 18,000 ft (5,488 m), and strata on the crest of the largest salt massif in the middle slope are as thin as 590 ft (180 m). Sediment thickness above salt in the slope (fig. 14, table 2) averages about 11,152 ft (3,400 m). Stratigraphic tests (40-40D′) drilled by Shell Development Company (Lehner, 1969) on the largest massif (figs. 14, 21) define a very thin section of Cenozoic clastic sediments underlain by thin horizons of Cretaceous carbonate mud and red siltstone of unknown age, which, in turn, are underlain by rock salt.

The stratigraphic sequence in structural basins and on the flanks of the massifs is mostly of Cenozoic age. Quaternary strata appear to consist of well-layered sediment in structural basins and homogeneous fine-grained deposits that drape the upper flanks and crests of structures (fig. 21). The Tertiary sequence has been considerably deformed by folding and faulting related to movement of salt. Tertiary strata are composed mainly of deep-water shales, and local accumulations of turbidite sands distributed in lenses that represent deposition in structural lows.

The province of structurally shallow salt massifs merges with deep-seated salt anticlines in the continental rise along the Perdido Escarpment. The escarpment is a feature of relatively steep relief which separates steplike basin and ridge topography on the Rio Grande Slope from relatively smooth gently sloping sea floor on the continental rise. The scarp is essentially the topographic expression of the seaward front of the salt massif province.

## Sigsbee Escarpment Area

The Sigsbee Escarpment assessment area lies on the lower Texas-Louisiana Slope in the north-central Gulf of Mexico (fig. 8). The escarpment is a distinct, but relatively minor, steepening of the sea floor that separates the lower continental slope of the northern Gulf of Mexico from the continental rise (fig. 2). The scarp extends discontinuously from the Alaminos Canyon in the west to the Mississippi Fan in the east. The escarpment is the expression of structurally shallow lobate salt masses that are covered by a thin veneer of late Pleistocene sediments and underlain by strata as young as early Pleistocene (figs. 15, 22, 23). Anomalous salt masses of this nature were initially recognized by deJong (1968) and Amery (1969) near DSDP drill site 92 just north of the assessment boundary (figs. 10 and 22), and have been described in more recent reports by Watkins and others (1978), Humphris (1978), Buffler and others (1978), and Martin (1980a). Study of all available seismic-reflection profiles in the Sigsbee Escarpment region shows that structurally shallow masses of salt underlie the escarpment and lower continental slope in a zone that generally ranges from 20 to 35 nmi (37 to 65 km) in width (fig. 15). The salt masses generally thicken northward into the interior of the lower slope and appear to be detached from deeply rooted salt stocks and ridgelike massifs that underlie most of the Texas-Louisiana Slope. The salt masses are generally shaped like inverted wedges pointed basinward, and have thicknesses ranging from 3,280 to 6,560 ft (1,000 to 2,000 m) upslope to only a few hundreds of feet thick along blunt, nearly exposed basinward edges. Bases of individual salt lobes appear to be in angular contact with Tertiary and Quaternary strata that dip basinward into the continental rise (figs. 22, 23). Lack of evidence of any appreciable deformation of Tertiary and Quaternary beds along this basal contact and along the basinward edges of lobes suggests that the salt masses were emplaced by flowage contemporary with deposition rather than by lateral intrusion into the shallow substrate. Such flowage probably took place in response to overburden pressure exerted on salt by rapid accumulation of large sediment volumes in the upslope regions of the margin during late Tertiary time (Humphris, 1978; Martin, 1980a). Detachment from the mother-salt and separation of the broad extrusive sheet into individual lobes likely took place in response to local sediment loads accumulated on the shallow salt surface during Pleistocene time.

Seismic-reflection data, for the most part, show no evidence of structural uplift or of the presence of salt structures in the sequence below shallow salt lobes[2] and thus, suggest that the salt has been extruded well beyond the basinward limits of Jurassic salt deposition (Martin, 1980a). Near the Alaminos Canyon and beneath the upper reaches of Keathley Canyon, broad subsalt anticlines are suggested in seismic-reflection data; these structures are probably part of the Perdido foldbelt more clearly expressed in the continental rise to the southwest (fig. 15). The Sigsbee Escarpment

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[2]Time-depth sections across the Sigsbee Escarpment are particularly misleading in that seismic sound is transmitted through shallow masses of salt at velocities much greater than those at which it is transmitted through underlying strata. The result is a disproportionate upward displacement (velocity pull-up) of reflection horizons below the salt relative to equivalent horizons in the section beyond the salt mass. When appropriate velocity functions are applied to the section, subsalt horizons are migrated into correct positions and are shown to pass smoothly beneath the extrusive salt in conformity with their counterparts in the continental rise sequence.

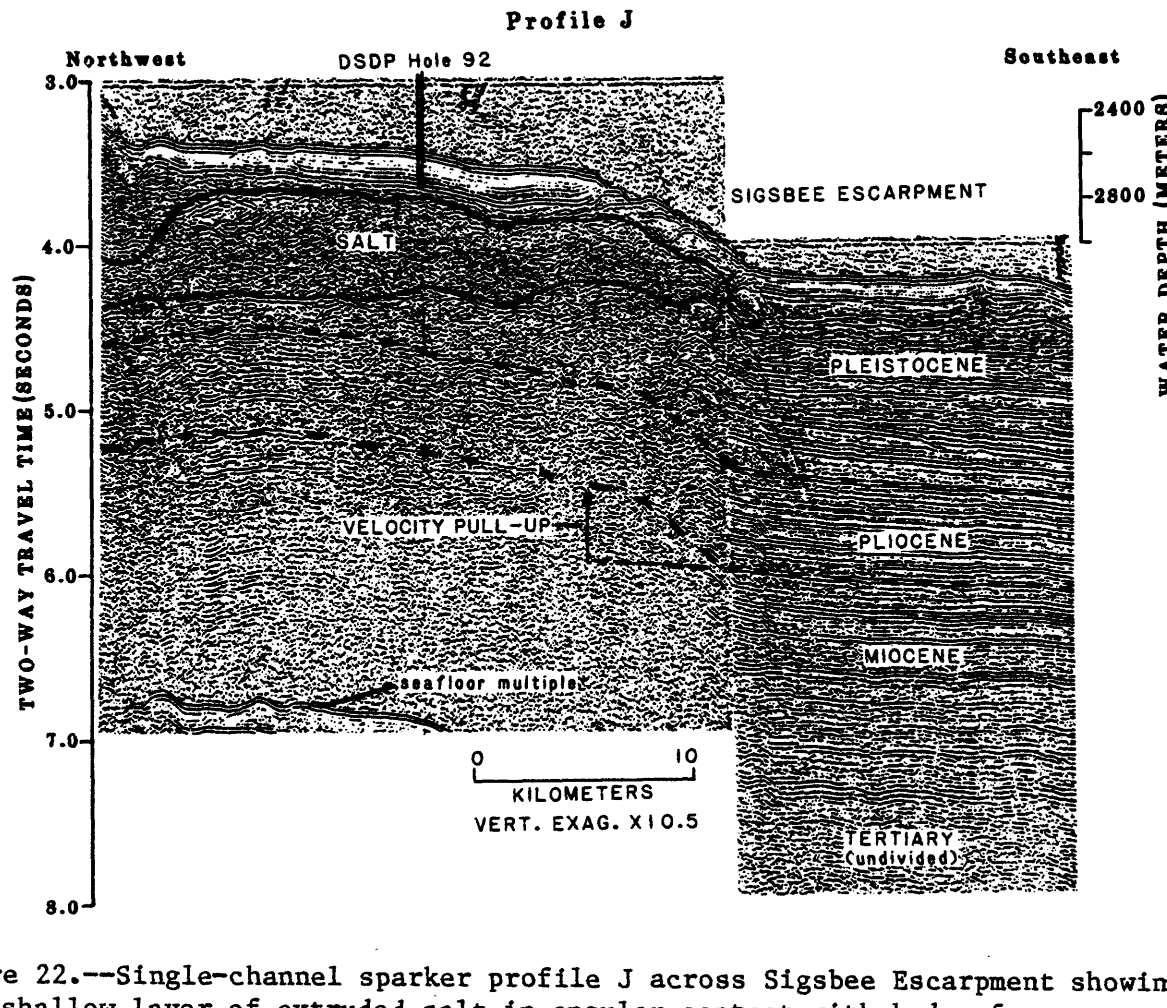


Figure 22.--Single-channel sparker profile J across Sigsbee Escarpment showing shallow layer of extruded salt in angular contact with beds of Pleistocene age. Reflections from strata below salt are recorded at time-depths earlier than reflections from counterparts in the sections south of the escarpment owing to the high-speed passage of seismic sound signals through the overlying salt layer. The location of profile J is shown in figure 12.

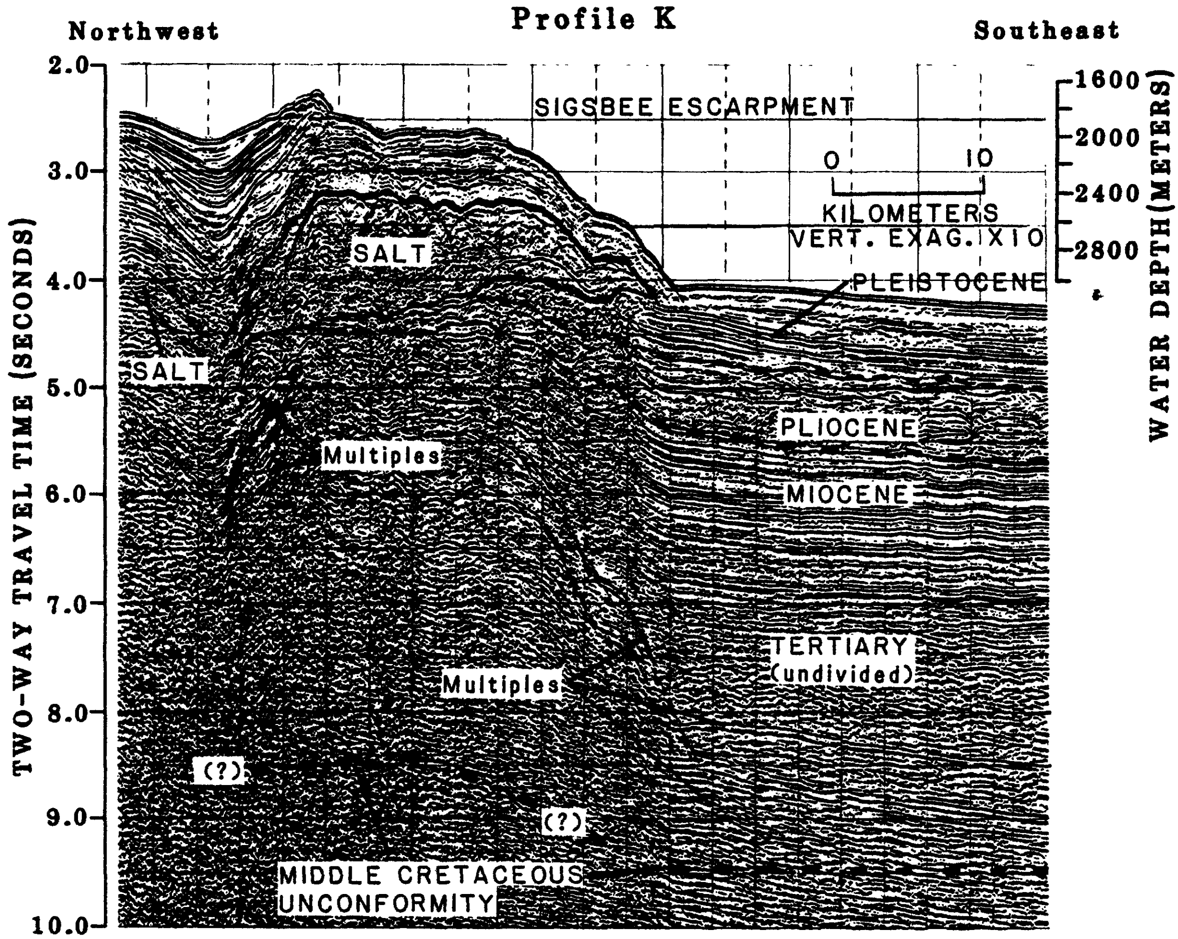


Figure 23.--Multichannel CDP profile K across Sigsbee Escarpment showing wedge-shaped mass of salt extruded seaward over beds of Miocene age and younger. Salt mass has become detached from main salt body upslope due to flowage away from load exerted by sediments accumulated in basin near left side of section. The location of profile K is shown in figure 12.

assessment area (fig. 8) is underlain by structurally shallow masses of extrusive salt that overlie undeformed strata equivalent to continental rise and deep basin sediments to the south (fig. 22).

Within the assessment area, sediments above shallow salt lobes range from a few tens of feet to as much as 6,560 ft (2,000 m) in thickness in broad basins depressed into the salt surface; average above-salt sediment thickness (fig. 14) is about 1,551 ft (473 m). DSDP drill hole 92 penetrated to within 120 ft (37 m) of the salt surface, bottoming in sediments of early Pleistocene age (fig. 22). Below the salt, measurements to the middle Cretaceous horizon indicate a average thickness of late Mesozoic and Cenozoic subsalt strata of 18,000 ft (5,488 m). Rapid deterioration of seismic resolution below this horizon prohibits estimation of the thickness of Lower Cretaceous and older strata. Thicknesses of the shallow salt bodies whose bases lie in apparent angular contact with early Pleistocene and Tertiary strata average 5,852 ft (1,784 m).

# PETROLEUM GEOLOGY OF THE GULF OF MEXICO MARITIME BOUNDARY ASSESSMENT AREAS

By

Richard Q. Foote, and Ray G. Martin

The study of the petroleum potential of the six assessment areas (fig. 8) focused on factors critical to the generation, migration, and entrapment of hydrocarbons, such as: structural and stratigraphic traps, source beds and maturation, reservoir rocks and seals, and timing of hydrocarbon migration relative to formation of traps.[1]

The six assessment areas were analyzed by use of all publicly available geophysical data recorded in the region (fig. 9, 11; table 1). Geophysical data include approximately 8,350 nmi (15,448 km) of seismic-reflection profiles ranging from shallow-penetration recordings to deep-penetration multichannel profiles. A limited amount of geological data obtained from drill holes within and adjacent to the area of study supplemented the geophysical data (fig. 10). Geological information relative to lithology and stratigraphic age of the upper few thousands of feet of strata in the study area were derived 1) from two Deep Sea Drilling Project (DSDP) sites in the study area (fig. 10), 2) from 10 shallow industry drill holes within the area of investigation, 3) from projections from as many as 10 deep stratigraphic tests drilled adjacent to the study area, and 4) from many bottom core samples collected by academic institutions at widespread locations in deep-water areas of the Gulf of Mexico. The important geological aspects of the six Gulf of

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[1]Each of these factors is discussed in detail in Appendix II, Petroleum Geology of the Gulf of Mexico.

Mexico assessment areas and factors favorable, or detrimental, to potential in-place accumulation of petroleum resources are discussed below.

## Rio Grande Margin Area

A thick section of Cenozoic clastic sediment overlies Mesozoic rocks, which are chiefly carbonate and evaporite deposits, throughout the Rio Grande Margin Area (fig. 8). The Mesozoic and Cenozoic section of the Rio Grande Shelf and upper continental slope region is estimated to be as much as 26,240 ft (8,000 m) thick (fig. 14, table 2).

The Rio Grande Margin contains a number of possible structural and stratigraphic traps in Cenozoic strata, including anticlines and faulted anticlines formed by deep-seated shale ridges, salt domes, and salt massifs (figs. 15, 21); closures against growth faults and normal faults; and a variety of stratigraphic traps. Stratigraphic traps probabaly occur in sands onlapping salt domes or anticlines, in facies changes from sands to impermeable shales in updip directions, and at angular unconformities.

In the continental shelf, Tertiary and Quaternary strata are arched over broad anticlines formed by deep unconsolidated shale masses. Both normal and growth faults are associated with the formation of these anticlines. The edge of the shelf is underlain by either a deep-seated salt stock or a shale mass--no salt domes or massifs are thought to be present under the shelf offshore southern Texas. There is also a possibility of traps being formed on the middle and outer shelf and upper slope by normally pressured Tertiary sands being sealed by abnormally pressured shales.

In the upper slope, the Cenozoic section is pierced and uplifted by small isolated salt diapirs. The middle and lower areas of the Rio Grande Slope are underlain by extremely large masses of salt. These salt massifs have fairly broad crests and are covered by strata as thin as 590 ft (180 m). The broad salt structures have steep flanks which plunge abruptly for many thousands of feet and are separated by narrow basins and troughs filled by as much as 18,000 ft (5,488 m) of clastic sediment. The sediments above the salt basement have an overall average thickness of about 11,152 ft (3,400 m) and are mainly Tertiary and Quaternary in age. Traps may be present over the deep-seated salt domes under the upper slope, but not over the very shallow penetrating salt massifs on the lower slope. Within the small mini-basins, or "potholes," the anticipated traps are in closures against faults both over and on the flanks of the salt, in sands truncated by salt, and at unconformities and in onlapping sands.

Generally, traps in Rio Grande Margin are expected to be in rocks of possibly Oligocene, Miocene, Pliocene, and Pleistocene strata. Exploratory drilling on the U.S. continental shelf immediately adjacent to the assessment area (fig. 10) shows the Miocene sequence to consist of mainly deep-water shales having only a few thin sands of limited horizontal extent and of poor reservoir qualities (Khan and others, 1975a and 1975b). Turbidite sands of Miocene, Pliocene, and Pleistocene age may be present in the upper and lower slopes in sand-filled canyon and deep-sea fan deposits. Oligocene sands may be present in the continental shelf but they would most likely be quite deep and possibly of poor reservoir quality. Sands of reservoir quality may be present in the narrow basins and troughs between the diapiric salt structures on the slope, but the lateral extent of any such sands would be quite limited. The lack of thick, widespread, high-quality reservoir rocks detracts from the potential of this area.

## Sigsbee Escarpment Area

The Sigsbee Escarpment assessment area is in the north-central sector of the Maritime Boundary region (fig. 8). The escarpment is the expression of extruded masses of Jurassic salt in the shallow subbottom (figs. 15, 22, 23). The salt lobes are covered by a veneer of mainly late Pleistocene pelagic muds and are underlain by continental rise and abyssal basin pelagic and turbidite deposits as young as early Pleistocene. The average thickness of sediments above the extruded salt in the assessment area is less than 1,551 ft (473 m) and, thus, is viewed as being nonprospective for oil and gas. The bases of extruded salt masses appear to lie in angular contact with Tertiary and Quaternary strata that dip basinward into the abyssal Gulf. Undeformed strata as old as Early Cretaceous can be mapped into the continental slope beneath the shallow salt bodies. Sediment thickness of post-middle Cretaceous strata below extruded salt is estimated to be as much as 18,000 ft (5,488 m). The Sigsbee Escarpment area has no apparent structural uplift or diapiric salt mass below the extruded salt layer that might provide oil and gas traps. The angular contact between the Tertiary and Quaternary strata and the overlying salt, however, may be locally favorable for providing trapping conditions. Stratigraphic traps also could be present in Cenozoic turbidite sands deposited in submarine canyon and deep-sea fan strata below the extruded salt layer. Structural traps may be present in this sequence against faults having minor displacements and in small folds of low relief.

## Perdido Foldbelt Area

The Perdido Foldbelt area (fig. 8) contains a series of large, mostly buried anticlines composed of well-layered clastic strata that are folded over a core of mobile salt (fig. 18). Parts of eight separate structures lie within the boundaries of the assessment area (fig. 15); maximum widths of the folds range from 1.5 nmi (2.8 km) to 3.5 nmi (6.5 km), and the average length is about 30 nmi (56 km). As much as 12,005 ft (3,660 m) of Cretaceous and Tertiary strata is folded and, in turn, covered by an additional 3,936 ft (1,200 m) of Tertiary and Quaternary sediments. Sediment thicknesses between structures range from about 16,000 ft (4,880 m) to about 20,992 ft (6,400 m).

Folding is estimated to have taken place in Miocene time. The limbs of the folds are asymmetrical and steeper flanks are on the landward side. The landward limbs of many of the structures are reverse faulted so that older strata overlie younger strata. Miocene and younger beds onlap the gently dipping seaward flanks.

We do not know whether the reverse faults contribute to or detract from the favorability of the structures. These faults and the associated fracturing of rocks could provide pathways for the migration of oil and gas from source beds.

Anticlines in the Perdido Foldbelt have large amplitudes; the crest to trough relief on deeper horizons is more than 4,000 ft (1,220 m). Although seismic data to map these structures in detail are insufficient, an area of at least 242 $mi^2$ (627 $km^2$) appears to be very favorable for oil and gas accumulation. All these structures have excellent trapping potential and the potential for containing multiple oil and gas zones in the deep clastic and carbonate strata of Mesozoic age and in the more shallow clastic rocks of Cenozoic age. Structural traps are formed by anticlinal closure and by faults. Stratigraphic traps are prevalent in the thick sequence of onlaps in late Tertiary beds on seaward flanks of the broad folds, and in complexly bedded canyon-mouth fan deposits in young Quaternary strata that cover the area.

Reservoir rocks are likely to be present in the section, especially in beds of middle and late Miocene age, because of the near proximity to sand sources on Miocene and younger continental shelves and to submarine canyon systems capable of transporting large quantities of sand down the adjacent continental slope.

## Sigsbee Knolls Area

The Sigsbee Knolls are surface expressions of only a few of the many large diapiric salt stocks that lie within a relatively narrow belt along and landward of the southern perimeter of the assessment area in the central Gulf of Mexico (fig. 8). Three of these structures lie within the assessed area (fig. 15). Strata surrounding the diapirs range in age from late Jurassic to Holocene. Mesozoic rocks are chiefly shallow-marine carbonates and carbonate detritus and are overlain unconformably by deep-water pelagic muds and sandy turbidite beds of Tertiary and Quaternary age. Strata range in thickness from only a few hundred feet on domal crests to as much as 18,040 ft (5,500 m) in synclinal depressions formed at the bases of the structures (fig. 19).

Salt diapirs within the assessment area generally are circular and have an average diameter of about 10 nmi (19 km). Strata of Miocene age and older are severely upwarped in a halo around the diapirs for a distance of about 2 nmi (3.7 km) away from the structures; the average area of the halo on each diapir is more than 79 $mi^2$ (205 $km^2$). Structural uplift of the sedimentary layers on the flanks of the domes is as much as 6,000 ft (1,829 m).

Therefore, each halo contains an average of 19 $mi^3$ (79 $km^3$) of severely uplifted strata in each halo, totaling 57 $mi^3$ (238 $km^3$) for the three knolls. This volume of strata is considered to be very favorable for hydrocarbon entrapment on the flanks of the diapir in structurally elevated onlapping sands and in sand pinch-outs toward the uplift. Closures against faults on the flanks of the diapirs would also be quite likely as structural traps. Beyond 2 nmi (3.7 km) distance from the edge of each diapir, there would be another halo containing about 60 $mi^3$ (250 $km^3$) of sediments which would also be favorable for stratigraphic traps but less attractive than sediments closer to the diapiric structures.

These salt diapirs, like the numerous productive salt domes of the Texas-Louisiana Gulf Coast, are highly conducive to hydrocarbon entrapment. The many different types of structural and stratigraphic traps associated with salt diapirs have the potential for containing multiple oil and gas reservoirs. Known tectonic activity in this area probably has caused faults and fractures to form; such faults could serve as passageways for migrating oil and gas. Oil was found in a rock sample of Jurassic age cored from the top of nearby Challenger Knoll, about 10 nmi (19 km) south of the study area perimeter.

Favorable structural traps might be present in arched strata and in closures against faults above salt pillows, and in possible stratigraphic traps on structural flanks of deeply buried salt masses.

## Campeche Escarpment Area

In the east-central Gulf of Mexico, off the northernmost point of the Campeche Escarpment (fig. 8), a small area of deep sea floor is underlain by a broad, gently tilted plateau composed of Jurassic and Cretaceous strata that are overlain unconformably by onlapping beds of Tertiary and Quaternary age (fig. 20). The older sequence of rocks is correlative with Mesozoic units that compose the foundation of the Yucatan carbonate platform to the south, and is composed largely of carbonate rocks that may include reef buildups and forereef talus deposits. This section appears to be block-faulted into horst and graben structures that were subject to infilling and erosional truncation. Mesozoic strata in this area may be as much as 10,000 ft (3,049 m) thick and are covered by onlapping Tertiary and Quaternary clastic basin-fill sediments ranging from 6,000 ft (1,829 m) to 18,000 ft (5,488 m) in thickness.

The entire Campeche Escarpment area has the potential of containing significant stratigraphic traps in both the Mesozoic and Cenozoic strata, such as reefs, forereef talus, pinch-out of sands, and onlap against older strata. Likely structural traps are low-relief anticlines and in strata draped over paleo-sea-floor highs, over the horst blocks, and in closures against faults.

## Abyssal Gulf Basin Area

The Abyssal Gulf Basin area (fig. 8) is underlain by an extremely thick section of sedimentary rocks that range in age from Jurassic, or older, to Holocene (figs., 13, 16, 17); the overall thickness of the sedimentary section ranges from about 13,000 ft (4,000 m) in the southeast between the Florida and Campeche Escarpments, to more than 30,000 ft (9,150 m) at the edge of the Sigsbee Escarpment. The Mesozoic section is generally too deeply buried to be considered prospective for oil and gas. Overlying Tertiary strata of Miocene age and older generally consist of pelagic muds and sandy turbidites. This sequence thins eastward across the abyssal basin. Deposits of Miocene age are especially well stratified throughout the basin and are presumed to consist of alternating layers of sandstone and shale; these sandstones could act as potential reservoir rocks. Many broad low-relief anticlines and faults of small displacement throughout the sequence could provide potential traps for hydrocarbons. In the Abyssal Gulf Basin area in general, faulting or fracturing may not have been sufficient to allow oil and gas to migrate upward from deep potential source beds into shallow traps.

Complexly bedded strata of Pliocene to Holocene age overlie the Miocene and older Tertiary section in the Mississippi Fan and continental rise areas of the abyssal basin. The Quaternary and uppermost Tertiary section is composed of 1) coalesced sedimentary aprons that were built seaward from the mouths of submarine canyons in the continental rise along the Sigsbee Escarpment; 2) complex channel-fill, slump, and apron deposits that form the Mississippi Fan in the eastern Gulf; and 3) nearly horizontally bedded turbidite deposits that cover the Sigsbee Plain in the central Gulf basin. Stratigraphic traps are most likely to be present in Mississippi Fan deposits and in continental rise strata. Cenozoic strata in Mississippi Fan and continental rise deposits of this assessment area may be especially likely to contain biogenic methane gas.

## Summary

From the foregoing discussions and those in Appendix II, Petroleum Geology of the Gulf of Mexico, several conclusions can be reached.

1. Structural and stratigraphic traps are present throughout the Maritime Boundary region. The largest and most attractive structural traps which might contain significant quantities of oil and gas are in the Perdido Foldbelt and Sigsbee Knolls areas.

Structural traps of lesser size, but still having resource potential, are present in the Abyssal Gulf Basin, Campeche Escarpment, and Rio Grande Margin areas. The Sigsbee Escarpment appears least promising of the six areas for structural traps. Stratigraphic traps having high resource potential are present on the flanks of anticlines in the Perdido Foldbelt and salt diapirs in the Sigsbee Knolls areas, and in onlaps against the middle Cretaceous unconformity in the Campeche Escarpment area.

These structural and stratigraphic traps appear to have formed early enough in geologic time to entrap migrating oil and gas. The trapping mechanisms began to be formed in the Miocene or earlier. Timing, as a factor in oil and gas accumulation, is favorable.

2. Source beds to generate natural hydrocarbons are present in part of the deep Gulf basin and are probably present under all the Maritime Boundary region. Further, the thermal history has been adequate to generate oil and gas. Crude oil was found in a core of Jurassic rock from DSDP Site 2 (fig. 10) atop Challenger Knoll. Tar from crude oil seeps was found in two bottom cores in the deep Gulf (fig. 10). Traces of thermogenic ethane were found in three DSDP sites. Further, published geochemical analyses of samples from industry holes show that the organic content of sediments increases from shallow- to deep-water depositional environments in the Gulf of Mexico. Biogenic methane also could be prevalent in the deep Gulf, particularly in the Mississippi Fan region.

3. Reservoir rocks are thought to be present in all six assessment areas, but their porosity and permeability may not be favorable. Jurassic, Cretaceous, and lower Tertiary (Paleocene) reservoir rocks in the Gulf of Mexico offshore Mexico sustain high production rates. Rocks of equivalent age having good reservoir properties could be present in the Sigsbee Knolls, Campeche Escarpment, and Perdido Foldbelt areas. Favorable reservoir rocks are probably present in turbidite sands deposited in Tertiary strata across the deep Gulf. In middle and late Miocene, these coarse, turbidite sands and gravel were transported from westerly sources into the Perdido Foldbelt area. The finer sands were distributed farther over the basin into the Sigsbee Escarpment and Sigsbee Knolls areas. Simultaneously, some turbidite sands may also have been deposited in the eastern Gulf region and in the Campeche Escarpment area from an ancestral Mississippi River source. During Pliocene and Pleistocene times, turbidite sands were supplied from northerly sources. Thick and laterally extensive sands should be present as potential reservoir rocks in Pliocene and Pleistocene strata in the Mississippi Fan region and extending southwestward into the Campeche Escarpment, Sigsbee Knolls, and Sigsbee Escarpment areas.

4. Seals over the reservoir rocks that prevent the upward escape of oil and gas should be prevalent throughout the Maritime Boundary region and in both Mesozoic and Cenozoic strata. Seismic data on all six assessment areas suggest that Tertiary strata contain alternating sandstone and shale sequences. Upon compaction and dewatering, some of these shales should have become effective seals.

5. On the basis of critical factors relative to the generation and accumulation of oil and gas enumerated above, the individual assessment areas in the Gulf of Mexico Maritime Boundary region are listed below in order of decreasing petroleum potential:

Perdido Foldbelt Area

Sigsbee Knolls Area

Abyssal Gulf Basin Area

Campeche Escarpment Area

Rio Grande Margin Area

Sigsbee Escarpment Area

# ESTIMATES OF UNDISCOVERED IN-PLACE PETROLEUM RESOURCES IN THE GULF OF MEXICO MARITIME BOUNDARY REGION

By

Richard B. Powers and Robert S. Pike

## Introduction

Undiscovered in-place resources are those resources, yet to be found, which are estimated to exist as a consequence of favorable geologic conditions. Total estimated in-place resources in the Gulf of Mexico study area range from 2.24 to 21.99 billion barrels of oil (BBO) and from 5.48 to 44.40 trillion cubic feet (TCF) of gas. The mean estimate for oil is 9.11 BBO and the mean for gas is 18.77 TCF (table 3). The designated study area covers 58,940 mi$^2$ (152,660 km$^2$) and has a sediment volume of 188,140 mi$^3$ (784,170 km$^3$); water depths range from 98 ft (30 m) to 12,270 ft (3,740 m).

## Resources Assessed

All amounts of oil and natural gas estimated in the Gulf of Mexico Maritime Boundary Region are of *undiscovered* petroleum resources in-place (not an estimate of recoverable quantities). Oil or gas *in-place* refers to all petroleum in-place in reservoirs, without qualification as to what part may be considered either currently or potentially producible, and without regard to any economic or technological constraints. The estimated amounts of undiscovered oil and gas in-place fall in the right-hand hachured column of the resource diagram shown in figure 24. Resources are defined as

Table 3.--*Summary of estimates[1] of undiscovered in-place oil and gas resources, areal sizes, and sediment volumes of assessed areas in the Gulf of Mexico*

| Assessment area | Areal size | Sediment volume | Oil in-place Billions of barrels (BBO) Low $^{2}F_{95}$ | High $^{3}F_{5}$ | Mean | M.P.[1] | Total gas in-place Trillion cubic feet (TCF) Low $^{2}F_{95}$ | High $^{3}F_{5}$ | Mean | M.P.[1] |
|---|---|---|---|---|---|---|---|---|---|---|
| a. Rio Grande Margin | 1,130 $mi^2$ (2,930 $km^2$) | 3,040 $mi^3$ (12,670 $km^3$) | 0 | 1.29 | .34 | .74 | 0 | 3.49 | 1.09 | .84 |
| b. Sigsbee Escarpment | 760 $mi^2$ (1,970 $km^2$) | 2,770 $mi^2$ (11,550 $km^3$) | 0 | 1.45 | .37 | .75 | 0 | 2.87 | .85 | .84 |
| c. Perdido Foldbelt | 760 $mi^2$ (1,970 $km^2$) | 2,700 $mi^3$ (11,250 $km^3$) | 0 | 6.00 | 1.74 | .87 | 0 | 10.27 | 3.22 | .93 |
| d. Sigsbee Knolls | 230 $mi^2$ (600 $km^2$) | 380 $mi^3$ (1,580 $km^3$) | 0 | 1.66 | .51 | .95 | 0 | 3.25 | 1.07 | .95 |
| e. Campeche Escarpment Area | 2,140 $mi^2$ (5,540 $km^2$) | 3,970 $mi^3$ (16,550 $km^2$) | 0 | 3.37 | .93 | .85 | 0 | 5.83 | 1.84 | .87 |
| f. Abyssal Gulf Basin | 53,920 $mi^2$ (139,650 $km^2$) | 175,280 $mi^3$ (730,570 $km^3$) | 0 | 16.39 | 5.22 | .91 | 0 | 33.53 | 10.70 | .92 |
| Aggregation Estimates | | | | | | | | | | |
| Total Study Area | 58,940 $mi^2$ (152,660 $km^2$) | 188,140 $mi^3$ (784,170 $km^3$) | 2.24 | 21.99 | 9.11 | 1.00 | 5.48 | 44.40 | 18.77 | 1.00 |

[1] The resource estimates are *unconditional*, that is, the marginal probabilities (M.P.), or risks, have been applied to the estimates.

[2] $F_{95}$ is the 95th fractile, corresponding to a 95% probability of *more than* that amount.

[3] $F_5$ is the 5th fractile, corresponding to a 5% probability of *more than* that amount.

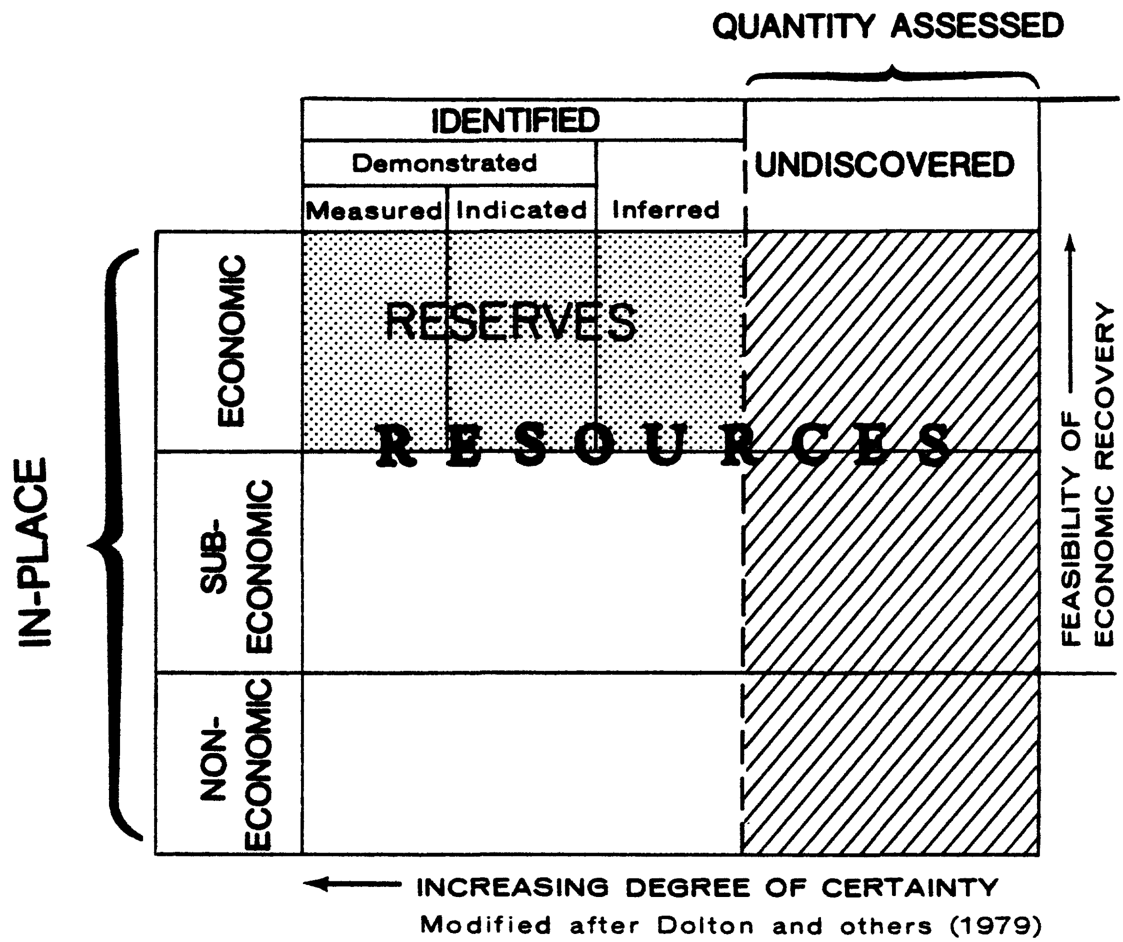


Figure 24.—Petroleum resource classification diagram; estimates of undiscovered in-place oil and gas resources in the Gulf of Mexico study area lie within the hachured column on the right.

"...concentrations of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form that economic extraction of a commodity is currently or potentially feasible" (U.S. Bureau of Mines and U.S. Geological Survey, 1976). In-place quantities, however, may include accumulations that are too small, dispersed or remote to be recoverable, or parts of economic deposits that are potentially or actually non-extractable in an economic or technologic sense (Dolton and others, 1979). In-place hydrocarbons are considered to be accumulations in discrete trapping features, not simply disseminated at random throughout the sedimentary rock system within a geologic basin. Amounts of *known* oil or gas in-place are defined as the estimated number of stock tank barrels of crude oil (42 gallons per barrel), or standard cubic feet of gas (14.73 PSI atmosphere, and 60$^{o}$F.) in subsurface reservoirs prior to any production (API, 1970).

## Speculative Recoverability of In-place Oil and Gas

On the basis of the geologic analysis of the six assessment areas, we speculate that oil and gas may be 1) contained in discontinuous or isolated sandstone reservoirs surrounded by and interbedded with low-permeability shales, 2) in other clastic reservoirs, and 3) in shelf carbonate reservoirs.

Recovery of in-place oil in discontinuous sandstone reservoirs in the assessment areas would probably be about 15 percent from primary methods and 15 percent from secondary recovery methods. Recoveries of gas from analogous, known developed gas reservoirs in discontinuous sandstones reach as high as 75 to 85 percent of the gas in-place. However, both secondary and tertiary recovery methods are expected to be very expensive and difficult to apply in deep-water areas in the Gulf of Mexico beyond the Continental Shelf (> 656 ft (200 m)).

Fractured shelf-carbonate reservoirs in analogous, known fields have recoveries of as high as 27 percent of the oil in-place and as much as 80 to 85 percent of the gas in-place. However, gas recoveries in highly fractured shelf-carbonate reservoirs would be reduced somewhat because of water encroachment.

Overall oil recoveries in the Gulf of Mexico Maritime Boundary Region from all recovery methods might average around 28 percent, and gas recoveries might average around 80 percent. However, the oil and gas recovery factors discussed here cannot be applied directly to the gross, estimated amounts of undiscovered in-place oil and gas resources. Because of the great uncertainties about reservoir properties, economics, and technology, we do not know, at this time, what percentage of the estimated in-place resources in the study area might ultimately be recoverable (R. F. Mast, written commun., 1981).

## Resource Assessment Procedures

Procedures for estimating volumes of undiscovered in-place oil and gas in the study area involved: 1) a comprehensive analysis of all available geological, geophysical, and petroleum-geology data; 2) analysis of the factors known to be significant to petroleum generation, migration, and entrapment; and 3) group appraisals using, as a "scaling factor," calculated volumetric-hydrocarbon yields per cubic mile of sediment from national (U.S.) yield factors and basin-type yields of Klemme (1975). Ordinarily, calculated hydrocarbon yields per cubic mile of sediment from analogous, *known* producing basins are applied against the sediment volume in a province being assessed, such as the Gulf of Mexico. These calculated yields are important in the assessment process because they provide the assessor with high, low, and average yields that serve as scaling factors in making subjective probability estimates. However, no appropriate productive analogs were known for the predominantly deep-water areas assessed in the Gulf of Mexico, and the national yields and Klemme (1975) basin yields were used in their stead.

After the data were analyzed, each appraiser individually made subjective probability estimates of undiscovered oil and total gas resources in-place. The estimates were arithmetically averaged and then processed by use of probabilistic methodology.

## Methods Used in Processing Estimates[1]

Because of the uncertainty involved in estimating undiscovered in-place resources, estimates of their quantities include a range of values corresponding to different probability levels. Initial estimates were made conditional upon the event "in-place oil (or gas) is present" for each assessment area as follows:

1. A *low* resource estimate corresponding to a 95 percent probability of *more than* that amount; this is the 95th fractile ($F_{95}$).
2. A *high* resource estimate corresponding to a 5 percent probability of *more than* that amount; this is the 5th fractile ($F_5$).
3. A *modal* ("most likely") estimate of the quantity of resource associated with the greatest likelihood of occurrence.

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[1]The authors wish to gratefully acknowledge the assistance of Robert A. Crovelli, U.S. Geological Survey, who devised probabilistic methodology, for processing the estimates in this report.

These conditional estimates determined for each assessed area a conditional probability distribution of the quantity of undiscovered oil (or gas) in-place. The conditional probability distribution is the probability distribution of the quantity of undiscovered in-place resource *conditioned* on the in-place resource being present. A lognormal distribution was used as a probability model for the conditional probability distribution.

In the initial resource estimate of the assessed areas, a condition was made that the defined resource is present in "some" quantity. This condition cannot be made with certainty in frontier areas, such as the Gulf of Mexico study area, in which no oil or gas, other than shows and seeps, has been discovered to date. Therefore, a probability had to be assigned to the condition that the resource is present in some quantity; this probability, or risk, is called the *marginal probability* (M.P.). For the estimates in each assessed area, a marginal probability was assigned by the assessors to the event "in-place oil is present" and to the event "in-place gas is present." An arbitrary cutoff of the size of oil and gas accumulations considered in making estimates was 1 million barrels of oil in-place and 2.5 billion cubic feet of gas in-place, respectively. The marginal probabilities are shown in table 3.

The marginal probability for each assessed area was applied to the corresponding conditional probability distribution to produce the probability distribution of the quantity of undiscovered in-place resource. For distinguishing purposes, this distribution is informally referred to as the *unconditional* probability distribution. Each probability distribution was described by means of a *more than* cumulative distribution function, which gives the probability of *more than* a specific amount. From this function the low ($F_{95}$), high ($F_5$), and mean estimates for each assessed area were obtained (table 3).

To arrive at total resource estimates for the entire study area, an aggregation of the six assessment areas was done by a Monte Carlo technique. The resulting aggregate probability distribution represents the probability distribution of the *total* quantity of undiscovered oil (or gas) in-place. From this distribution, the *low* ($F_{95}$), *high* ($F_5$), and *mean* estimates for the total study area were obtained (table 3). The probability curves for these estimates are shown in figures 25, 26, and 27, and the aggregation estimates for the total area of study are shown in figure 28.

## Summary

The highest estimate of undiscovered in-place resources in the Gulf of Mexico study area is that in the Abyssal Gulf Basin assessment area, which is influenced to a great degree by its large areal size and volume of sediment (tables 2, 3). However, the smaller Perdido Foldbelt and Sigsbee Knolls assessment areas have higher hydrocarbon "richness" factors when the estimated amounts of oil and gas are compared with both their relatively small areas and sediment volumes.

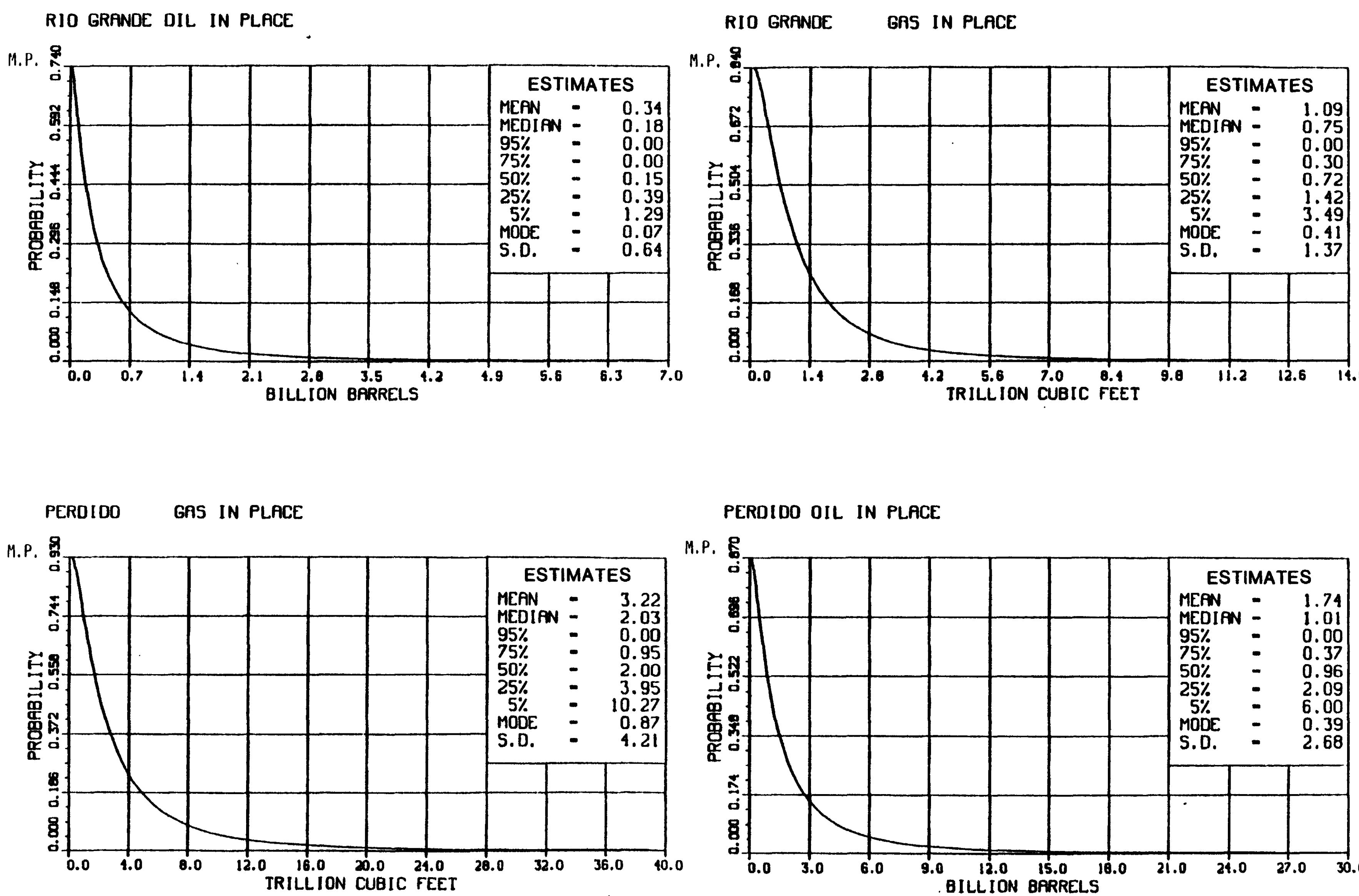



Figure 25.--Probability distribution curves, Rio Grande Margin and Perdido Foldbelt areas. M.P., marginal probability; S.D., standard deviation.

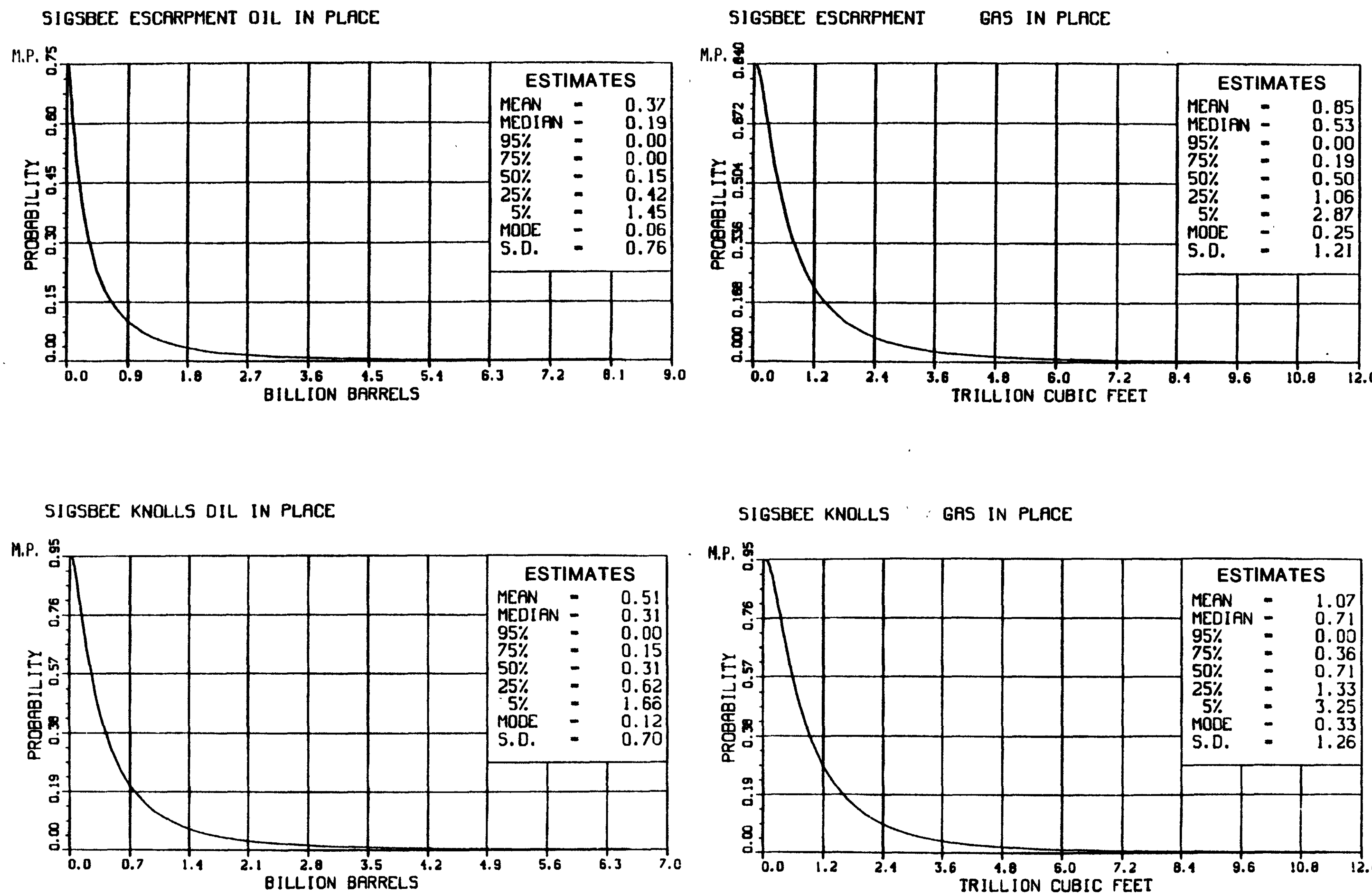



Figure 26.--Probability distribution curves, Sigsbee Escarpment and Sigsbee Knolls areas. M.P., marginal probability; S.D., standard deviation.

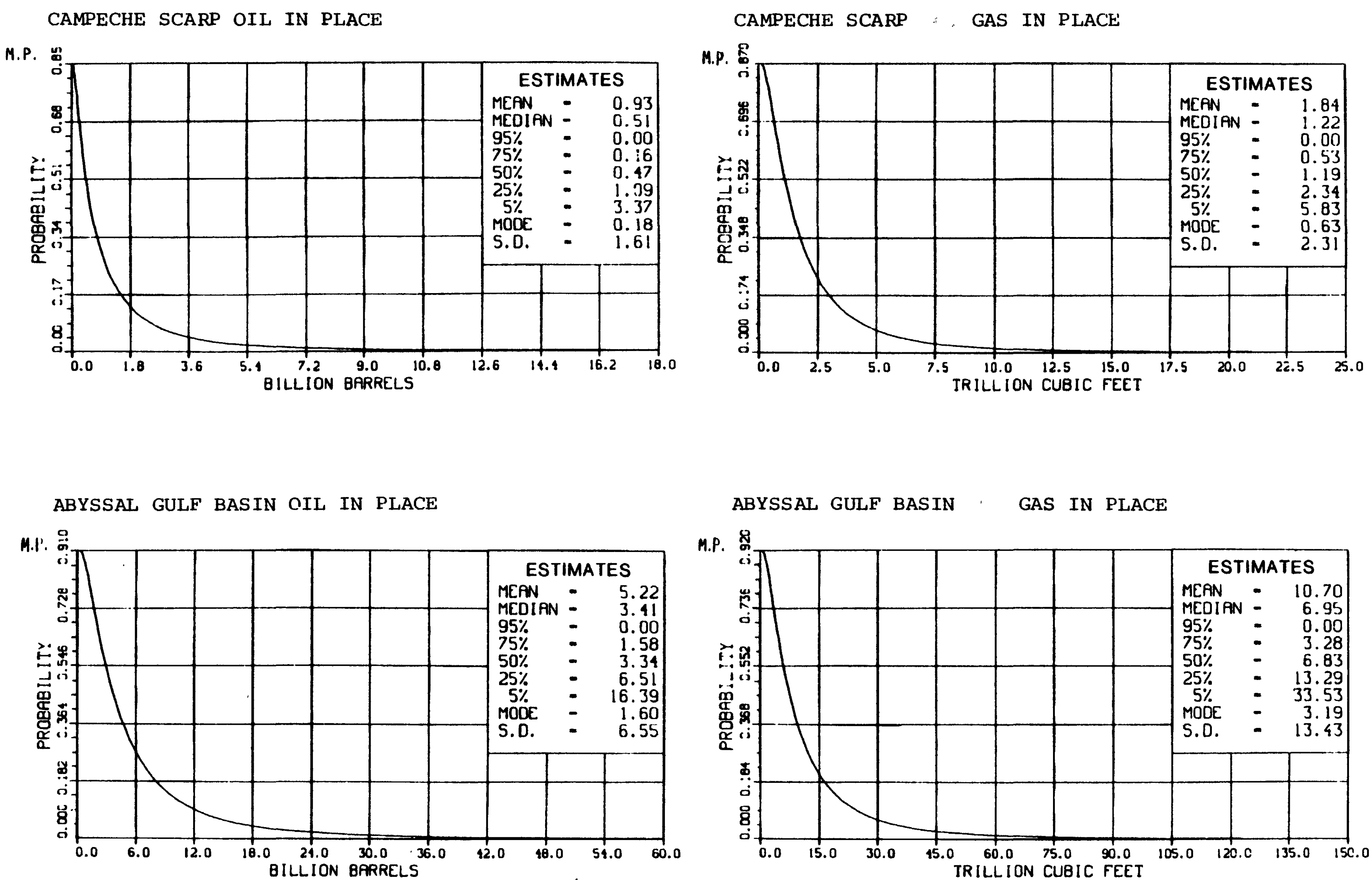
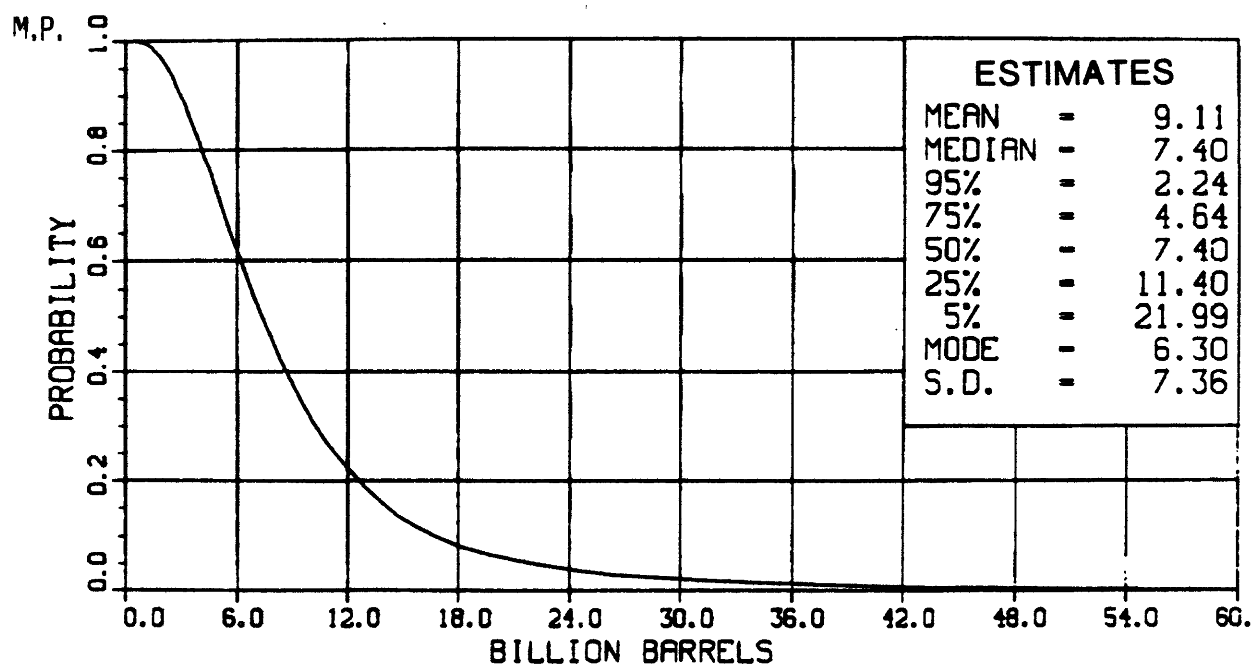



Figure 27.--Probability distribution curves, Campeche Escarpment area and Abyssal Gulf Basin area. M.P., marginal probability; S.D., standard deviation.

## AGGREGATED TOTAL OIL IN-PLACE




## AGGREGATED TOTAL GAS IN-PLACE

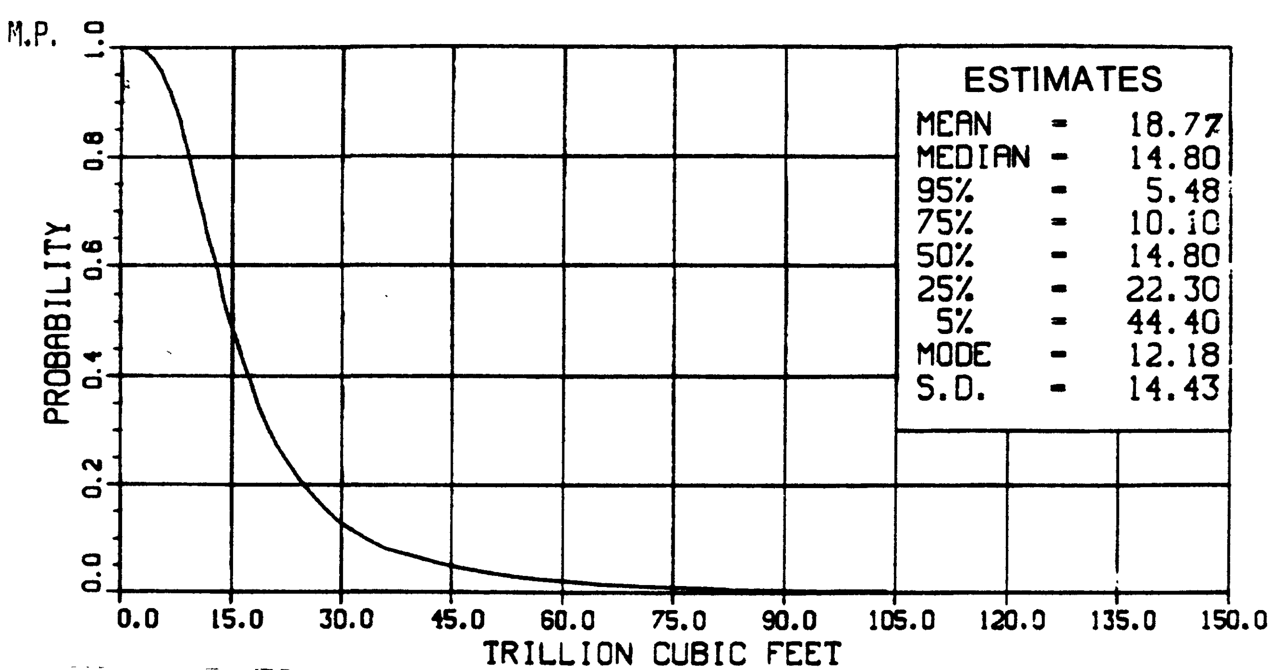



Figure 28.--Aggregated probability distribution curves, Gulf of Mexico Maritime Boundary region.

# MINERAL AND GEOTHERMAL ENERGY RESOURCES IN THE GULF OF MEXICO MARITIME BOUNDARY REGION

By

Ray G. Martin and Richard Q. Foote

## Introduction

Subsea resources are generally limited to deposits that can be exploited by dredging, extracted in solution from drill holes, or mined under the seabed from onshore and artificial-island entries. Mineral-resources production from the world's continental shelves in recent years includes dredge mining of placer concentrates (heavy-mineral suites), non-metallic bulk materials deposits (sand, gravel, shell, lime, mud, etc.), and diamonds; borehole extraction of elemental sulfur deposits and salt; and undersea mining of consolidated mineral resources such as coal, iron, copper, limestone, and a few other minerals (McKelvey and Wang, 1969; Cruickshank, 1974). Subsea minerals production to date has been confined to shallow waters nearshore where such deposits are most common, and where they can be mined and transported to markets at costs competitive with onshore counterparts. In addition to mineral commodities presently mined, the potential exists for future shallow- and deep-ocean production of phosphorites, ferro-manganese oxide deposits, and metalliferous muds by dredging; potassium-rich evaporite deposits, fresh ground-water resources, and geopressured-geothermal energy resources by borehole extraction; and vein, massive, and disseminated ores and consolidated mineral deposits in bedrock by subsurface mining and seabed quarrying (Mero, 1965, 1967; Austin, 1966; Degens and Ross, 1969; Jones, 1969a; McKelvey and Wang, 1969; Barnes, 1970; Cruickshank, 1974).

## Mineral Resources Potential

Information concerning the mineral-resources potential of the offshore Gulf of Mexico, and the Maritime Boundary region in particular, is scant. Subaqueous dredge production of non-metallic bulk materials, chiefly shell deposits, and Frasch-process[1] extraction of elemental sulfur have been generally confined to bay, estuary, lagoon, and nearshore waters of Texas and Louisiana (fig. 29). Except for oyster shell, bulk materials for construction industries are abundant on land in the United States and Mexico and are not likely to be exploration objectives in the offshore. On the other hand, demand for sulfur, potash, and unconventional energy resources generally exceeds supply, making future subsea exploration for these deposits likely. Phosphoritic sands and ferro-manganese oxide crusts and nodule deposits locally may be present within the Maritime Boundary region, but geological sampling of the sea floor suggests that quantities are meager. Coal, lignite, metalliferous mud, and ore minerals are not considered prospective in the shallow substrate of the region because of the general absence of sedimentary and igneous processes favorable for their accumulation or emplacement.

Mineral-resources deposits are exceptionally difficult to identify in marine geophysical data. Examination of the seabed by analysis of core, dredge, and drill-hole samples and bottom photographs provides the only viable means for discovery and appraisal of subsea mineral-resource potential; even so, the resource base cannot be quantified accurately without closely spaced sampling sites. Although the Gulf of Mexico quite literally has been a pincushion for hundreds of geological sampling expeditions, existing data are

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[1]A process of solution mining whereby sulfur and soluble salt deposits are melted by injection of superheated water and recovered through drill holes.

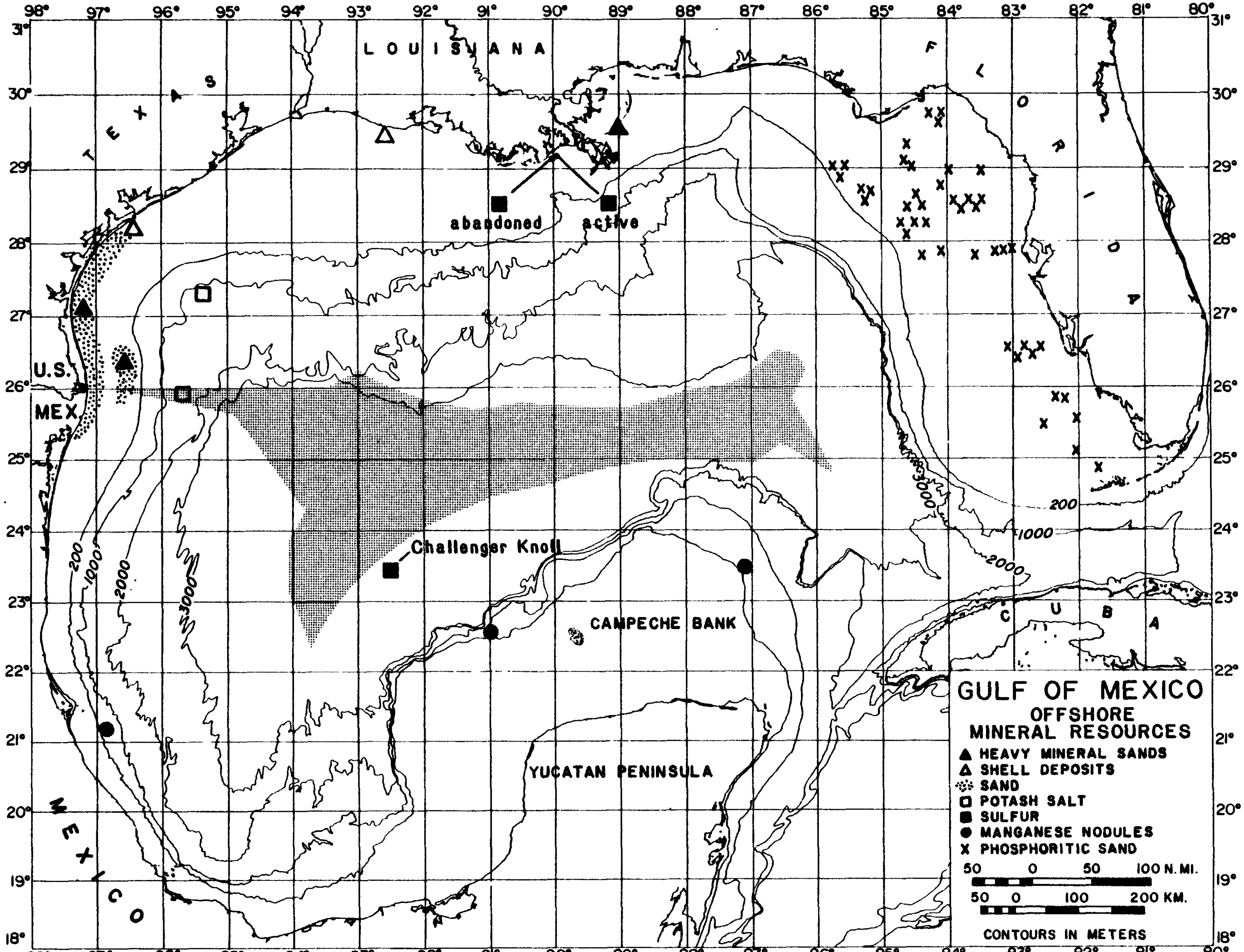


Figure 29.--Map of Gulf of Mexico region showing distribution of proved and potential subsea mineral resources. Compiled from Davis and Bray (1969), Lehner (1969), McKelvey and Wang (1969), Shideler and Flores (1976), Halbouty (1979), and Berryhill and Trippet (1980a). The study area is shaded.

not of the quality or quantity needed for mineral-resource appraisal. Nevertheless, such data provide useful information for addressing the mineral-resources potential of the basin and the Maritime Boundary region in general.

Placer Deposits

Offshore placer deposits are restricted to the continental shelf and contain a generally low percentage of heavy minerals of specific gravity 4.0-8.0 that were derived from a variety of terrestrial sources, transported by streams and rivers, and concentrated chiefly in subaerial and inner shelf environments by wave action. Heavy-mineral concentrations in marine placers commonly contain minerals composed of oxides of tin, titanium, iron, thorium, chromium, zirconium, and yttrium; locally placers may contain particles of elemental gold, platinum, silver, and copper and exotic gemstones such as diamonds. In the terrigeneous shelf environments of the northern and western Gulf of Mexico, placer concentrations may be widely distributed in submerged beach and sand bar deposits laid down during low stands of Pleistocene sea level (fig. 29). Heavy-mineral concentrations in samples of surficial sediment on the south Texas shelf adjacent to the Maritime Boundary region locally amount to as much as 32 percent by weight, but generally average less than 4 percent (Shideler and Flores, 1976); mineral composition is overwhelmingly iron rich, and titanium and zirconium oxides are only minor components. Placer deposits of heavy minerals in the Rio Grande Shelf area are thus not perceived as having significant resource potential.

## Non-metallic Bulk Materials

Surficial sediments on the Rio Grande Shelf within and adjacent to the Maritime Boundary region consist chiefly of clay and clayey silt; a veneer of fine-grained sand covers the inner shelf and is present in broad patches on the outermost shelf (fig. 29). Sand deposits generally range in thickness from only a few inches to a few feet (few centimeters to a few meters) and cover a hard clay "bottom" of late Pleistocene age that is often exposed on beaches of southernmost Texas during winter months when sands are transported offshore in response to currents generated by winter storms. Exploitation of sand resources on the Rio Grande Shelf and along the lower Texas and northern Mexico coasts, thus, is likely to have significant effect on local sand budgets and resulting detriment to recreational beachfronts in the coastal area. Comprehensive sampling of surficial shelf sediments in the immediate vicinity of the Maritime Boundary region shows no appreciable quantities of gravel and shell; gravel-sized constituents generally were found to be less than five percent by weight (Berryhill and Trippet, 1980a). The fine-grained character of sediments in the Rio Grande Shelf further suggests that basins and surficial deposits on the adjacent continental slope also are unlikely sites to explore for bulk materials.

## Evaporite Deposits

Appreciable quantities of rock salt, or halite, are contained within the many diapiric stocks, massifs, and extruded lobes within the Rio Grande Margin, Sigsbee Escarpment, and Sigsbee Knolls assessment areas (figs. 8,15). Salt, however, is an extremely abundant commodity in both coastal and nearshore regions of the United States and Mexico and, thus, is not likely to be exploited in waters deeper than a few hundreds of feet. A potentially more important use of salt domes in offshore areas ultimately may be for use as undersea storage chambers (opened by solution mining through drill holes) for petroleum storage and radioactive-waste disposal (Halbouty, 1967, 1979; Pendery, 1970; McKelvey and Wang, 1969).

Potash-bearing minerals such as sylvite, carnallite, kainite, and polyhalite may have been precipitated during late stages of cyclic evaporite deposition in the Louann, Challenger, and Salinas salt basins of the northern, central, and southwestern Gulf basin. Potash deposits, especially sylvite, constitute important resources used extensively as fertilizers. Drill-core samples into salt on a large massif in the Rio Grande Slope (figs. 21, 29) and several other domes on the continental slope are reported to contain as much as 10 percent sylvite (Lehner, 1969). Although the discovered percentages of potash-salt are relatively low, drill cores have penetrated only a few feet into salt in these structures. Until more exploratory drilling into salt bodies is accomplished in the Maritime Boundary region, and elsewhere in the continental margin and abyssal plain of the Gulf of Mexico, the potential for subsea Frasch recovery of potash-bearing minerals should not be ruled out.

## Sulfur Deposits

The production of sulfur, whether from natural deposits or as a by-product of petroleum refining and smelting processes, is critical to world needs, which are increasingly exceeding supplies. Converted to sulfuric acid, sulfur is an important catalyst in petroleum refining and in the manufacture of fertilizers, chemicals, paints and pigments, iron and steel, film, explosives, paper, fabrics, and numerous other products. As demand continues to increase, subsea sulfur resources are perceived as being a significant factor in world production. McKelvey and Wang (1969) reported that nearly 60 percent of the world's production of elemental sulfur comes from Frasch-recovered deposits associated with anhydrite in bedded evaporite deposits or on salt domes. Sulfur has been produced from anhydritic caprock deposits on salt domes in the coastal regions of Texas and Louisiana and in southern Mexico, and in the shallow waters off Louisiana (fig. 29); cumulative production from 33 domes during the period from 1894 to 1975 amounts to more than 250 million long tons (Halbouty, 1979). Anhydrite forms the caprock of many salt domes on the Texas-Louisiana Slope (Lehner, 1969) north of the Maritime Boundary region and is easily recognized in seismic profiles as a strong reflection that outlines the crest and upper flanks of the salt stock. A "caprock" reflection outlines the top of an undrilled asymmetrical salt anticline beneath the outer edge of the Rio Grande Shelf (fig. 21), Elemental sulfur, however, has not been reported in anhydritic caprock deposits drilled on the continental slope. The lack of strong high-amplitude "caprock" reflections in seismic data across salt massifs and stocks in the Rio Grande Slope diminish the likelihood that quantities of elemental sulfur are available for solution mining in this part of the Maritime Boundary region. Davis and Bray (1969) reported a calcite-sulfur zone containing 19 percent elemental sulfur in caprock deposits drilled on Challenger Knoll (figs. 19, 29).

## Authigenic Mineral Deposits

Surficial deposits of authigenic minerals in subsea environments include phosphorite sands and nodules (Mero, 1965; McKelvey and others, 1968; Barnes, 1970); glauconite sands (Cruickshank, 1974); ferro-manganese oxide crusts, pavements, and nodules (Mero, 1965, 1967; McKelvey and Wang, 1969); and barite-nodule concentrations (Revelle and Emery, 1951; Arrhenius and Bonatti, 1965; McKelvey and others, 1968). Authigenic deposits are widely distributed in the surficial sediments of the world's oceans as chemically precipitated coatings on nuclei of sand grains and rock fragments, and occur in subsea environments ranging from shallow shelf to deep sea floor. Such deposits are not now mined but may in the future constitute important resource potential for the production of phosphate (from phosphoritic sands and nodules); iron and potassium (from glauconitic sands); nickel, copper, and cobalt (from ferro-manganese oxide deposits); and barium and sulfur (from barite-nodule concentrations). In the Gulf of Mexico region, low-grade phosphoritic sands have been reported in areas of deep-water upwellings on the West Florida Shelf (fig. 29; Birdsall, 1978), and manganese nodules have been found in bottom samples taken on the Yucatan Shelf and the continental slope off eastern Mexico (McKelvey and Wang, 1969); no occurrences of glauconite sands and barite nodules in the Gulf are known. Samples of surficial sediments retrieved by gravity coring and bottom-grab operations within the abyssal areas of the Maritime Boundary region are abundant and show no significant concentrations of authigenic minerals.

## Bedrock Deposits and Metalliferous Muds

Consolidated deposits of coal, bedded iron ore, and limestone have been successfully mined by underground methods beneath the sea floor off the coasts of Great Britain, Canada, Finland, and Chile (Cruickshank, 1974). In addition, resources of bauxite, barite, and vein minerals are known or anticipated in many shallow-water regions of the world (McKelvey and Wang, 1969; Cruickshank, 1974). The potential for significant bedrock mineral resources in the Gulf of Mexico and the Maritime Boundary region is not good. Chemical-grade limestones and dolomites might be mined beneath shallow waters off the coasts of Florida and Yucatan at some time in the future; however, such deposits do not exist in the Maritime Boundary region unless perhaps buried at great depth. A thin coal seam of Jurassic age is reported at a depth of 10,335 ft (3,151 m) in a well drilled in Apalachee Bay off the northwest coast of Florida (Maher and Applin, 1968), but depth alone rules the deposit subeconomic. Strata of the terrigenous margins of the northern and western Gulf probably contain numerous thin seams of lignitic material deposited in brackish environments during multiple transgressive and regressive depositional stages of Tertiary and Quaternary time. However, the rapidity of transgressions and regressions combined with relatively short stillstands of sea level suggest the unlikelihood of appreciable accumulation of organic matter available for coalification under heat and pressure generated by burial. If Tertiary coal deposits were to exist beneath the terrigenous shelf, their exploitation would be exceedingly costly in view of the semiconsolidated character of the strata. The lack of a history of igneous activity in strata of Cenozoic age in the Maritime Boundary region precludes prospects for vein, disseminated, or massive mineralization by intrusion and hydrothermal alteration. The occurrence of metalliferous muds mineralized by metal-rich hydrothermal brines similarly is reasoned not to be probable in the Maritime Boundary region.

## Geopressured-Geothermal Energy Resources

Tertiary strata of the lower Gulf Coastal Plain of Texas and Louisiana form at least eight wedges of sandstone and shale which dip and thicken into the adjacent offshore areas (Hardin, 1962). Some of these Tertiary strata have geopressured zones containing subsurface waters which are hot, are confined under pressure higher than normal, and are presumed to be saturated with dissolved methane at formation pressure, temperature, and salinity. These subsurface waters contain potential geopressured-geothermal energy in the form of thermal energy (high temperatures), mechanical energy (fluids under high pressure), and the energy represented by dissolved methane.

A geopressured zone is defined as any zone in which the subsurface fluid pressure exceeds that of the weight of a column of water extending from the depth of the zone to the surface. For sediments in the northwestern part of the Gulf of Mexico basin, the normal hydrostatic pressure gradient is approximately 0.465 pounds per square inch (psi) for each foot of water column (Jones, 1969a).

A favorable geopressured-geothermal prospect should have a large, high-pressured sandstone reservoir filled by high-temperature water that is relatively low in total dissolved solids and is saturated with methane. Porosity is an important physical reservoir property because it controls the amount of water and, hence, dissolved gas that can be contained in the reservoir rock. The reservoir rock should have porosities of 20 percent or greater. Culbertson and McKeta (1951) conducted laboratory studies which indicate that approximately 40 cu ft of natural gas, primarily methane, may be dissolved in each barrel of water, depending on the temperature, salinity, and pressure of the water. At this solubility level, production of 40,000 barrels of water per day would yield 1.6 million cubic ft of gas, if all dissolved methane were extracted. Large quantities of methane potentially available in water solution (assuming saturation) are a function of high pressure, high temperature, and low salinity (Wallace and others, 1977).

The wedge of sediments thickening seaward into the Gulf Coast basin was characterized by Thorsen (1964) and Norwood and Holland (1974) as 1) massive sandstone in which sandstones equal or exceed 50 percent of the sediment volume, 2) alternating sandstone and shale facies in which sandstone content ranges from 15 to 40 percent of the sediment volume, and 3) massive shale facies containing less than 15 percent sandstone by sediment volume. Each of these sequences contained water from the depositional environment (continental, esturine, or marine) which was trapped and buried between the mineral grains as the porosity was reduced during the burial and compaction process. As the sediment overburden increased, more water was squeezed out, and the volume of sediments was reduced even more. Fluid pressures are generally normal in the massive sandstone facies because pore waters have been free to drain, allowing the sand to compact as sedimentary load increased and thereby permitting the dissipation of pressure (Dickenson, 1953). Wallace and others (1979) have pointed out that facies boundaries, growth faults, salt tectonic activity, or post-depositional alterations have effectively isolated sandstone bodies in some areas and have prevented compaction and fluid expulsion; thus, geopressure can be developed and be retained locally in massive sandstone facies.

Fluid pressures higher than normal are more commonly associated with the alternating sandstone and shale facies and with the massive shale facies (Wallace and others, 1979). Fluid pressure in these facies may be high because expulsion of fluids is restricted or retarded by relatively impermeable barriers, particularly growth faults. As the sedimentary overburden increases, pressure on the retained waters is increased until normal hydrostatic pressure is significantly exceeded and geopressure exists. In addition, thermal expansion of water and addition of water from dehydration of clay tend to increase the volume of pore water. Fluids in geopressured rocks must support a part of the weight of the overlying sediments. Moderately high salinity, moderately high temperatures, and intermediate fluid-pressure gradients (0.5 to 0.7 psi/ft) are generally associated with alternating sandstone and shale facies. Low salinity, high temperature, and high fluid-pressure gradients (0.7 psi/ft or greater) are usually associated with massive shale facies. Wallace and others (1979) stated that these relationships indicate that sandstone reservoirs having potential for development of geopressured-geothermal resources will be most common within the alternating sandstone and shale facies and will be less common within the massive shale facies.

A map showing the depth to the top of geopressured zone for the Texas and Louisiana Gulf Coastal Plain and Continental Shelf areas has been published by Wallace and others (1979, Map No. 3). As a general rule, the top of the geopressured zone is shallower and occurs in progressively younger rocks in a seaward direction (Wallace and others, 1979, fig. 17).

The presence of a broad band of geopressured sediments on the Gulf Coastal Plain and offshore Texas and Louisiana has been known for years (Jones, 1969b). Across the Texas Coastal Plain, this band contains three geopressured trends, or geopressured corridors (as designated by the Texas Bureau of Economic Geology). These geopressured corridors are: 1) Wilcox Group, Eocene age; 2) Vicksburg Formation, Oligocene age; and, 3) Frio Formation, Oligocene age (fig. 30). Extensive studies of the geopressured-geothermal resources in these three geopressured corridors have been conducted by the Texas Bureau of Economic Geology and Center of Energy Studies, University of Texas at Austin, under programs funded by The U.S. Department of Energy. Prospective areas within each corridor have been discussed in detail by Dorfman and Kehle (1974); Bebout and others (1976a); Bebout and others (1975); Loucks and others (1977); Bebout and others (1978); and Loucks (1979).

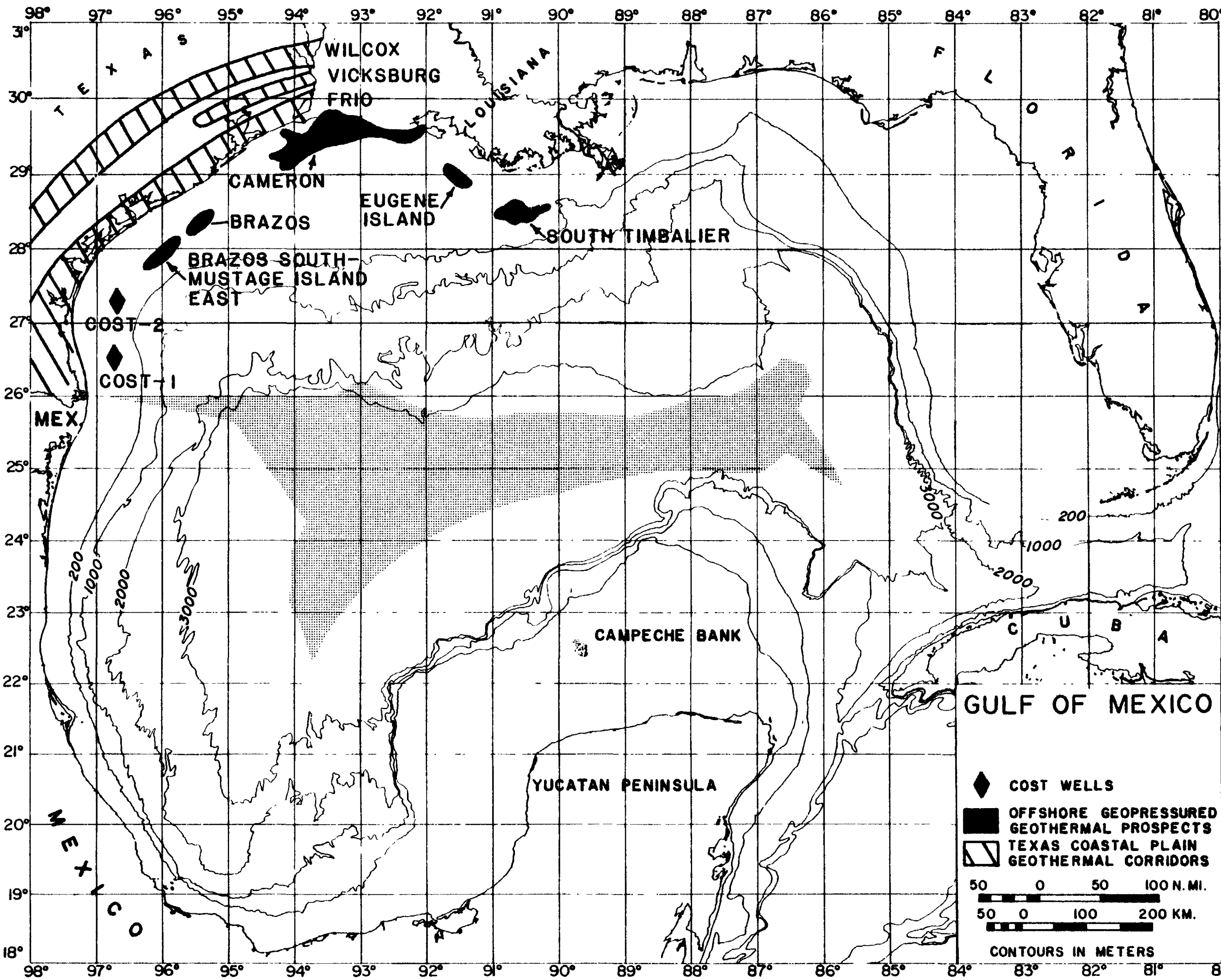

Figure 30.--Map showing locations of Texas Coastal Plain geothermal corridors and geopressured-geothermal prospects in the continental shelf, northwestern Gulf of Mexico. From Bebout and others (1978) and Wallace (1979).

Studies of the geopressured-geothermal resource potential onshore Louisiana include the deep Cretaceous strata extending generally east-west across the central part of the state and lower Tertiary strata on the Gulf Coastal Plain. In one of the original studies of Tertiary strata on the Louisiana Coastal Plain, sixty-three potential areas of interest were identified (Bernard, 1977).

On the continental shelf areas offshore Texas and Louisiana, Wallace (1979) has identified and discussed five highly prospective areas for geopressured-geothermal resources (fig. 30). These prospective areas are: Brazos South-Mustang Island East Prospect; Brazos Prospect; Cameron Prospect; Eugene Island Prospect; and South Timbalier Prospect. The study in which these prospects were identified and the studies by Wallace and others (1979) did not reveal geopressured-geothermal prospective sites on the lower Texas Continental Shelf near the Rio Grande Margin assessment area.

Analysis of well logs and samples from COST (Continental Offshore Stratigraphic Test) wells No. 1 and No. 2 (figs. 10, 30) has been reported by Khan and others (1975a, b). Both wells penetrated geopressured strata, but neither well has sandstones combining sufficient thickness, lateral extent, and permeability to qualify as a geopressured-geothermal prospect. The Lower Miocene sediments in COST well No. 1 were predominantly gray marine shale having an illitic clay component ranging from 30 to 55 percent. The sediments appear to have been deposited in an environment in which a sand/shale sequence could have been deposited if sand had been available to this area during Lower Miocene. The Upper Miocene sediments are massive shales that were deposited in a deep marine environment. However, a gradual change in depositional environments to a shallow outer neritic environment to the west is indicated by the alternating sandstone and shale sequences encountered in the coastal plain areas (Khan and others, 1975a). Shallower strata of Pliocene and Pleistocene age are also not favorable geopressured-geothermal prospects in COST well No. 1. The stratigraphic sequence penetrated in COST well No. 2 is very similar to that of COST well No. 1. The Upper and Lower Miocene strata in COST well No. 2 are primarily gray marine shales containing clay minerals; the late Miocene formations show alternating sandstones and shales having sand percentages of about 15 percent (Khan and others, 1975b). Pliocene strata in this well are normally pressured and are primarily gray marine shales deposited in outer neritic environments. Pleistocene strata are shallow, normally pressured, and thin (about 770 ft (235 m) thick) and consist of alternating sandstones and shales.

Wallace and others (1977) evaluated the potential geopressured-geothermal resources in beds of Oligocene and Miocene age of the lower Rio Grande embayment of Texas. The prospective areas identified in that study extend slightly offshore and north of the mouth of the Rio Grande. Interpretations of seismic data and well logs by Khan and others (1975a) suggest that the thickness and lateral extent of sandstones will not meet the minimum requirements for geopressured-geothermal prospects east of a point about 10 miles (16 km) east of South Padre Island.

Thus, sandstones in the Rio Grande margin area of the Maritime Boundary region are likely not to be suitable in thickness, extent, and permeability for consideration as geopressured-geothermal prospects. However, favorable sands could possibly have been deposited in the deep marine canyons and fans of Miocene, Pliocene, and Pleistocene ages on the outer shelf and slope. The other five Maritime Boundary areas appear to have massive shales deposited in deep-water marine environments, possible turbidite sands, and alternating sandstone and shale sequences. Geologic samples and shallow core data do not reveal geopressured sediments in any of the areas. However, the samples and cores are from shallow depths, and geopressured zones may be present at greater depths. Certainly, those parts of the study area having deeply buried massive shale facies must be considered as possible geopressured zones.

Estimates of the geopressure-geothermal energy contained in pore waters of sedimentary rocks to a depth of 21,500 ft (6,553 m) in the Texas and Louisiana Gulf Coastal Plain and offshore areas to water depths of 656 ft (200 m) were reported by Wallace and others (1979). Similar estimates for the Maritime Boundary areas have not been prepared for this report because a longer time period and a larger budget are needed to assimilate and interpret geological, hydrogeological, and other critical data and to complete a resource appraisal by computer methods.

POTENTIAL GEOLOGIC HAZARDS IN THE GULF OF MEXICO

MARITIME BOUNDARY REGION

By

Richard Q. Foote and Ray G. Martin

## Introduction

Characteristics of potential geologic hazards known to be present in the Gulf of Mexico that might adversely affect oil and gas exploration, production, and pipeline transportation are described in detail in Appendix III. Appendix III is provided to give insight into the geologic processes involved in the origin and characteristics of these potential hazards. The risk of earthquakes adversely affecting the Maritime Boundary region was reviewed as part of the resource assessment. Because of the lack of seismicity data and the apparent low probability of large earthquakes taking place in the deep Gulf of Mexico outside the southern Gulf of Campeche, earthquake-related potential geologic hazards will not be addressed in the discussions of each of the six assessment areas. The Maritime Boundary region is treated as a single area in Appendix III.

Few studies exist of potential geologic hazards on the lower continental slope and in the deeper waters of the Gulf of Mexico. Site-specific studies in these two regions are confined to DSDP sites 1-3 and 85-97 (fig. 10). Therefore, the following discussions of potential geologic hazards in the areas of interest will be based 1) on a preliminary analysis of widely spaced seismic profiles in the deep-water area, 2) on the synthesis of information from a limited number of publications, and 3) on comparisons of known or suspected potential geologic hazards in the study area with similar features in areas that have been more thoroughly studied. The intent of the following discussion is to characterize these categories of geologic hazards only in a general sense and not to infer or predict the magnitude and probability of risk for any area.

## Rio Grande Margin Area

Since 1975, members of the U.S. Geological Survey (USGS) have been studying environmental geology geohazards on the Texas-Louisiana Shelf and upper slope as part of the U.S. Bureau of Land Management's OCS (Outer Continental Shelf) Environmental Studies program. The USGS study area extends south to lat 26$^{o}$ N, which is the north side of the resource assessment area (fig. 8) on the Texas shelf. The results and conclusions from that study can be extrapolated into the Rio Grande Margin area.

Many reports and publications are available from the above-mentioned research. The publications most appropriate for the Rio Grande Shelf and Slope are those by Berryhill (1977, 1979, 1980); Berryhill and others (1975, 1979); and Berryhill and Trippet (1980a, b, c, d, e). The following discussion is based upon the results in these and other publications as cited and upon a limited amount of geophysical data.

### Soil Movements

The seaward bulge in this area of bathymetric contours on the outer edge of the shelf reflects the progradational effect of Pleistocene deposition. Surficial and shallow subsurface sediments on the lower south Texas shelf are typically fine grained and characteristically are soft rather than firm and compact (Berryhill and Trippet, 1980d). About one-quarter of the Rio Grande Delta (which covers all the Rio Grande Shelf) must be classed as a potentially mobile area; localized areas are subject to future movement. Sediments have been displaced by gravity sliding or slumping along the sea floor at the outer edge of the ancestral Rio Grande Delta. Within the South Texas OCS area, slumps of relatively large scale displacement occur at the outer edge of the shelf coincident with the upper continental slope. Slumps of similar magnitude, as well as downslope sediment creep, are to be expected at the outer edge of the shelf and on the upper slope of this resource assessment area. Mass movement of sediments has produced low-relief, hilly, hummocky features on the steeper part of the lower slope.

## Active Faults

Sea-bottom scarps along some faults indicate relatively recent movement. Displacement of the most recently deposited sediments confirms that gravity and tectonic adjustments within the continental shelf and slope are continuing. Small scarps have been detected on the continental shelf (Berryhill and Trippet, 1980c) near the assessment area and similar features caused by mild gravity tectonism are expected in it.

The lower Rio Grande Slope is characterized by hilly and hummocky topography resulting from salt tectonics. Some diapirs have penetrated to within a few hundred feet of the sea floor (fig. 21). Faulting and fault-related features are common on such diapirs in the Gulf of Mexico continental slope, including the Rio Grande Margin (fig. 31). Faults of this type which penetrate the uppermost sediments can be classified as active even though the rate, period, and magnitude of movement cannot be documented.

## Buried Stream Channels

Stream channels were likely cut across the Rio Grande Shelf and upper Slope during the low sea stand caused by Pleistocene glaciation. Sediments

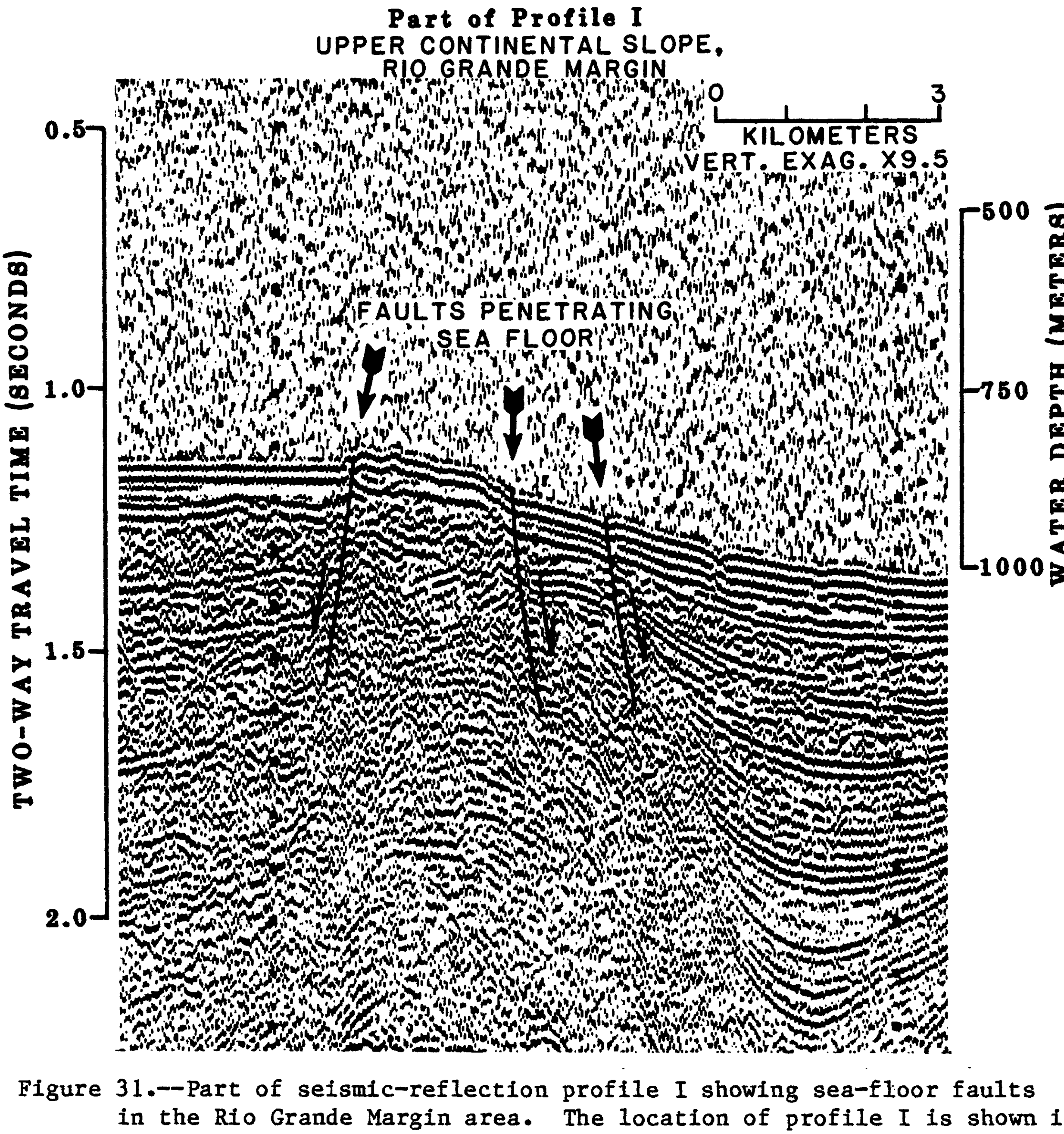


Figure 31.--Part of seismic-reflection profile I showing sea-floor faults in the Rio Grande Margin area. The location of profile I is shown in figure 12.

filling such old stream channels are highly variable in depositional structure and texture. Lateral and vertical variations in sediment types and characteristics can occur in very short distances (e.g., from the old channel to the channel bank). These variations can cause abrupt changes in cohesiveness and bearing strength, which should be addressed in siting facilities. Gas is also sometimes generated from organic material buried in stream channels.

Shallow Gas

The South Texas OCS study (Berryhill, 1977) has noted plumelike traces directly above faults that either extend to the sea floor or lie at shallow depths beneath the sea floor; these plumes may be due to natural gas seepage. Gas seeps and seep mounds are generally considered an order of magnitude less hazardous than gas-charged sediments and high-pressure gas zones because of their distinctive structure on seismic survey records. Gas-charged sediments, high-pressure gas zones, and gas-saturated sediments in delta areas are potential hazards, however. Similar potential hazards could be present in the Rio Grande Margin assessment area.

## Perdido Foldbelt Area

Bathymetric and structural maps (figs. 2, 15) show a system of elongate sea-floor features extending along the East Mexico continental slope northeastward into the Alaminos Canyon and the lower Texas-Louisiana Slope. Each water-bottom expression probably represents a buried anticline bounded by synclines. In the Perdido foldbelt, the sea floor is roughened (fig. 18), but the surface expressions of the subsurface anticlines are not as distinct as the Mexican Ridges (fig. 1) to the south-southwest. The roughened bottom is probably the result of 1) tectonic forces (compressional) of sufficient magnitude to distort the sea-floor sediments, 2) mass movement of sediments downslope, and 3) sea-floor scour by turbid flows in and from nearby submarine canyons.

## Active Faults

Many of the anticlines in the Perdido foldbelt, including those in the assessment area, have a reverse fault on the landward flank. These faults may, in some areas, extend to and displace the sea floor suggesting relatively recent movement. If movement has recently taken place on these faults, then gravity and tectonic processes are continuing in the Gulf of Mexico.

## Mass Slumping

The irregular and hummocky water bottom surface combined with moderate sea-floor gradient (fig. 32) shows that mass slumping of sediments has taken place on the Perdido Escarpment. The age and characteristics of the slumped sediments and the triggering mechanism are not known. However, significant quantities of unconsolidated fine-grained sediments probably were deposited in this area during the most recent low stand of sea level in the last period of glaciation. As the sediments accumulated, a critical point was reached, at which time gravitational movement took place.

## Shallow Gas and Clathrates

The types of seismic profiles recorded in the area are not ideally suited to detect gas in shallow sediments. However, the presence of methane in DSDP samples and the presence of shallow gas on the continental slope offshore Louisiana, indicate that shallow gas may exist in this area.

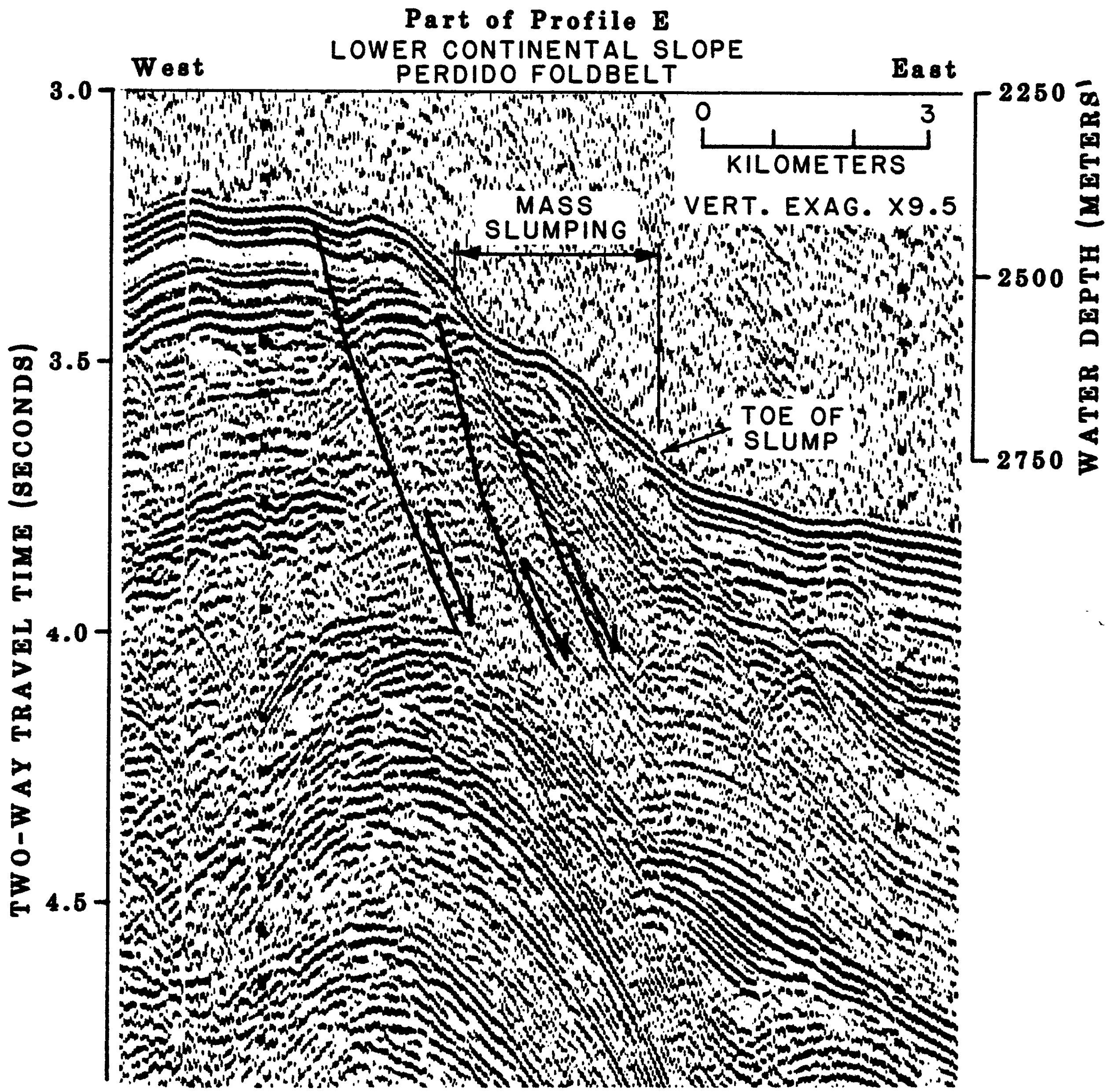


Figure 32.--Part of seismic-reflection profile E showing mass slumping on Perdido Escarpment. The location of profile E is shown in figure 12.

Within the Perdido foldbelt, water depths and the depositional environments of shallow sediments favor the generation and entrapment of gas hydrates, or clathrates. However, seismic evidence of such gas deposits have not been detected. Gas hydrates could be undetectable because reflections from the top of such zones would be so close to paralleling the shallow strata that they would be indistinguishable.

## Sigsbee Escarpment Area

Sedimentary strata in the Sigsbee Escarpment assessment area (fig. 8) range in thickness from a few tens of feet above the shallow salt lobes to as much as 6,560 ft (2,000 m) in broad basins depressed in the salt surface (figs. 22, 23). Potential geologic hazards will most likely be associated with the sedimentary cover, which is predominantly of Pleistocene age.

### Active Faults

Faulting and fault-related topographic features are common on and around diapiric structures. The hilly and hummocky water bottom and possible scarps indicate movement during recent geologic times. Therefore, salt-lobe extrusion can be considered an active geologic process, and the associated faulting is also active even though the time period between movements may exceed the life expectancy of oil and gas fields.

### Shallow Gas

Biogenic gas is associated with deltaic sediments. Also, shallow accumulations of both thermogenic and biogenic gas are commonly found on and around diapiric salt structures. It is then logical to assume that shallow gas may be prevalent in the Sigsbee Escarpment, Sigsbee Knolls, and Rio Grande

Margin assessment areas, as well as in continental rise and submarine fan deposits in the Abyssal Gulf Basin. Further discussions of biogenic methane gas may be found in Appendices II and III.

### Mass Slumping

Surficial slumping or sliding can be expected because such deformation is frequently found on and around diapiric structures. Also, shallow faulting can trigger the movement of sediments that otherwise would have been in equilibrium. The broad basins depressed in the salt surface were rapidly filled by mostly Pleistocene sediments. Buried zones of low bearing capacity could be present in the substrate of these basins.

## Sigsbee Knolls Area

Potential geologic hazards in the Sigsbee Knolls assessment area (fig. 8) most likely are related to or caused by diapiric salt stocks (fig. 19) that have uplifted the sedimentary layers on the flanks of the domes as much as 6,000 ft (1,829 m). The largest of the three salt stocks in the assessment area has a surface expression (fig. 2, 15); therefore, intense faulting most likely accompanied the deformation.

### Active Faults

Fault scarps on the sea floor over the tops and the flanks of the domes are to be expected. The rates, periods of movements and growth of faults are not known, but at least minor movement during Holocene would be consistent with movement known to have taken place near other large, shallow penetrating salt diapirs in the Gulf of Mexico.

### Shallow Gas and Deeper Gas

Methane and ethane were detected in samples from DSDP Site 2 on Challenger Knoll (fig. 19). Although the concentrations of gases in those samples and at other DSDP sites were too low to constitute a geologic hazard, potential dangers need to be recognized. The potential hazard of deeper gas would be a possible blowout where the drill-stem might intersect faults. Such potential problems would normally be addressed in casing and drilling mud programs.

### Mass Slumping

The water bottom is hilly and hummocky over the salt diapir that penetrates near the surface (fig. 2). On the basis of the analysis of geologic hazards by Berryhill (1977) over shallow penetrating salt domes on the U.S. OCS areas having similar appearing surface features, slumping of sediments is thought to be likely. The rate and magnitude of such slumping may vary from glacierlike creep to mass failure, depending on sediment type, cohesiveness, and other factors.

## Campeche Escarpment Area

The deep sea floor of the Campeche Escarpment area is characterized by very gentle gradients (fig. 20) except in a small area where the perimeter of the assessment study passes across the base of the exposed escarpment (fig. 2). Sediments beneath the sea floor are distal submarine fan deposits and consist primarily of fine-grained silts and clays and minor amounts of turbidite sand and carbonate detritus. Sea-floor stability conditions in this assessment area are, thus, likely to be similar to those found over most of the Abyssal Gulf Basin area and discussed below.

## Abyssal Gulf Basin Area

The resource assessment area in the abyssal Gulf basin (fig. 8) includes the Western Gulf Rise, the lower Mississippi Fan, and the Sigsbee Plain. The sea floor is flat in the Sigsbee Plain (figs. 13, 19) but has gentle slopes in the Western Gulf Rise (fig. 16) and lower Mississippi Fan (fig. 17) regions.

The stratigraphic succession of the deep Gulf of Mexico basin was divided into three major sequences as described in the section on Geology and Geophysics of the Maritime Boundary Assessment Area. The youngest of these sequences, Pliocene and Pleistocene strata, represents huge sediment volumes deposited in the deep Gulf during periods of glaciation; these strata are of primary interest in terms of potential geologic hazards.

On the Sigsbee Plain, the uppermost few hundred feet of sediment appear to be nearly horizontally stratified turbidite layers. The upper Mississippi Fan and the lower fan apron show evidence of Pleistocene submarine channel and over-bank deposits. The Western Gulf Rise is characterized as having broad sedimentary aprons built seaward from the mouths of submarine canyons.

Seismic-reflection profiles over the area are not of the type and quantity to analyze geologic hazards; however, some observations can be made.

### Soil Stability

Throughout the area, the water bottoms are flat or gently sloping. Mass movement of sediments would not be expected. Sediment creep on very gentle slopes could be a factor in localized areas. The upper sequence contains zones of unstratified material that are ancient debris-flow deposits. However, these deposits are deep enough in the section to be handled by casing programs under normal drilling conditions.

## Shallow Gas and Clathrates

Shallow gas accumulations probably are widespread throughout the deep Gulf, although there is no confirming evidence on available seismic profiles. Pleistocene strata, particularly in the lower Mississippi Fan, appear to be ideally suited to contain biogenic methane gas because they contain source material (woody debris). Clathrates may also be present, but again, no seismic evidence of these deposits has been found.

## Active Faults

Seismic profiles in the area show numerous small faults, but these are not considered to be active in a tectonic sense. Bouma (1972) noted that for a surprising number of cores, several rather distinct faults were observable in radiographs as well as in visual examination. He concluded that these faults are due to settling differences during consolidation and (or) the result of tension released from downward movement of sediment along a slope.

# TECHNOLOGICAL FEASIBILITY OF DEEP-WATER DRILLING AND PRODUCTION IN THE GULF OF MEXICO

BY

Kent Stauffer, Maurice Adams,

Richard Habrat, and Dan Bourgeois

## Introduction

This discussion summarizes what is known about the technological feasibility of drilling for and producing hydrocarbons in the study area, which is in the Gulf of Mexico and which has been identified as having petroleum-resource potential. The discussion consists of a summary of current petroleum industry technology and projected time frames for new equipment and techniques that will be required to drill for and produce hydrocarbons in remote, deep water locations.

The assessment areas in the Gulf of Mexico that have been identified as having petroleum-resource potential are in water depths ranging from 98 to 12,270 ft (30 to 3,740 m). The areas of relatively shallow water depth can be exploited by use of current technology. However, for most of the areas (those in water depths greater than 1,200 ft (365 m)), exploration and production technology is *not* presently available to exploit any of the estimated petroleum resources.

In this section, we discuss the major phases of oil and gas exploitation, including the operations involved, the current level of technology, and technologies that will be needed for deep-water operations.

## Deep-water Drilling

Exploratory-drilling technology has progressed well in advance of the technology for development drilling, producing, storage, and loading facilities in deep water. Exploratory wells have been drilled in depths approaching 5,000 ft (1,525 m), whereas the deepest water where production has been established is slightly deeper than 1,000 ft (305 m).

The U.S. petroleum industry has several drilling vessels that can drill in as much as 6,000 ft (1,830 m) of water (fig. 33). The water depth capacity of some of these vessels could be extended to 8,000 ft (2,440 m) by a few modifications. However, only one or two of these vessels have adequate space to store more than 6,000 ft (1,830 m) of riser; therefore, larger vessels will be required.

Drilling technology is sufficiently advanced to support the engineering requirements of continuing to extend the water depth capability of drilling units, but almost every single element of the entire drilling system will have to have more capability and greater reliability than now available. The main extensions of technology needed are:

1. Further refinement of dynamic positioning, which replaces conventional mooring systems.
2. Further refinement of remote-controlled reentry and sea-floor manipulation systems, which replace conventional guideline systems.
3. Development of larger and stronger blowout preventors and further refinement of electro-hydraulic control systems.
4. Improvement of buoyancy methods and disconnect systems of marine risers, and strengthening of couplings to withstand high tension and pressure.

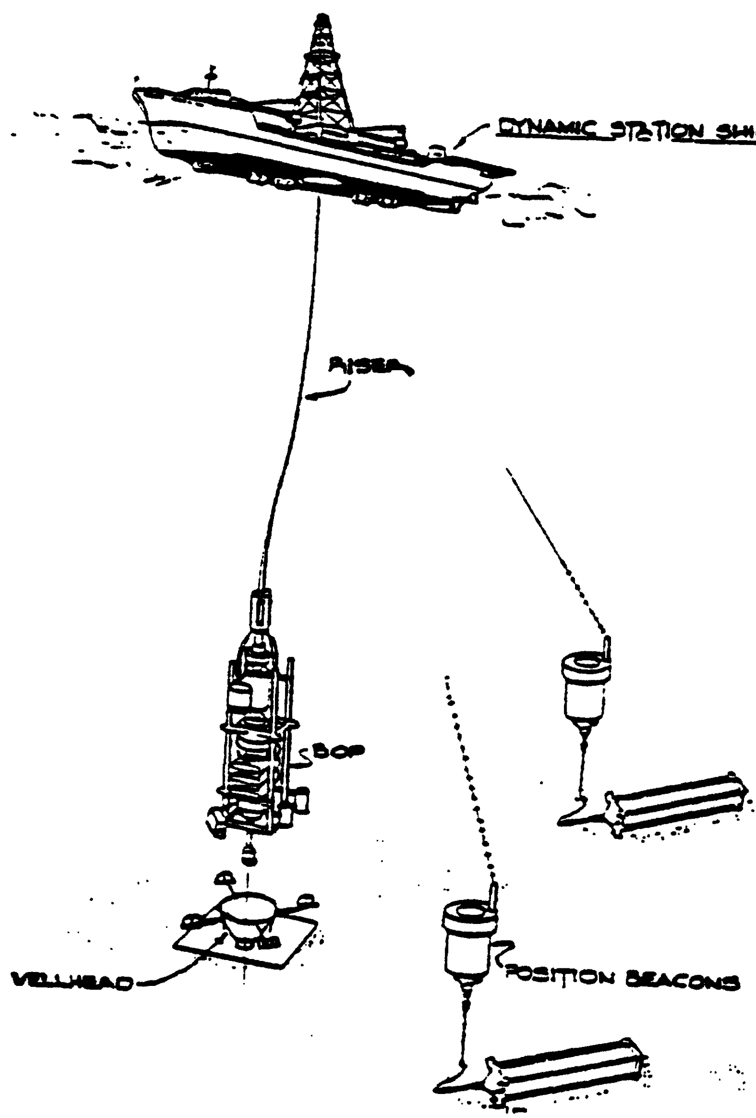


Figure 33.--Diagram of dynamically positioned drill-ship.

The National Science Foundation, with the technical and financial assistance of several U.S. petroleum companies, is studying the possible conversion of the Glomar Explorer to a drilling vessel in an attempt to extend some of these technologies. If this project is carried out as planned, the capacity for drilling exploratory wells in water depths as great as 13,000 ft (3,962 m) could be available by 1984.

Technology is currently being devised to provide the methods and equipment for drilling in such deep-water locations. The extent to which this effort will materialize in the Gulf of Mexico will be mainly a function of the amount of petroleum resources, production capability (i.e. barrels of oil per day), and favorable economic incentives, rather than a lack of technology.

## Deep-water Production Systems

Deep-water production technology is lagging behind deep-water exploratory drilling technology. However, during the last several years, the oil industry has begun an intensive program to design equipment and analytical tools, perform model tests, and conduct full-scale tests in preparation for drilling development wells and producing oil and gas in deep water. The major types of production systems being considered and their feasibility for use in deep water are discussed below.

Fixed platforms.--Nearly all offshore fields have been developed from bottom-founded, fixed-leg platforms (fig. 34). The present water depth record for a fixed-leg platform is 1,025 ft (312 m) (Shell's Cognac Field Platform in the Gulf of Mexico). The size of these platforms is approaching the economic

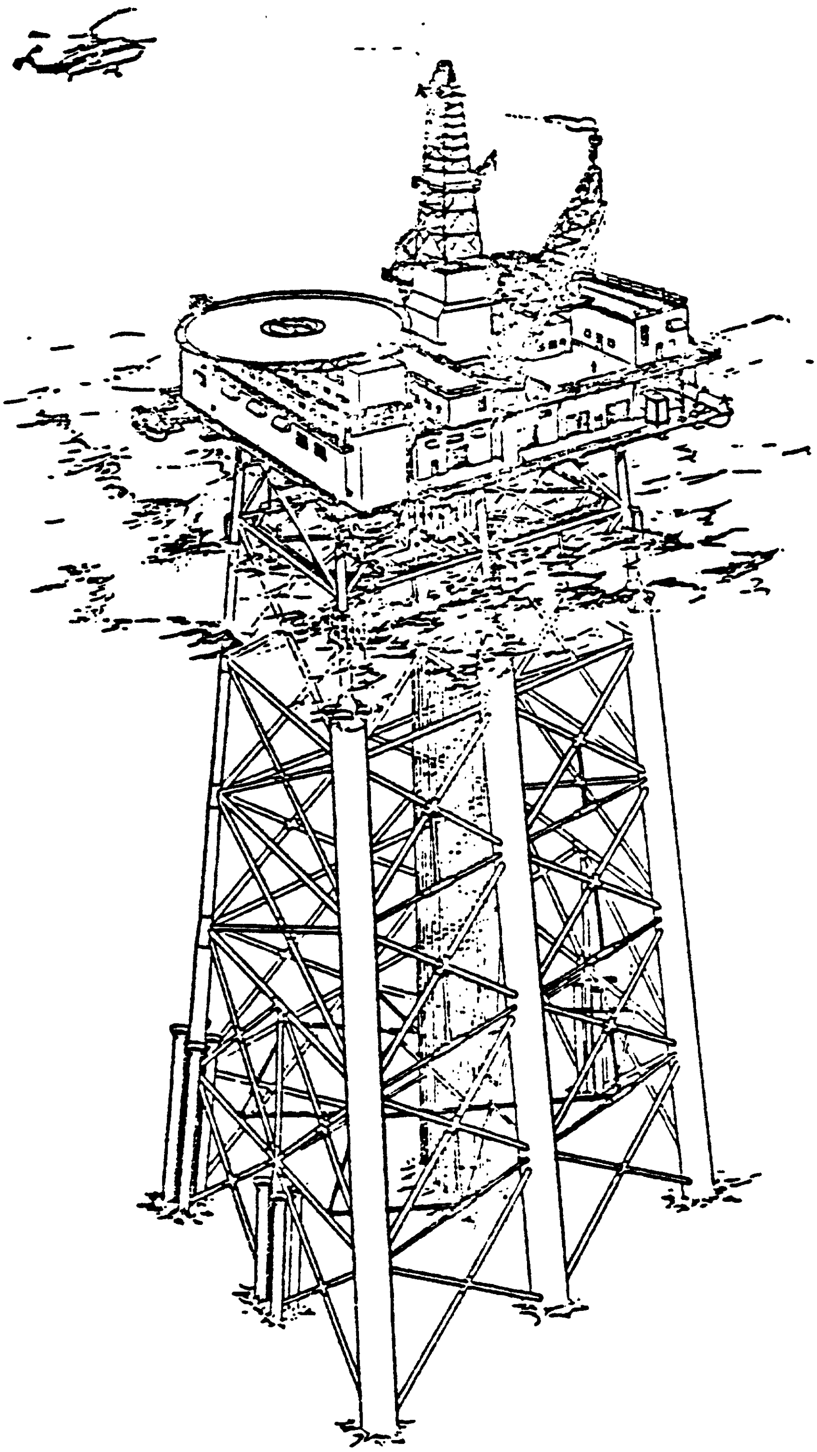

Figure 34.--Diagram of fixed drilling platform.

limit for fixed-leg structures because of the very large amount of steel required and limitations of fabrication and installation methods. Several concepts have been proposed for extending the water depth capability of platforms.

Guyed towers.--A guyed tower is a compliant structure, which is designed to move with environmental forces rather than rigidly resist them (fig. 35). Guy lines are used to hold the tower in a vertical configuration. A scale model of this tower has been successfully tested in 300 ft (91 m), and it is planned to use a guyed tower to develop a Gulf of Mexico field in 1,000 ft (305 m) of water. This type of structure may be applicable in 2,000 - 2,500 ft (610-762 m) of water, but too much steel is required for such towers to be used in deeper water.

Tension-leg platforms.--A tension-leg platform is also a compliant structure (fig. 36). It is a large floating platform, similar to a semisubmersible drilling rig, connected to the sea floor by vertical tension members. A scale model of this type has been successfully tested in 200 ft (61 m) of water. Plans have been announced by some companies to use a tension-leg platform in the North Sea in 485 ft (148 m) of water. Studies indicate that this type of structure may be used in 2,500-3,000 ft (762-914 m) of water, and predictions have been made which forecast future applicability of tension-leg platforms in 8,000 ft (2,438 m) of water and greater.

Subsea production systems.--All three platform concepts discussed above offer the important advantages of drilling, maintaining, and repairing wells in a conventional manner from a platform deck. The other major type of deep-water

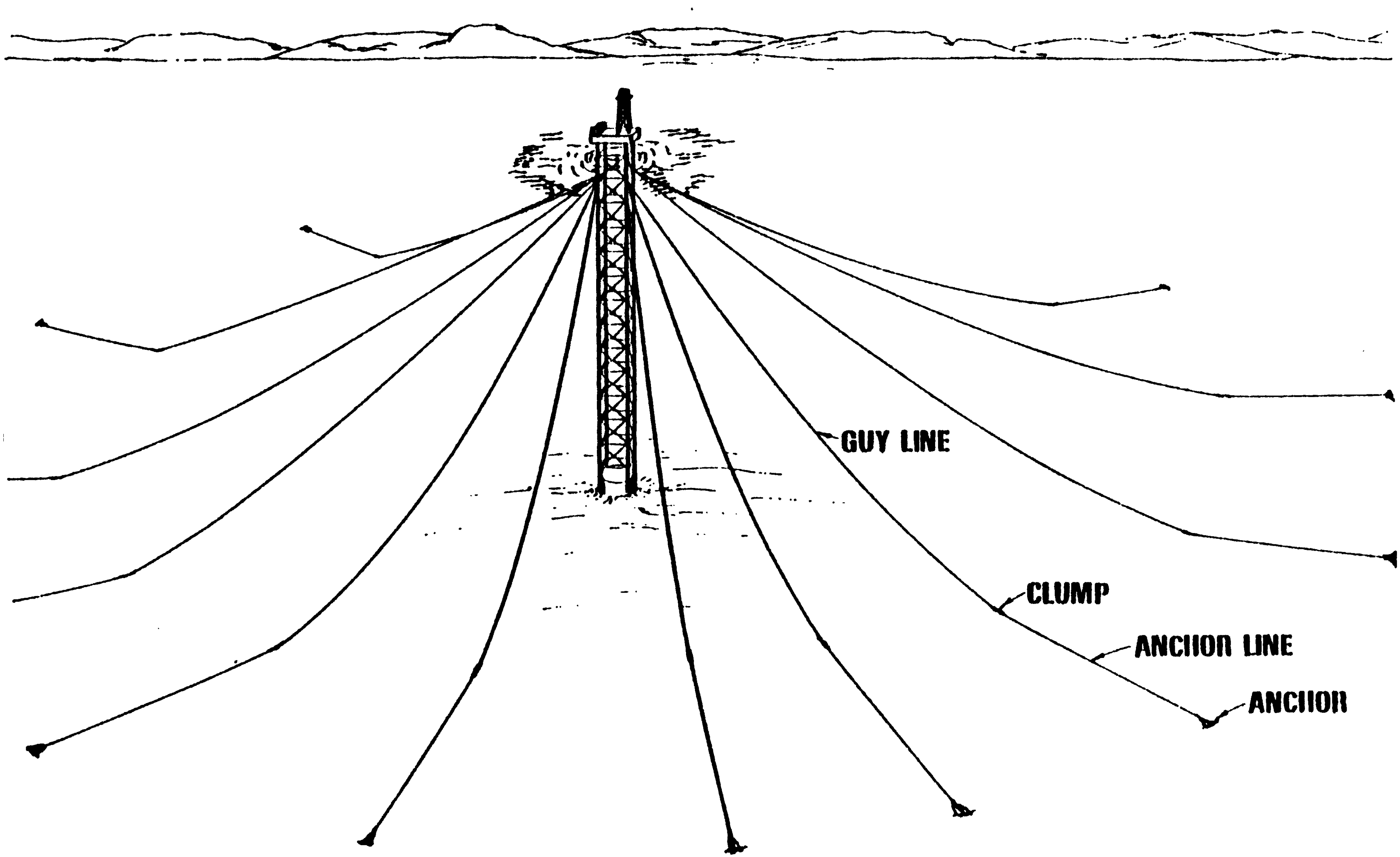


Figure 35.--Diagram of guyed-tower drilling platform.

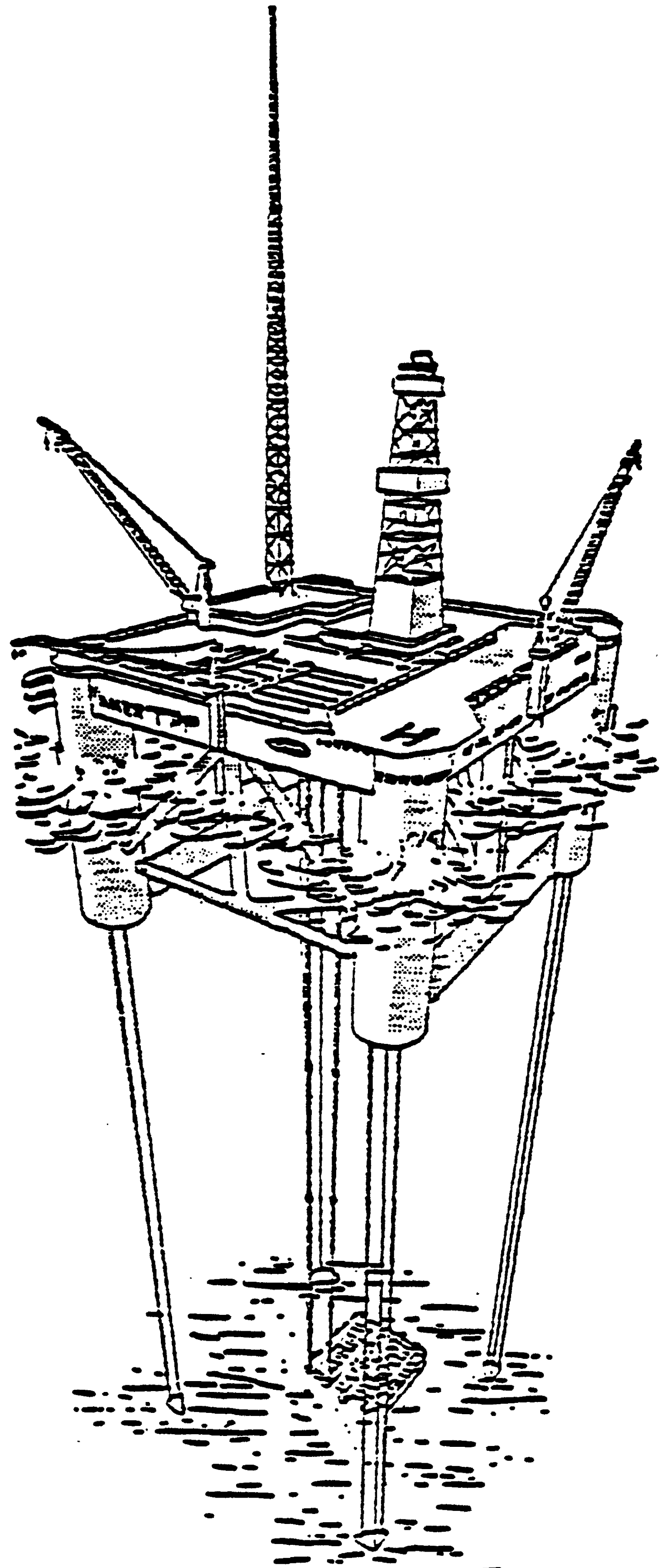

Figure 36.--Diagram of tension-leg drilling platform.

production technology involves subsea production systems, which consist of wells completed at the sea floor and connected by flowlines and controls back to a surface facility. These systems would be used when platform installation is prohibited by cost or water depth. In recent years, several systems using subsea wells producing to floating facilities have been installed which offer potential for application in deep water. A few of these systems are summarized below.

Semisubmersible production system.--This system consists of subsea satellite wells completed as "wet trees" and connected by flowlines to a subsea base (fig. 37). A production riser carries fluid to a semisubmersible vessel, which is kept on station by conventional mooring and which contains process facilities. All sea-floor equipment is remotely controlled from the surface. Separated oil is pumped down the riser, through a sea-floor pipeline, up a single-point mooring facility, to a shuttle tanker. Systems of this type have been installed in 300 ft (91 m) of water, proven for 1,000 ft (305 m), and considered feasible for water as deep as 8,000 ft (2,438 m).

Subsea atmospheric system.--This system consists of wells drilled through a template and completed as "wet trees" (fig. 38). The wells are connected to a manifold center housed in a large chamber which contains breathable air at one atmosphere. Workers may be transferred to this chamber in a tethered bell or submersible to conduct various routine maintenance operations. The manifold is connected by pipeline to a production riser, then to production facilities on a floating surface vessel. This system has been installed in 225 ft (83 m) of water, proven to 1,500 ft (457 m) of water, and considered feasible for water as deep as 8,000 ft (2,438 m).

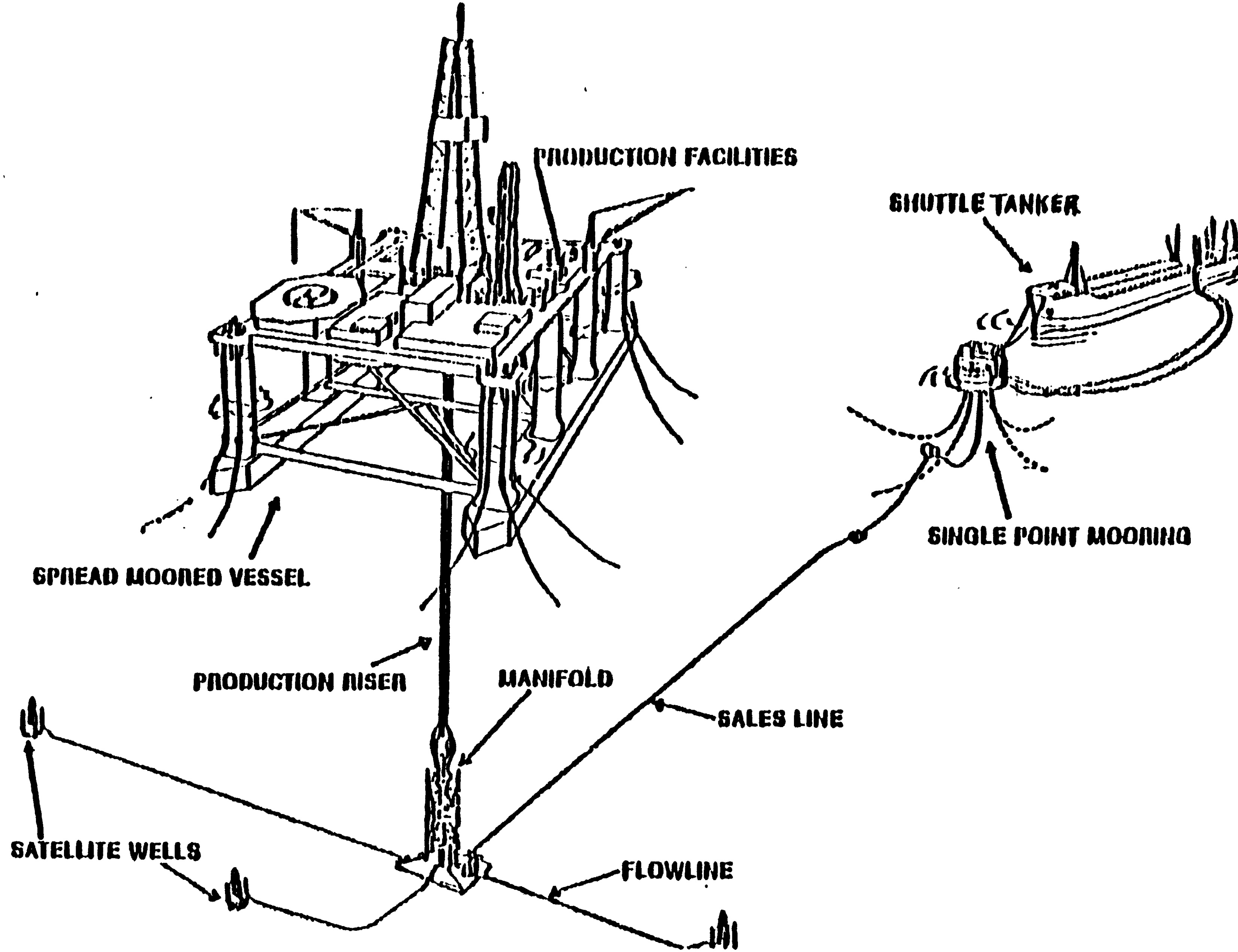


Figure 37.--Diagram of semi-submersible production system.

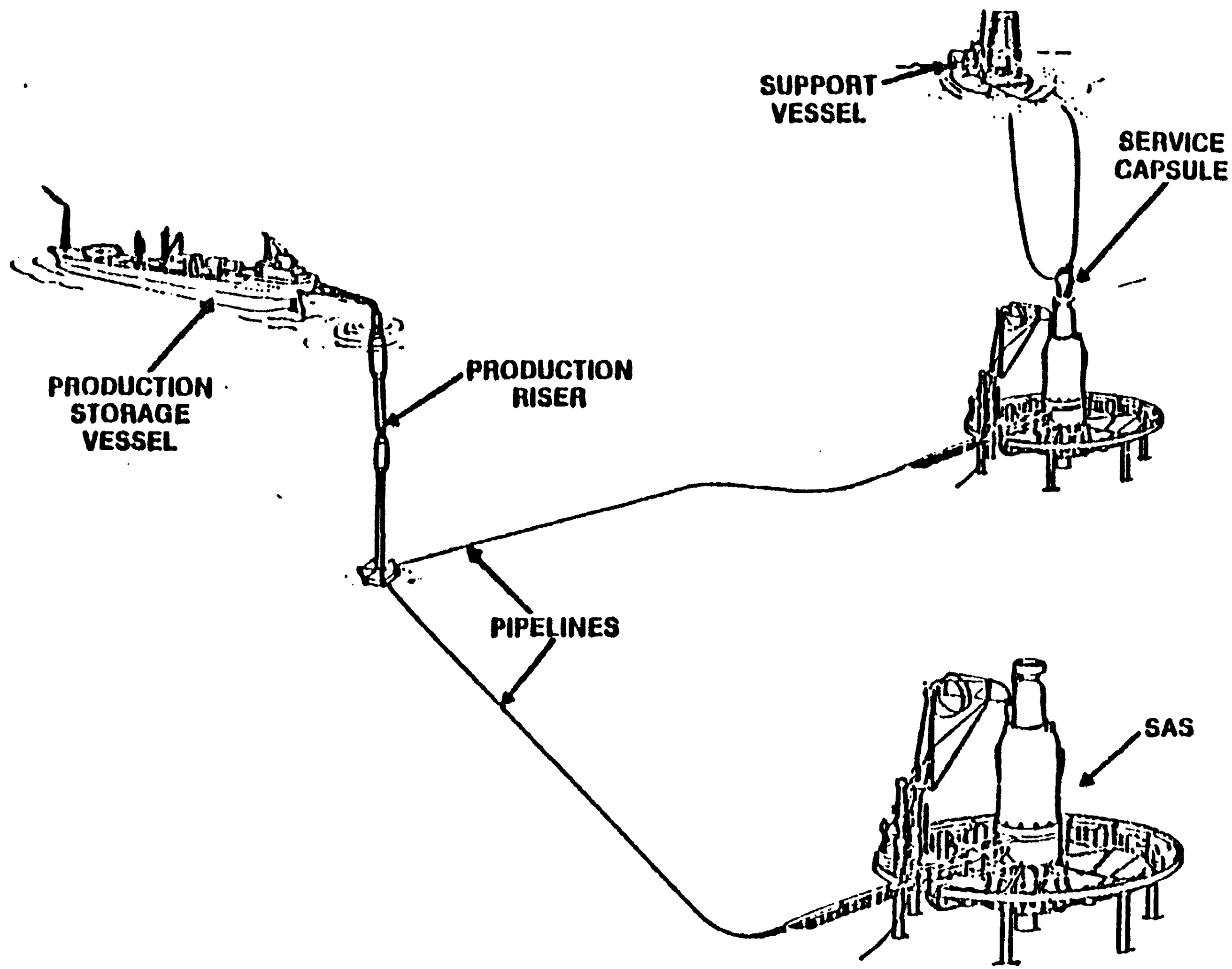


Figure 38.--Diagram of subsea atmospheric production system (SAS).

Subsea production system.--This system consists of wells drilled through an on-bottom template and completed as special subsea trees that connect to a manifold circling the well bay area (fig. 39). The manifold is connected by pipeline to a production riser and then to production facilities on a floating vessel. Wells are maintained by use of "through flowline" tools from the surface. Sea-floor equipment is maintained by a special-purpose manipulator operated from the surface which runs on a track around the well bay area. This system has been installed in 270 ft (81 m) of water, and tests indicate the capability of the system to 2,000 ft (610 m) of water and greater.

One-atmosphere system.--This system consists of subsea satellite wells and a manifold center housed in dry chambers (fig. 40). Workers can enter the chambers from a manned, tethered bell to conduct routine maintenance on sea-floor equipment. Wells are maintained by use of "through flowline" tools from the surface. The manifold center is connected by pipeline to the base of a single-point-mooring production riser, which is connected to production facilities installed on a tanker. Oil is transported to market by shuttle tankers which dock periodically depending upon production storage capacity. This system has been installed in 450 ft (137 m) of water and has been designed for application in 3,000 ft (914 m) of water.

Although deep-water production technology is lagging behind deep-water drilling technology, we believe that subsea facilities and possibly platforms can eventually be installed in water depths comparable to those achieved by floating drilling. The main extensions of technology needed are:

1. For subsea systems, technology to allow subsea power generation, shore-based submarine servicing of underwater installations, and sea-floor storage and pumping facilities.

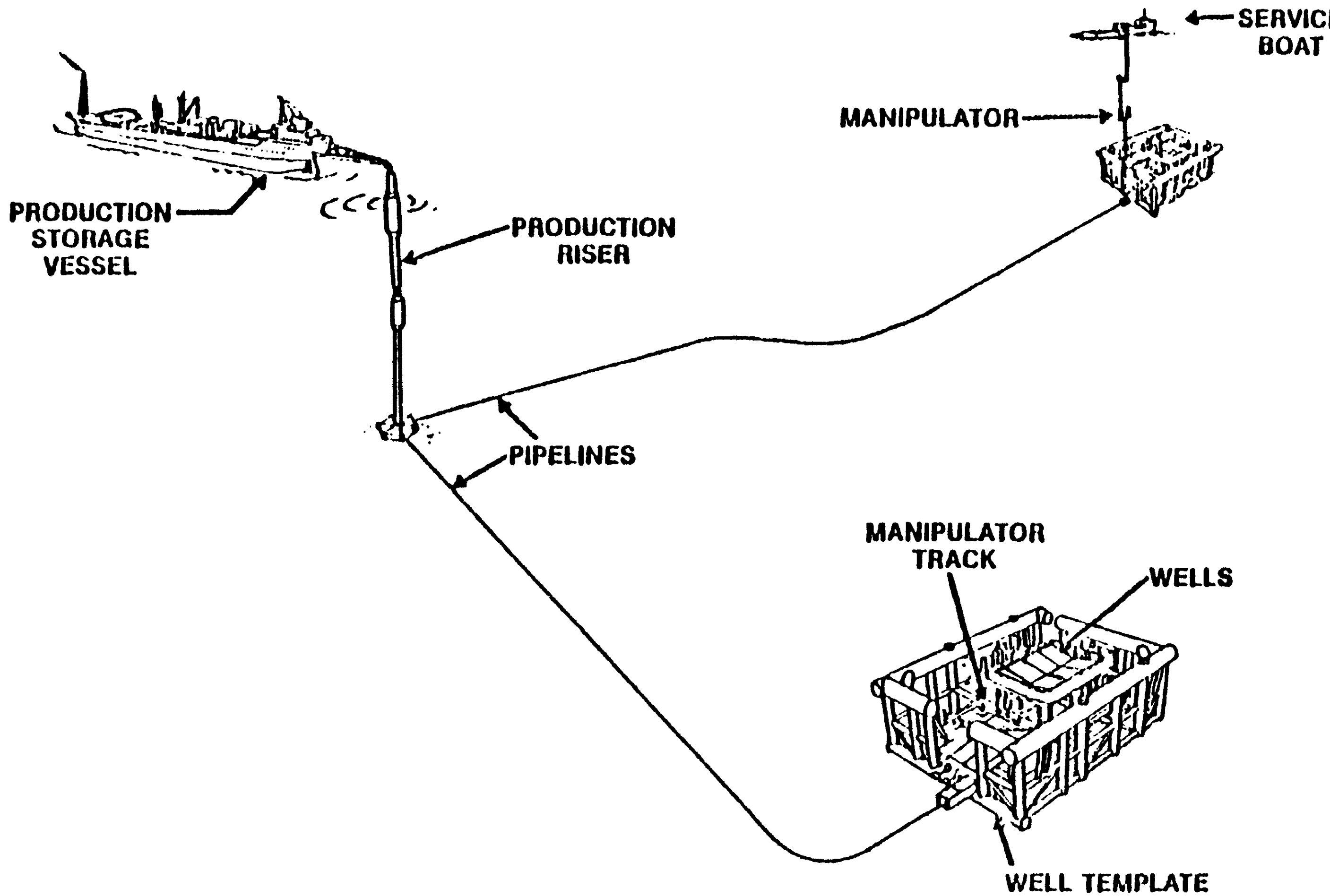


Figure 39.--Diagram of subsea production system (SPS).

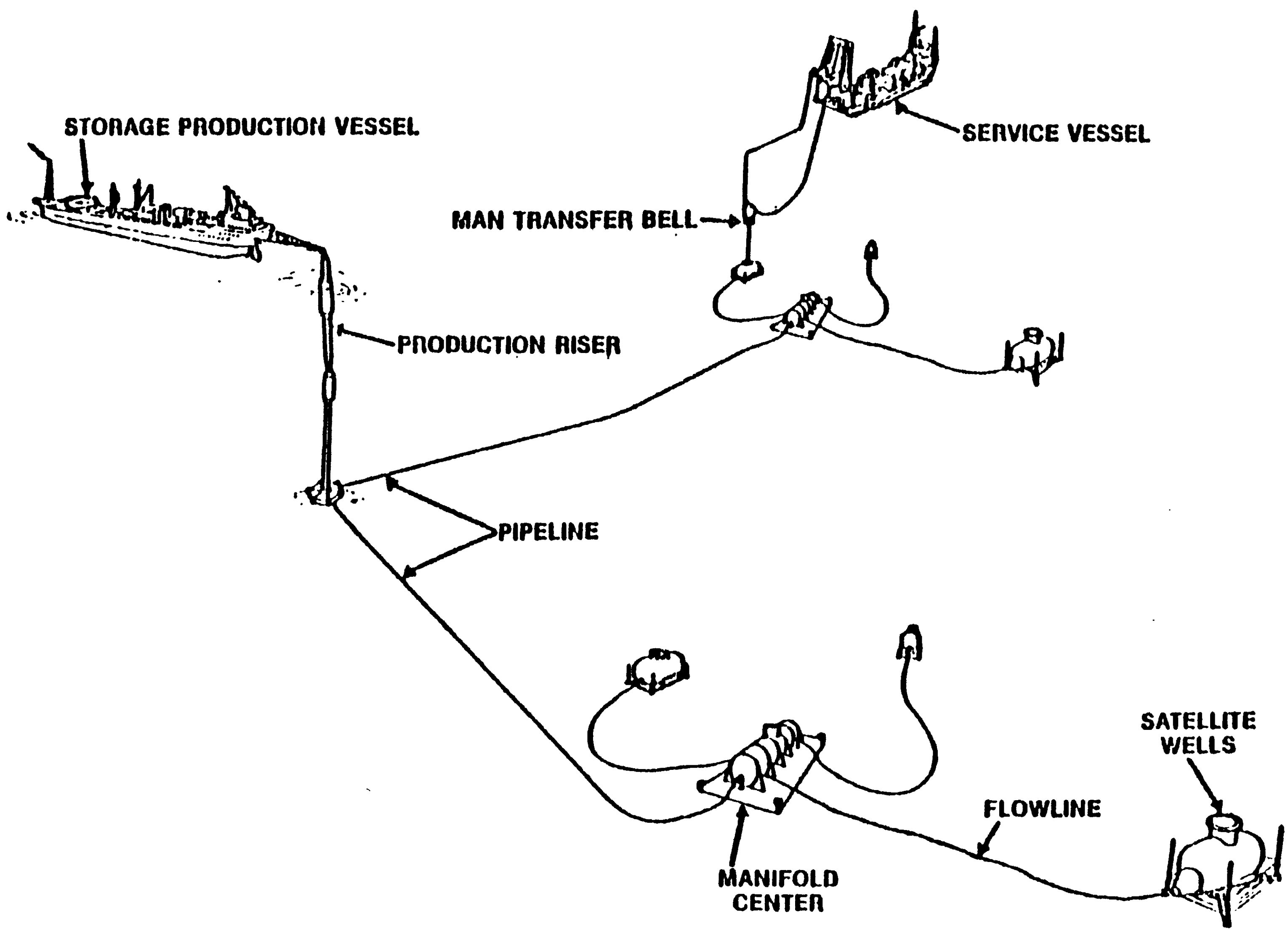


Figure 40.--Diagram of one-atmosphere chamber production system.

2. Production risers able to withstand high tension and pressure.

3. Further refinement of dynamic positioning techniques for surface vessels.

Technology is currently being devised to provide the methods and equipment for oil and gas production in deep water. The success of future endeavors in the Gulf of Mexico in deeper water will depend on economics and petroleum resources because adequate technology will be available.

## Deep-water Pipelines

Pipelines are an integral part of any large-scale production operation. During the past several years, the petroleum industry has focused a considerable amount of attention on the subject of deep-water pipelines. Equipment capable of installing deep-water pipelines has been designed, built, and tested, and several deep-water pipelines have been installed. The present water depth record for pipeline installation is 2,000 ft (610 m). Some pipeline installation methods are described below.

Conventional lay method.--In this method, pipe joints are welded together on a lay barge and then lowered to the seabed in a controlled configuration (fig. 41). The main limitation of this method is the stress that affects the bending areas of the suspended pipe. As water depth increases, more tension and mooring-system capacity is required to control bending of the pipe.

Inclined-ramp method.--An inclined-ramp method eliminates the bending stress in pipe as it leaves the barge (fig. 42). Rapid welding techniques, currently being devised required to make this system economical. A project which is in the planning stage would use this method to lay a pipeline in 6,000 ft (1,829 m) of water.

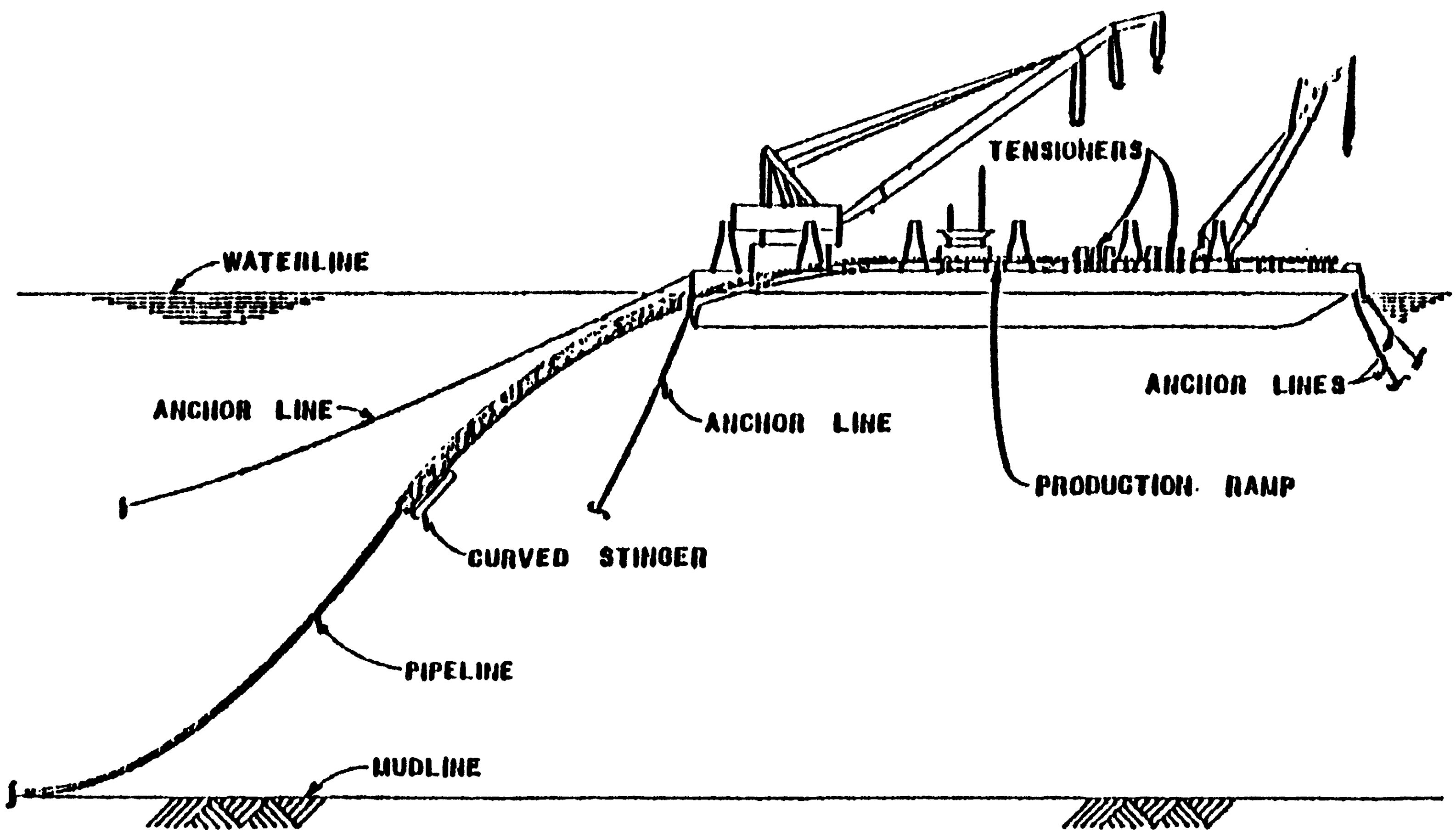


Figure 41.--Diagram of conventional pipeline lay-barge and stinger system.

Reel method.--This method uses a continuous pipe string assembled onshore and coiled onto a reel (fig. 43). During laying operations, the pipe is pulled off the reel and straightened as it leaves the ship. The main limitations of the reel method are mainly due to the consequences of coiling and uncoiling the pipe. By use of this method, pipe as great as 16" (41 cm) in diameter can be laid in water as deep as 3,000 ft (914 m), and smaller diameter pipe can be laid in even deeper water.

Bottom-tow method.--In this method, pipe is fabricated onshore and fitted with buoyancy and compensation weights, which hold the pipe just off the sea floor during the tow (fig. 44). When the pipe is in place, the weights are removed to settle the pipe to the sea floor. The major limitations of this method are the vulnerability of the pipe to environmental conditions during the tow and the difficulty in maneuvering long strings of pipe. Feasibility studies indicate that this method can be extended to a water depth of at least 8,000 ft (2,435 m).

The major extensions of technology needed to continue to increase the water depth capacity of pipeline installation and operation are:

1. Practical single-station pipe-joining techniques.
2. Improved barge mooring-systems.
3. Reliable mechanical pipe connectors to replace welding.
4. Unmanned systems for inspection, repair, and other activities required to support offshore pipeline installation and maintenance.

The pipeline industry currently has the capability to lay large-diameter pipe in water depths exceeding 1,000 ft (305 m). Studies indicate that pipe at least 20 in. (51 cm) in diameter can be laid in depths of 3,000 ft (914 m)

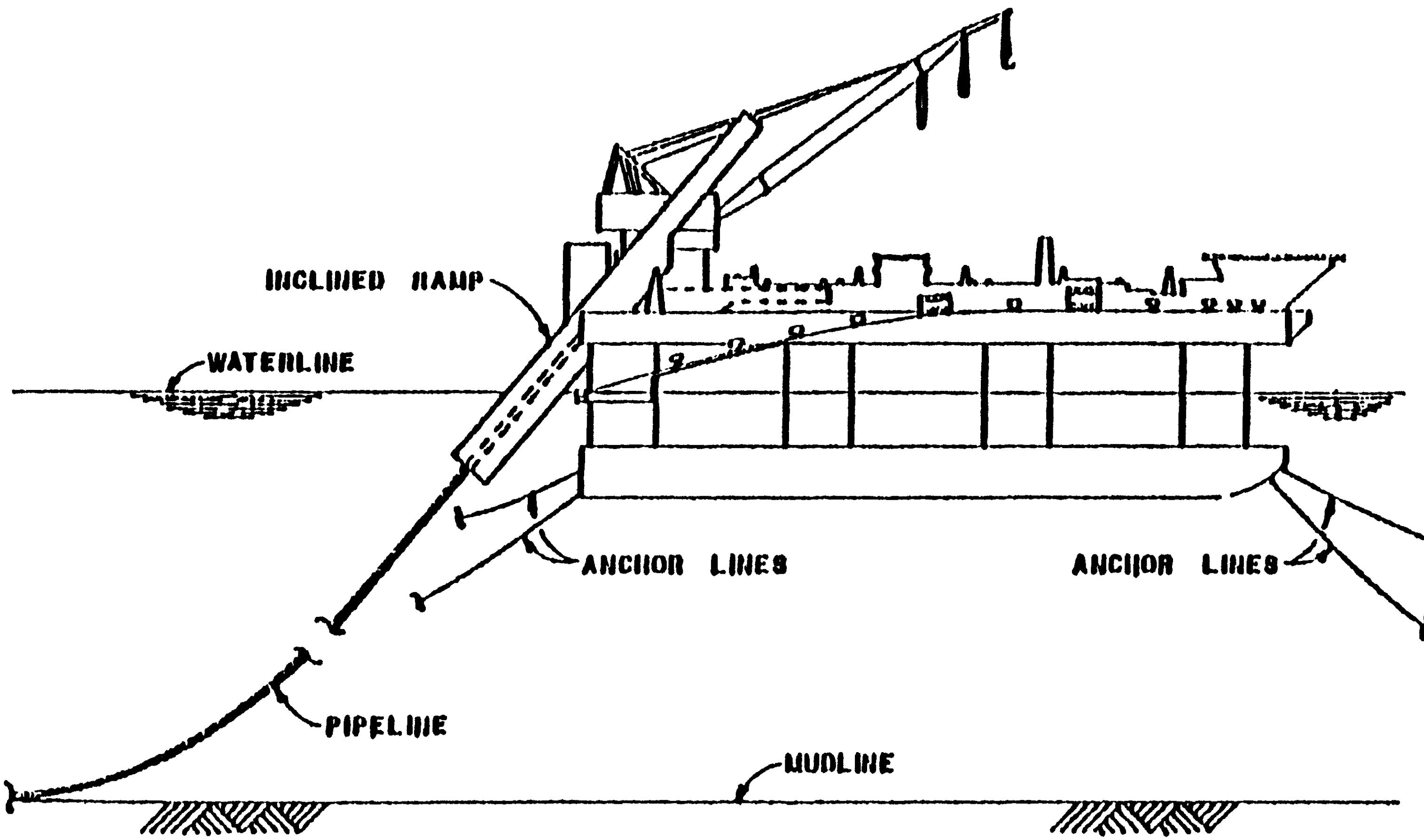


Figure 42.--Diagram of inclined ramp pipeline lay-method.

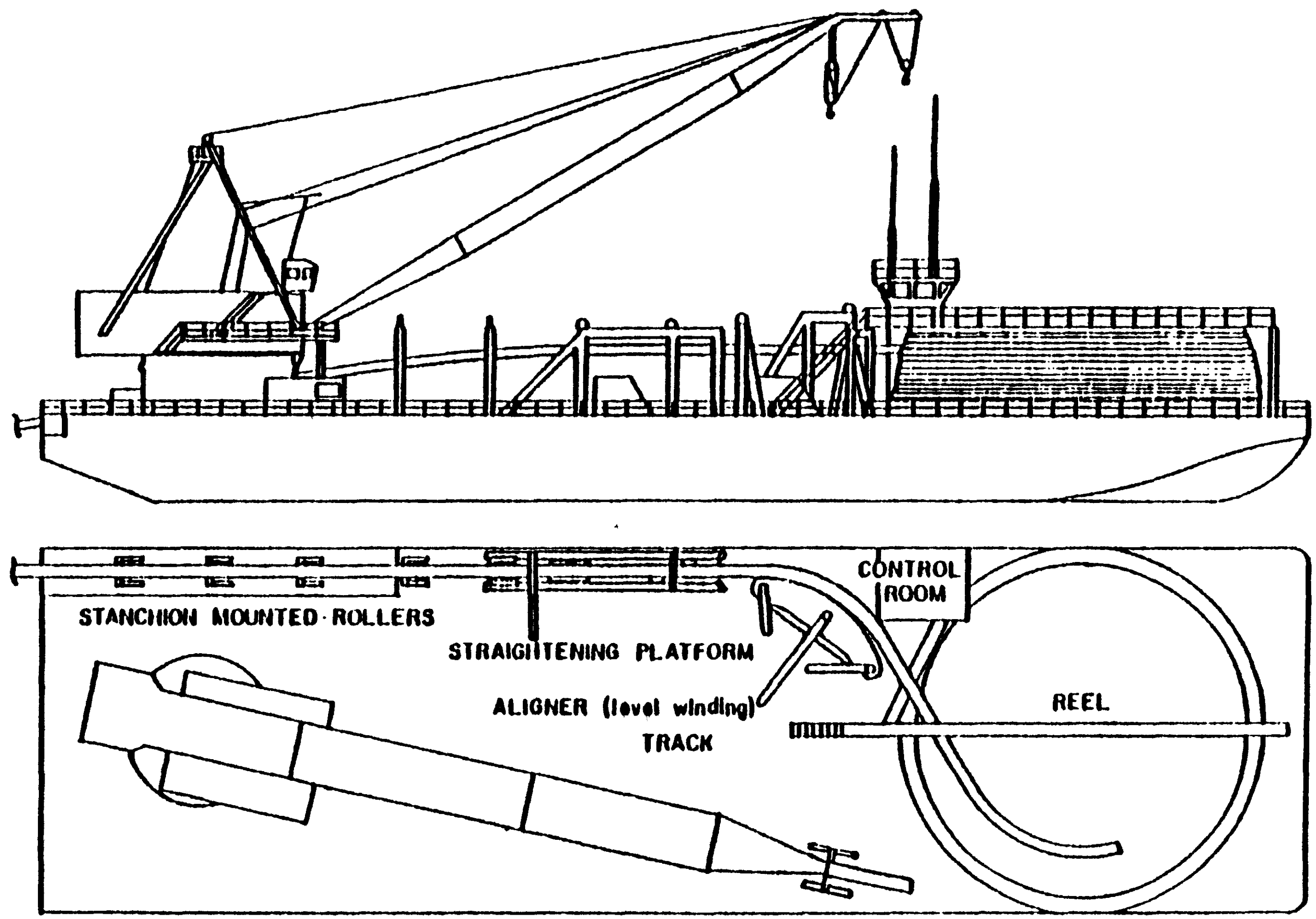


Figure 43.--Diagram of reel-barge pipeline lay-method.

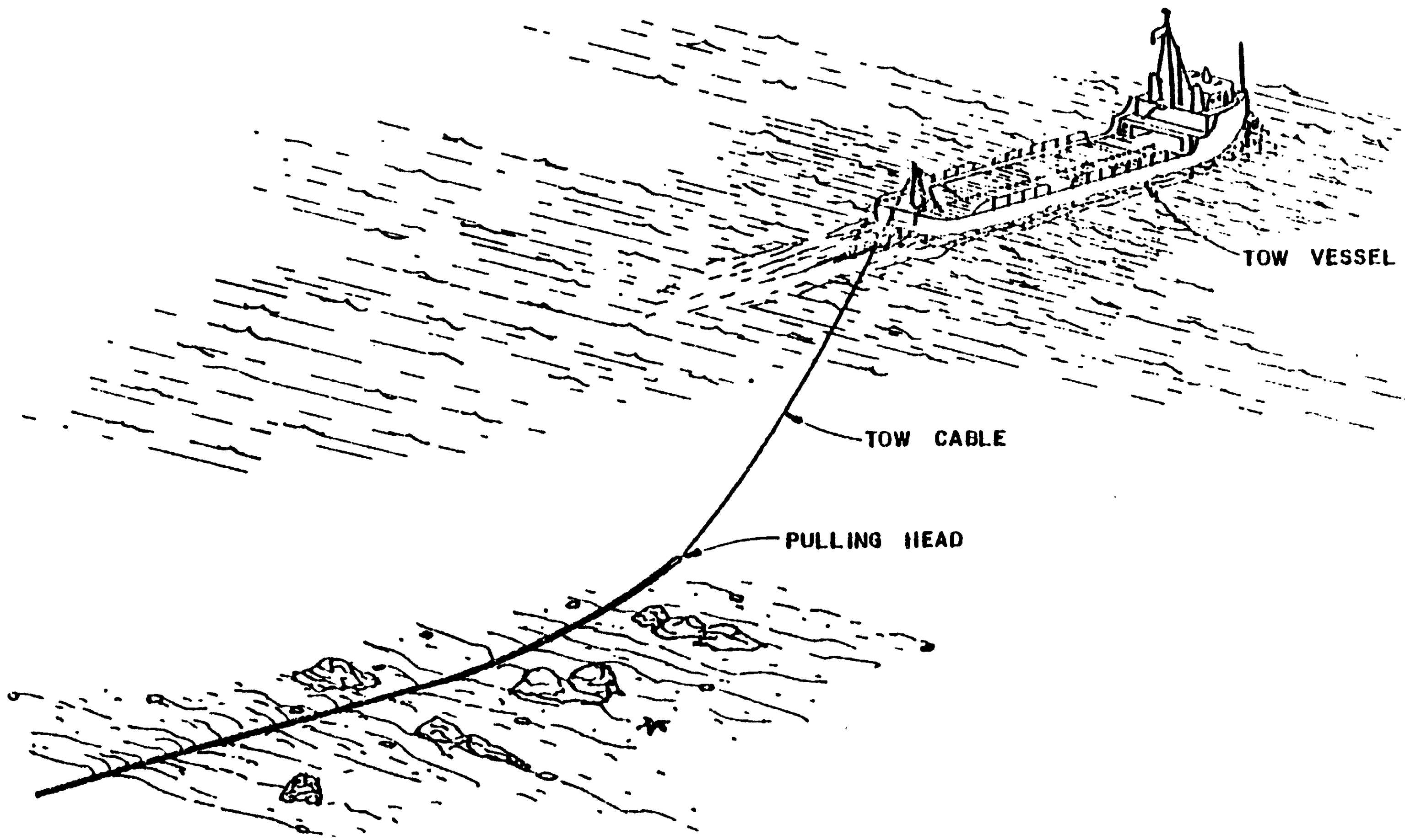


Figure 44.--Diagram of bottom-tow pipeline lay-method.

by use of existing techniques and knowledge. Pipe 30 in. (76 cm) in diameter is now available for 3,000 ft (914 m) of water. If economic conditions are favorable and petroleum resources are adequate, deep-water pipeline technology can be developed as an extension of existing conventional techniques.

## Offshore Loading Terminals

In the event that petroleum products cannot be transported from a deep-water location by a pipeline, some form of offshore loading terminal will be required instead. Three loading systems that are potentially applicable for use in deep water are the SALM (single anchor leg mooring), the ALP (articulated loading platform), and the SPAR (fig. 45).

The SALM system consists of a buoy at the surface, which is attached to a base on the sea floor by a single anchor chain or leg. Oil is pumped through a flexible hose from the sea floor to a tanker at the surface. The deepest SALM presently installed is in 530 ft (161 m) of water.

The ALP system consists of a base structure and a universal joint connected to a vertical articulated column. At the top of the column is a structure having a rotating head and a flow boom to support a loading hose. This system is designed for uninterrupted loading operations in high winds and rough seas. The deepest ALP presently installed is in 475 ft (145 m) of water.

The SPAR system consists of a vertical floating storage tank. It is stationed in the water by a multileg catenary mooring. Off-loading is accomplished by a retractable boom mounted on a turntable. The deepest SPAR presently installed is in 460 ft (140 m) of water.

Experts on off-loading terminals believe that present technology will allow existing SALM and ALP systems to be used in water as deep as 2,000 ft

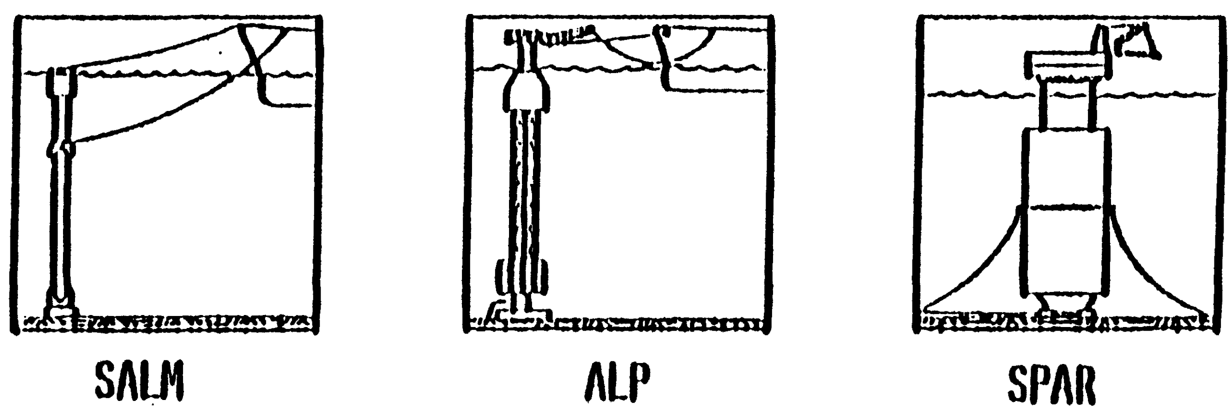


Figure 45.--Diagram of rigid or moored single-point moorings (SPM).

(610 m). Studies indicate that terminals for water depths greater than 2,000 ft (610 m) may utilize a combination of various concepts known today. It is likely that in very deep water, pipelines will carry oil to loading terminals in shallower water.

### Supporting Systems for Installation, Inspection, and Repair

Because most of the water depths in the study area exceed the range in which divers can work effectively, inspection, maintenance, and repair of underwater installations will have to be accomplished by alternative methods which extend work capabilities beyond the range of conventional diving. Underwater work systems are of two major types--manned maintenance systems and remotely controlled maintenance systems.

Figure 46 shows some examples of manned systems. The suits have depth capabilities of 2,000 ft (610 m) and can be built for 3,000 ft (914 m). The manipulator bell has a depth capability of 4,500 ft (1,372 m). Some untethered submersibles can be operated in 8,300 ft (2,530 m) of water.

Remotely controlled vehicles totally eliminate risks to human life, while providing many of the capabilities of the manned systems. These systems are integral parts of any deep-water production system or pipeline.

The capability exists today to provide underwater inspection, maintenance, and repair services safely and efficiently in water as deep as 3,000 ft (914 m). No major technological problems are known that would prevent us from extending this capability should the need arise.

## Summary

If oil and gas are found in commercial quantities in the assessment areas of the Gulf of Mexico, the resources will probably be exploited by use of extensions and refinements of current technologies. Breakthroughs in technology or radical changes in concepts will probably not be required.

Knowledgeable observers predict that, by the year 2000, the methods and equipment for drilling and production operations in water as deep as 10,000 ft (3,048 m) will be available (figs. 47, 48, and 49). However, many factors, including the political climate, leasing programs, lag times of 6 to 10 years from inception to completion of projects, and producing wells of low volume would tend to delay actual production from these areas by several years. Although developing and producing oil and gas in deep water will be extremely expensive, the findings of this study indicate that no insurmountable barriers will exist that would prevent deep-water production in the study area in the Gulf of Mexico within the next 20 to 30 years. The petroleum industry is confident that existing technology can be extended to develop oil and gas fields in deeper water.

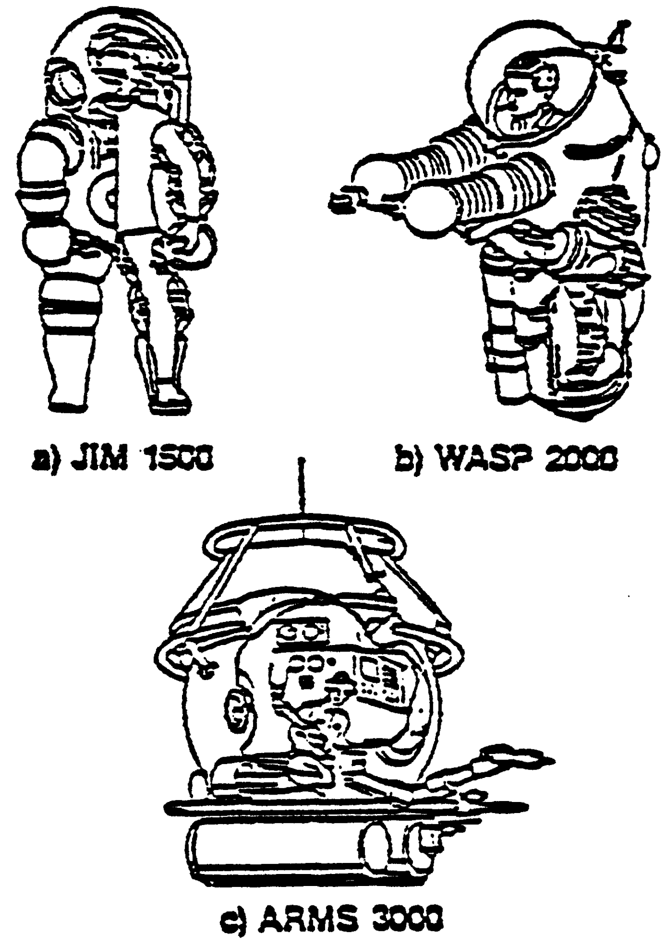


Figure 46.--Diagrams of manned subsea maintenance systems.

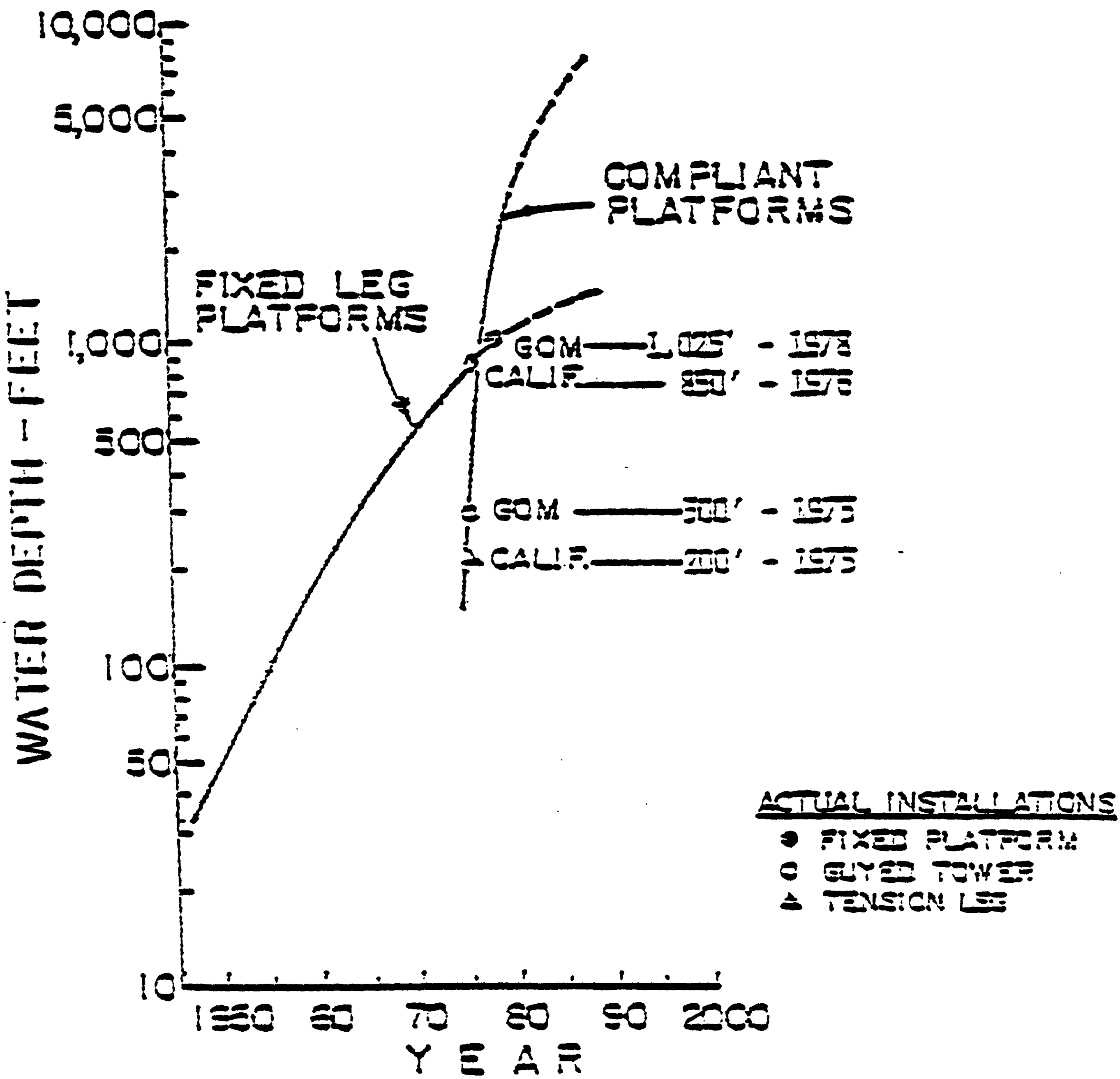


Figure 47.--Graph showing projection of platform installation capability. GOM, Gulf of Mexico.

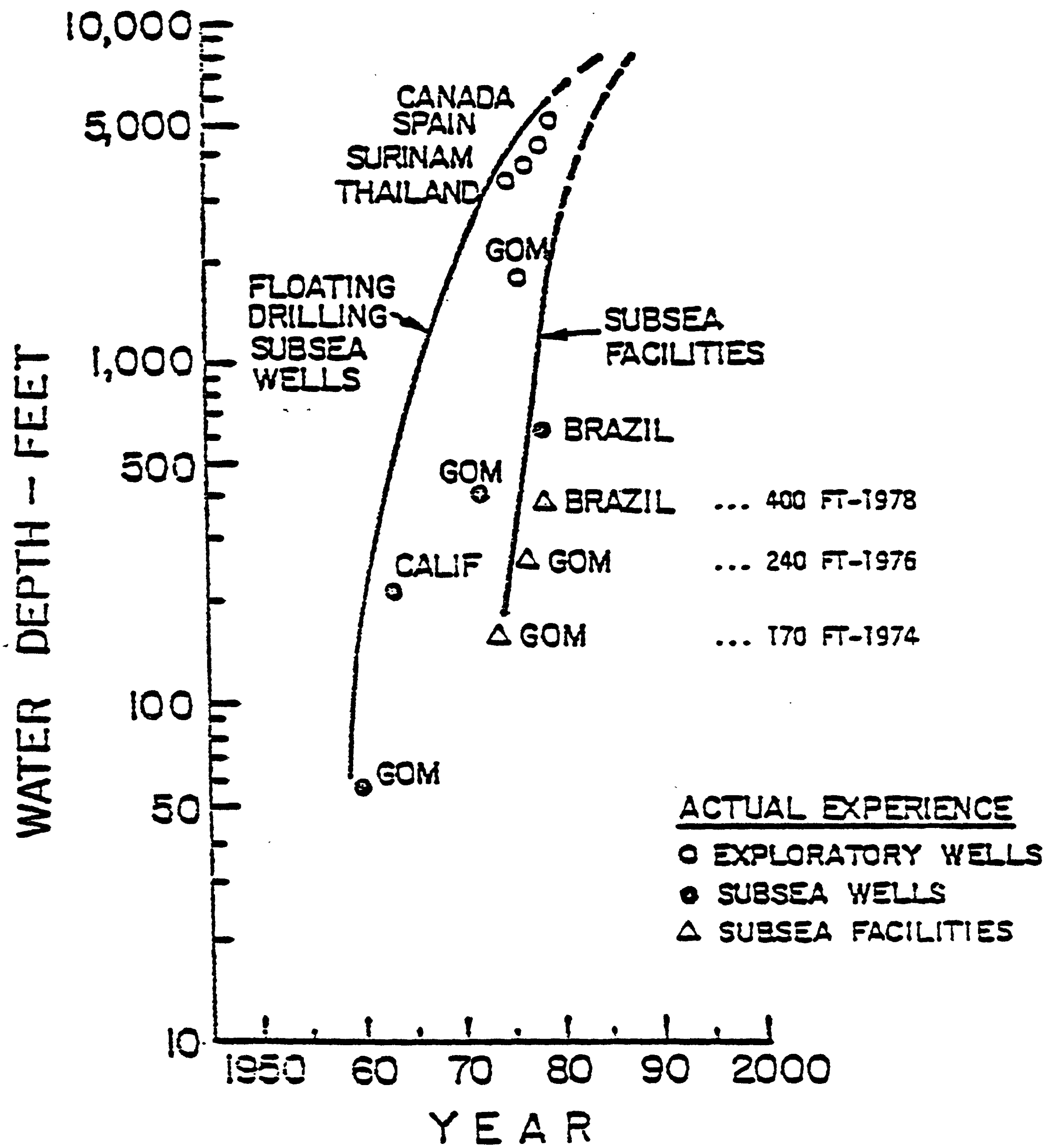


Figure 48.--Graph showing projection of floating and subsea drilling facilities. GOM, Gulf of Mexico.

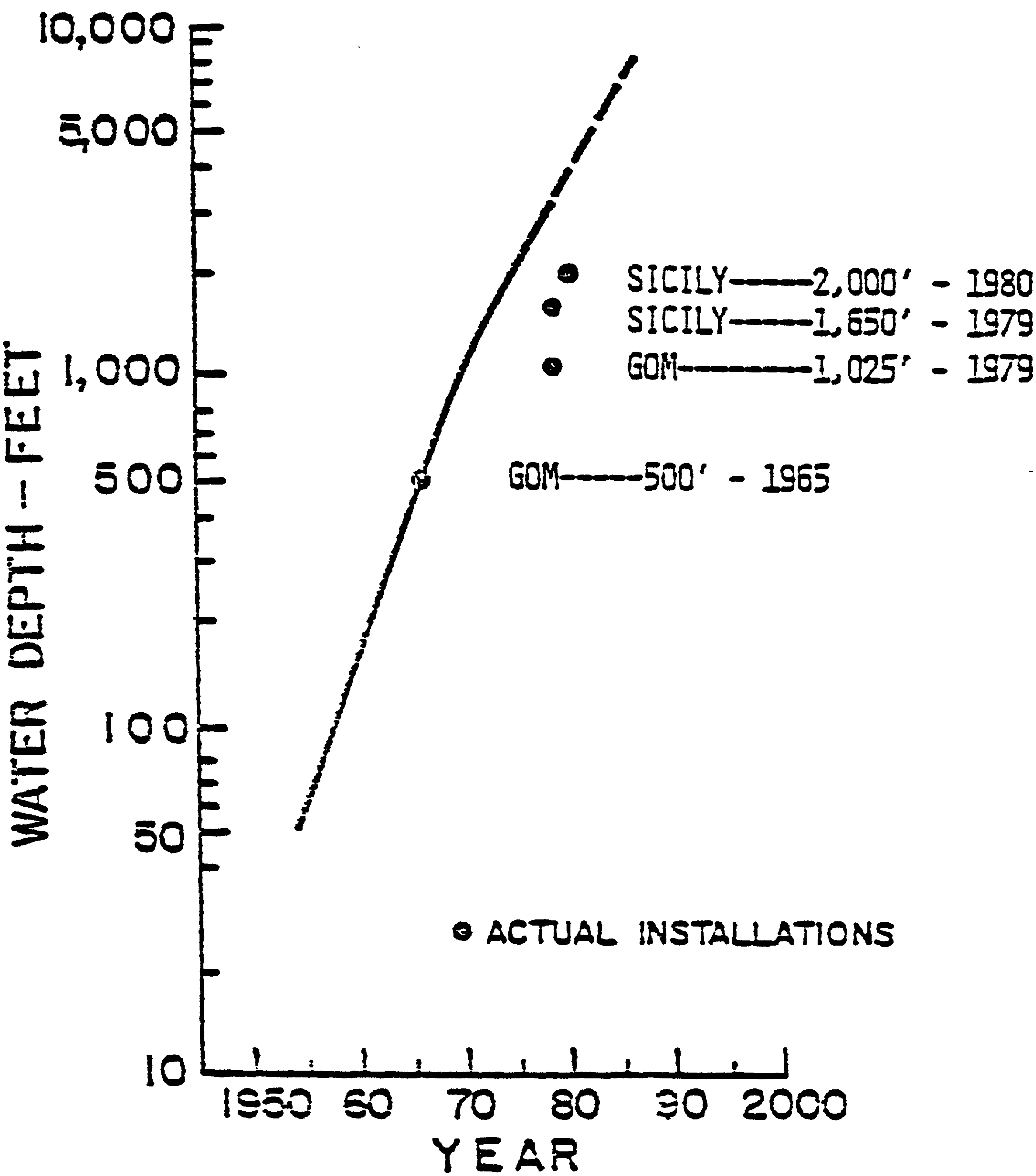


Figure 49.--Graph showing projection of pipeline-laying capability. GOM, Gulf of Mexico.

Appendix I

GEOPHYSICAL METHODS AND INTERPRETATION

By

Ray G. Martin and Richard Q. Foote

## Reflection Seismology

The technique of recording seismic-reflection data at sea is based on the generation of a series of seismic-energy pulses in the water at precisely controlled and closely spaced intervals of time. The downward directed wave front of each pulse travels toward the sea floor and is partially reflected at boundaries between materials of differing seismic impedance. Such boundaries occur at the sea bottom and at various subbottom layers across which physical properties change. The energy reflected from these horizons returns to the sea surface where it is detected by an array of hydrophones, converted to electrical energy, and transmitted through amplifiers and band-pass filters to recording instruments.

Seismic-energy sources used to produce the reflection profiles for this study range from single-channel, small-volume air guns and air-gun arrays consisting of a variety of volumes, to electrical-arc units. Seismic-energy pulses are generated by air-guns by the instantaneous release of a measured volume of compressed air. Electrical-arc sources produce seismic pulses by the instantaneous release of electrical energy which arcs through the seawater from a source tip to the grounded frame of the arcer array. Air-gun arrays are commonly used for multichannel seismic recording because they characteristically provide a sharp, quickly decaying pulse. USGS-USNAVOCEANO and most other single-channel surveys in the assessment area used electrical-arc energy sources.

Single-channel-Profiles

Single-channel seismic-reflection profiles are recorded aboard the vessel synchronously with the arrivals of reflected energy. Such profiles are generated on a graphic recorder whose function is to transform reflected signals into a mode that reveals geological information. This is accomplished by using a stylus to produce a burn mark each time a sound pulse in the proper frequency range is detected as the stylus moves across the recording paper. Because the stylus traverses the paper at a predetermined rate of speed, incoming reflection signals are spaced in vertical relationship dependent upon the time of their arrival relative to the originating time of the sound pulse. The repetition of shot after shot as the ship moves over the bottom and the resulting alignment of marks burned side by side on the slow-moving recorder paper integrates the successive signals reflected from a given horizon into a line whose position on the record indicates the depth of the horizon below the sea surface. Reflection signals from the various horizons beneath the ship's track are thus summed by the recorder into an approximation of a geologic cross section. The seismic-reflection profile, however, is only an approximate cross section because reflecting horizons are scaled in units of time required for seismic waves to travel from the source to the horizon and be reflected back.

Seismic-reflection profiles available for this study are depth scaled in seconds of two-way seismic travel time; such profiles are referred to as "time-depth sections". Because of the general increase in the velocity of seismic waves with depth as they pass through the various media of water and strata, reflections which represent stratigraphic layers are increasingly displaced upward in the section as deeper and deeper layers are reflected. The result is a cross section which is increasingly compressed proportional to depth and overall recording time. In order to gain a perspective of true depths and thicknesses in a time-depth section, velocity functions which express the distance of seismic-wave transmission through rock units per unit of time must be applied. True depths to a given horizon can thus be computed by multiplying the average velocity of the overlying section by one-half the travel-time depth to the horizon. Unit thicknesses may be computed by subtracting the depths of successive horizons. Conversion of time-depths requires that velocities at which the sound waves traveled through the various media be known. Velocity information, however, cannot be derived solely from single-channel recordings.

In single-channel recordings, repetitive sound pulses customarily are generated at predetermined increments of time (every 6 seconds, for instance) completely independent of changes in the ship's speed and position along track. The horizontal scale of a typical single-channel recording is thus, disproportionate to the distance made along course per unit of time. Because of the variations in velocity in sediment layers below the sea floor and the variations in the ship's speed over the bottom, vertical and horizontal scales vary continually. The distortions, however, are generally small in single-channel records illustrated in this report.

## Multichannel Seismic Profiles

Multichannel seismic data are recorded on magnetic tape, and reflection arrivals at individual hydrophones, or hydrophone clusters (channels), are kept separate. Data thus recorded are processed through complex computer programs that composite the signals arriving from common depth points in the substrate. Common-depth-point events are scaled vertically with respect to composite arrival times to produce a trace of reflection events arising from individual horizons. Consecutive reflection traces are recorded from a computer-generated image producing a cross section of seismic-reflection horizons much in the same manner as single-channel data are displayed on a graphic recorder. Unlike conventional single-channel recording, however, shot-times are based on the ship's position relative to the bottom regardless of the time required for the ship to travel the predetermined distance. For example, multichannel data are commonly recorded on the basis of one shot every 164 ft (50 m) of ship travel over the sea floor. Horizontal scales in multichannel data are thus constant. Multichannel data are still scaled vertically in seismic travel time (from source to reflector to receiver), but because differences in reflection arrival times from a given depth point for a horizon are known for each channel in the receiving array, velocities of sound transmission through the various media can be determined and used to compute true depths and interval thicknesses in the seismic section.

## Refraction Seismology

Seismic-refraction data depict the layered structure of the Earth's crust at relatively widely spaced points on a long line of survey extending as much as 50 nmi (93 km). Early refraction surveys used two vessels, one for generating the seismic energy pulse and the other for recording arrival times of seismic waves. When sufficient time-distance information had been collected, the roles of the vessels were reversed in order to correct for geologically and geometrically induced aberrations in the data. More modern techniques use a single vessel and ocean-bottom seismometers placed at each end of the survey line. The seismometers transmit arrival times back to the vessel as it steams from one end of the line to the other. Graphs of arrival time versus distance provide a measure of crustal velocities and depths of velocity contrasts. Seismic-refraction data yield information relative to the structure and thickness of the deep crustal layers (basement) and the upper regions of the mantle. Seismic-refraction data thus provide a gross picture of the structure of the Earth's crust, whereas seismic-reflection profiles provide the minute detail of the depositional and structural characteristics present in the upper layers of the crust.

## Gravity and Magnetic Data

Data relating geologically induced variations in the Earth's gravity and magnetic fields in the Gulf of Mexico region were not extensively used in this resource-assessment study. Variations in these potential fields, or anomalies, generally emanate from geological changes within the crustal layers of the basin. These data corroborate the presence of a relatively thin, dense oceanic basement crust in the central sector of the basin, grossly identify areas underlain by continental and transitional crust, reflect the general extent of salt-diapir provinces in the margin and deep basin regions, and suggest the general absence of tectonic belts and intrusive igneous rocks in the prospective sequence of strata in the assessment province.

## Interpretation of Geophysical Data

The geological analysis of specific assessment areas is largely based on interpretations drawn from seismic-reflection profile data supplemented by information provided by seismic-refraction surveys, stratigraphic test drilling, and projection of onshore and subsurface geology. Seismic-reflection data portray the cross-sectional aspects of the depositional and structural history of the basin. Quantitative data generated by seismic-reflection and seismic-refraction surveys allow reconstruction of the true dimensions of stratigraphic layers and structural features and describe in relative terms their depositional and deformational histories. Where drill-hole data are present, more precise interpretation of geophysical data, such as geochronologic (stratigraphic age) and lithologic (distinction of gross rock properties such as sand, shale, limestone, etc.) determinations, can be applied. Seismic-wave velocities derived for the various seismic-stratigraphic intervals can be equated with gross lithologic aspects owing to the relationship between velocity and rock density. For instance, it is relatively easy to distinguish clastic sediments (sands and shales) from carbonate rocks (limestones), evaporites (salt and anhydrite), and basement (igneous and metamorphic) rocks on this basis, but virtually impossible to discriminate sand from shale without nearby well control. Familiarity with the depositional history and lithologic characteristics of the stratigraphic sequence present in the basin as derived from surface and subsurface geologic information onshore and from shallow coring and deep drilling in the offshore forms a general basis for gross assumptions supportive of lithostratigraphic interpretation of geophysical data.

In the Gulf of Mexico Maritime Boundary region, seismic-reflection profiles portray a variety of characteristics peculiar to lithostratigraphic units. Well-layered units defined by frequent, closely spaced reflections in an area known or presumed to be a site of clastic deposition at the time the interval was deposited generally are considered to consist of alternating beds of sand and shale. Such units, however, can be seismically well stratified and devoid of appreciable amounts of sand as a result of significant changes in physical properties through a sequence of fine-grained sediment. Units in a clastic province characterized by discontinuous reflection events and seismically transparent zones may be interpreted either as fine-grained muds or shales deposited as particles that settled slowly through the water column or as sediment dumped rapidly from downslope soil movements and debris flows. Seismic units representing carbonate rocks are characterized by relatively high interval velocities and range from seismically well stratified to amorphous units not characterized by any coherent and continuous reflections. Evaporitic deposits, such as salt, are similar in character and interval velocity structure to seismically amorphous carbonate strata composed of incoherent reflections. Deposits of stratiform evaporites are not, therefore, easily distinguished from carbonate strata. On the other hand, Gulf of Mexico salt deposits have mobilized and flowed into pillowlike features and broad piercement structures (diapirs) under the influence of pressure exerted by overlying sediment. Such features are not characteristic of competent, carbonate rocks and, thus, deformed evaporite deposits can easily be distinguished from seismically amorphous carbonate strata. In addition, gravity, magnetic, and velocity data provide information that distinguish salt structures from igneous plugs and flows.

Except in areas near drill-hole control, where geological aspects of the sequence are known to the depth of drilling, stratigraphic age and lithologic interpretations in the following discussions represent projections and assumptions drawn from a variety of information and inferrence available from within the offshore Gulf basin and around its emergent margins. Our stratigraphic interpretations, particularly for the Mesozoic sequence, then must be considered at best, as approximations predicated on extensive research rather than factually based conclusions.

APPENDIX II

# PETROLEUM GEOLOGY OF THE GULF OF MEXICO[1]

By

Richard Q. Foote and Ray G. Martin

## Habitat of Oil and Gas

Significant accumulations of hydrocarbons depend on many factors: 1) substantial thicknesses of sedimentary rocks deposited in a marine environment and containing large amounts of organic material; 2) a regional thermal history and suitable environment for the maturation of organic material into oil and gas; 3) hydrodynamic conditions permitting migration of hydrocarbons; 4) proper timing of petroleum generation and migration to ensure entrapment of hydrocarbons; 5) adequate geologic traps for the accumulation of hydrocarbons; 6) an impermeable seal over the reservoir to prevent the upward escape of hydrocarbons; and 7) porous and permeable reservoir rocks (R. E. Miller, oral commun., 1978).

The Gulf of Mexico has long been a major oil and gas producing region because these conditions are met, and exploration has followed the natural progression from onshore, bay, and estuary development to the offshore areas.

## Gulf of Mexico Producing Areas

The Gulf of Mexico basin can be divided into three distinct producing regions: 1) The northern Gulf region, consisting of the clastic province onshore and offshore Texas, Louisiana, and Mississippi; 2) the Golden Lane region in the western Gulf, and 3) the Gulf of Campeche in the southwest.

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[1]This appendix addresses factors critical to the generation and accumulation of petroleum resources and summarizes the magnitude of petroleum production on the continental shelves adjacent to areas discussed under Petroleum Geology of the Gulf of Mexico Maritime Boundary Assessment Areas.

Three additional prospective regions exist: 1) the eastern Gulf carbonate platform offshore Florida and Alabama; 2) the Campeche Bank, from the Yucatan Channel to the Gulf of Campeche; and 3) the deep Gulf of Mexico, including the Mississippi Fan, Sigsbee Plain, and Sigsbee Knolls (fig. 1).

## Northern Gulf Region

Bryan and others (1980) reported that 416 oil and gas fields have been discovered in the U.S. Gulf of Mexico OCS. Estimates of original recoverable resources for the 385 of these fields that have been mapped are 7.52 billion barrels of oil and 76.3 trillion cubic feet of gas. Production during more than three decades has resulted in a cumulative yield of 4.76 billion barrels of oil and 39.3 trillion cubic feet of gas. The number of still productive fields has been reduced to 370 (Bryan and others, 1980); 15 previously active fields are now depleted and abandoned. The remaining recoverable reserves in active fields are 2.76 billion barrels of oil and 37 trillion cubic feet of gas.

As of December 31, 1979, the status of wells in the Gulf of Mexico OCS areas was:

| | |
|---|---|
| Active wells | |
| Oil | 2,576 |
| Gas | 3,266 |
| Shut-in wells | |
| Oil | 1,039 |
| Gas | 704 |
| Plugged and abandoned wells | 7,319 |
| Other wells | 1,360 |
| TOTAL wells | 16,264 |

Production during calendar year 1979 was: 274,604,462 barrels of crude oil and condensate (an average of 752,340 barrels per day) and 4,670,112 million cubic feet of gas (an average of 12,794.8 million cubic feet per day) (U.S. Geological Survey, 1980).

The hydrocarbon-producing region in the northern Gulf is part of the Gulf Coast basin which forms the northern Gulf margin. The northern Gulf margin is primarily a Cenozoic terrigeneous basin (fig. 7) in which the cumulative thickness of the sediments is greater than 10 km (fig. 6). Although Jurassic, Cretaceous, and lower Tertiary strata are widespread in the basin, the main hydrocarbon-bearing intervals offshore are of Miocene, Pliocene, and Pleistocene age. Figures 50, 51, and 52 show the general areas of Miocene, Pliocene, and Pleistocene production, respectively, in the Gulf of Mexico OCS. Oligocene production in State of Texas offshore areas is not shown although these strata account for significant onshore production. In the offshore, reservoirs of Miocene age contain the greatest percentage of discovered gaseous and liquid hydrocarbons (table 4).

## Golden Lane Region

In the western Gulf of Mexico, 11 oil-producing fields are grouped in three offshore areas (fig. 53). The three areas are: Faja de Oro, a complex of nine platforms atop nine separate Lower Cretaceous reef fields; Arenque, a three-platform field; and Santa Ana, a seven-platform field at the south end of the Gulf of Campeche. Production at Arenque is from a Jurassic reef and the source beds are Jurassic shales.

Production information for some fields in the offshore Faja de Oro is presented in table 5. Information on offshore Mexico oil and gas fields has also been reported by LeBlanc (1979) and is shown in table 6.

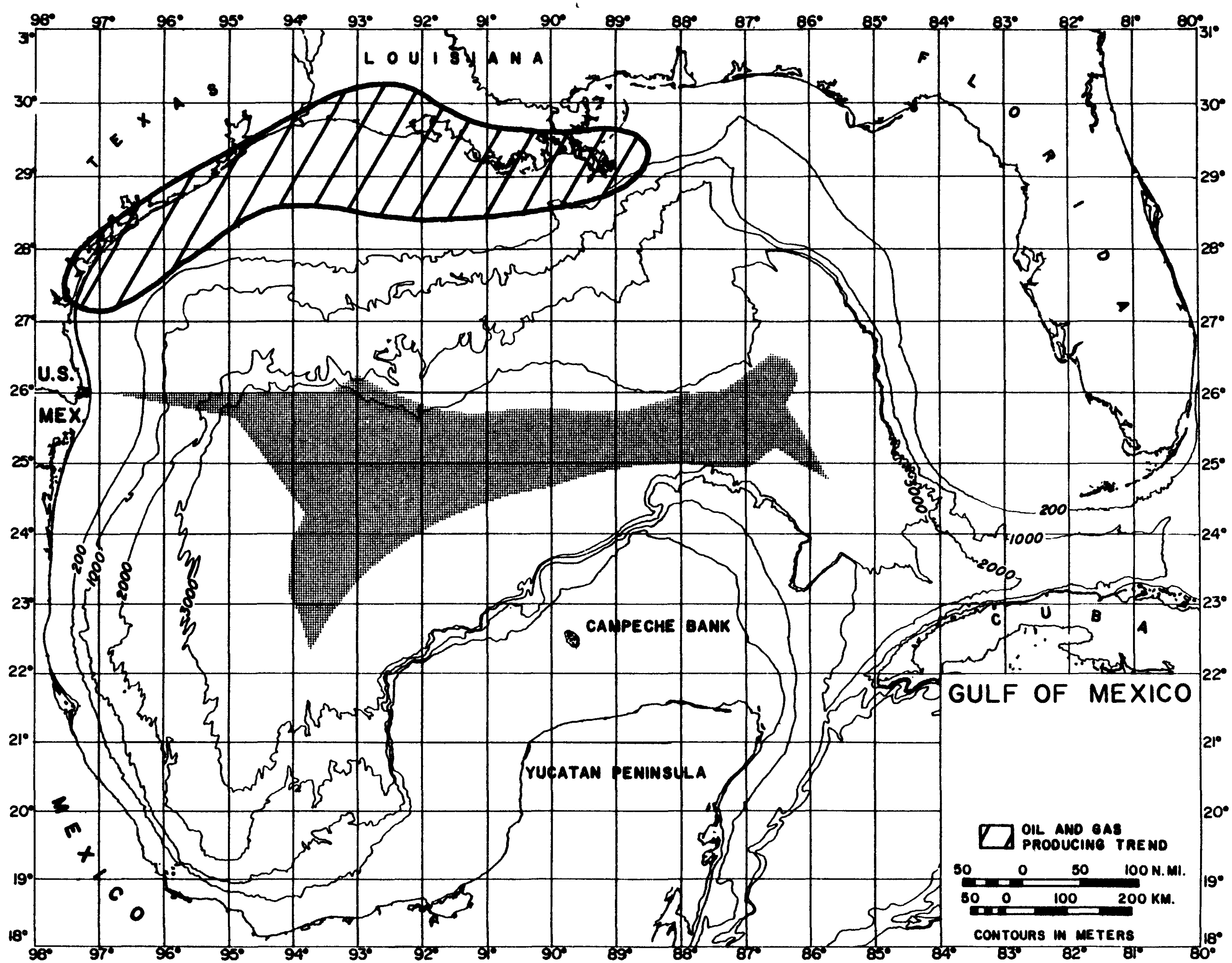


Figure 50.--Map showing oil and gas producing trend in Miocene strata, northwestern Gulf of Mexico basin (after Rice, 1980).

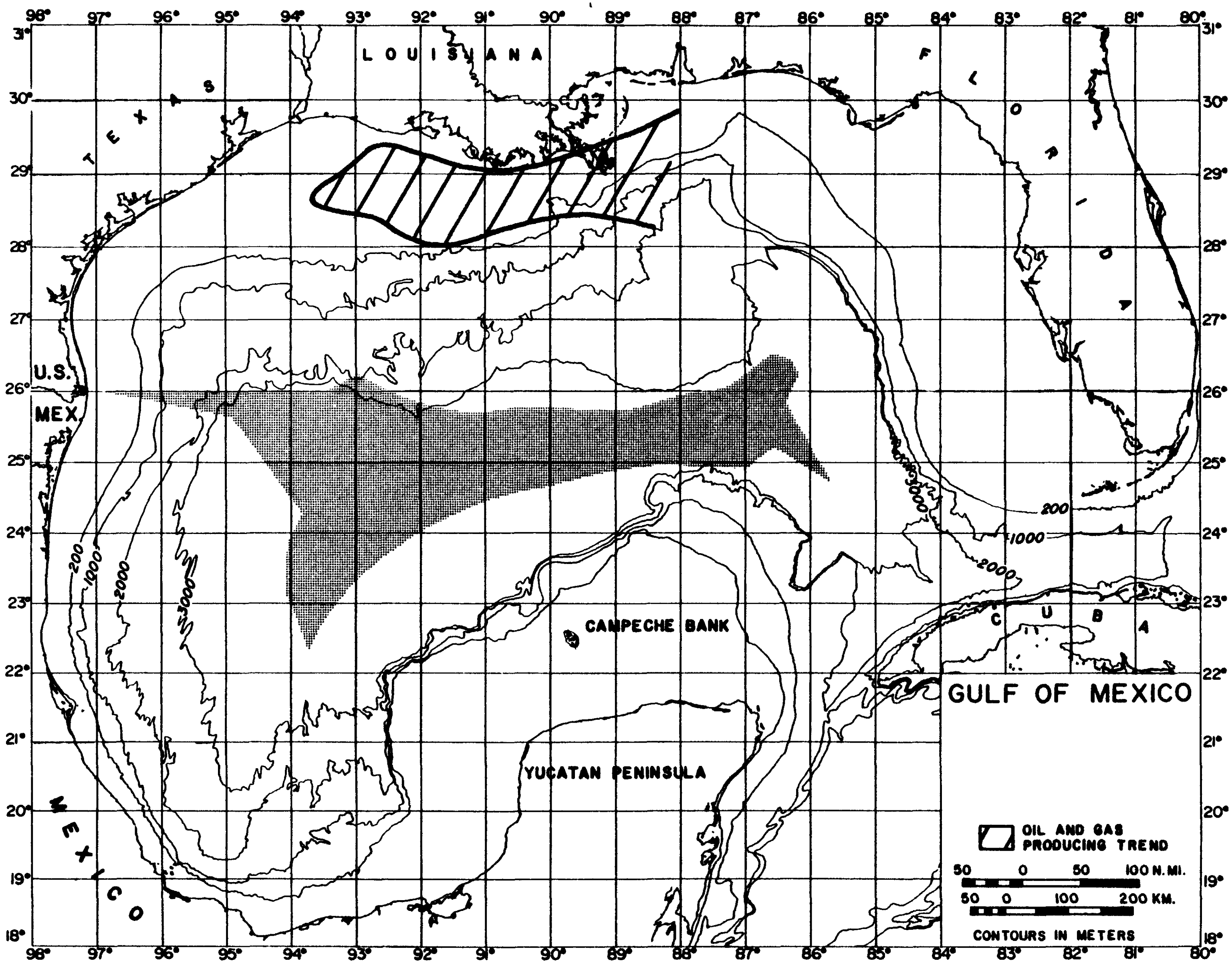


Figure 51.--Map showing oil and gas producing trend in Pliocene strata, northwestern Gulf of Mexico basin (after Rice, 1980).

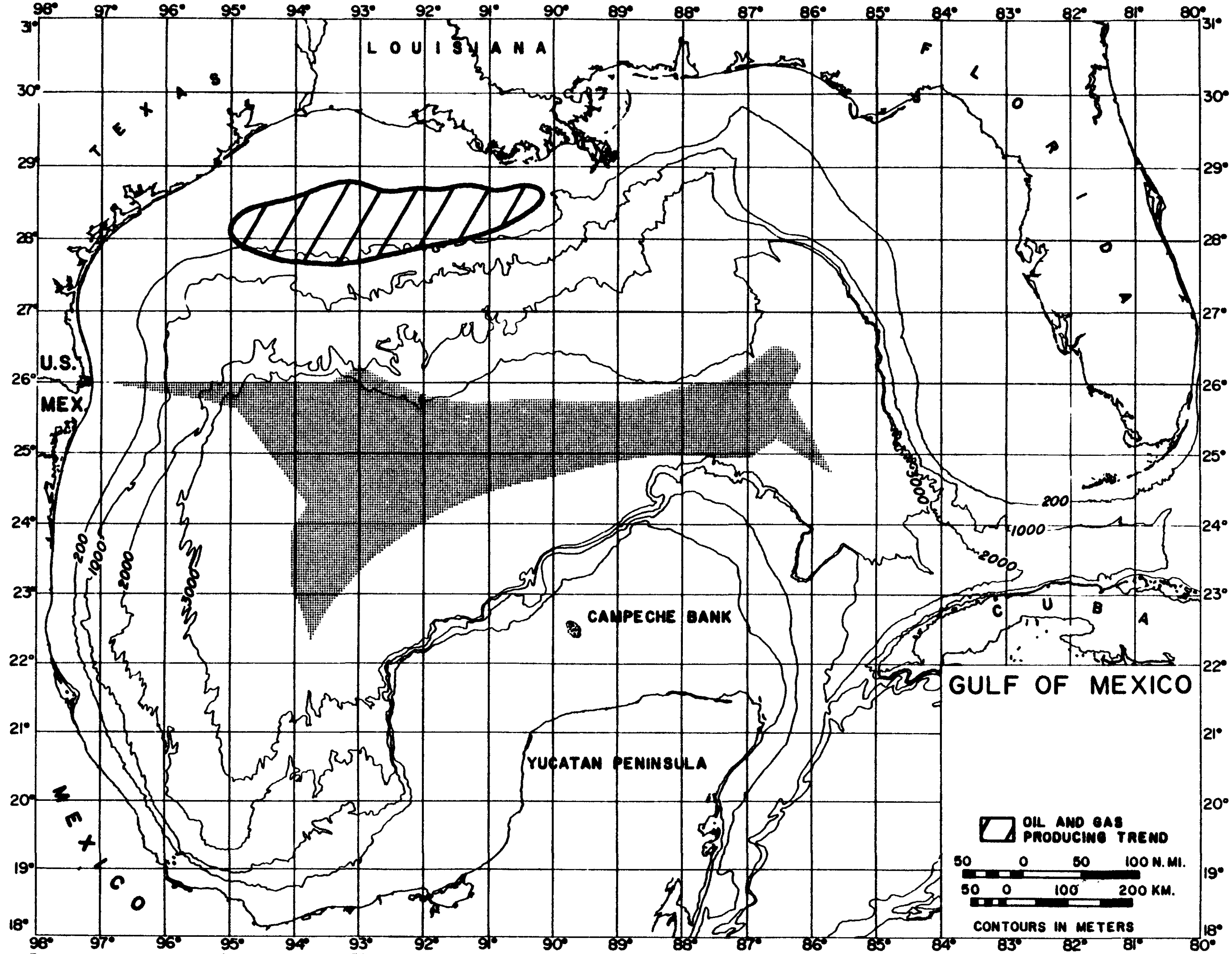


Figure 52.--Map showing oil and gas producing trend in Pleistocene strata, northwestern Gulf of Mexico basin (after Rice, 1980).

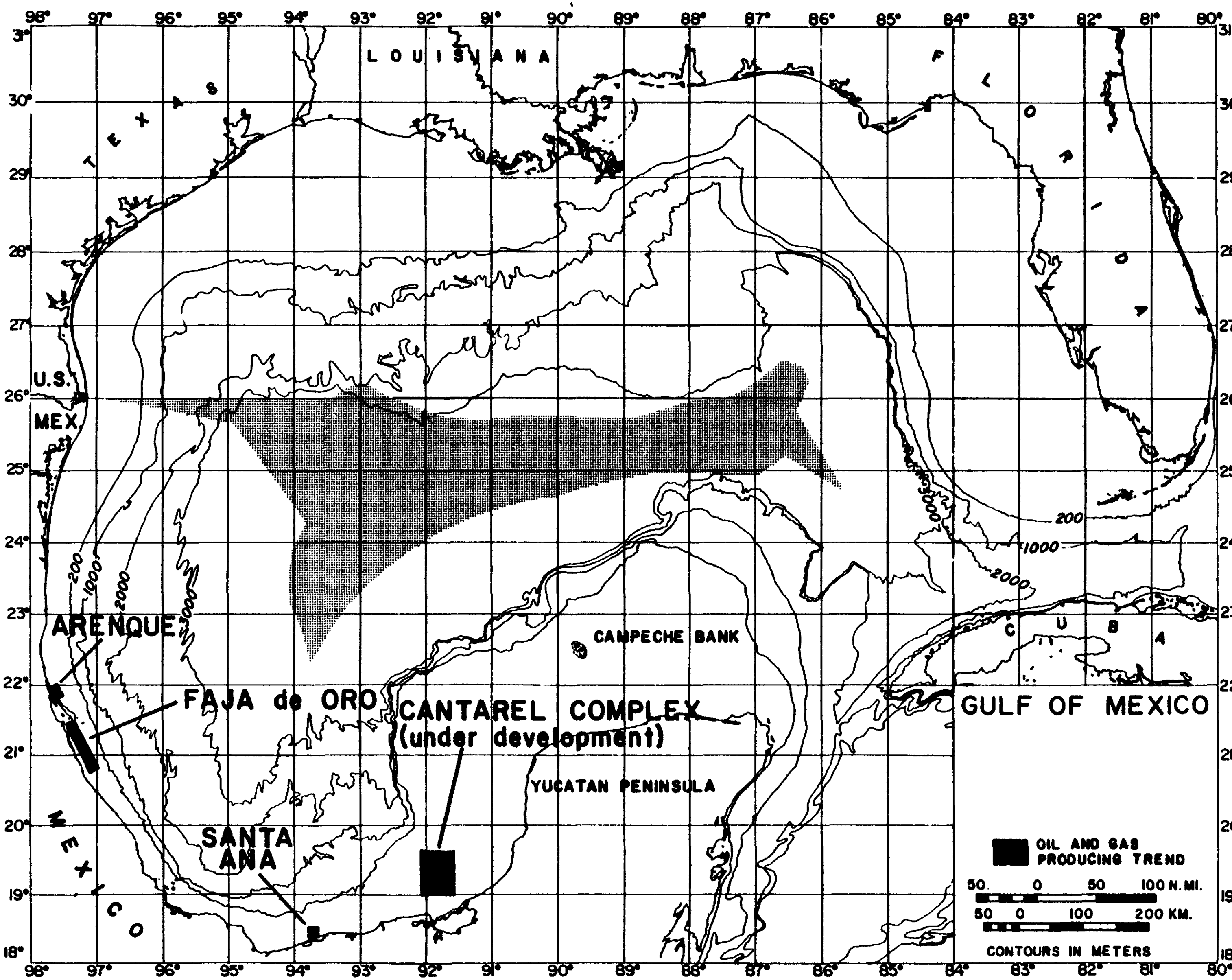


Figure 53.--Map showing locations of oil and gas producing areas in southwestern Gulf of Mexico, offshore Mexico (after Le Blanc, 1979).

Table 4.--*Percentage of discovered in-place volumes of hydrocarbons by age, offshore Louisiana and Texas. U.S. Geological Survey, unpublished data, 1979.*

| Age | Percentage of crude oil | Percentage of natural gas |
|---|---|---|
| Pleistocene | 6 | 18 |
| Pliocene | 11 | 13 |
| Miocene | 83 | 69 |

Table 5.--*Offshore Production, Faja De Oro* (from Le Blanc, 1979).

| Field name | Year developed | Producing depth (ft) | Flowing wells* | 1977 Avg. flow barrels per day | Current flow barrels per day |
|---|---|---|---|---|---|
| Bagre | 1973 | 10,9191 | 10 | 11,945 | 11,300 |
| Atun | 1966 | 9,040 | 4 | 1,067 | 4,000 |
| Marsopa | 1974 | 10,198 | 8 | 5,114 | 3,480 |
| Isla de Lobos | 1963 | 6,875 | 3 | 1,233 | 700 |
| Tiburon | 1965 | 7,314 | 5 | 365 | 470 |
| Morsa | 1971 | 10,434 | 1 | 459 | 400 |
| Escualo | 1969 | 9,840 | 1 | 239 | 350 |
| Totals | | | 32 | 20,422 | 20,700 |

*No wells reported shut-in,

Table 6.—*Data on Offshore Mexico Oil and Gas Fields (from LeBlanc, 1979).*

| | Arenque | Faja de Oro | Santa Ana | Cantarel |
|---|---|---|---|---|
| Date of discovery | 1968 | 1963 | 1959 | 1974 |
| Development began | 1970 | 1965 | 1962 | 1978 |
| Wells drilled | 36 | 57 | 38 | ND |
| Production units installed | 3 | 9 | 7[a] | b |
| Producing wells | 22 | 50 | 7 | c |
| Producing area (sq mi) | 19 | ND | ND | ND |
| Producing depth (feet) | 11,084 avg. | 5,248-11,400 | 8,026 avg. | 3,608-5450 avg. |
| Current production | | | | |
| Oil (million barrels/day) | 22,800 | 25,000 | 800 | 1,000,000[d] |
| Gas (million cu ft/day | 59 | 32 | 1 | 260[d] |
| Cumulative production (1-1-79) | | | | |
| Oil (million barrels) | 48.05 | 100.55 | 30.15 | ND |
| Gas (trillion cu ft) | 69.40 | 126.62 | 36.18 | ND |
| Gravity (API) | 24 | 36 | 34 | 20-24 |
| Porosity (average in percent) | 15 | 17 | 19 | ND |
| Permeability (millidarcies) | 22 | 2,000 | ND | ND |
| Viscosity (centipoise) | 65 | 6 | 10 | 820 |

ND - No data.
a - 3 major and 4 satellite producing units.
b - Platforms planned: 23 drilling; 5 production; 1 linking; 4 accommodation.
c - Initial development program: 92 production wells; 26 outpost wells; and 10 injection wells. Additional development program: 69 production wells.
d - Planned production.

## Gulf of Campeche Region

Recently, the primary interest in the Gulf of Campeche has been on the Campeche Shelf trend extending from the shoreline northward across the shelf and possibly into deeper waters (fig. 53). This trend has just begun to be explored and the estimates of recoverable reserves are already very large. For example, the Cantarel complex contains five separate geologic structures which are being developed as a unit. Production plans for the Cantarel complex are given in table 6. The production rate from this complex is planned to be 260 million cubic feet of gas and 1 million barrels per day of crude oil, which is about 33 percent more oil than produced in all the U.S. Gulf of Mexico OCS areas.

Seismic mapping programs and exploratory drilling continue on the Campeche Shelf. Although the number and size of untested structures in this trend have not been released, Le Blanc (1979) reported in all 230 structures have been mapped on the Campeche Shelf and some are larger than the Cantarel fields. The results obtained from the drilled structures and the number and size of the remaining prospects in this trend have led to a several estimates of reserves and undiscovered resources. In 1980, the estimates for crude oil were 20 billion barrels of proved reserves and an additional 27 billion barrels of probable reserves (where oil has been found on a structure but the structure is not yet completely drilled), the estimates for gas were 70-85 trillion cubic feet; Mexican officials are expecting an additional 200 billion to 300 billion barrels of oil to be found in this trend (Le Blanc, 1979, and Oil and Gas Journal, 1980).

Production from the Campeche Shelf appears to be from very porous reefs and reef talus of Paleocene age. Source beds for the hydrocarbons are probably organic-rich Late Jurassic shale. The hydrocarbons migrated from the source beds to the reservoir through fractured Cretaceous reefs and porous reef talus (Oil and Gas Journal, 1980).

## Traps

Geological and geophysical data indicate that many varieties of traps known to accumulate hydrocarbons elsewhere may occur in the Maritime Boundary region. Two classifications of traps are discussed: 1) structural and 2) stratigraphic.

Structural Traps

Structural traps are formed by the bending or breaking of rock strata so that oil and gas migration is stopped. The varieties of structural traps present in the Maritime Boundary region are:

- o *Anticlines* - These may be normal, asymmetrical, faulted, drape or compaction over a deeper dome, and doming or arching of sedimentary strata over a piercement salt dome, deep salt pillows, or shale ridge.
- o *Faults* - The most common types of faults in the Gulf of Mexico basin are normal and growth faults. Reverse faults occur in the Perdido foldbelt in the northwestern Gulf of Mexico (fig. 18). Fault traps are formed by fracturing and movement of layered rocks along a surface so that the higher, or up-dip edge of a reservoir layer terminates against impermeable beds across the fault. Some traps allow oil and gas to leak along the fault surface, and this phenomenon is very important in the migration of oil and gas from source beds to reservoir rocks (see discussion below on Source Beds). In other traps, the fault surface sealed the edge of the reservoir bed by smearing an impermeable layer of rock along the edge of the reservoir bed during the movement.
- o *Salt and shale domes and ridges* - Salt structures are prevalent in Rio Grande Margin, Sigsbee Escarpment, and Sigsbee Knolls assessment areas (fig. 15). Figures 19 and 21 show that traps produced by piercement salt domes, salt massifs, and nonpiercement salt pillows include anticlines and faults formed by the movement of the salt. Fault traps and stratigraphic traps can be formed on the flanks of salt structures. Traps can also be formed at the piercement contact between the reservoir bed and the impervious salt body.

### Stratigraphic Traps

Although stratigraphic traps are more difficult to detect and to map, they are also thought to be common throughout the Maritime Boundary region. A stratigraphic trap results from a change in permeability laterally within a reservoir bed so that fluids or gases migrating upward within it are stopped by a change in the characteristics of the sedimentary unit. Stratigraphic traps may occur at angular unconformities and in sands onlapping disconformable surfaces, flanks of salt domes, and limbs of anticlines. An accumulation of oil and gas in the porous zone at the top of an ancient reef is classified by some as being a stratigraphic trap and, by others as being in a distinct type of trap. For simplicity, reefs and talus (broken fragments of reefs) accumulated on the flanks or at the base of the reef will be considered a stratigraphic trap.

## Source Beds and Maturation

Dow (1978) has suggested that oil and gas are formed from disseminated sedimentary organic matter (kerogen) by a series of predominantly first-order chemical reactions. The rates of these reactions depend primarily on temperature and the duration of heating. He described three basic types of organic matter which are available for incorporation into sediments: 1) terrestrial material derived from higher order land plants; 2) amorphous material from lower order aquatic life; and 3) recycled organic material from erosion of uplifted sedimentary rocks. The first type will yield primarily gas and some condensate; the second type oil; and the third type very little gas and no oil. Nearshore facies generally have higher percentages of terrestrial organic material, especially near deltas of rivers draining large areas of high-order land-plant productivity. The organic matter incorporated into sediments depends on 1) a supply greater than the ability of dissolved oxygen and heterotrophic organisms to destroy it, 2) reasonably quiet water and minimum current activity, and 3) a moderately rapid sedimentation rate. Dow (1978) suggested that favorable sites for the deposition of sediments rich in oil-generating aquatic organic matter include: 1) sites having irregular bottom topography and closed bathymetric basins on some continental slopes (caused by folding, faulting, or salt diapirism and associated slumping); 2) sites in the oxygen-minimum zone on some continental slopes where organic productivity, usually the result of upwelling, is so high that anoxic conditions prevail in unrestricted, open-marine environments; and 3) sites on continental rises and submarine fans which receive organic-rich turbidites from unstable continental slope deposits.

Organic-carbon content and organic-matter type were determined in 264 cutting samples from 12 deep wells and 62 core samples from eight shallow Caldrill holes in the Louisiana Gulf Coast area by Dow and Pearson (1975). The mean organic-carbon content was determined in six depositional zones (inner shelf, 0-66 ft (0-20 m); mid-shelf, 66-328 ft (20-100 m); outer shelf, 328-656 ft (100-200 m); upper bathyal, 656-1,640 ft (200-500 m); lower bathyal, 1,640-6,562 ft (500-2,000 m); and abyssal, greater than 6,562 ft (2,000 m). The analyses revealed a systematic increase from a low of 0.17 weight percent in inner shelf shales to a high of 0.63 weight percent in deep-water abyssal shales. Therefore, the continental slopes, rises, and abyssal regions of the Gulf of Mexico should be favorable sites for potential oil and gas source beds.

Rice (1980) analyzed gas samples from 116 wells representing 55 different gas fields in offshore Louisiana and Texas. From this study, he concluded: 1) isotopically light, methane-rich gas occurs at shallow depths and was probably generated by anaerobic microorganisms in rapidly depositing marine sediments; 2) non-associated gases of Miocene age in the western part of the province are the result of either thermal cracking of liquid hydrocarbons to wet gas and condensate by high temperatures, or generation from a different type of organic matter than that from which the shallow-depth gases were generated; and 3) many gas accumulations result from separation and migration (e.g., the gas phase was physically separated from a petroleum accumulation).

Claypool (1979) traced the formation of biogenic methane and the subsequent stages of natural gas generation in sedimentary rocks as a function of temperature. He noted that temperature ranges of 100°C to 150°C (212°F to 302°F) are important in an actively subsiding sedimentary basin. In that temperature range, the transformation of organic matter into early thermogenic gas also results in the generation of liquid petroleum. At temperatures above 150°C, late thermogenic gas is the dominant hydrocarbon product, resulting from thermal decomposition of both liquid hydrocarbons and solid organic matter.

Geothermal gradient information is scant for deep-water areas of the Gulf of Mexico. The gradients are generally expected to be consistent with the Gulf Coast average of 1.4°F/100 ft (2.6°C/100 m) reported by Dow (1978). Significantly higher values in the geothermal gradient are encountered in some parts of the Gulf of Mexico OCS areas because of increased temperatures associated with geopressured zones and salt domes and massifs. Geothermal gradient increases would be expected to be associated with similar geologic features in deeper water. Relatively high geothermal gradients may have been imposed on Gulf of Mexico strata well into Tertiary time as a result of thermal radiation from cooling of igneous crust emplaced in the region during Mesozoic time.

The above discussion indicates that the northern Gulf of Mexico oil and gas production is from thermally immature rocks. Crude oil and thermogenic natural gas probably migrated into the traps via deep-seated faults and piercements, and their associated fracture systems.

Oil and gas (ethane and methane) within the assessment area were detected in the analysis of samples from DSDP Sites 2, 88, 90, and 91 (fig. 54). Site 2 was drilled to a depth of 472 ft (144 m) and encountered immature oil in a core of Jurassic age taken at 447 ft (136 m) from the caprock of Challenger Knoll (fig. 19). Analysis of the sample revealed that the oil was of post-Cretaceous age (Ewing and others, 1969b). Worzel and others (1973a, b) described the analysis of cores from Sites 88, 90, and 91. At Site 88, gas odors were detected in all cores. Methane was dominant with a lesser ethane component in 11 samples from depths of 177 ft (54 m) to 1,233 ft (376 m) and ranging from late Pleistocene to early Pleistocene age. Cores from Site 90 contained methane in depths from 426 ft (130 m) to 2,515 ft (767 m). These samples range in age from middle Miocene to early Pleistocene. Traces of ethane were found in middle and late Miocene samples. The cores from Site 91 did not show the volume of gas as those discussed above; gas was present, however, in 18 samples to a depth of 2,748 ft (838 m). The age range of the samples was from middle Miocene to late Pleistocene.

Worzel and others (1973a, b) suggested that the methane found in DSDP cores is the result of biogenic activity and that the methane is attributable to the high rates of Pleistocene sedimentation. Seismic profiles across the Mississippi Fan and Sigsbee Plain indicate high rates of sedimentation. These seismic data show that very large submarine-fan distributary channel systems traversed the present Mississippi Fan during periods of glacially lowered sea level in Pliocene and Pleistocene time. Undoubtedly, large quantities of

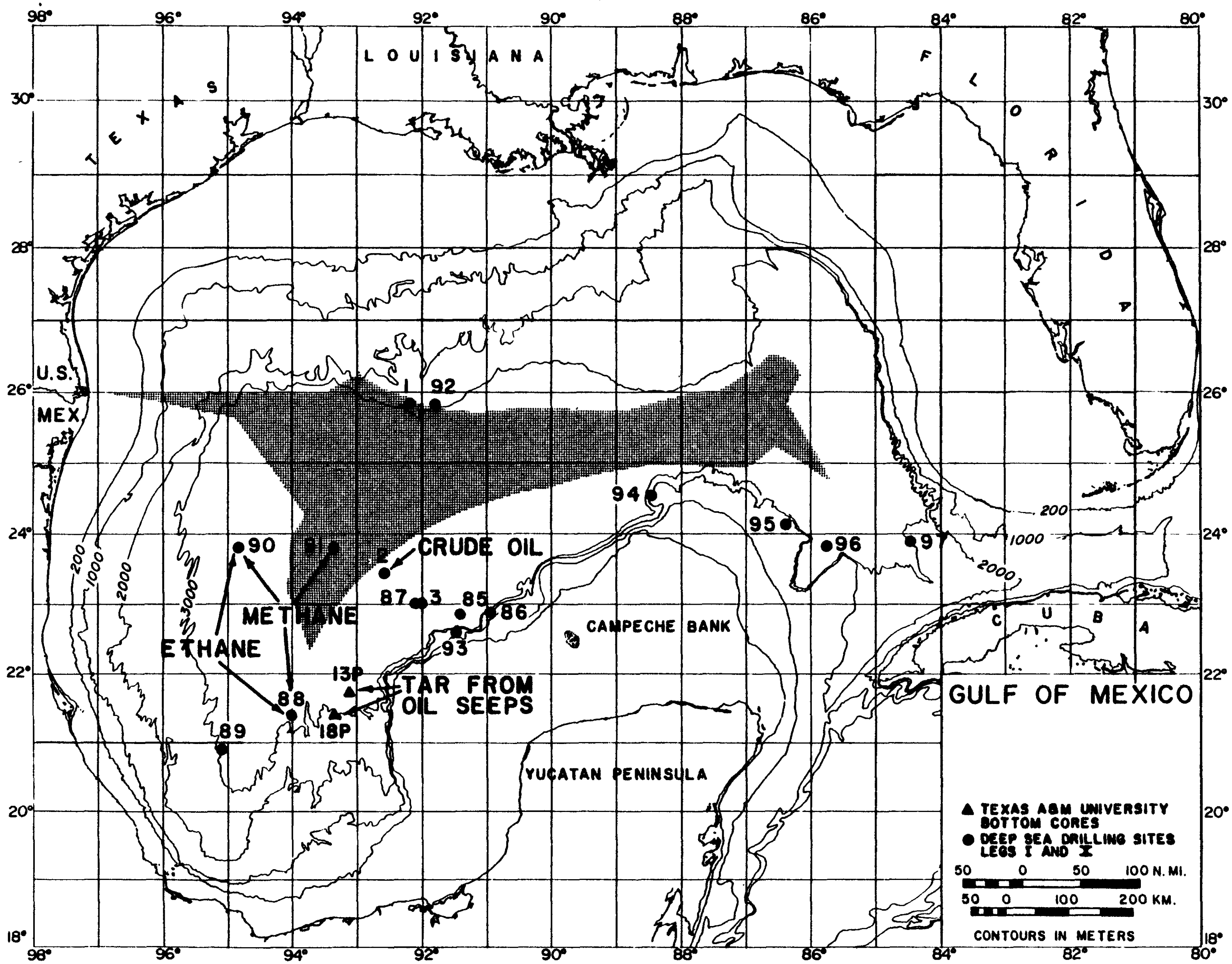


Figure 54.--Map showing locations of crude oil and methane shows, traces of ethane, and oil-seep tars in DSDP drill holes and Texas A&M bottom cores in deep Gulf of Mexico basin.

woody debris and organic material were transported by these submarine distributaries and deposited in Pliocene and Pleistocene strata on the fan and in the Sigsbee Plain.

Cores taken by Rezak and others (1969) at locations 13P and 18P (fig. 54) in the area between the Campeche Canyon and the Sigsbee Knolls (fig. 1) contained natural hydrocarbons from a seep or series of seeps on the deep ocean floor. At location 13P, a large piece of tar was recovered at the base of a 31-cm-long core collected in 8,520 ft (2,795 m) of water. These authors reported a strong indication of upward movement of hydrocarbon particles and numerous cracks released a strong hydrogen sulfide odor. The piston core at 18P was 185 cm long and was recovered in 9,864 ft (3,226 m) of water. There were 58 cm of solid hydrocarbons near the top of the core, followed by 102 cm of calcilutite and then another 20 cm of tar. The deeper layer must have been thicker because of the broken surface of tar in the core nose. Sectioning of the tar layer revealed gas bubbles and shell fragments. The authors concluded that an assemblage of nannofossils in the lower tar layer was picked up by the oil as it migrated upward through sediments as old as Eocene.

From the foregoing discussion, we can conclude that source beds for biogenic methane gas are most likely present in middle Miocene to late Pleistocene strata in the deep Gulf. There is evidence also that thermogenic ethane and crude oil are present in upper Miocene and earlier Tertiary source beds, possibly having migrated into these strata from older and deeper rocks.

A strong possibility also exists that substantial thicknesses of Jurassic source beds rich in organic matter may be present in the Maritime Boundary region, particularly in the Perdido Foldbelt, Sigsbee Knolls, and Campeche Escarpment assessment areas (fig. 8). As discussed above Jurassic shales are the source for crude oil at the Arenque field. Because these source beds are so thick at Arenque - more than 3,281 ft (1,000 m) - it is likely that they are widespread and present under the Perdido foldbelt. Late Jurassic source beds provide the crude oil and associated gas produced at the Cantarel complex on the Campeche Shelf. Possibly source beds of similar age are present in the Sigsbee Knolls, Campeche Escarpment, and parts of the Abyssal Gulf Basin areas.

Evidence has been presented by Lancelot and Siebold (1978) that organic matter of pelagic origin may be preserved on the sea floor to form the organically rich "black shales" found in large areas of the North Atlantic. They suggested that both sapropelic and humic organic matter were preserved because of generalized stagnation or much reduced circulation at the water-sediment interface during middle Cretaceous time in most of the North Atlantic; the same condition may have persisted slightly longer in more isolated basins. If there was a similar stagnation or much reduced circulation at the water-sediment interface when Cretaceous seas covered the Gulf of Mexico, then significant amounts of organic material may have been preserved to provide potential source beds.

## Reservoir Rocks

A reservoir is a porous, permeable rock formation containing quantities of oil and (or) gas enclosed or surrounded by layers of less permeable or impervious rock. The following discussion will focus on prospective reservoirs in the assessment areas (fig. 8) of the Maritime Boundary region.

Throughout Cenozoic time, the northern Gulf of Mexico basin received a massive influx of clastic sediments derived from northern and western sources. Sedimentation was accompanied by subsidence and a net progradation of the continental-shelf edge. Centers of maximum deposition, referred to as depocenters, formed along the shelf edge during each successive stage of Cenozoic time (Kupfer, 1974; Woodbury and others, 1973). These depocenters shifted laterally as a result of changing sediment source. The depocenters shifted to the northeast during early Tertiary time and to the south and southwest during the latter part of the Tertiary and Quaternary. On the basis of sandstone percentages, which are strongly dependent on depositional environments, three gross depositional facies are identified in the Gulf Coast basin of the northern Gulf; they are, in ascending order: deep-water bathyal, neritic, and continental facies. Beginning at the outcrop and extending basinward, a complete sedimentary sequence consists of (1) a continental, lagoonal, and deltaic facies--generally characterized by a section of massive sandstone; (2) a neritic facies of interbedded sandstone and shale deposited in a continental shelf environment, and (3) a bathyal facies, which is predominantly shale deposited mainly in a continental slope environment. The massive sandstone facies of a particular age occurs along the paleo-shoreline and the age-equivalent sandstone-shale and massive shale facies lie progressively seaward of it. Because of progradation, this pattern of facies continues through time so that the sandstone-shale facies (reservoir rocks) of one age overlies an older massive shale (source beds).

Turbidite Sand Reservoirs

The term "bathyal facies" was used by Powell and Woodbury (1971) for sediments deposited on the continental slope, and the term does not have lithologic connotation. Turbidites, as used here, refers to sands, or carbonate debris, deposited on the continental slope and abyssal plain as fan deposits, which probably cover a relatively large area, and as fill material in submarine canyons.

The potential for major hydrocarbon accumulations in the bathyal facies on the continental slope is poorly known. Sandstone of reservoir quality has been deposited in bathyal and abyssal depositional environments off the coast of California (Shepard and others, 1969). Hydrocarbon production from sandstone units deposited in these environments in California has been described by Natland and Kuenen (1951). Possible reservoir sandstones deposited on the Gulf of Mexico continental slope would be "gravities" or turbidites (Natland, 1967) derived from sediment deposited on, or transported across, the continental shelf. As such, they would be expected to have many of the same physical characteristics as the neritic sandstones from which they are derived. Conditions were most favorable for the formation of reservoir rock in this environment during the glacial epochs, when the shorelines and sediment sources were in close proximity to the outer edge of the continental shelf.

The study of 33 cores led Ewing and others (1955) to the conclusion that the distribution of sediments in the Gulf of Mexico was profoundly influenced by turbidity currents. A detailed topographic study, supplemented by 124 piston cores taken in the gulf (Ewing and others, 1958), led to the conclusion that silty sediments, supplied in quantity by the Pleistocene Mississippi River and distributed by turbidity currents, covered the floor of the Gulf.

On Leg 10 of the Deep Sea Drilling Project, Sites 85-97 were drilled in the Gulf of Mexico (fig. 10). A summary of some results from that program is presented below. A more detailed analysis is contained in volume 10 of *Initial Reports of the Deep Sea Drilling Project* (Worzel and others, 1973c).

Site 90 yielded a section which demonstrates the transition from continental rise to abyssal plain. The Pleistocene section reflects the introduction of terrigenous material to the site via low-energy turbidity currents. Source material is probably from the nearby continental slope, and subsidiary amounts may have come from the north and northeast. The Miocene sequence may represent a transition from low-energy, turbidity-current-related sedimentation in Late Miocene time to relatively high energy, turbidity-current sedimentation of very fine to coarse terrigenous sands of middle Miocene age in cores from 2,496 ft (761 m) to 2,519 ft (768 m). The presence of coarse sand in Miocene sediments suggests eustatic changes in sea level; during low sea stands, fluvial processes were able to deliver coarse clastic material across a narrow continental margin in the western Gulf. As in Pleistocene time, progradation was limited by a steep bottom gradient at the shelf edge, the coastal plain was narrow, and the shelf edge slumped more frequently than during high stages of sea level. The higher stream gradient during stages of low sea level caused coastal fluvio-deltaic systems to deliver coarser sediments to the shelf edge.

The Miocene sediment facies penetrated at Site 91 are comparable to those at Site 90. The lowermost core contains the coarsest debris in the entire sequence drilled--gravelly, very coarse sand. In addition, Cretaceous limestone and dolomite fragments, dark cemented sandstone fragments, shell debris, and coral fragments are found in the material. The presence of considerable amounts of disturbed gray sand in the lower cores indicates an increasing sand percentage and grain size toward the bottom of the hole. Worzel and others (1973c) interpreted this sequence to indicate the presence of thicker and coarser grained turbidites below the section cored. Core 25 appears to represent the thickest and coarsest sand units recovered from the deep-water Gulf of Mexico. The sequence of Miocene turbidites indicates a prolonged period of turbidite sedimentation. Most Miocene sediments are interpreted as having their source to the west, mainly the Rio Grande embayment. As discussed for Site 90, this source interpretation appears to support the theory of changes of sea level during middle Miocene time.

The presence of turbidites in Pliocene sediments at Site 91 and their general absence at Site 90 suggests that these turbidites had a northern or northeastern source.

The Pleistocene section consists of sands, coarse silts, and clays. The gradual shift in prime sediment source upwards through the section penetrated at Site 91 suggests either that depocenters shifted on the northern Gulf clastic-dominated shelf or that the abyssal plain has had a varied bathymetric configuration during upper Cenozoic sedimentation. Both factors may operate concurrently.

From Site 87, Core 1 was described as a predominatly horizontally laminated, very poorly sorted, commonly texturally graded, silty, very fine sand to slightly gravelly, fine sand. The coarser sediments are intercalated with thin, light-olive-gray, faintly laminated, sparsely burrowed, silty clay or clay. Organic carbonaceous detritus is common throughout. The sediments can be interpreted as a continuation of turbidite-dominated sedimentation first encountered at about 1,969 ft (600 m) in Site 3, less than 4 miles (6.4 km) east. The compositional immaturity of the sands and a marked similarity to equivalent age sands at Sites 90 and 91 would indicate a source to the northwest. The section shows continuing Miocene bathyal deposition with frequent turbidite contributions both from the southwest (the carbonate and volcanic parts) and probably from the north and east (terrigenous silts and clays).

The above-mentioned analyses of samples from DSDP holes and seismic data indicate that coarse-grained turbidite sands deposited in the assessment areas from middle Miocene to Pleistocene time may be potential reservoir rocks. Figures 55 and 56 show possible distributions of these sands for middle Miocene and Pleistocene strata.

Potential reservoir rocks of Cretaceous and, possibly, Paleocene ages are reefs, reef talus, porous limestones, limestone debris, and dolomites. The reefs and reef-talus zones are at the seaward edges of shallow Cretaceous and Paleocene banks such as those formed in the eastern and southern Gulf of Mexico. Limestones and dolomites were deposited on broad carbonate banks around the periphery of the basin during most of Cretaceous time. Carbonate debris eroded from these banks and porous and fractured zones in the limestones and dolomites could be potential reservoir rocks, particularly in the Sigsbee Knolls and Campeche Escarpment areas.

## Seals and Timing

The well-layered sedimentary units over the Maritime Boundary region have been described in preceding parts of this volume. These units are considered to be alternating sands and shales, on the basis of their seismic characteristics and geologic knowledge of depositional environments. These shales should, upon compaction, be effective seals. In addition, deep-water pelagic oozes were deposited in the region from Early Cretaceous through Pleistocene time. These oozes should also be effective seals if compacted.

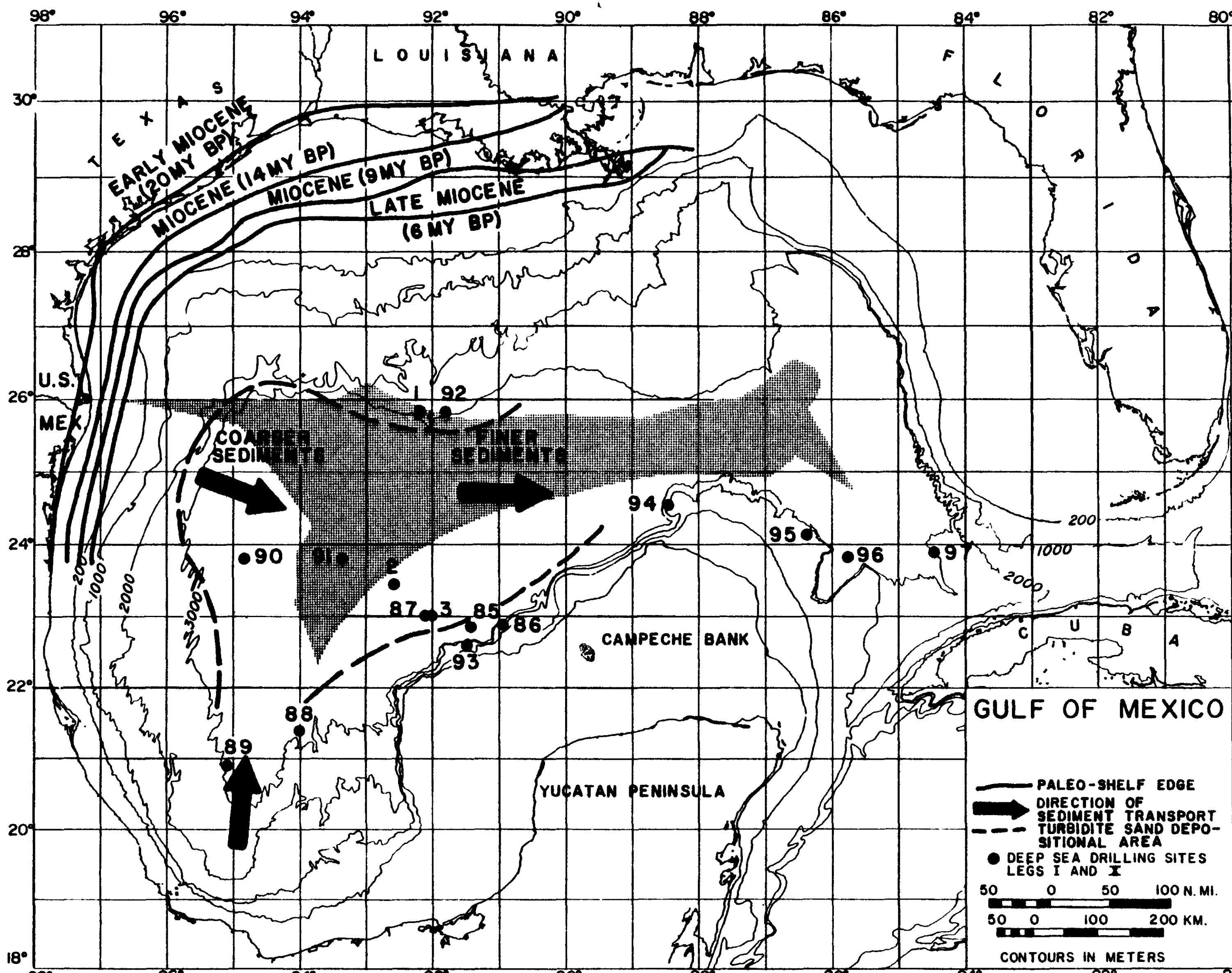


Figure 55.--Sketch map showing Miocene paleo-shelf edges in northwestern Gulf of Mexico and outline of turbidite sand depositional area in abyssal Gulf basin during mid-Miocene. Paleo-shelf edge positions in millions of years before present (millions of years ago). The assesment area is shaded.

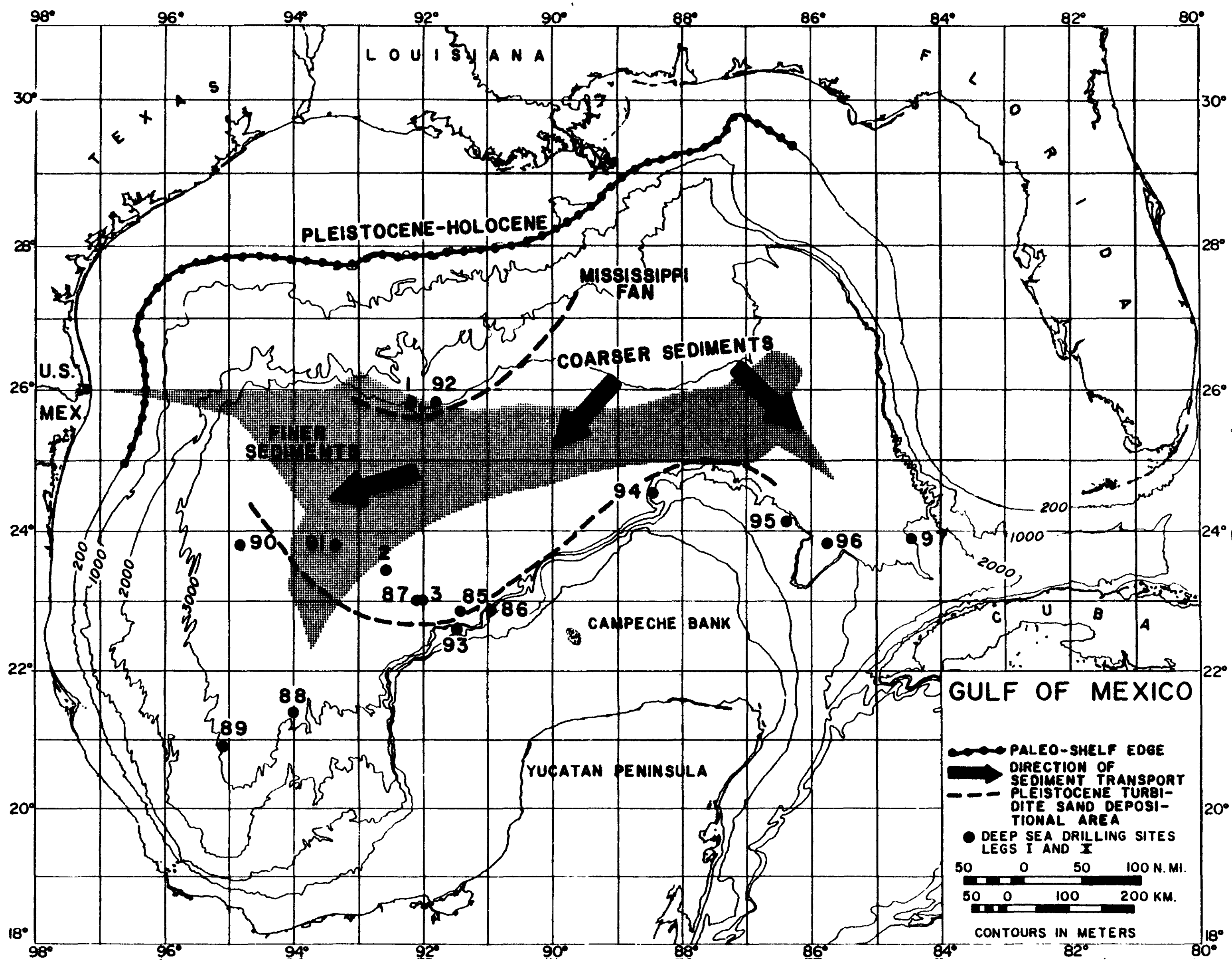


Figure 56.--Sketch map showing Pleistocene paleo-shelf edge in northwestern Gulf of Mexico and outline of turbidite sand depositional area in abyssal Gulf basin during Pleistocene.

The Mesozoic sequence contains shales that serve as seals at Arenque, Faja de Oro, and Cantarel. Similar-type shales or dense limestones should be present in the assessment areas to seal possible Mesozoic reservoir rocks.

As discussed above, most oil produced in the northwestern Gulf of Mexico is considered to be immature. That is, the oil is believed to be produced from reservoir rocks whose maturation is not sufficient to have generated it. In addition, geologic evidence suggests that the average oil in produced fields has been in place about 8.7 million years. Therefore, traps formed even as late as Pleistocene would have been ready to accumulate migrating oil and gas. Thus, timing does not seem to have been a critical factor in most Gulf of Mexico oil and gas fields.

APPENDIX III

# BACKGROUND DISCUSSION OF GEOLOGIC HAZARDS IN THE GULF OF MEXICO[1]

By

Richard Q. Foote and Ray G. Martin

Studies of the bottom sediments and near-surface geology of the Gulf of Mexico OCS areas are conducted to evaluate potential geologic hazards that could adversely affect the management of petroleum resources. These studies are part of the U.S. Geological Survey's offshore program and support the U.S. Department of the Interior's OCS oil and gas leasing, management, and pipeline transportation activities.

Regional environmental geology studies have been undertaken over large parts of the Gulf of Mexico continental shelf and on the upper continental slope, particularly off the Mississippi Delta, western Louisiana, and Texas. These studies help to identify regional geologic hazards, give insight into the geologic processes involved in their origin, and provide a basis for extrapolating geologic hazards potential into the Maritime Boundary region.

Site-specific geologic hazard surveys have been conducted in the past on tracts offered for oil and gas leases in the U.S. Gulf of Mexico OCS. These studies are used to determine the locations, types, and expected magnitude of

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[1]This appendix is provided as amplification on the characteristies and geomorphic settings of potential geologic hazards that locally may be present in specific assessment areas addressed earlier in this volume under Potential Geologic Hazards in the Gulf of Mexico Maritime Boundary Region.

potential geologic hazards and to identify ways to avoid or to mitigate their possible effects.

A good overview of topics directly and indirectly related to geologic hazards can be found in *Contributions on the Geological and Geophysical Oceanography of the Gulf of Mexico* edited by Rezak and others (1969). The specific topics covered in that book range from broad geographic coverage of structure and sedimentary environments to detailed descriptions of relatively small but representative features found on the continental shelf and slope and of local animal/sediment relationships from the Mississippi Delta to the carbonate province of the Yucatan Shelf.

## Types of Potential Geologic Hazards

Geologic conditions that may endanger drilling, production, or pipeline transportation operations in the Gulf of Mexico can be grouped under the following headings: 1) Soil movements (unstable slopes/sediment instability), 2) active faults, 3) shallow gas accumulations, 4) thick, soft sediment accumulations, and 5) earthquakes. The risks presented by these hazards, except earthquakes are fairly well known from the experience of more than three decades of petroleum operations offshore Texas and Louisiana. Operational practices to avoid or to mitigate the risks are commonplace in Gulf of Mexico OCS areas. The intent of the following discussion is to characterize these categories of geologic hazards only in a general sense, and not to infer or predict the magnitude and probability of risk for any area.

Soil Movements

A special set of geologic hazards exists on the submerged deltas of large rivers, such as the Mississippi River, where large volumes of river-borne sediments are deposited each year. Under these conditions, the processes of normal dewatering cannot keep pace with the addition of new sediments, and the weak undercompacted sediments are subject to deformation and to movements of various types. Soil movements can exert net forces on structural members of offshore facilities, including conductor pipe and pipelines. Depending upon the soil properties and the rate of movement, these soil forces can range from insignificant to forces having magnitudes that approach or exceed those of other environmental loads. The rates of movements can vary from very slow "creep" to "mass slumping" or catastrophic sliding; the sediment mass may be an isolated small block of sediment to very large masses of sediment moving down the continental slope. Therefore, the extent and rate of soil movement, if any, must be estimated for the planning and design of offshore facilities in such environments.

Regional geophysical surveys and more localized studies of bottom stability provide insight into the types of deformational features occurring in the offshore near-surface zone (Garrison, 1974; Coleman, 1975). From an examination of geophysical records taken in the Mississippi Delta region and along the continental slope of the Louisiana and Texas coasts, several structural geological features that indicate soil movements have been identified and classified. The principal features of soil movements and their appearances on some geophysical records (Coleman, 1975, and Watkins and Kraft, 1976) are described below.

Surface Mudflows.--Mudflows are prone to develop in the Mississippi Delta area off the mouths of the principal passes that empty into the Gulf. Mudflows have the form of a slow glacierlike flow of soft soil over the sea floor. The fronts of the flow frequently form steep scarps that may attain heights of 50 ft (15 m) or more. The downslope margins of these features are characterized by some degree of surface relief, forming noses or scarps at their leading edges. Small slumps along these leading edges generally create an irregular sea-floor configuration. Surface offsets are usually less than 10 ft (3 m), and slump planes are generally confined within the flow. Surface mudflows are usually less than 50 ft (15 m) thick and commonly have a well-defined base. Downslope advance of these features may be either slow and continuous or intermittent between periods of essential standstill.

As mudflows advance downslope over the sea floor, they load the underlying deposits and may induce secondary failures and movements within the seabed. The loading may initiate sliding along a slip surface that cuts through the mudflow and into the underlying soils. Failure may also take place wholly within the mudflow if the mud nose becomes oversteepened. Today, the mudflows are actively moving across the continental slope and extend locally into the upper continental slope.

Slumps.--Slumps of the peripheral type may exhibit a form of "stairstep" faulting that is generally restricted to the upper 50 ft (15 m) of sediment and is usually subparallel to the bathymetric contours. In many slumps, the top of the stairstep is tilted in an upslope direction. Fault planes along the slump face decrease in steepness as depth increases and commonly become unrecognizable below more than about 50 ft (15 m) of sediment cover.

Shallow Faulting.--Shallow faults of the graben type appear on the sea-floor surface as parallel-trending scarps that are generally oriented subparallel to the bathymetric contours. The shallow valleys between these scarps often have smooth, flat-bottomed floors, but where smaller secondary faults occur, valley floors may be quite irregular and display small depressions and hills. The primary fault planes forming the graben generally extend less than 100 ft (33 m) below the mudline. Grabens probably represent a principally vertical movement of the sediment in response to tensional stresses generated by subsurface transfer of material outward from beneath areas of greater surface loading. Shallow faulting caused by soil movements can also be classified as an active type of faulting.

## Active Faulting

Although much of the faulting in the Gulf of Mexico is considered active on a geologic time scale, most of these faults are not "active" on a time base scaled to the life of engineered structures (significant movement in less than about 50 years). Fault activity on the latter scale, however, could possibly pose a hazard to exploration and development unless due allowance is made. Such faults are most common in areas that are rapidly subsiding owing to the withdrawal of formation fluids such as water and oil. Significant fault movement might also take place in areas of rapid deposition, such as the Mississippi Delta, or on steep slopes where stress due to sediment loading may accumulate for long periods of time but be relieved with relative suddenness by faulting. A study of the continental shelf and upper continental slope in the northwestern Gulf of Mexico indicates that the latter type of faulting may be most prevalent at the shelf edge and on active diapirs on the upper slope (Berryhill, 1976; Bouma and others, 1980).

Growth faults are common along the shelf edge. Like classical growth faults elsewhere, these features exhibit progressively greater offset as depth increases. The fault plane is generally well defined, linear or concave upward, and moderately steep and extends more than 500 ft (152 m) below the sea floor. Classic "rollover" structures, which become more pronounced as depth increases, are associated with these faults.

Surface and subsurface convex faults are similar in form to the growth faults described above but differ in that many convex faults extend to or very near the surface, where a scarp of considerable magnitude can develop. Interval thicknesses normally increase progressively downdip and from the upthrown to the downthrown sides of these features. Subsurface offsets of 20 ft (6 m) or more are common for these faults, and they may extend to depths of 500 ft (152 m) or more below the mudline. A preliminary map of the distribution of these features in the Mississippi Delta has been prepared by Garrison (1974).

Faulting in sediments overlying diapirically rising salt domes is quite common in the northern Gulf of Mexico where a great many such faults create small escarpments on the sea floor. Some of these faults are active on an engineering time scale; slope steepening of 1.2 inches per year (3 centimeters per year (cm/yr)) to 3.2 inches per year (8 cm/yr) within the lifetime of oil and gas fields has been reported by Bouma and others (1980).

Faults that offset the sea floor or approach within a few tens of feet of it are usually detectable in high-resolution seismic profiles. Such features should be examined carefully and avoided if possible in siting offshore structures.

## Shallow Gas Accumulations

The presence of gas in shallow, high-pressure zones beneath the shelf and upper slope has been a cause of blowouts during offshore drilling operations (U.S. Bureau of Land Management, 1979). These localized pockets of gas might consist, as discussed in Appendix II, either of biogenic methane generated in place by bacterial action, or of natural gas leaking from a deeper reservoir. However, such accumulations of either type of gas are generally detectable geophysically as "bright spots," anomalous reflections on high-resolution seismic profiles, or as a loss of reflected signals (i.e. a "wipe-out"). Many shallow gas accumulations are associated with swarms of gas seeps, which may be revealed on seismic profiles as mud mounds on the sea floor from which streams of escaping gas often are recorded in high-resolution seismic data. Ship-towed instruments that detect gas ("sniffer" surveys) also reveal increased levels of methane in the sea water around areas of numerous gas seeps.

On the Texas-Louisiana Shelf, shallow gas accumulations are most common in old channel systems and in areas affected by salt uplift where numerous faults form passageways to the near-surface sediments and thin clay layers offer sealing conditions for the small gas pockets. On the Mississippi Delta, gas in near-surface sediments is largely biogenic.

## Earthquake Hazards

Figure 57 shows the locations of earthquake epicenters in the U.S. Gulf Coastal States for the period 1865-1968 and the Gulf of Mexico and the adjacent onshore areas of Mexico for the period 1961-1971 (Algermissen, 1969). The risk of earthquakes in the northern Gulf of Mexico is low, and damage to offshore installations by earthquake activity has never been

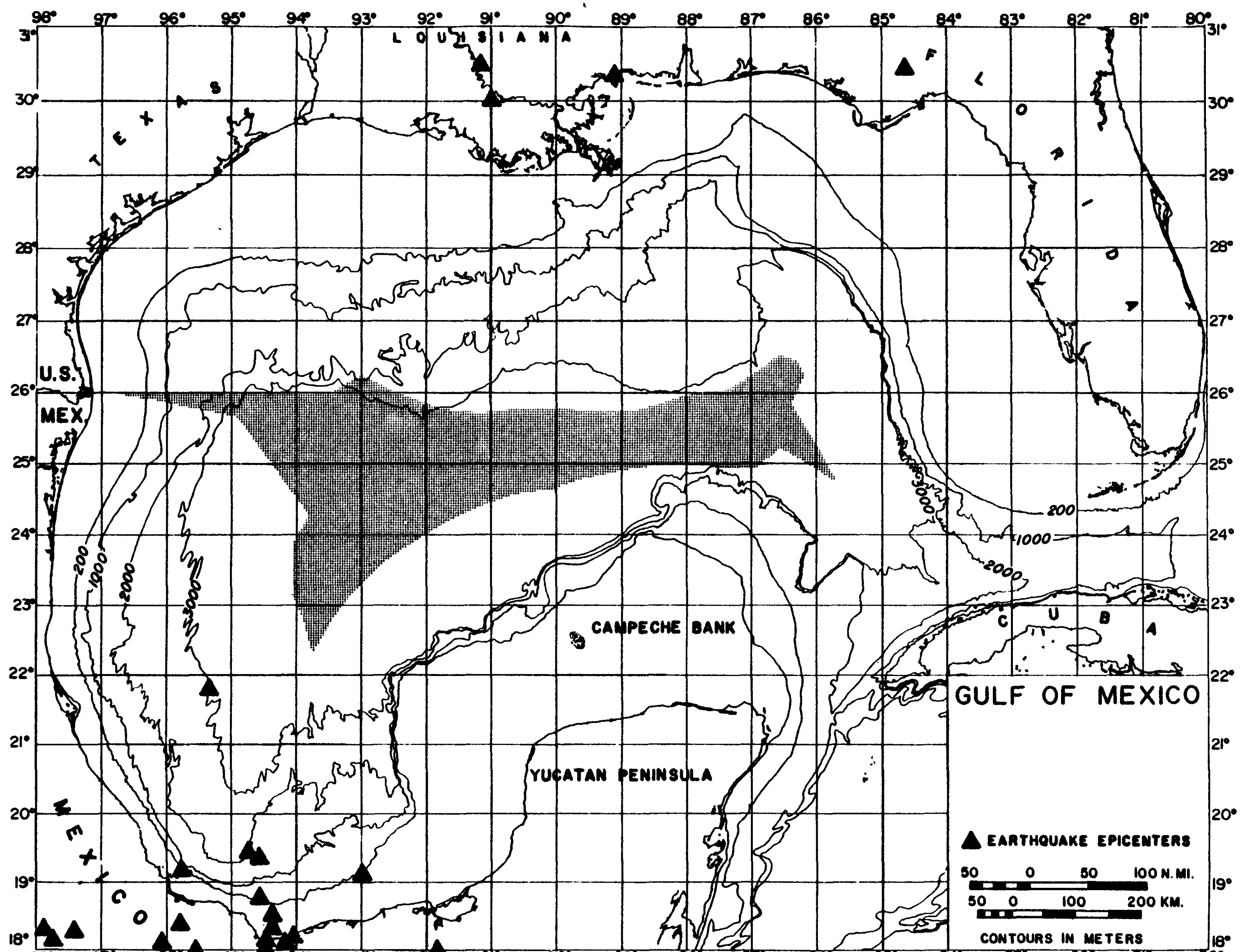


Figure 57.--Map showing locations of earthquake epicenters in the United States Gulf Coastal States for the period 1865 - 1968 and the Gulf of Mexico and the adjacent onshore areas of Mexico for the period 1961 - 1971. From Algermissen (1969) and various earthquake information of the Environmental Data Service, U.S. National Oceanographic and Atmospheric Administration.

reported. A seismic risk map for the United States shows the predictions of the degree of damage believed possible for a given area on the basis of historical data and geological evidence (Algermissen, 1969). Extrapolation of the mapped ratings into the offshore areas suggests that the Louisiana and northern Florida shelf areas might be in Zone 1, but for the remainder of the northern Gulf, no earthquake risk is assumed. Seismic Zone 1 indicates the possibility of earthquake intensities to V or VI on the Modified Mercalli Intensity Scale, during which ground motion might be felt but damage would be minor. A quake of intensity VI was recorded in Assumption Parish, Louisiana in 1930, and another of intensity V near Baton Rouge in 1958. Tremors of lesser intensity have been felt in central Florida and near Gulfport, Mississippi.

A band of seismic activity extends across Mexico along which earthquakes take place very frequently in two distinct zones of seismicity. The two zones of seismicity are: (1) the Trans-Mexican seismic zone of shallow-focus earthquakes; and (2) the Pacific seismic zone of deep-focus earthquakes (Martin and Case, 1975).

The Trans-Mexican seismic zone extends from the Trans-Mexican volcanic belt almost due east along lat 19° N to the extreme southwest corner of the Gulf of Campeche. The points at which the first motion of earthquakes originate, the hypocenters, along this lineament generally range from 0 to 124 mi (200 km) in depth. No earthquake focus was deeper than 124 mi (200 km) in this zone during the 1961-1967 period (Barazangi and Dorman, 1969).

The Pacific seismic zone is at about a right angle to the Trans-Mexican seismic zone, and it extends from approximately long 95° W southeastward along the west coast of Central America. The Pacific seismic zone is defined by a large concentration of earthquakes whose foci may be as deep as 186 mi

(300 km). Martin and Case (1975) noted an abrupt decrease in the frequency of earthquakes having hypocenters at depths of 62-124 mi (100-200 km) and an absence of foci deeper than 124 mi (200 km) (Barazangi and Dorman, 1969) west and northwest of long 95° W. The locations of these two zones are almost coincident with the proposed Salinas Cruz left-lateral fault (Viniegra, 1971) which crosses the Isthmus of Tehuantepec from the Pacific into the Gulf of Campeche. Alignment of shallow-focus earthquakes along the Salinas Cruz fault suggests that the fault is presently active (Martin and Case, 1975).

The relative closeness of the two seismic zones and the Salinas Cruz active fault to the southern part of the Gulf of Campeche indicates that some risk exists of earthquake hazards to drilling and production operations on the southern part of the Campeche Shelf and at the Santa Ana Field. There appears to be little or no risk of earthquake hazards in the Maritime Boundary region from these seismic features because the closest point in the boundary area is at least 240 mi (386 km) distant. Therefore, the ground shaking from even a large earthquake should be attenuated by the time the seismic waves reach the boundary area, unless some unknown wave guide effects exist. The possibility exists, however, that unknown seismic zones or active faults exist nearer the study area which could cause significant earthquake hazards, but large-scale studies would be needed to locate and to verify the existence of such features.

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