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Summary report on the regional geology, petroleum potential, environmental consideration for development, and estimates of undiscovered recoverable oil and gas resources of the United States Gulf of Mexico Continental Margin in the area of proposed Oil and Gas Lease Sales Nos. 81 and 84

Edited

by

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SUMMARY REPORT ON THE REGIONAL GEOLOGY, PETROLEUM POTENTIAL, ENVIRONMENTAL CONSIDERATION FOR DEVELOPMENT, AND ESTIMATES OF UNDISCOVERED OIL AND GAS RESOURCES OF THE UNITED STATES GULF OF MEXICO CONTINENTAL MARGIN IN THE AREA OF PROPOSED OIL AND GAS LEASE SALES NOS. 81 AND 84

INTRODUCTION

The first formal step in an Outer Continental Shelf (OCS) oil and gas lease offering is the preparation of a Resource Report (Summary Geology Report). The resource estimates developed for this report are then used in the preparation of the next required document, the Exploration and Development (E&D) Report. These two reports provide information needed in the selection of the Area of Geologic Potential, the area identified by the Under Secretary, Department of the Interior, in the formal Call for Information.

The purpose of the Resource Report is to describe both narratively and graphically the general geology, petroleum geology, resource estimates and environmental geology of an entire planning area, such as the central Gulf of Mexico. The Resource Report is a synthesis of relevant publicly available data and reports; it is written in a style and format that is useful to geologists, economists, petroleum engineers, environmental scientists, and decision-makers.

This report summarizes our general knowledge of the geologic framework, petroleum geology, and potential problems and hazards associated with development of petroleum resources in the Central and Western Gulf of Mexico OCS Planning Areas for proposed oil and gas lease sales 81 and 84, respectively. These areas encompass the submerged continental margin of the northern Gulf of Mexico from the vicinity of Mobile Bay to the Rio Grande and from State-Federal offshore boundaries to the deep Gulf floor along latitude 26°N (Fig. 0-1). The Central Gulf Planning Area (Sale 81) lies offshore the states of Louisiana, Mississippi, and Alabama, and encompasses some 39 million acres of seabed. The Western Gulf Planning Area (Sale 84) lies principally offshore Texas, but includes deepwater tracts south of western Louisiana; approximately 33 million acres of seabed are contained in this area. Final sale sizes, however, are subject to exclusion of tracts selected on the basis of environmental concerns, military usage, low geologic potential, and other considerations. Water depths in the combined call-area range from about 60 to 10,200 feet; generalized bathymetry and physiographic features of the region are shown in Figure 0-2.

The Gulf of Mexico OCS in the region of proposed lease sales 81 and 84, is the most productive offshore region in the United States. Over 94 percent of the petroleum liquids and 99 percent of the natural gas produced from the U.S. OCS in 1981 were taken from the central and western Gulf OCS off Louisiana and Texas (Havran and others, 1982). The U.S. Minerals Management Service Gulf of Mexico Regional Field Names Committee lists 521 active oil and gas fields in the Gulf of Mexico OCS as of December 31, 1982. An additional 16 fields have been depleted and abandoned. Estimates of original recoverable reserves for 468[1/] active fields and 16 depleted fields amount to 8.56 billion barrels of oil (BBO) and 98.1 trillion cubic feet (TCF) of gas; remaining recoverable reserves in these fields, as of December 31, 1982, are estimated at 3.0 BBO and 39.8 TCF of gas (Hewitt and others, 1983).

The following chapters are arranged to provide general information on the regional framework and petroleum geology of the central and western Gulf of Mexico, followed with information on petroleum potential and seafloor

[1/] Hewitt and others (1983) do not consider 53 of the 489 active fields to be sufficiently developed to permit reasonably accurate estimates of reserves at this time.

hazards more specifically tied to the areas proposed for leasing in Sales 81 and 84. References cited and illustrations have been included with individual chapters for convenience.

References

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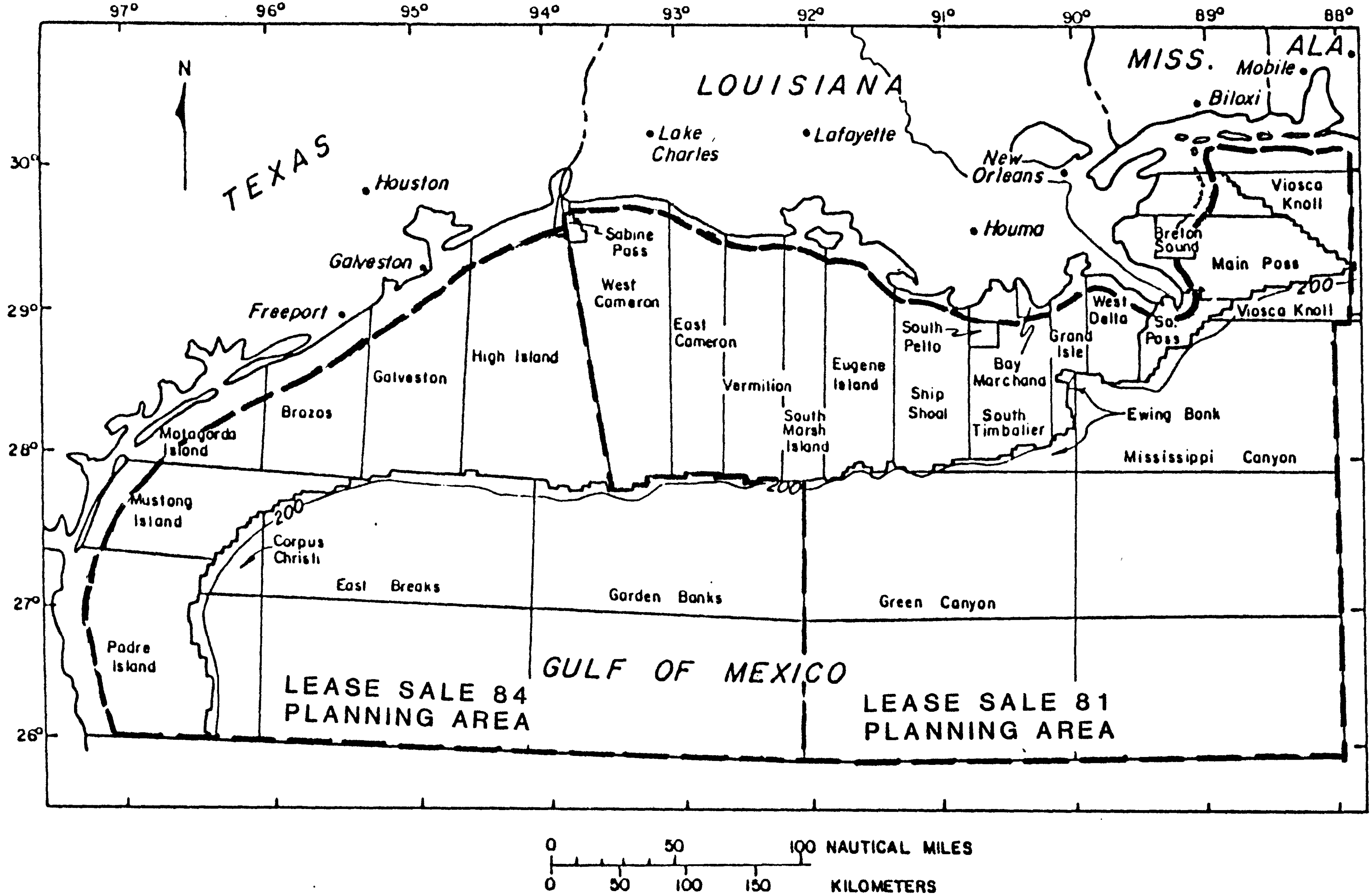

Figure 0-1. Map of northwest Gulf of Mexico showing Central and Western Gulf OCS Planning Areas for proposed Lease Sales 81 (Central) and 84 (Western).

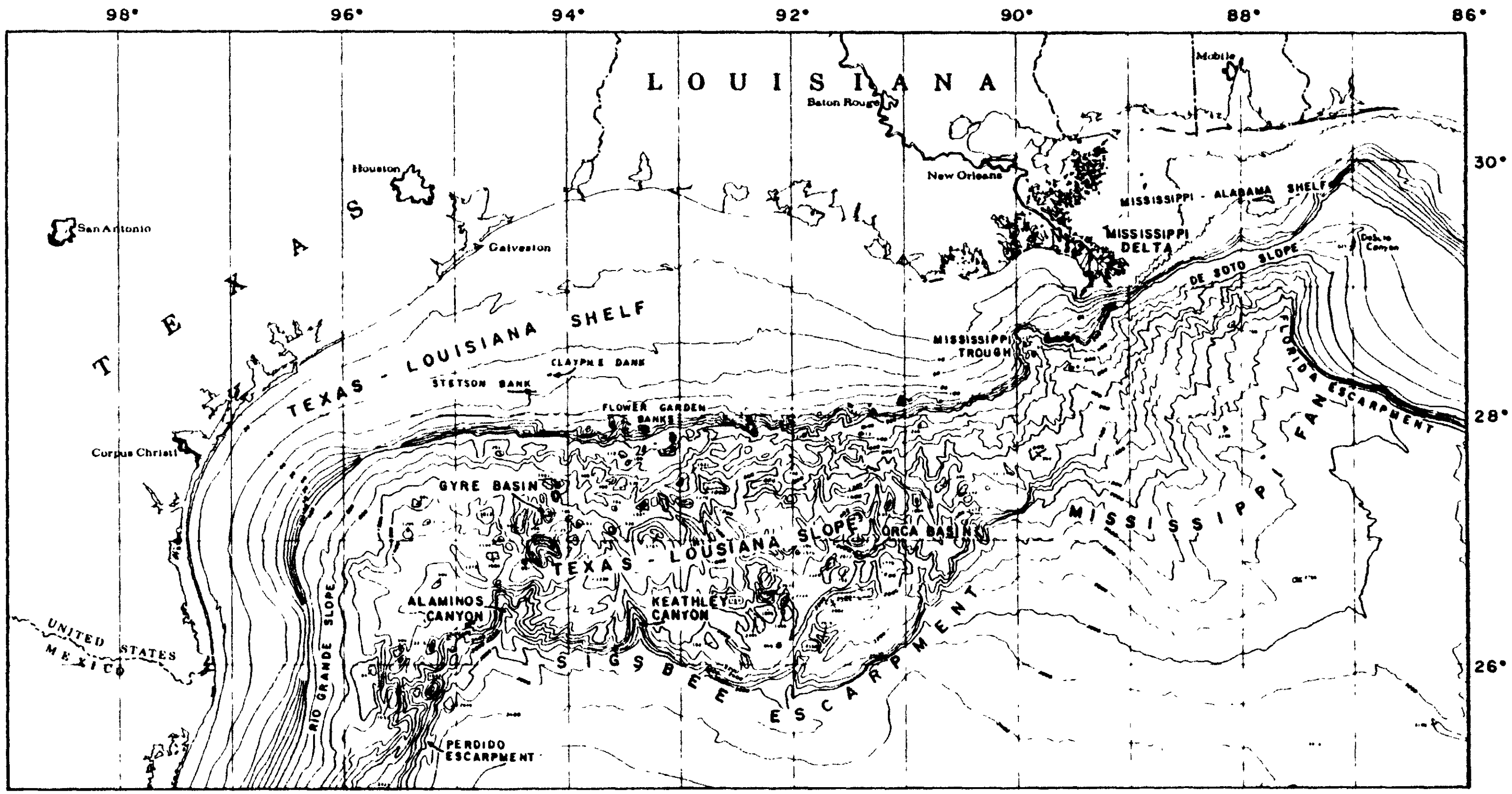

Figure 0-2. Map of northern Gulf of Mexico region showing bathymetry and principal physiographic feature in area of proposed Lease Sales 81 and 84. Contour intervals: 0 to 200 m in 20-m isobaths; greater than 200 m in 200-m isobaths. From Martin and Bouma (1982).

CHAPTER I

REGIONAL GEOLOGIC FRAMEWORK: CENTRAL AND WESTERN GULF OF MEXICO OCS REGIONS

by

Ray G. Martin

GENERAL

Outer Continental Shelf Oil and Gas Lease Sales Nos. 81 and 84 are proposed for the central and western Gulf of Mexico regions lying principally off the states of Texas and Louisiana. These regions include the continental shelf and adjacent continental slope and the deep seabed of the north central and northwestern Gulf of Mexico generally west of longitude 88°W and north of latitude 26°N (Fig. O-1). Water depths in the combined sale area range from about 60 to 10,200 ft; bathymetry and physiographic features in this area are shown in Figure O-2 of the Introduction of this report.

This chapter addresses the geologic setting of the proposed sale areas, first by a general discussion of the regional geology of the Gulf of Mexico basin, and second by a more detailed review of the stratigraphic and structural frameworks of the northern Gulf margin.

REGIONAL GEOLOGIC SETTING

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 the Straits of Florida and the Yucatan Channel. The central deep-water region of the Gulf is underlain by dense oceanic basement rocks (Fig. I-1), 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. I-2; 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 and intrabasin sedimentary-tectonic processes.

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 seismic reflection data in the peripheral coastal plains, on the continental shelves, and in the deep basin suggests that the basin is relatively young. At the close of the Paleozoic era and during the earliest Mesozoic time, the present Gulf basin appears to have been occupied by an emergent region periodically invaded by shallow epicontinental seas. During this period, the region 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 this time, much of North America was part of a supercontinent that included large parts of the present South American, African, Antarctic, Indian, and European continents. 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 separation 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 continental plates continued through the Triassic and Jurassic, establishing by the beginning of the Cretaceous the basic configuration of the present 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 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 fissures. As this complex process proceeded, the crust was slowly attenuated 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 has combined with subsequent sediment load to cause maximum subsidence of about 30,000 ft (9,146 m) since mid-Jurassic time in the central Gulf basin and possibly as much as 50,000 ft (15,244 m) in major depocenters along the northern Gulf margin (Fig. I-2).

By mid-Jurassic time and perhaps earlier, shallow seas began to invade the region periodically. For long periods, these shallow bodies of seawater were restricted from circulation with open-ocean waters, and large amounts of salt precipitated across wide areas 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 were 10,000 to 15,000 ft (3,048 to 4,572 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. I-1; Martin, 1980). It is not known whether these vast deposits of salt accumulated in one broad basin, separated during the Late Jurassic by active sea-floor spreading (Buffler and others, 1980; Dickinson and Coney, 1980; Walper, 1980), or whether they were deposited in isolated graben-basins in essentially their present geographic positions. However, the crust beneath the deep Gulf floor between the present salt-dome provinces of the northern and southern Gulf has physical properties similar to that of oceanic basement formed by sea-floor spreading (Fig. I-2) and implies that the Jurassic salt basins were rifted apart, probably during the Late Jurassic or earliest Cretaceous.

A thin section of pre-middle Cretaceous strata above oceanic crust in the central Gulf is shown by refraction and reflection data used in the construction of cross sections A-A' and B-B' (Fig. I-2). Thicker sections of pre-middle Cretaceous, Jurassic, and possibly older deposits are indicated by geophysical data in the areas of attenuated continental crust (Fig. I-2) flanking the oceanic terrane, thus supporting a model of late-stage rifting of the central Gulf basin with implacement of mafic crust and attendant drift of Middle to Late Jurassic salt basins.

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 terrigenous 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. I-3). 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 expose part of these Early Cretaceous platforms.

In mid-Cretaceous time, a profound increase in the subsidence rate and sea level affected the carboate depositional environment throughout the Gulf region. As the Late Cretaceous seas expanded, 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 overwhelmed carbonate environments in the northern and western regions of the basin (Fig. I-3). Carbonate deposition persisted, however, on the Florida and Yucatan Platforms in the eastern and southern Gulf.

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. I-3) 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. I-2). Alternate periods of load-induced subsidence and up-building of sediments followed by less subsidence and out-building of sediments produced the multiple transgressions and regressions of depositional environments that are characteristic of the Tertiary sequence in the northern and western Gulf margins. Sediment supplies during Cenozoic 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 Pleistocene glaciation. Sea level rose and fell in concert with climatic conditions that controlled the retreats and advances of 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. I-3). Thick accumulations of Pleistocene strata extend southeastward to the topographically high approaches to the Straits of Florida and southwestward 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. Clastic sediments from land areas to the north and northwest of the Florida Platform were deposited as far south as the middle shelf region as minor Tertiary components in an otherwise carbonate environment. 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 relatively stable areas in which tectonism caused by sediment loading and 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 Cenozoic shale. Large regions of the northern Gulf margin have been complexly deformed by load-induced flowage of these water-saturated, undercompacted shales. 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. I-I, I-2).

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 and attendant plastic flowage of underlying materials 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 (Figs. I-1, I-2). Outside of the Sigsbee Knolls diapir field, 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 of relief. In the massive carbonate platforms of the eastern and southern Gulf, post-Jurassic deformation has resulted largely from broad regional uplift and crustal warping.

These structural features are contained within the wedge of sediments and although generally related to crustal subsidence, are not direct products of major crustal events. Structural deformation resulting from dynamic earth processes appears primarily to affect pre-Cretaceous strata over much of the region, and Mesozoic-Cenozoic deposits in a small part of southernmost Bay of Campeche.

GEOLOGIC FRAMEWORK OF THE PROPOSED SALE AREAS

The continental margin of the northern Gulf of Mexico from the De Soto Canyon to the Rio Grande is composed of thick sequences of clastic sediments deposited in offlapping wedges that have been deformed by the movement of salt and undercompacted shale during Cenozoic time (Figs. I-4,I-5,I-6). Cumulative sediment thickness of Tertiary-Quaternary clastic material possibly amounts to more than 15 km (50,000 ft) in the region of the continental shelf off Louisiana and Texas, herein referred to as the "Gulf Coast basin" but also known as the Gulf Coast Geosyncline of Bornhauser (1958) and Hardin (1962). The landward limit of the basin is considered to be the updip edge of basal Tertiary deposits in the inner coastal plain while its southern flank is described by the near convergence of the descending topography of the continental slope and the ascending surface of mobile Jurassic salt (Fig. I-4).

Beneath the coastal plain the basin is characterized by centers of maximum deposition that occurred in the Rio Grande, Houston-East Texas, lower Mississippi, and Apalachicola Embayments (Fig. I-5). The Llano and Monroe Uplifts and the southern terminus of the Appalachian foldbelt are transversely aligned to the basin axis and reflect a Paleozoic and Precambrian framework that protrudes Gulfward between the embayments as salients of the continental foundation. Other structurally positive elements which, in varying degrees, affected Cenozoic depositional patterns within the basin include the San Marcos Arch in south-central Texas, the Sabine Uplift in northeast Texas and Louisiana and the Wiggins Arch in southern Mississippi.

Stratigraphy

The Gulf Coast basin is composed of thick transgressive and regressive sections of Tertiary-Quaternary clastic sediments deposited in offlapping wedges over mainly carbonate beds of Cretaceous age (Fig. I-4). Dark-colored paralic sediments, carbonates, redbeds, and evaporites of Jurassic age and possibly older underlie the Cretaceous strata; and, along the northern margin of the coastal plain, rest unconformably on complexly structured units of the Ouachita system (Flawn and others, 1961; Vernon, 1971; Woods and Addington, 1973).

Pre-Jurassic strata in the northern Gulf Coast basin were deposited upon and coastward from the orogenic geosynclinal facies of the Ouachita tectonic belt (Fig. I-6). They include late-orogenic Pennsylvanian and Permian paralic clastics and shelf carbonates (Woods and Addington, 1973) and post-orogenic Triassic fluviatile to deltaic redbeds (Eagle Mills formation) deposited mainly in graben structures that parallel the basin rim. Triassic strata unconformably overlie Paleozoic beds of several ages and are in turn overlapped by Jurassic and Upper Cretaceous deposits. Pre-Jurassic strata are known from only a limited number of deep wells drilled along the northern perimeter of the basin in the inner coastal plain and are believed to plunge far below the economic and geologic limits of exploration in the area of OCS Lease Sales 81 and 84.

Jurassic strata in the northern Gulf margin are represented by lithologic types ranging from redbeds and evaporite deposits to marine clastics and carbonates (Newkirk, 1971). The youngest of these strata represent a continuation of the post-orogenic redbed accumulation that followed truncation of Triassic graben deposits. Important to hydrocarbon accumulation in the Gulf Coast basin is the Louann Salt of Middle to Late Jurassic age (Callovian to Oxfordian; Imlay, 1980) which has been deformed into diapirs, domes, and anticlines that pierce and uplift the Cenozoic-Mesozoic section. The Louann belongs to the upper part of the post-orogenic sequence and is underlain and overlain by, and interfingers with, redbeds that range in age from Permian to Jurassic (Lehner, 1969; Tyrell, 1972). Jurassic salt deposits underlie the Gulf Coast basin along three prominent belts whose extents are described by fields of diapiric structures shown in Figure I-6: 1) an inner belt consisting of the Mississippi, North Louisiana, and East Texas salt basins; 2) a middle belt containing the Louisiana-Texas coastal and inner shelf salt dome areas and isolated diapirs in the Rio Grande Embayment; and 3) an outer belt which includes nearly all of the continental shelf and slope from the De Soto Canyon to northern Mexico.

Physical correlation between the salt that forms domes on the continental slope and that which underlies the northern part of the Gulf Coast basin is not firmly established. Geophysical evidence that top-of-salt lies at depths of 9-12 km (30,000-40,000 ft) along and below Cretaceous shelf deposits in eastern Texas (Newkirk, 1971), and the recovery of redbeds overlain by Cretaceous carbonate sediments from the crest of a large salt massif off south Texas (Lehner, 1969) provide the rationale for inferring the salt in the continental slope to be stratigraphically equivalent to the Louann. Watkins and others (1976) suggest, however, that the salt of the lower Gulf Coast, shelf and slope was deposited in a basin separate from the Louann but that it is probably equivalent to the Louann and to the Challenger salt (Ladd and others, 1976) of the south-central Gulf basin.

Upper Jurassic and Cretaceous strata in the Gulf Coast consist mostly of shallow-marine carbonate rocks deposited over broad shelf areas that extended counter-clockwise around the open Gulf from southern Florida to Yucatan. Clastic sediments derived from northern and northeastern sources dominate the Upper Jurassic and Lower Cretaceous sections in northeastern Louisiana and southern Mississippi and Alabama. Shallow-marine carbonate rocks comprise most of the Lower Cretaceous strata in southwest and central Texas, and in the coastal part of eastern Texas. Interbedded carbonate and silicate clastic rocks of neritic origin are predominant in northeast Texas and adjacent parts of Louisiana and Arkansas (Rainwater, 1971) landward of the Edwards Reef trend.

As the result of a rapid increase in the rate of subsidence of the basin, Upper Cretaceous strata transgress all older Mesozoic rocks in the northern Gulf except those on the Edwards Plateau in central Texas (Holcomb, 1971). Upper Cretaceous strata are represented in the Gulf Coast by mainly transgressive sands, shales, marls, and chalks. Locally, reef-like carbonate beds accumulated on the Monroe and Jackson Uplifts and coal sequences were deposited in the upper Rio Grande Embayment (Holcomb, 1971).

Since early Cenozoic time, the Gulf Coast basin has received a great influx of terrigenous sediments from northern and western sources as a result of Laramide orogenesis which uplifted much of the North American continent. Most of the petroleum exploration targets in the Central and Western Gulf OCS are in sedimentary sequences of early Miocene through

Pleistocene age, representing a maximum stratigraphic accumulation of more than 10 km (33,000 ft) in the vicinity of the Mississippi Delta.

Cenozoic deposition was generally cyclic, with minor periods of transgression repeatedly interrupting the overall pattern of regression. Tertiary-Quaternary stratigraphic units generally grade seaward from thick-bedded sandstones, deposited in continental, lagoonal and deltaic environments through alternating sands and shales of the inner and neritic environments, into thick, outer neritic and deep marine shales and turbidites of the bathyal or continental slope environment (Fig. I-7; Braunstein and others, 1973). In gross geometry, Miocene, Pliocene, and Pleistocene strata, consist of three major facies deposited simultaneously in zones that generally paralleled the shoreline; these facies represent the intercoastal, shelf, and slope environments of deposition (Shinn, 1971). The landward facies consists primarily of continental, lagoonal, and deltaic sediments, predominantly sandstones, which were deposited near the shore and are referred to as the "massive sands" or "deltaic plains complex" (Figs. I-7,I-8A). The middle facies consists of alternating sandstones and shales deposited in the neritic and upper bathyal environments, while mud was deposited in the outer neritic, bathyal, and possibly abyssal environments and dominates the "deep water", or seaward facies.

These facies represent persistent environments that have migrated steadily seaward throughout the Cenozoic in conjunction with the progradation of the northern Gulf clastic embankment. Caughey (1975) characterized the Pleistocene section of the north-central Gulf margin as a regresional sequence of fluvial, delta-plain, delta-front, and prodelta deposits distinguished on the basis of lithologic and paleontologic criteria (Fig. I-8B). Fluvial facies consist predominantly of discontinuous massive sandstone units separated by intervals of sandy shale. Delta-plain facies fringe the down-dip margin of fluvial deposits and consist of nonmarine to inner neritic progradational sequences that contain 25 to 50% sandstone. Thickest sandstone accumulations are present as a result of superposed channel-mouth bar and distributary channel deposits. Delta-plain deposits are transitional downdip into the brackish to inner-neritic, delta-front facies. Delta-front deposits contain sand in amounts of 10 to 30% of the total section and are characterized by thin to moderately thick sand units having gradational bases and sharp upper contacts. Delta-front sandstones thin basinward and disappear into massive prodelta and slope mud deposits.

In concert with Cenozoic progradation of the northern Gulf margin, centers of maximum deposition within the basin have migrated laterally in response to the shift of sediment supply from the Rio Grande to the Mississippi River drainage basin (Hardin, 1962). Thickest accumulations of lower Tertiary strata occur in the Rio Grande Embayment, Miocene strata in southern Louisiana, Pliocene deposits under the central shelf and Pleistocene along the present shelf edge (Fig. I-9); Shinn, 1971; Powell and Woodbury, 1971; Woodbury and others, 1973).

More specific details regarding the stratigraphy of prospective Tertiary and Quaternary sections, sand-bearing facies, and depositional patterns of Cenozoic strata are presented in the following chapter on Petroleum Geology.

Structural Features

The Gulf Coast basin is a region of major vertical subsidence and relatively simple gravity tectonics. Principal structural features in the basin are salt domes, regional "growth" faults, and masses of mobilized undercompacted shale (Fig. I-6) that have resulted from the presence of an underlying Jurassic salt basin and the depositional and lithological characteristics of the Cenozoic sedimentary wedge that gradually advanced gulfward across it. These structural features are contained within the young sedimentary prism and are little related to deep-seated tectonic forces.

The configuration of the rim of the Gulf Coast basin from Alabama westward through Arkansas to southwest Texas (Fig. I-6) was inherited from the trend of the Ouachita tectonic belt formed in the late Paleozoic from the "Llanorian geosyncline" which flanked the North American craton (Flawn and others, 1961; Woods and Addington, 1973). Upper Paleozoic to lower Cenozoic strata along the inner margin of the basin have been greatly affected by post-orogenic vertical movements resulting from a relaxation of compressional forces that had acted on the late Mississippian-Pennsylvanian continental margin. Mesozoic tensional stress on the inner margin of the basin is reflected by systems of faults that formed contemporaneously with deposition in Triassic to Tertiary. Faulting in the younger peripheral graben zones (Fig. I-6; Balcones, Mexia-Talco, Pickens-Gilbertown-Pollard) was caused locally by plutonic and volcanic activity, differential subsidence, basinward sediment creep, and salt flowage (Bornhauser, 1958; Cloos, 1968; Hughes, 1968; Bishop, 1973). A similar structural framework for pre-middle Cretaceous strata in the offshore region of the northern Gulf is likely.

Salt Structures

Salt diapirs in the Gulf Coast basin are distributed in interior basins in east Texas, northern Louisiana and central Mississippi and along the Texas-Louisiana coast from the San Marcos Arch to the Mississippi Delta (Fig. I-6). The coastal province of domes continues beneath the Texas-Louisiana Shelf and extends along the continental slope from a small grouping of structures in the De Soto Canyon westward into the slope off northeastern Mexico. The basinward limits of diapirism in the northern Gulf of Mexico are well defined by the abrupt topographic steepening along the lower slopes that form the Sigsbee and Rio Grande Escarpments in the central and western sectors of the region. These limits are poorly marked in the Mississippi Fan province, where thick late Quaternary deposition has obscured nearly all topographic expression of underlying structure.

The diapiric movement of salt is considered to be due to density and strength differences between salt and surrounding sediment that occur at an overburden thickness of no less than 1000 m (3000 ft) (Thrusheim, 1960). The actual start of mobilization is probably determined largely by temperature (Heroy, 1968 and Gussow, 1968), but is also dependent on other factors such as salt thickness and purity, and slope of the underlying surface (Trusheim, 1960). The processes of differential loading and plastic flow within the salt are believed to have been maximized along successive fronts of the gulfward advancing sedimentary embankment (Hanna, 1958).

In the early stage of deformation, salt is displaced into broad gentle pillows which form in areas of less overburden pressure (Bornhauser, 1958). Withdrawal of salt from beneath areas of greater loading causes subsidence of the overburden mass allowing for the accumulation of more sediments that will cause further structural growth. As the sediment load increases and expands into other parts of the basin, the deformation pattern matures and the salt is gradually squeezed into stocks and, ultimately, into narrow spine-like domes (Lehner, 1969).

The distribution pattern of diapir fields in the northern Gulf margin represents the overall extent of the Louann Salt basin of Middle to Late Jurassic time (Fig. I-6). "Domeless" areas in the margin are underlain either by salt accumulations too thin to be mobilized into diapirs or by time-equivalent non-evaporitic facies. Diapir fields onshore and offshore represent areas of thickest Jurassic salt accumulation (McGookey, 1975; Martin, 1978, 1980). Variations in the sizes of individual salt structures within the fields result from relative differences in the thickness of the original salt available for diapiric injection and in the total thickness and rates of accumulation of the sedimentary overburden that induced and perpetuated salt mobility (Amery, 1978).

In the Gulf Coast basin, salt movement was probably initiated soon after deposition in the Late Jurassic and reached its acme in the interior coastal plain during Late Cretaceous and early Tertiary times (Bornhauser, 1958; Halbouty, 1967, 1979; Kupfer, 1974). Rapid gulfward advance of the continental margin during the late Tertiary and Quaternary produced maximum diapirism in the lower coastal plain and continental shelf during the Miocene and Pliocene and in the outer shelf and slope regions in the Pleistocene (Lehner, 1969; Woodbury and others, 1973; Kupfer, 1974).

Coastal Plain and Continental Shelf--Deeply rooted salt diapirs, commonly shaped like slender columns with enlarged and occasionally mushroomlike tops; diapiric and nondiapiric salt anticlines; and deep-seated nondiapiric salt pillows are characteristic of the interior coastal plain salt basins, coastal areas of Texas and Louisiana and the continental shelf from Florida to Texas (Fig. I-10). The diameters of salt diapirs range from less than 0.6 mi (1 km) to as much as 19 mi (30 km); salt anticlines, including those in the Mississippi salt basin and the Destin structure off northwestern Florida, range from 9 mi to 43 mi (15 km to 70 km) in length. Diapiric structures in the coastal plain and inner continental shelf regions generally are less than 5 mi (8 km) across. Large salt stocks are commonly situated along intricate networks of growth faults in the middle shelf and

Mississippi Delta regions off Louisiana and in the outer shelf off Texas (Fig. I-6).

Seafloor expressions of salt domes in the forms of mounds and banks that were produced by arching and faulting of strata over diapiric centers are common along the outer shelf-edge. Some of the more prominent banks along the shelf-edge consist of carbonate caps built by faunal growth active since late Pleistocene time. That these reefs thrived in the photic zone, and that some continue to thrive on East and West Flower Garden Banks (Fig. 0-2) over a period of time marked by subsidence, high sedimentation rates, and a wide range of sea level fluctuations, indicates a recent and continuing history of vertical salt uplift (Martin and Bouma, 1982).

Upper Continental Slope—Large salt stocks surrounded by thick sheaths of deformed shale and ridgelike masses of diapiric salt are typical of the diapiric structural style of the shelf-edge and upper continental slope regions in water depths ranging from 295 to 3,280 ft (90 to 1,000 m) from the Mississippi Delta vicinity westward to the Rio Grande Slope off south Texas (Fig. I-11). Structural sizes of salt stocks range from 3 to 19 mi (5 to 30 km) across, and some salt anticlines extend for more than 31 mi (50 km). Salt structures are separated by broad sedimentary basins that are filled to near-capacity and only moderately expressed in the sea floor topography. Upper slope basins commonly contain about 6,500 to 11,500 ft (2,000 to 3,500 m) of sediment and some, especially those in the Mississippi Fan and western slope regions, contain bedded deposits exceeding 16,400 ft (5,000 m) in thickness.

As many as 24 individual salt structures penetrate and uplift Cretaceous units and Tertiary strata as young as late Miocene in the upper slope region near De Soto Canyon just east of the Central Gulf OCS Planning

Area (Fig. I-6). Other piercement domes and nondiapiric salt swells are known to exist in the area between the De Soto Canyon diapiric field and the large salt uplifts of the Destin Dome area to the northeast, and some domes not shown on figures included here are reported in the shelf and upper slope south of Mobile Bay. The apparent detachment of these structures from the main diapiric province to the west may be due to depositional and paleostructural factors (Martin, 1980).

Middle Continental Slope—Between the Mississippi Fan province and the Alaminos Canyon (Fig. I-5), the middle slope region is characterized by the presence of very broad, steeply-flanked diapiric stocks and ridges distributed in a totally random pattern (Fig. I-6). In cross-section these structures appear as thinly covered salt massifs separated by deep topographic depressions and canyons filled with thick, bedded deposits (Fig. I-13). Sediment distribution patterns on the slope are controlled principally by the growth of salt structures which have often blocked active submarine canyon systems, or coalesced to form topographic depressions in noncanyon areas (Martin and Bouma, 1978; Trabant and Presley, 1978; Bouma and Garrison, 1979; Martin and Bouma, 1982). Sedimentary loading on thick subsurface salt deposits in such local basins thus may be a prime factor in the evolution of the random structural pattern of salt diapirs in the Texas-Louisiana Slope (Watkins and others, 1978; Martin and Bouma, 1982).

Lower Continental Slope—Salt structures on the lower Texas-Louisiana Slope between the Mississippi Fan and Alaminos Canyon consist mainly of gentle, pillowlike swells that rise only a few hundred meters above an almost continuous mass of relatively shallow salt (Fig. I-14). Structural crests are covered by thin sections of moderately deformed bedded sediments and slump deposits. In contrast to the thick sections of downbuilt sediments

(Humphris, 1978) that occupy deep interdomal basins and canyons elsewhere in the Texas-Louisiana Slope and structural troughs between salt ridges in the Mississippi Fan province, the sedimentary cover of the lower slope region is relatively thin (1,600 to 6,500 ft [500 to 2,000 m]) and is perched on the shallow salt surface. The almost continuous body of shallow salt that underlies the lower slope region is divided into broad, lobelike masses by submarine-canyon systems that open onto the continental rise and extend from several tens of kilometers into the slope province as pronounced topographic features. These canyons, and a number of broad basins and troughs which separate lower slope salt masses from the large diapiric stocks and ridges on the middle slope, contain substantial thicknesses of well-stratified deposits. Along the Sigsbee Escarpment at the foot of the Texas-Louisiana Slope, these thinly covered salt tongues (Fig. I-15) overlie continental rise strata that range in age from Miocene to early Pleistocene. Salt tongues of this nature were initially recognized by deJong (1968) and Amery (1969) near longitude 92°W, in the area of the southernmost bulge in the escarpment, and were described in later reports by Watkins and others (1975, 1978) and by Humphris (1978). Seismic-reflection data show that such salt tongues are not local features, but extend well into the slope province (Fig. I-16) along the escarpment from near longitude 91°W westward to longitude 94°W. Salt thicknesses range from 1.0 to 1.5 km upslope to only a few tens of meters thick along nearly exposed basinward edges. Basal surfaces of individual salt tongues are in angular contact with the Quaternary and Tertiary strata that continue basinward into the adjacent Sigsbee Wedge (Wilhelm and Ewing, 1972) sequence (Fig. I-15). It is apparent that the salt tongues are the result of lateral flowage, probably contemporary with the deposition of late Tertiary and Quaternary strata so that the leading edges of individual flows were never buried more deeply than they are at present. Collectively, the flows represent the leading edge of a large salt body that extruded seaward in response to the rapid accumulation of regional sediment loads during late Tertiary and Quaternary time. That there is little evidence of salt intrusion or uplift in the strata beneath the salt tongues further suggests lateral salt flowage beyond the basinward limits of Jurassic salt deposition (Martin, 1980).

Northwest Continental Slope--The structural styles of salt diapirs and uplifts of the continental slope regions off south Texas and northeastern Mexico (Fig. I-5) contrast markedly with those of the Texas-Louisiana Slope region just described. In the elbow area of the continental slope off south Texas, where the trend of the slope swings from east-west to north-south, the structural style of salt deformation is considerably subdued (Fig. I-6). Most of the middle and lower slope regions are underlain by a shallow salt layer whose surface has been deformed into gentle anticlinal and irregularly shaped forms that uplift and fault the overlying strata but commonly do not intrude them. Steeply flanked, well-defined diapiric anticlines and stocks are common features in the upper slope and near Alaminos Canyon, but are the exception elsewhere. To the south in the Rio Grande Slope province (Figs. I-6,I-17), isolated diapiric stocks and narrow anticlines are the predominant salt-forms of the upper slope region to about 1,000 m water depths. Structures are covered and separated by thick sections of sedimentary deposits, and few are topographically expressed. The ridge and knoll topography of the middle and lower slope region is formed by very large, northeast-trending salt anticlines separated by deep basins and troughs which contain thick sections of clastic sediment. Large anticlines, possibly cored with nondiapiric salt, lie beneath the continental rise southward from Alaminos Canyon (Figs. I-6,I-18).

Mississippi Fan--The middle slope region of the Mississippi Fan province is underlain by a system of northeast-trending salt anticlines (Figs. I-6, I-12) first recognized by Shih and Watkins (1974). Salt ridges range from 0.6 to 9 mi (1 to 15 km) in breadth and from 19 to as much as 87 mi (30 to 140 km) in length. Narrow troughs between the ridgelike structures commonly contain stratified sedimentary sections 6,500 ft (2,000 m) or more thick. Thick deposits of Late Quaternary strata over the entire region obscure all but the most subtle topographic expression of the underlying salt-ridge structure. The morphological contrast between the subparallel ridge system of the Mississippi Fan province and the random pattern of salt structures in the Texas-Louisiana Slope region to the west may be the result of a more uniform distribution of prograding sediment loads in the relatively younger deltaic-slope province (Watkins and others, 1978).

The seaward edge of the northern Gulf diapiric province is less well-defined in the Mississippi Fan region than elsewhere along the margin. Small, isolated diapiric plugs and nondiapiric, pillowlike swells (Figs. I-1,I-6) pierce and uplift Cretaceous and early Tertiary strata in a poorly-defined belt that lies subparallel to the Florida Escarpment and that extends from the salt-ridge system of the upper fan southeastward to near latitude 25°N in the Eastern Gulf OCS. These structures are presumed to be salt-domes on the basis of morphological characteristics and on the general stratigraphic level at which they are rooted.

Undercompacted Shale Structures

Beneath the shelf off south Texas, salt diapirs are virtually unknown and the broad, linear uplifts and complex fault systems (Figs. I-6,I-19) that affect the Cenozoic section there, have, instead, resulted from mobile masses of undercompacted shale (Bruce, 1973). Elsewhere over the Texas-

Louisiana OCS, large masses of mobile shale "sheaths" commonly accompany salt diapirs. Shale anticlines and domes are the result of deep water marine clays being subject to essentially the same processes of loading and plastic flowage that are operative in the formation of salt domes. Gulf coast shale structures consist typically of low-density, water-saturated clay and contain abnormally high fluid pressures. Compaction of these clays has been prematurely terminated by the rapid accumulation of overlying sediments causing a drastic reduction in permeability and thereby preventing the normal expulsion of pore water (Bruce, 1973). Abnormally high fluid pressures in the shales thus result because pore water, rather than sediment, bears the bulk of the overburden load.

Modern multichannel seismic reflection data from the region of the Central and Western Gulf OCS Planning Areas have shown that structures produced by mobilized undercompacted shales are more common than previously thought. Many of the structural features identified on Figure I-6 as "salt diapirs" may include thick sheaths of deformed shale that are more the result of shale flowage related to overburden load than flowage in response to salt mobilization. Also, some of the structures mapped as salt from analysis of single-channel seismic data may in fact be composed entirely of deformed shale.

Faulting

Major systems of principally down-to-the-basin faults occur along the Texas and Louisiana Gulf Coast seaward of the trend of the Lower Cretaceous shelf edge, and extend from the Mississippi-Alabama Shelf westward into northeastern Mexico (Fig. I-6). Faults are observed in great numbers in most seismic reflection profiles crossing the shelf and upper slope regions of the Texas and Louisiana OCS. Publicly available data and published compilations, however, are not sufficient to permit mapping of the complex pattern of fault systems in the OCS for this report.

Faults generally have formed contemporaneous with deposition, resulting in a marked thickening of beds in the downthrown block, and hence have been termed growth faults (Ocamb, 1961; Hardin and Hardin, 1961), and syndepositional faults (Shinn, 1971). Displacement along "growth-fault" planes is normal and throw increases with depth (Fig. I-20). Fault planes are commonly steep near their upper limits but show progressive flattening with depth. Rotation of the downthrown block often accompanies movement along the concave-basinward fault plane resulting in a downward increasing reversal of dip of the sedimentary layers from gently gulfward to gently landward (Fig. I-20). The pseudo-anticline or "roll-over" (Durham and Peoples, 1956) thus formed seaward of the fault trace is a product of both movement and differential sedimentation.

Although predominantly down-to-the-basin, major growth fault systems in the shelf and slope region of the Central and Western Gulf OCS offset late Tertiary and Quaternary strata in both down-to-the-basin and down-to-shore directions. The regional pattern of faulting in the middle and outer shelf regions appears to be oriented mainly in northwest-southeast and northeast-southwest directions. Along the coast and in the inner shelf, regional fault systems generally parallel the shore from northern Mexico to the Mississippi Delta vicinity.

Regional faults have formed generally along Tertiary and Quaternary hinge lines (paleo-shelf edges), where the inclination of the sea floor steepens, where stratigraphic sequences thicken appreciably, and where gross lithology changes from interbedded sandstones and shales to predominantly deep-water shale (Hardin and Hardin, 1961; Bruce, 1973). Because the hinge line, or flexure, for each succeedingly younger unit lies farther seaward, growth-fault systems of the Gulf Coast basin become successively younger in a gulfward direction (Shinn, 1971).

The principal growth fault systems of the outer shelf region are directly related to flowage of undercompacted shales as a result of overburden loads. The model for regional growth-fault formation espoused by Bruce (1973) for the shelf offshore south Texas may be applicable to most of the central and western Gulf of Mexico OCS region. On a more local scale, the complex fault pattern of the Gulf Coast basin is accentuated by the common occurrences of peripheral and radial systems of growth faults associated with ascending masses of piercement salt and undercompacted shale.

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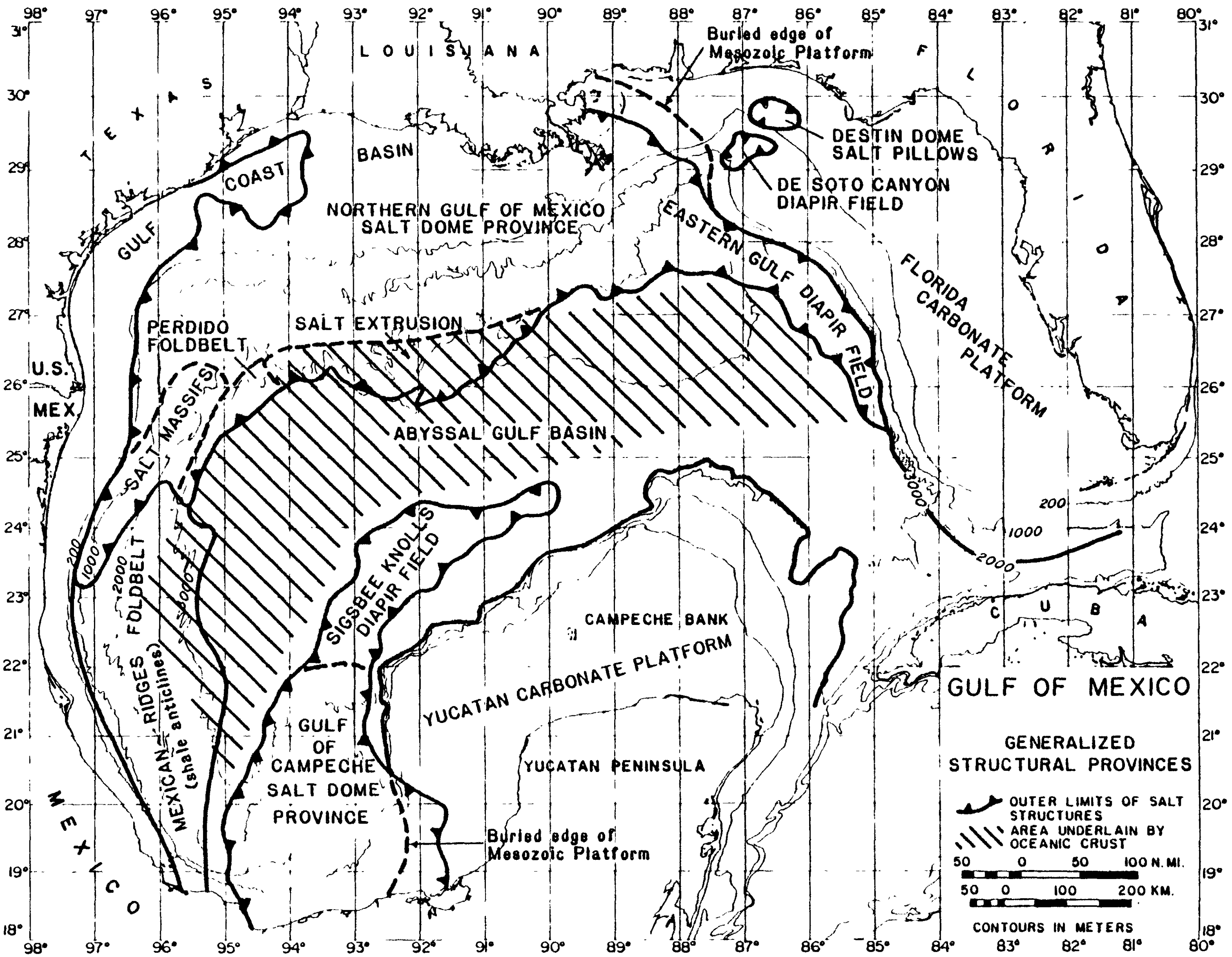

Figure I-1. Map of Gulf of Mexico region showing generalized structural provinces, distribution of diapiric salt structures (Martin, 1980), and extent of oceanic crust (Buffler and others, 1980).

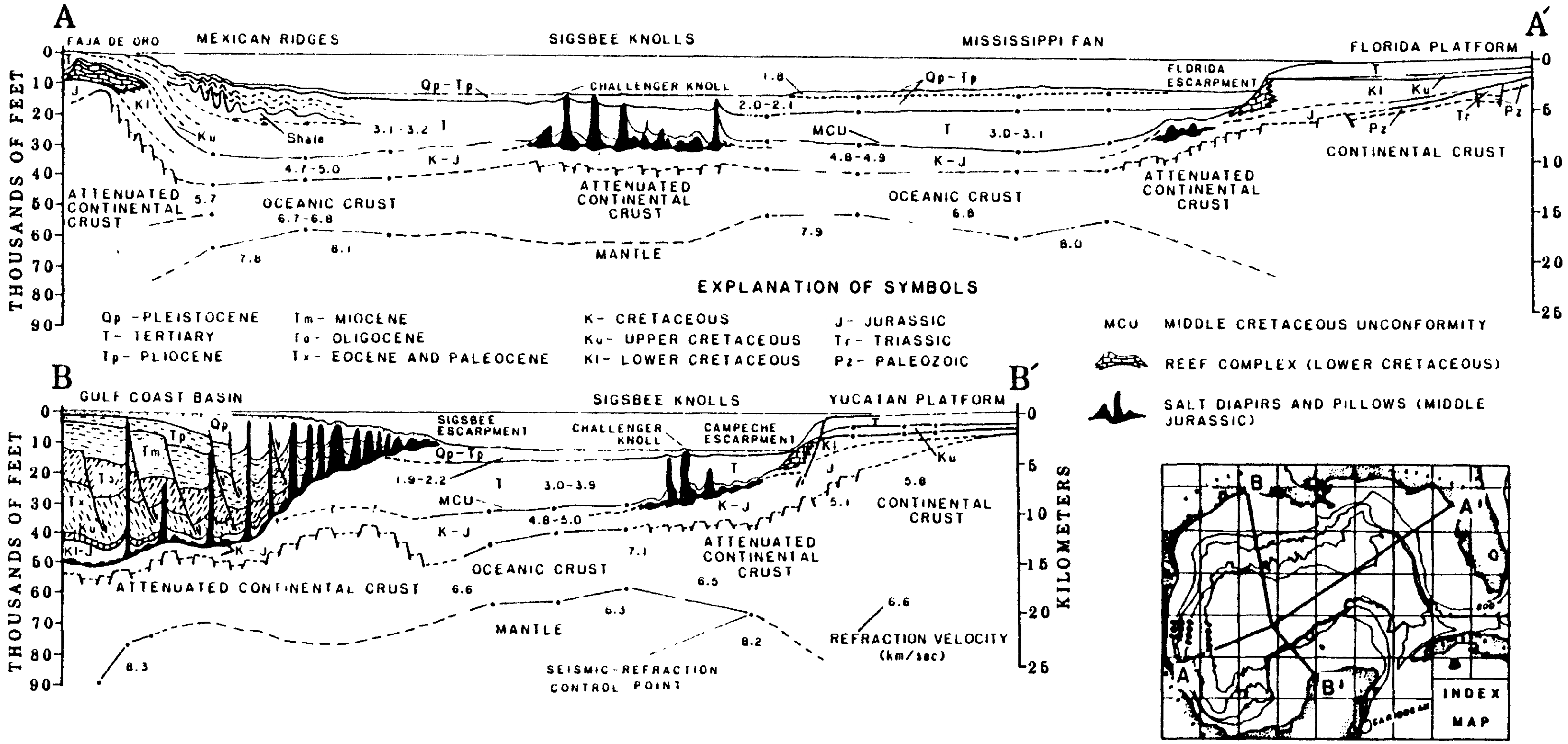

Figure I-2. Diagrammatic crustal sections across continental margin and deep ocean basin regions of the Gulf of Mexico. Based on: (1) published cross-sections (Lehner, 1969; Dorman and others, 1972; Antoine and others, 1974; Martin and Case, 1975; Martin, 1978); (2) interpretation of seismic-reflection 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, 1980; Ibrahim and others, 1981); (4) drill-hole information from Florida, Yucatan, and Faja de Oro (Maher and Applin, 1968; Lopez-Ramos, 1975; Vinegra O. and Castillo-Tejero, 1970).

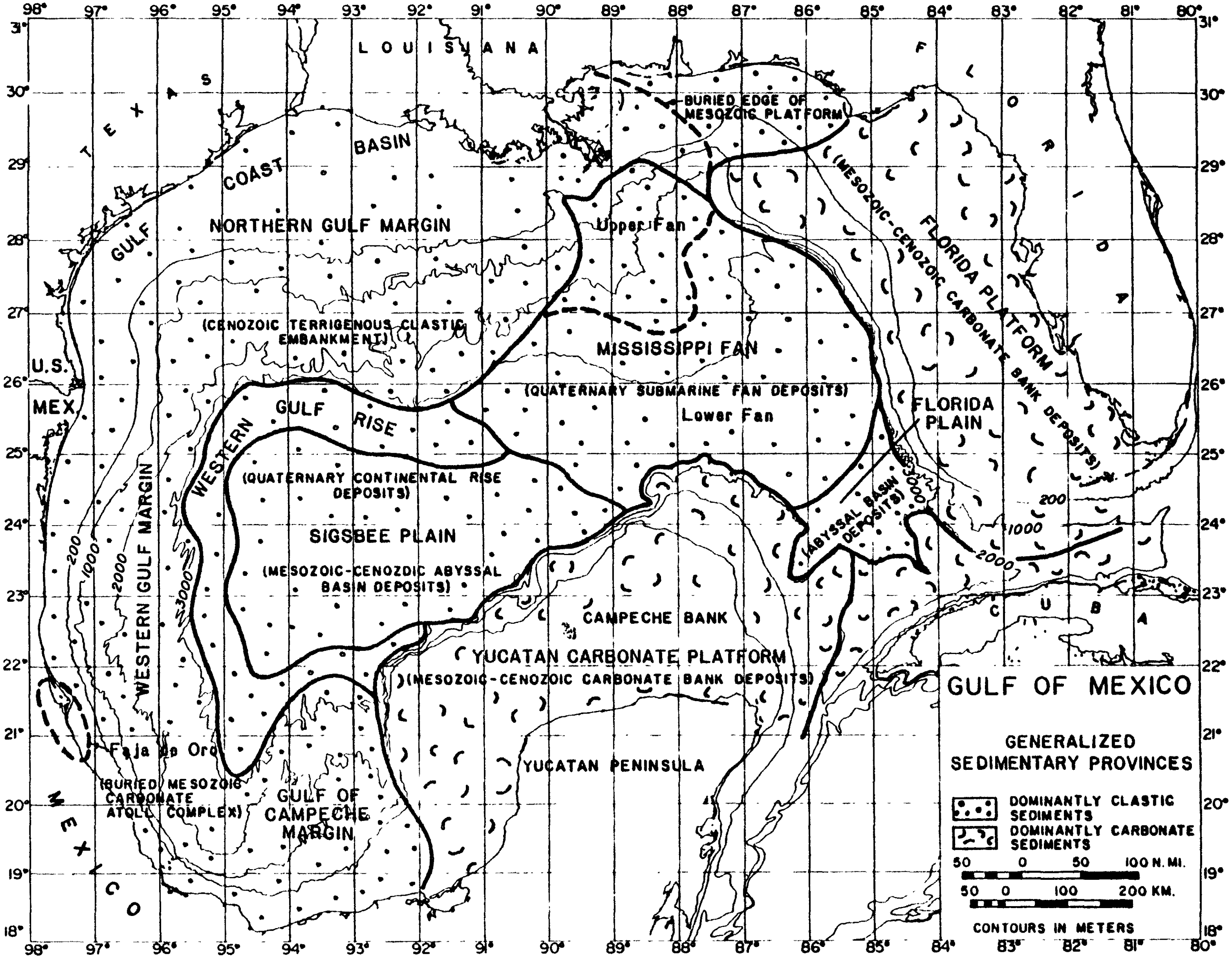

Figure I-3. Map of Gulf of Mexico region showing generalized sedimentary provinces.

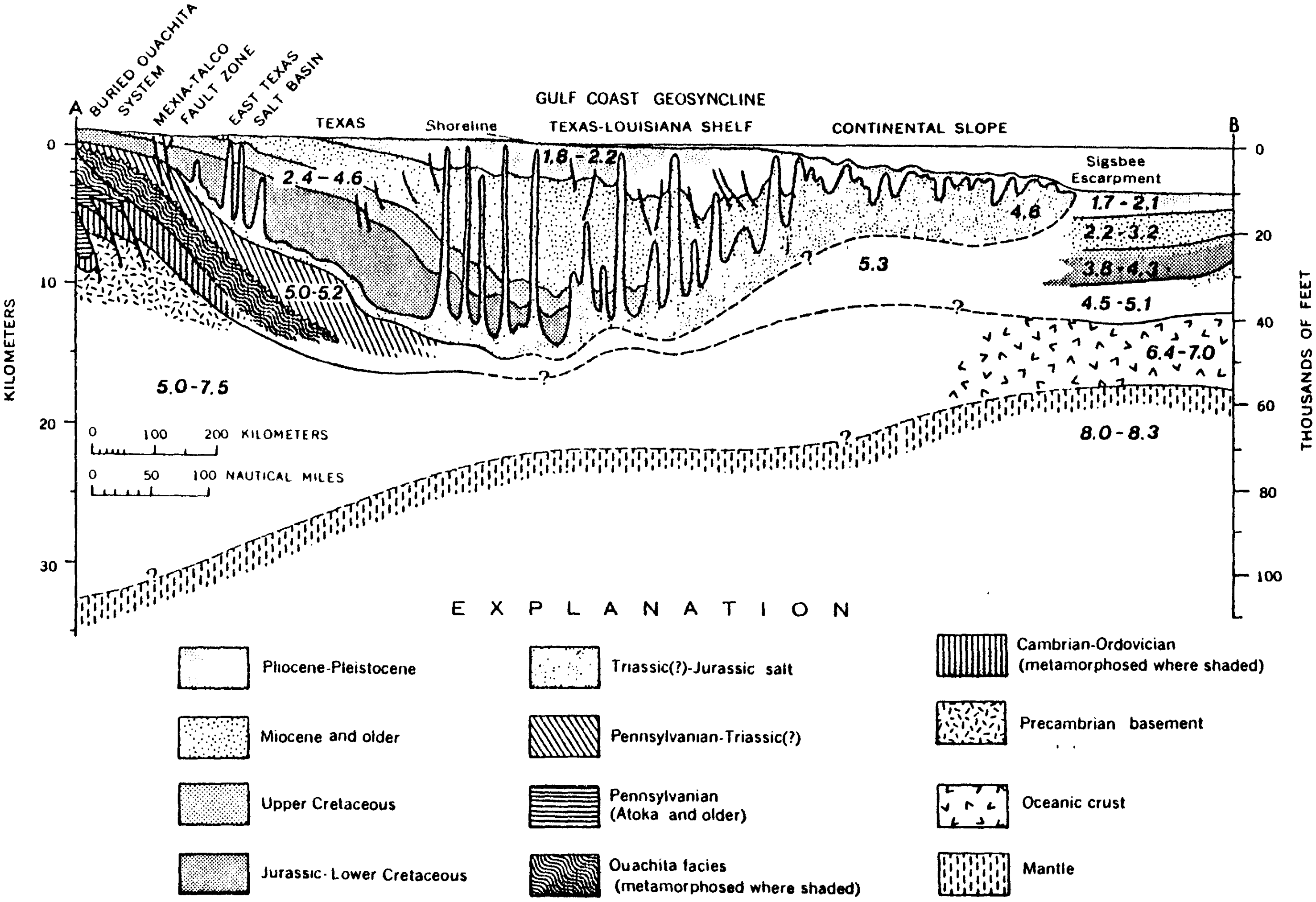

Figure I-4. Generalized cross-section of northern Gulf of Mexico continental margin. Seismic velocities in km/sec and shown in heavy numerals. Location of section shown on Figure I-5. Adopted from Lehner (1969), Dorman and others (1972), Antoine and others (1974), and Martin and Case (1975).

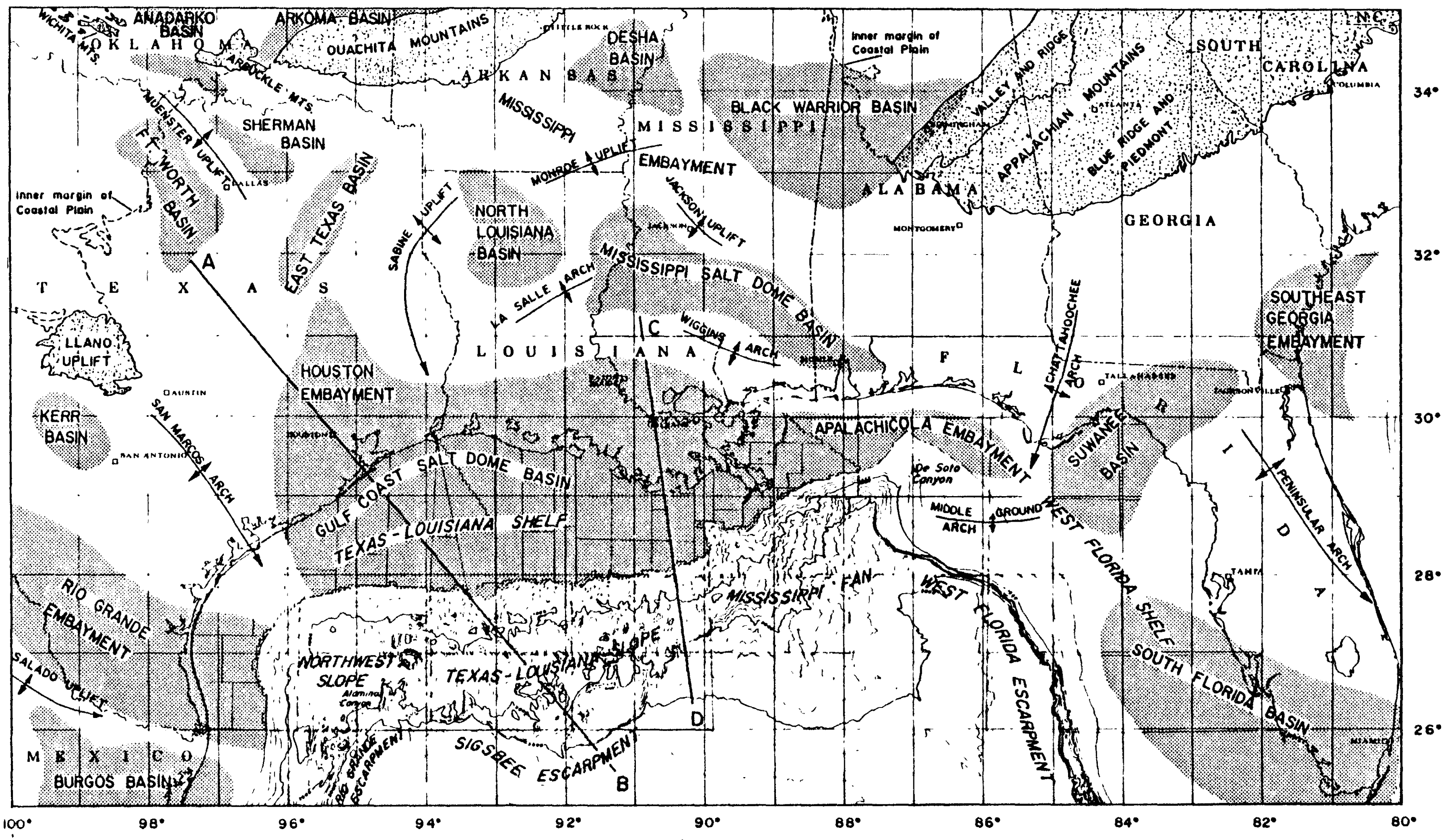

Figure I-5. Physiographic and geologic provinces and subsea topography of northern Gulf of Mexico. Contour interval, 200 m; scale approximately 1 cm = 120 km.

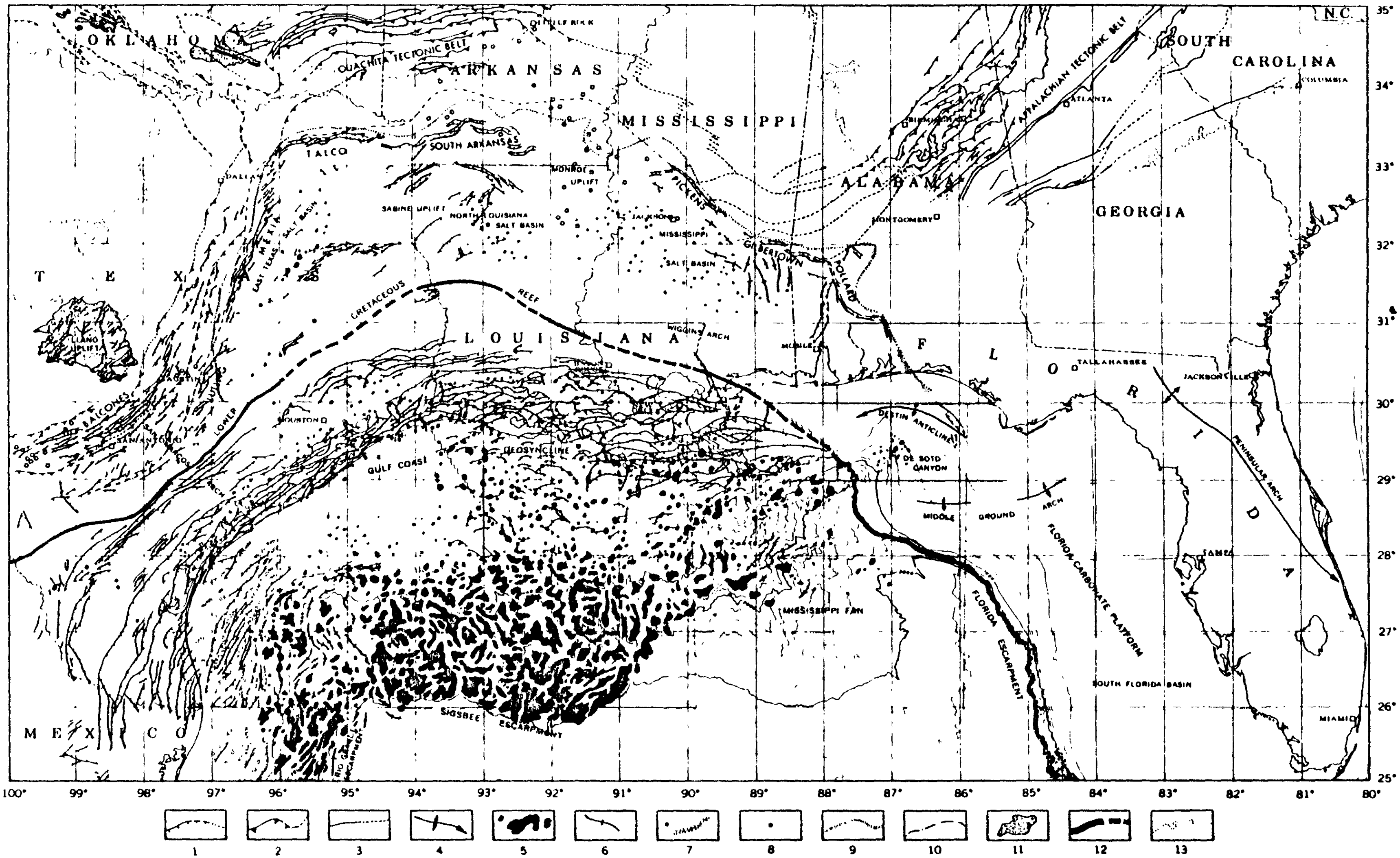

Figure I-6. Tectonic map of northern Gulf of Mexico region. Compiled mainly from G.C.A.G.S.-A.A.P.G. (1972); Flawn and others (1961); King (1975); King and Beikman (1974); Bebout and Loucks (1974); Berryhill and others (1976); and unpublished U.S.G.S. data. Explanation of patterns and symbols: 1) normal fault, 2) reverse fault, 3) fault of undetermined movement, 4) broad anticline or arch of regional extent, 5) salt diapirs and massifs, 6) salt anticlines and pillows, 7) shale domes and anticlines, 8) Mesozoic plutonic and volcanic rocks, 9) updip limits of Louann salt, 10) known downdip extent of buried Ouachita tectonic belt, 11) exposures of Paleozoic strata and Precambrian basement, 12) Lower Cretaceous shelf-edge reef system, and 13) Inner margin of Cretaceous and Tertiary strata. Bathymetry in meters (200 m interval); scale approximately 1 cm = 120 km.

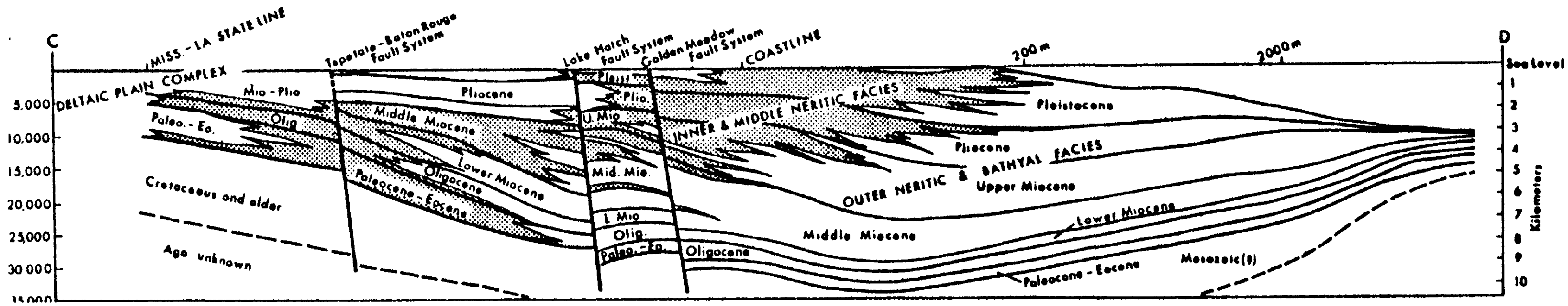

Figure I-7. Diagrammatic cross-section of Gulf Coast basin showing migration of megafacies through time. Salt domes removed for simplicity. Adopted from Lafayette and New Orleans Geol. Socs. (1968) and Kupfer (1974). General location of section shown on Figure I-5.

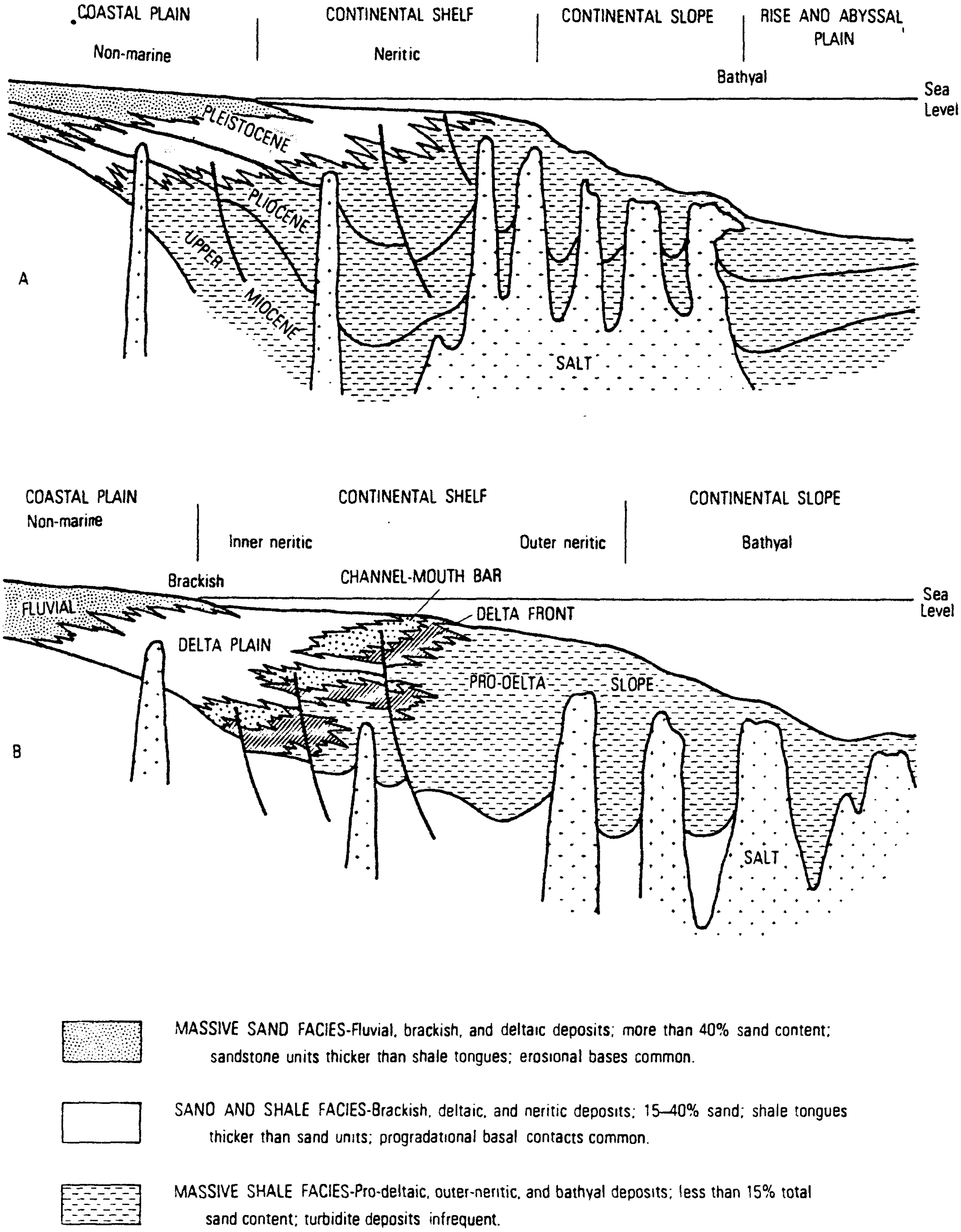

Figure I-8. Diagrammatic cross-sections showing lithofacies relations in Quaternary and Tertiary sediments of Gulf Coast basin: A - gross depositional model for Cenozoic sediments depicting net regression of continental-deltaic (massive sands), neritic (sandstone-shale), and bathyal (massive shale) magnafacies through Cenozoic time (adopted from Powell and Woodbury, 1971; and Kupfer, 1974); B - depositional model for Pleistocene sediments in Texas-Louisiana Shelf region (from Caughey, 1975).

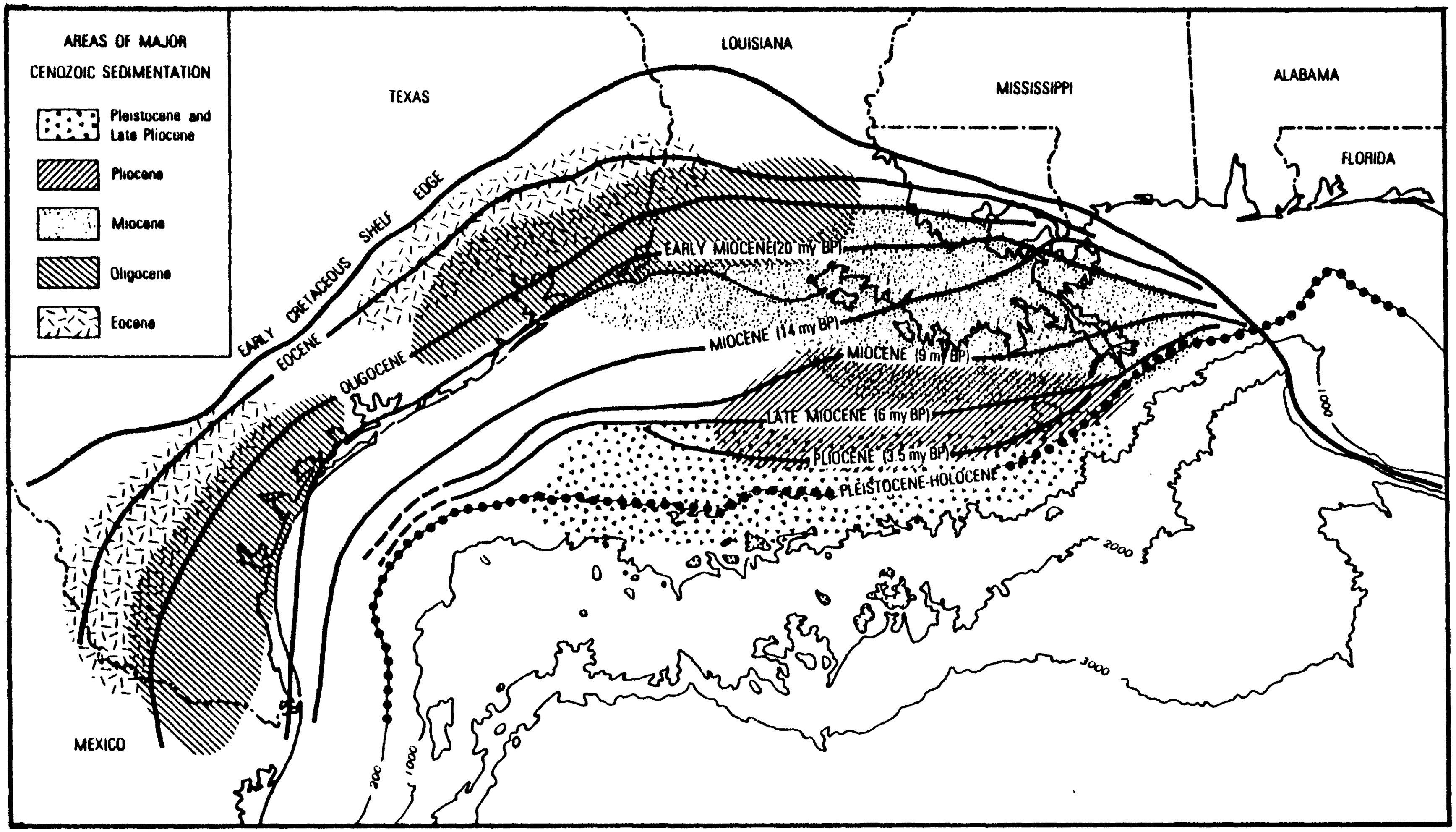

Figure I-9. Sketch map showing paleoshelf edges in Gulf Coast basin and distribution of major Tertiary depocenters. Modified from Hardin (1962), Woodbury and others (1973), Caughey (1975), and McGookey (1975).

Figure I-10. Twelve-fold common depth point (CDP) seismic section across outer Texas-Louisiana Shelf showing typical salt stocks and faulting. Strong reflections from crest of diapiric structure in center of section may represent indurated shale or caprock.

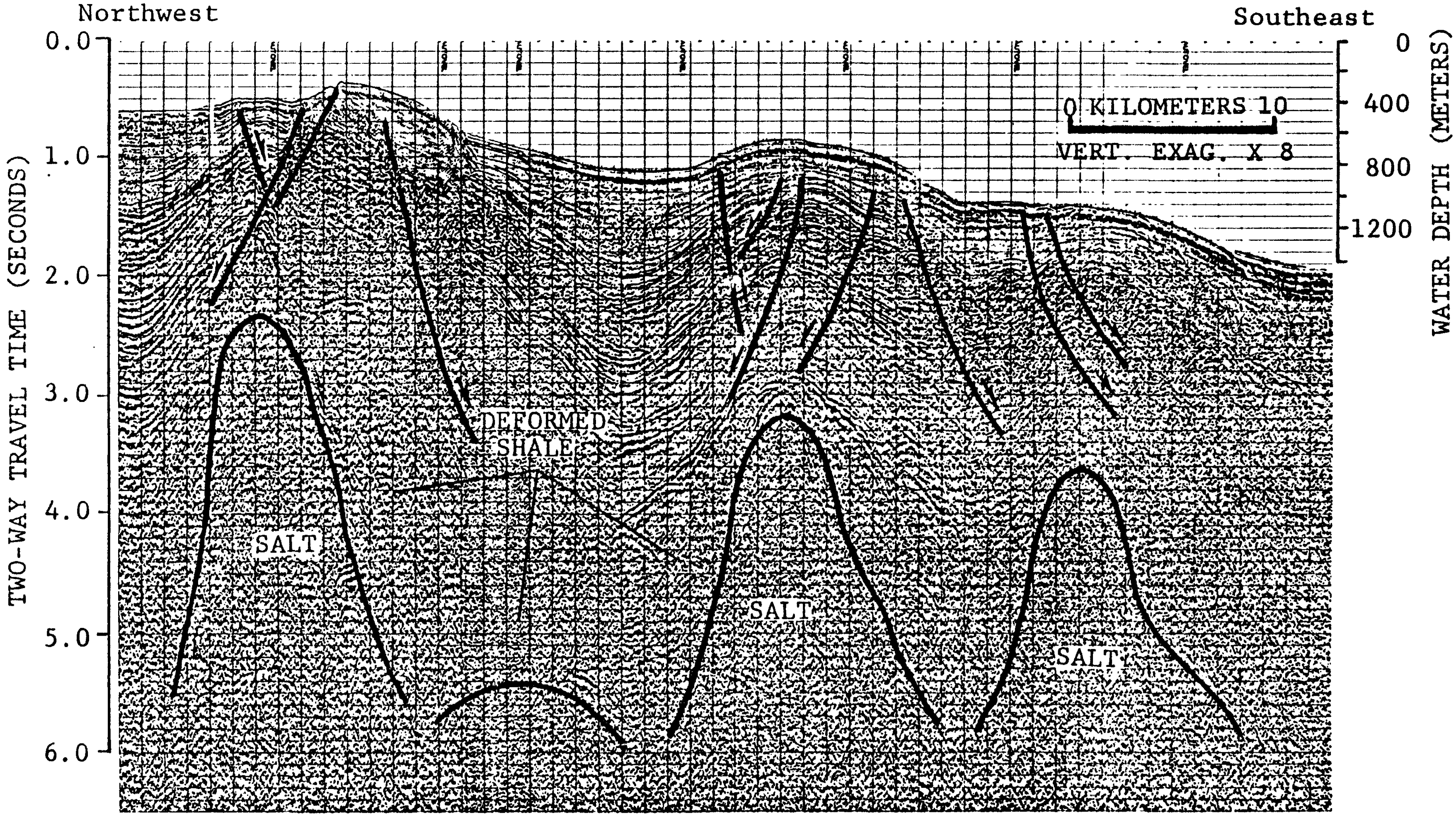

Figure I-11. Multifold seismic reflection profile from upper Continental Slope off Texas showing salt diapirs flanked by thick sections of deformed shale, and faults formed in response to diapiric uplift and shale flowage.

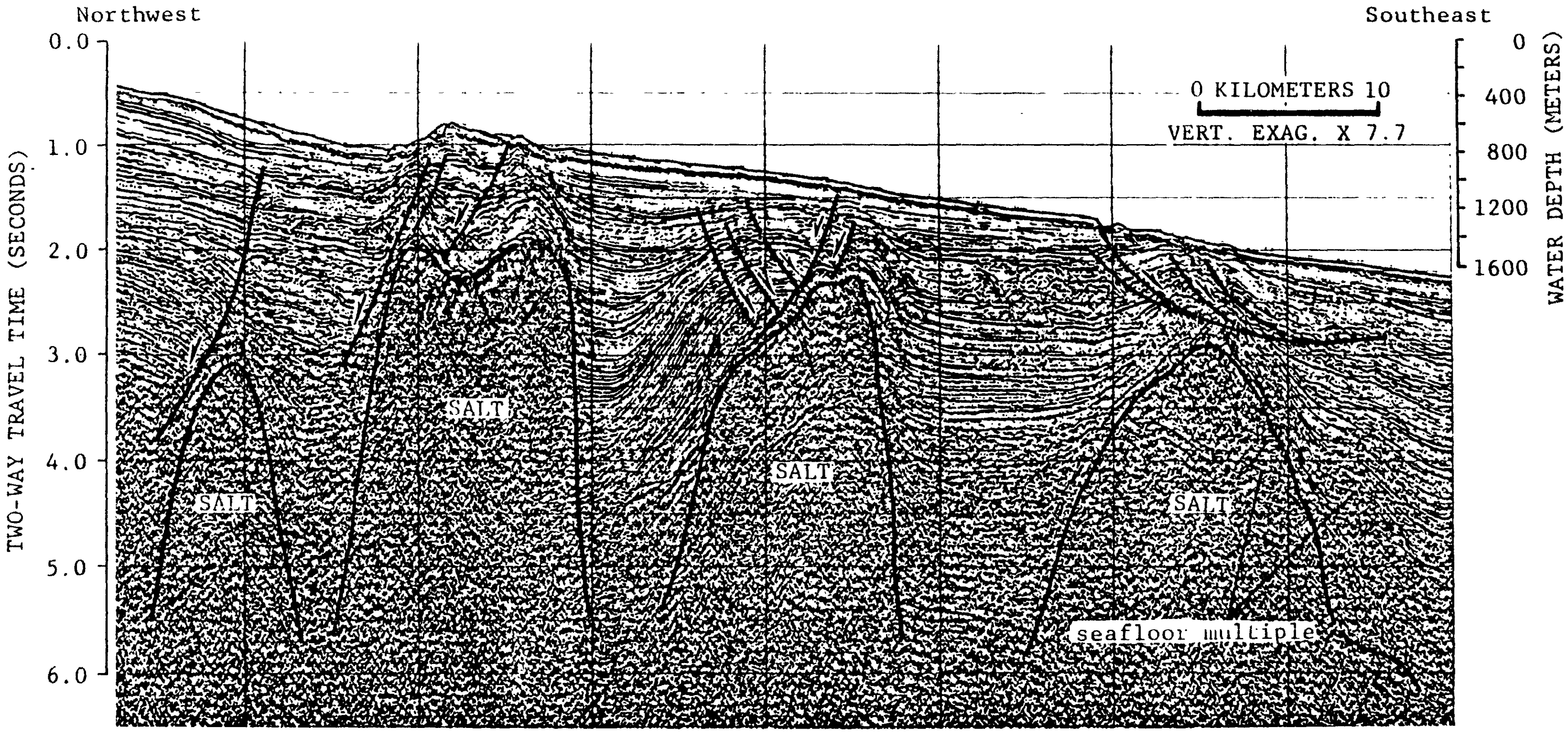

Figure I-12. Multifold seismic reflection profile across upper Mississippi Fan salt-ridge system.

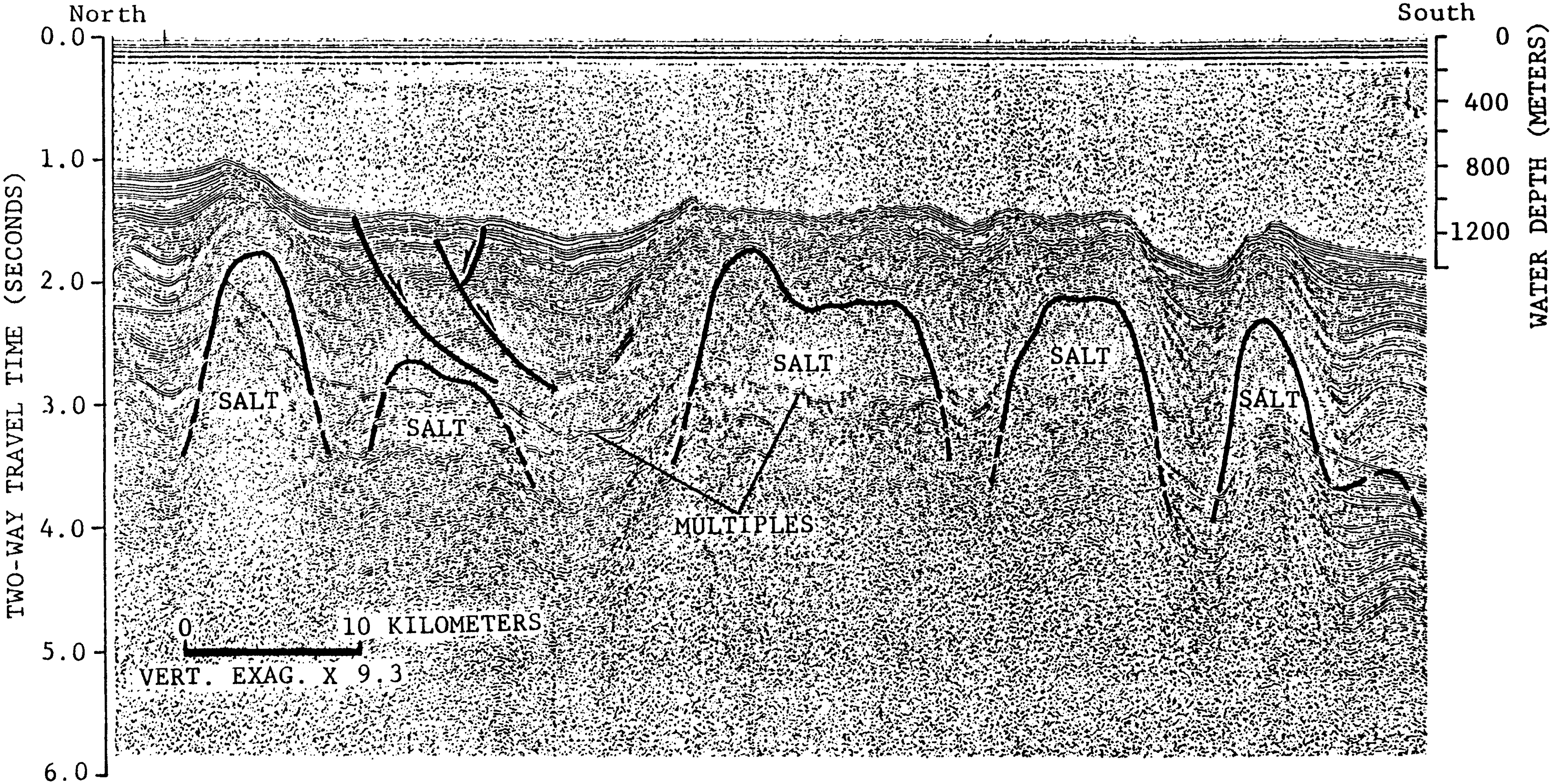

Figure I-13. Single-channel seismic reflection profile across middle Texas-Louisiana Slope region showing very broad salt stocks and thick sections of pierced and deformed sediments. Note downbuilding characteristics of stratigraphic units in basin between salt structures near south end of section, and shale deformation with attendant faulting in basin left of center.

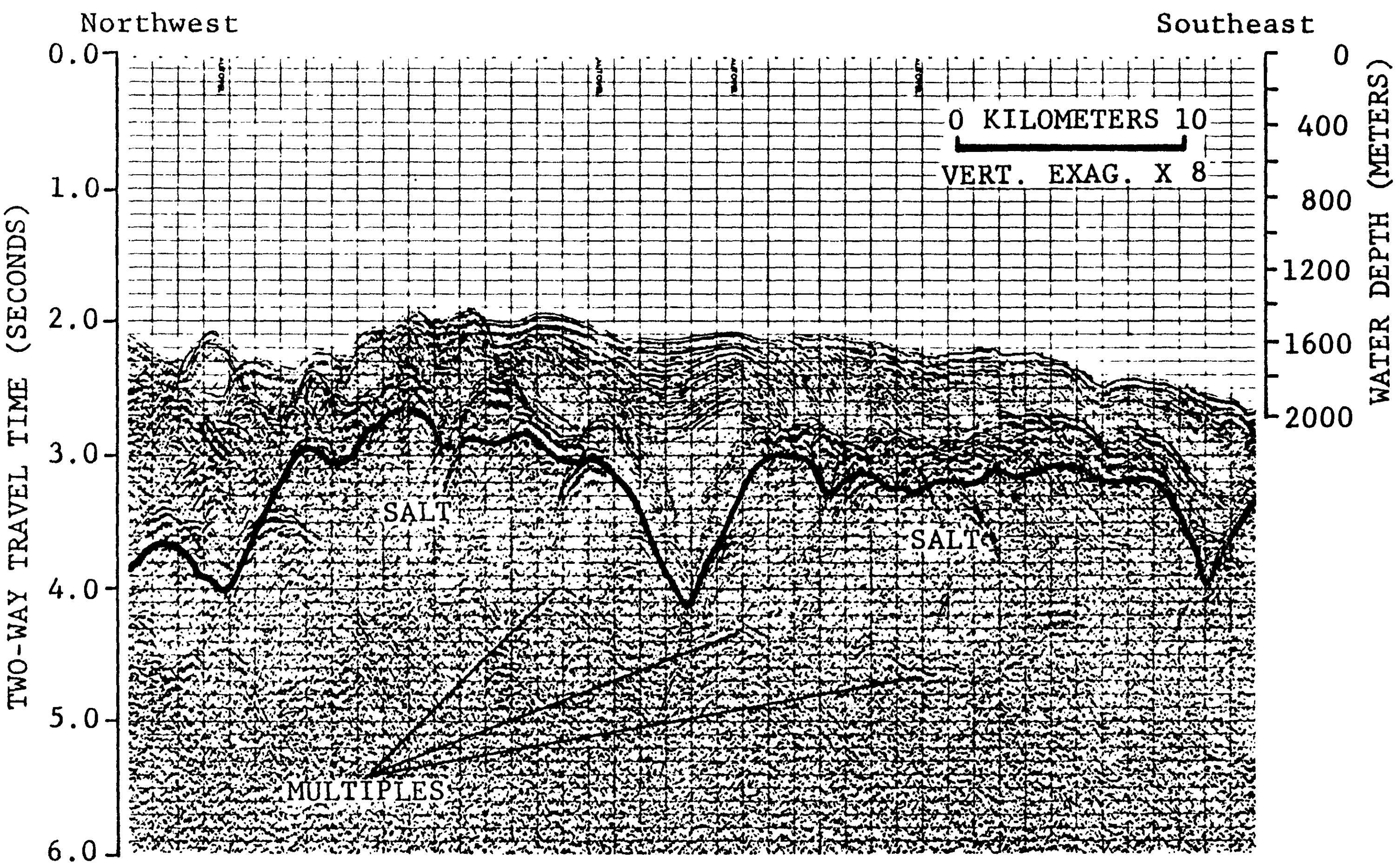

Figure I-14. Multifold seismic reflection profile from lower Texas-Louisiana Slope region showing structurally shallow, nearly continuous masses of salt covered by a relatively thin veneer of deformed sediments.

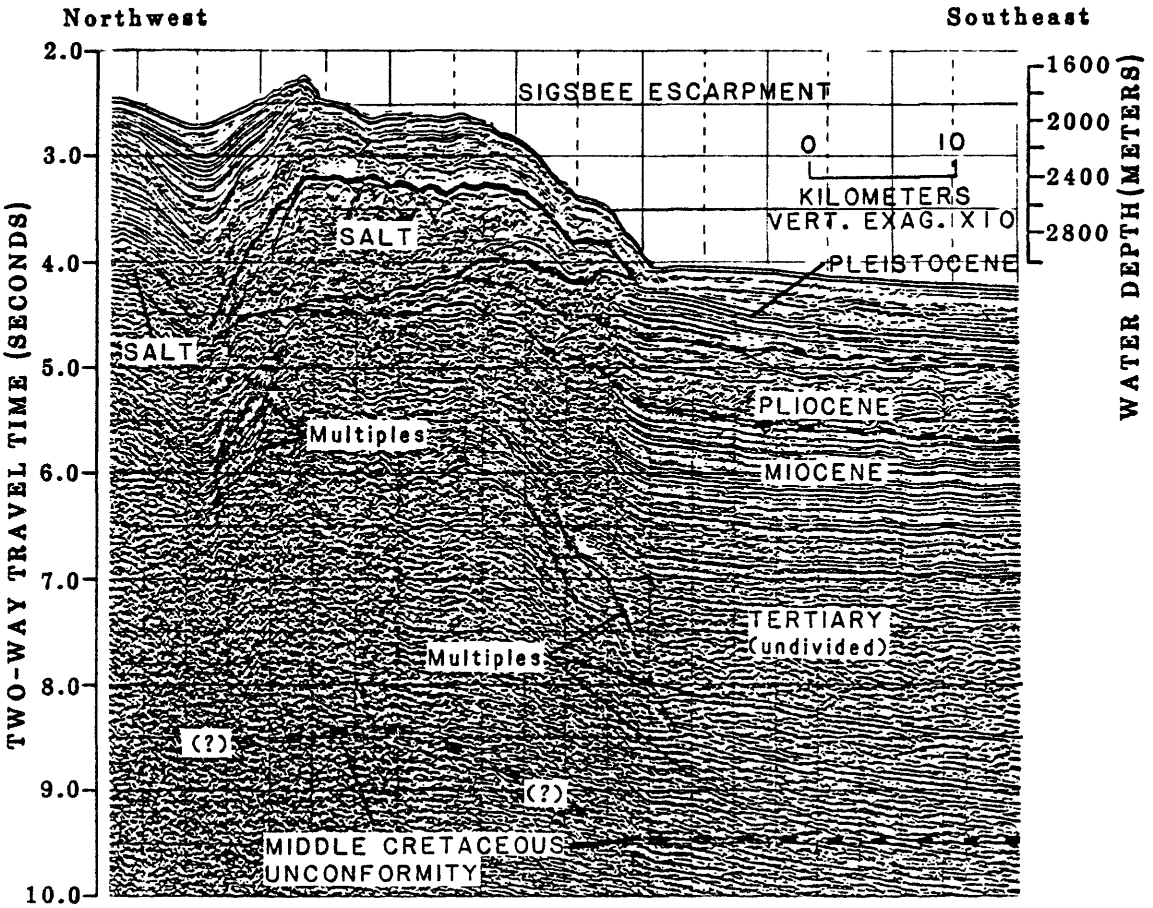

Figure I-15. Multifold seismic reflection profile across Sigsbee Escarpment showing wedge-shaped mass of salt extruded seaward over beds of Miocene age and younger. Salt mass became detached from main salt body upslope as a result of flowage away from sediment loads exerted by rapid accumulations of large volumes of sediments upslope. Region of salt extrusion is shown in Figure I-16.

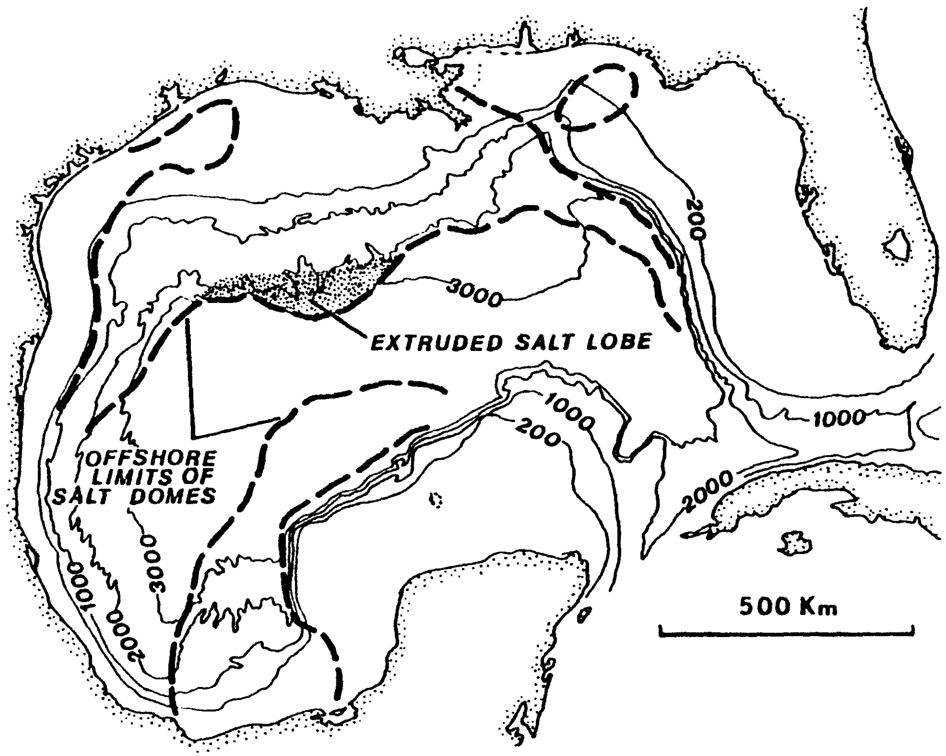

Figure I-16. Region of lower Texas-Louisiana Slope determined from seismic reflection data to be underlain by structurally shallow masses of extruded salt. Bathymetric contours in meters.

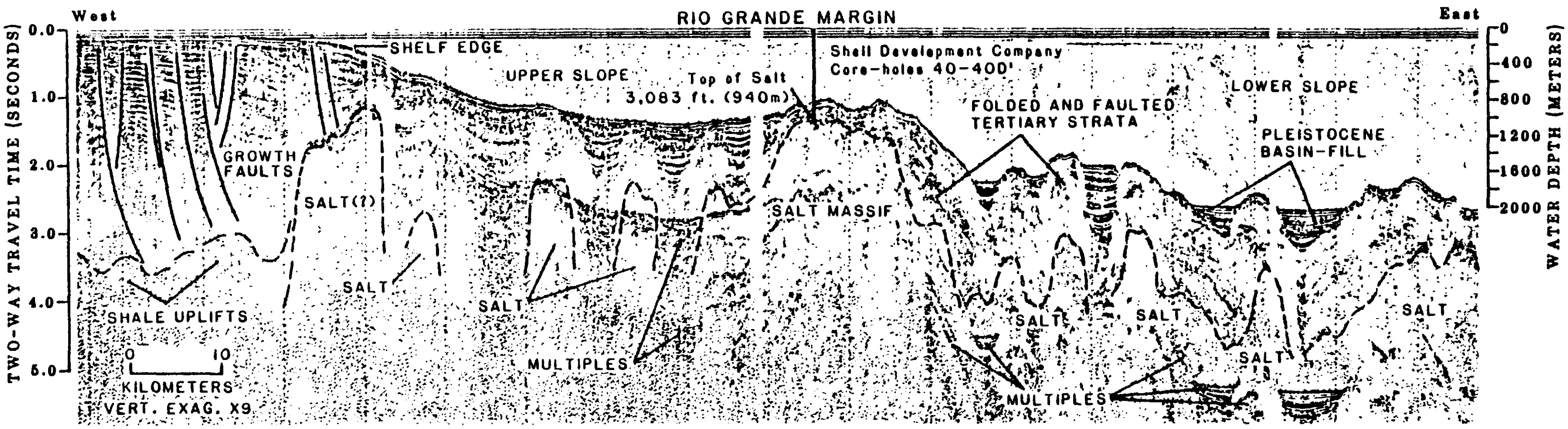

Figure I-17. Single-channel sparker profile across Continental Shelf and Slope east of the Rio Grande showing variation of structural deformation in Tertiary and Quaternary strata from movement of undercompacted shale and diapiric intrusion by narrow salt plugs and broad salt massifs.

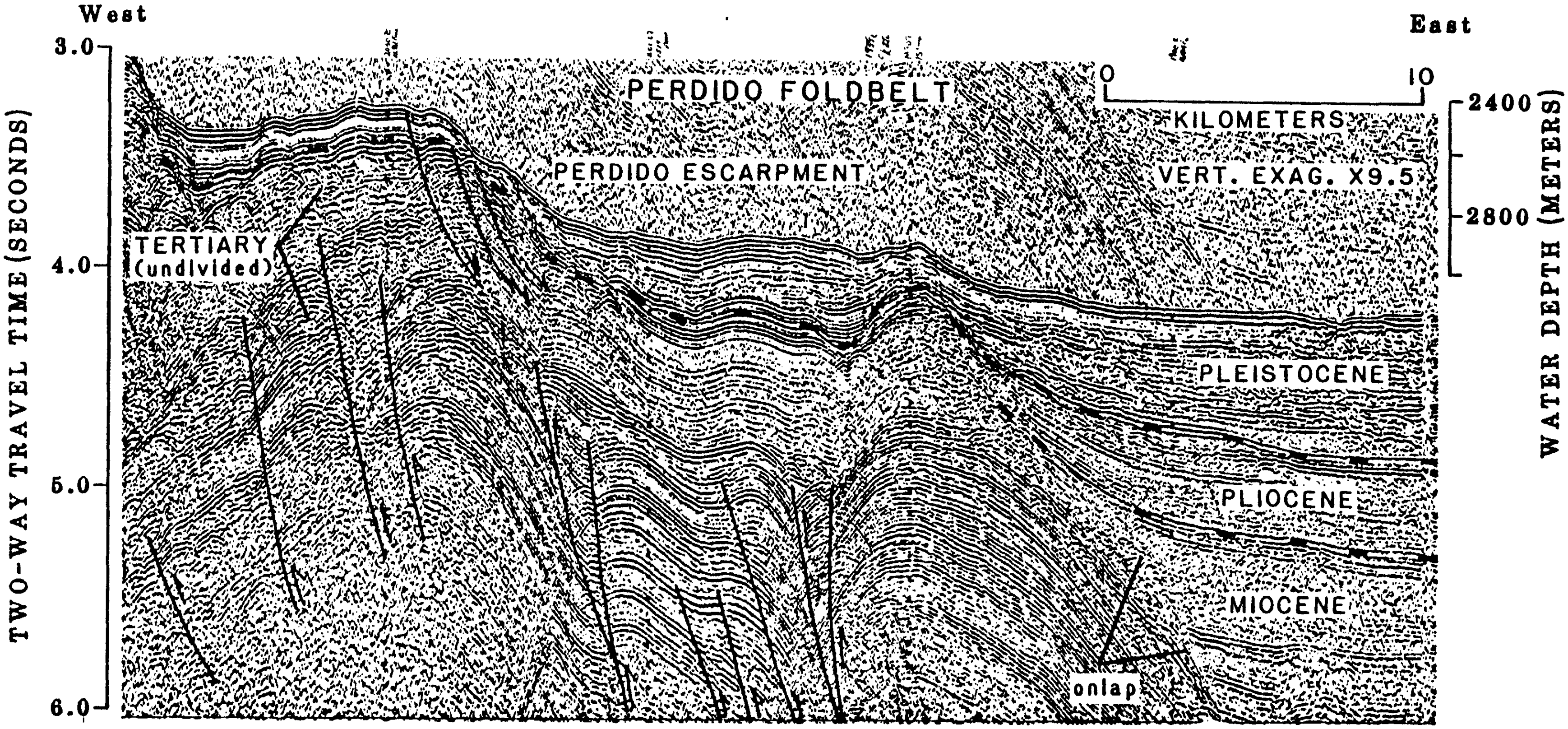

Figure I-18. Single-channel sparker profile across the Perdido foldbelt (Martin and Foote, 1981) at the foot of the Continental Slope east of the Rio Grande. Well-layered section of folded strata is probably of middle Miocene age and older. Younger strata onlaps seaward flank of fold on right. Folded Cretaceous strata and nondiapiric, pillowed Jurassic (?) salt lie several tenths of a second below base of profile. Folds trend northeast-southwest (Fig. I-6) into deep-water sector (Alaminos Canyon) of OCS Sale 84 planning area.

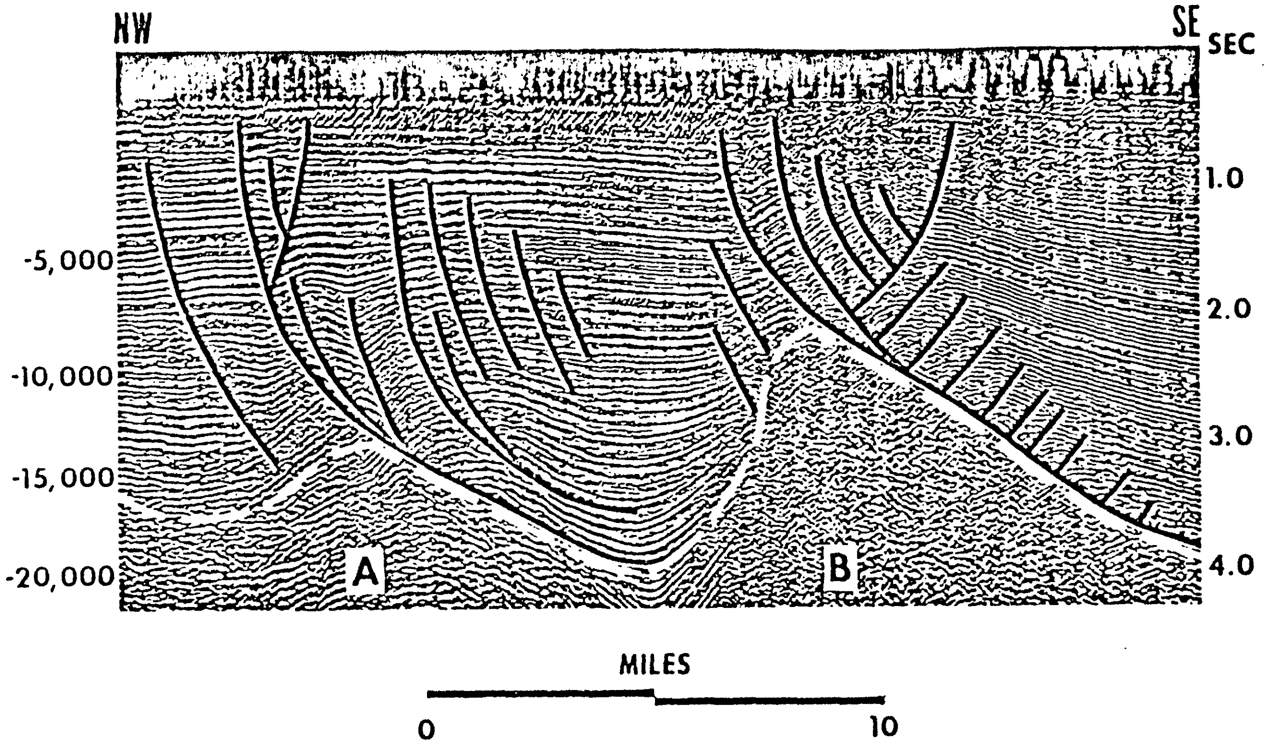

Figure I-19. Seismic reflection profile from Continental Shelf off South Texas showing anticlines (A & B) composed of deformed, undercompacted shale (Fig. I-6) and faulting in overlying strata that resulted from shale movement. From Bruce (1973).

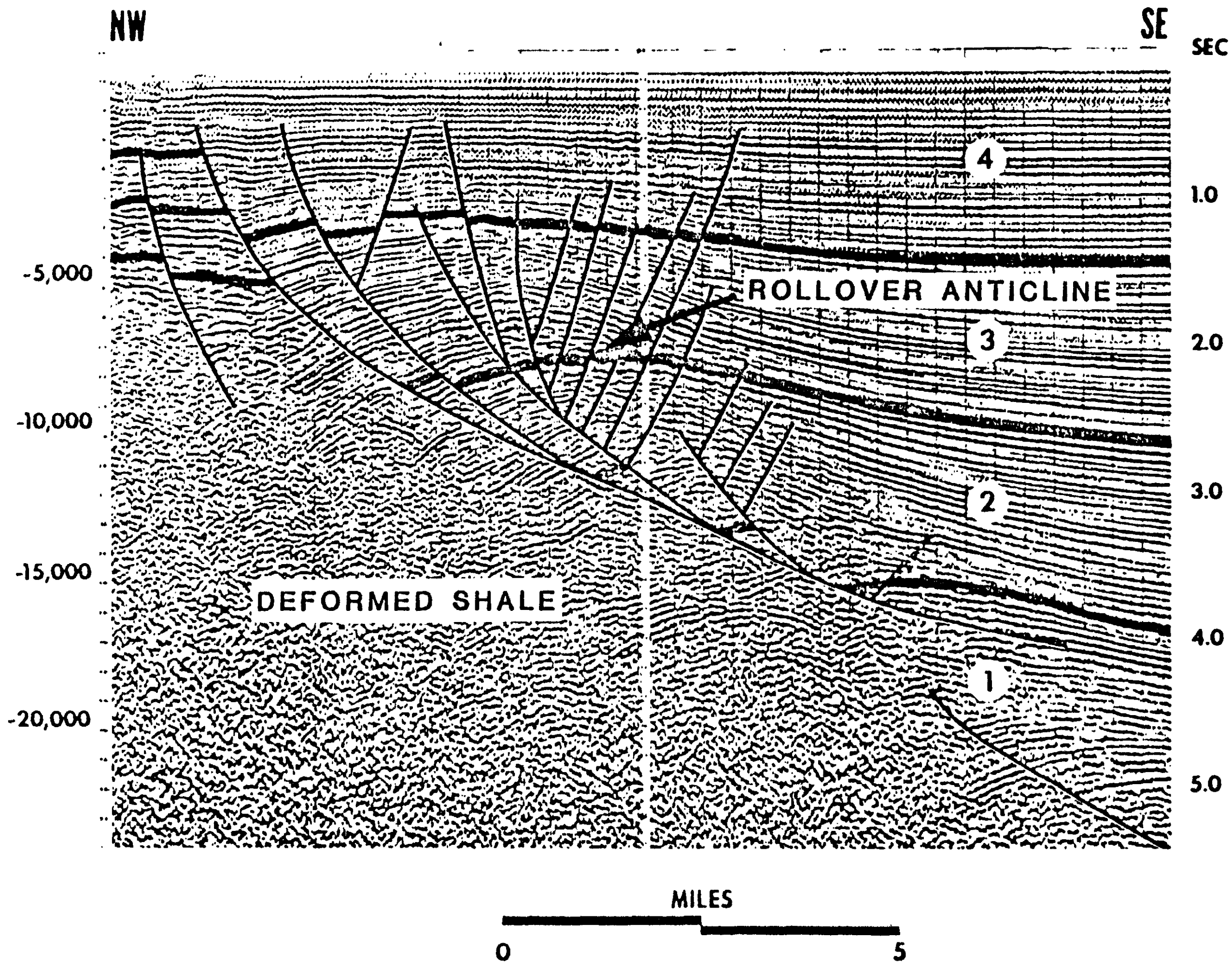

Figure I-20. Seismic reflection profile from Continental Shelf off South Texas showing bedding-plane growth fault system and typical "rollover anticline" formed against steep flank of deformed shale mass. From Bruce (1973).

Chapter II

PETROLEUM GEOLOGY: OCS LEASE SALES 81 AND 84 PLANNING AREAS

by

R. Q. Foote and R. G. Martin

INTRODUCTION

Significant accumulations of hydrocarbons depend on many factors: 1) substantial thicknesses of sedimentary rocks deposited in a marine environment (with notable exceptions) 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.

The northern Gulf of Mexico has long been a major oil and gas producing region because these conditions are met. Exploration has followed a natural progression from onshore, bays, and estuaries to the continental shelf and, more recently, to the upper continental slope. Hewitt and others (1983) reported that 537 oil and gas fields have been discovered in Federal waters on the Texas-Louisiana Continental Shelf and on the Louisiana Upper Continental Slope. 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. Figure II-1 shows the general areas of Miocene, Pliocene, and Pleistocene production in the Gulf of Mexico OCS. Oligocene production in the state waters offshore Texas is not shown although these strata account for significant onshore production.

In the OCS, reservoirs of Miocene age contain the greatest percentage of discovered gaseous and liquid hydrocarbons (Table II-1). Two prospective frontier regions exist within the Planning Areas for Lease Sales 81 and 84: 1) the Cretaceous carbonate platform offshore eastern Louisiana, Mississippi, and Alabama; and 2) the deep Gulf of Mexico, including the Texas-Louisiana Slope, the Mississipi Fan, and the northern Gulf Continental Rise along the Sigsbee Escarpment (Fig. 0-2).

This chapter highlights the findings of numerous studies by government, industry, and research institutions on the petroleum geology of Lease Sales 81 and 84 Planning Areas.

SOURCE BEDS AND MATURATION

Oil and gas produced on the continental shelf and upper continental slope offshore Texas and Louisiana are probably from numerous, widespread source beds ranging in age from Jurassic to Quaternary. Jurassic marine shales also appear to be the source beds for gaseous and liquid hydrocarbons recently discovered in Jurassic age rocks onshore and in state waters offshore Alabama (Foote and Martin, 1981).

Lower Cretaceous rocks are the most widespread and have the greatest volume of any Gulf Coast stratigraphic division. Depositional environments of Lower Cretaceous strata were favorable for the accumulation and preservation of vast amounts of hydrocarbon source material (Rainwater, 1970).

Many large deltas were constructed through east Texas to Mississippi and Alabama during Late Cretaceous. Seaward of these deltas, thick deposits of marine shales were deposited which served as source beds for many of the Upper Cretaceous oil and gas reservoirs (Rainwater, 1968).

With reference to both Mesozoic and Cenozoic rocks in the Gulf of Mexico, the types and amounts of organic material, depositional environments, regional thermal history, maturation environments, and pathways of migration have significant effects on what types of hydrocarbons are generated and entrapped. Dow (1978) has suggested that oil and gas are formed from disseminated sedimentary organic matter (kerogen) by a series of predominantly first-order chemical (thermogenic) 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 matter 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 produces oil; and the third type generates very little gas and no oil. Natural gas of thermogenic origin accounts for about 25 percent of the production from Pleistocene reservoirs offshore Texas and Louisiana; an estimated 75 percent of the natural gas is biogenically generated at low temperatures by decomposition of organic matter by anaerobic microorganisms (Rice, 1980). Biogenic gas appears to have been generated in the Gulf of Mexico in recent geological times (Claypool, 1979; Rice, 1980).

Nearshore sedimentary facies containing high percentages of terrestrial organic material are likely to be gas-prone, especially near deltas of rivers draining large areas of high-order land-plant productivity. Terrestrial organic material can also be transported with sediments across a narrow continental shelf into deep channels and submarine canyons on the slope and delivered directly into bathyal and abyssal environments. It is likely that such deep-water areas will also be prone to biogenically-generated methane gas.

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) suggests that favorable sites for the deposition of sediments rich in oil-generating aquatic organic matter include: 1) those having irregular bottom topography and closed bathymetric basins (caused by folding, faulting, or salt diapirism and associated slumping) on some continental slopes; 2) sites in the oxygen-minimum zone in 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 environments.

Published geochemical analyses of Cenozoic-age samples from industry holes show that the organic-carbon content of sediments increases significantly from shallow- to deep-water depositional environments in the Gulf of Mexico (Dow and Pearson, 1975). Therefore, the continental slopes, rises, and abyssal regions of the Gulf should be favorable sites for potential oil and gas source beds. Source beds to generate natural hydrocarbons are most likely present throughout the Lease Sales 81 and 84 Planning Areas. Further, the thermal history has been adequate to generate oil and gas.

SEALS AND TIMING

Cenozoic and Mesozoic shales and dense limestones serve as seals in producing oil and gas fields in the Gulf Coast basin. Generally, similar type shales or dense limestones should be present in the unexplored shallow and deep water parts of Lease Sales 81 and 84 Planning Areas to seal possible lower Quaternary, Tertiary and Mesozoic reservoir rocks. Geological and geophysical evidence to support this hypothesis are presented below.

Cenozoic sedimentary units of clastic origin over the broader part of the deep Gulf of Mexico are considered to be well-layered alternating sands and shales, based upon their seismic characteristics and our geologic knowledge of depositional environments. In addition, deep-water pelagic and hemipelagic sediments were deposited in the region from Early Cretaceous through Pleistocene time. Some of the fine-grained sediments in these sequences should, upon compaction, become effective seals.

Turbidite sandstones, as those of Miocene, Pliocene, and Pleistocene age in the northern Gulf of Mexico basin, should follow the normal pattern of turbidite deposits and grade laterally and vertically into marine shales consisting of very fine silts, clay minerals and other deep-water deposits. This pattern could result in a particularly favorable association of reservoirs and seals.

The timing of the oil and gas migration relative to the formation of the traps seems to have been favorable in most parts of the northwestern Gulf of Mexico. Some migration appears to have occurred in very recent geologic times. For example, the timing of the hydrocarbon migration into the Eugene Island Block 330 field, the largest oil-producing field in U.S. OCS waters, appears to have occurred in the last 500,000 years (Holland and others, 1980). Therefore, traps formed even as young as Pleistocene age would have been ready to accumulate migrating oil and gas in Holocene times.

MESOZOIC RESERVOIR ROCKS

Jurassic

The oldest producing reservoirs on the Gulf Coastal Plain are of Late Jurassic age (Fig. II-2). The southeastern part of the Upper Jurassic producing trend extends across southern Mississippi and Alabama and into Alabama state waters near Dauphin Island, Alabama. This trend may continue southeastward into the OCS; the prospective reservoir rocks will most likely be confined to the very northeastern part of Lease Sale 81 Planning Area because porosities and permeabilities may be unfavorable for commercial production southwestward toward the deeper Gulf.

Jurassic stratigraphic units in the subsurface of southwest Alabama in ascending order are the Werner Formation, the Louann Salt, the Norphlet, Smackover, and Haynesville Formations and the Cotton Valley Group. The stratigraphic units range in age from Middle to Late Jurassic, with the Jurassic-Cretaceous boundary possibly occurring in the upper part of the Cotton Valley Group (Tolson and others, 1982). Deposition was influenced by pre-Late Jurassic paleohighs, differential subsidence within the Gulf Coast basin and, to a lesser extent, by movement of the Louann Salt in response to overburden loads. The Louann Salt is generally a termination point for oil and gas test wells. All of the Jurassic section above salt can be considered to have potential reservoir rocks in the southwest Alabama Coastal Plain and in state waters offshore Alabama; some of these potential reservoir rocks should extend into the OCS.

The Norphlet Formation in the subsurface of southwest Alabama includes an updip conglomeratic sandstone, a discontinuous and localized basal shale, red beds, and an upper quartzose sandstone that constitutes most of the formation. The Norphlet was deposited in alluvial plain, braided stream, eolian, intertidal, and/or beach shoreface environments. The Smackover Formation is predominantly a lime mudstone, wackestone, or dolostone; the upper part is generally a dolomitized limestone deposited in supratidal to subtidal environments. The Smackover reservoir is classically a grainstone. The Buckner Anhydrite Member at the base of the Haynesville Formation consists of massive anhydrite with interbedded finely crystalline dolomite which accumulated in supratidal environments and siliciclastics. The Haynesville includes the uppermost record of evaporitic deposition and generally consists of siliciclastics and anhydrite and includes carbonate rocks. The Cotton Valley Group at the top of the section was deposited in a paralic environment, and includes limestone, dolomitic limestone, fine to coarse-grained sandstones and shale (Tolson and others, 1982).

Lower Cretaceous

During Neocomian, a basal sandstone unit was deposited across the entire lower Gulf Coast region, onlapping Upper Jurassic sediments. A shallow epicontinental sea then advanced over the western Gulf Coastal Plain and regions to the south and west. In this area and on the seaward parts of the eastern coastal plain, shallow-shelf carbonate rocks were deposited as the area slowly subsided. Deposition of carbonates alternated with regressive periods when the land masses to the west and north were uplifted and deposition of clastics occurred. Lower Cretaceous sediments (mostly sand and shale) eroded from the southern Appalachians were deposited in the Mississippi Embayment (Fig. I-5) and the eastern Gulf Coast at irregular rates and interspersed with carbonate deposits (Rainwater, 1968).

Depositional environments of Lower Cretaceous were favorable for the formation of stratigraphic traps and for the development and preservation of many reservoir rocks (Rainwater, 1970). Oil and gas are presently being produced from Lower Cretaceous sandstones and carbonates along a trend from Texas to southwestern Alabama (Fig. II-2). Each stratigraphic unit of Lower Cretaceous on the Gulf side of the producing trend has potential for undiscovered oil and gas. The prospective reservoir rocks under the present-day continental shelf of Mississippi, Alabama, and Florida are deltaic and turbidite sandstones, carbonate reefs developed on the landward side of positive blocks, and shell zones.

Upper Cretaceous

The deep Tuscaloosa gas trend across South Louisiana is one of the most significant exploration efforts in the U.S. in recent years. The trend is about 30 miles wide and over 200 miles long, extending from about the Texas line on the west, past Lake Ponchatrain and into Lake Borgne on the east (Fig. II-2). The Tuscaloosa reservoir sandstones are of Late Cretaceous age, and are overlain by the Eagleford shale and the Austin-Taylor-Navarro chalk section. Lower Cretaceous carbonates and shales of Lower Cenomanian-Albian age underlie the Tuscaloosa section.

The Tuscaloosa sandstones in this trend are thought to have originated as clastics eroded from Lower Cretaceous sediments in north Louisiana and south Arkansas (Funkhouser and Bland, 1980). These eroded sediments were transported southward across the shelf and deposited as a series of deltas in an embayment formed by the Early Cretaceous bank edge (Figs. I-6,I-9). Localized sand development suggests that the deltas are of slightly different ages and reflect changing distributary systems. The deep Tuscaloosa gas trend may extend southeastward across the eastern Louisiana-Mississippi Continental Shelf and under the continental slope in the easternmost part of Lease Sale 81 Planning Area.

There are questions, however, whether these or other delta systems will be present in the Federal OCS and whether the sediments will grade into deep-water type shales.

In the continental slope and rise parts of Lease Sales 81 and 84 Planning Areas, the Mesozoic section is generally too deeply buried to be considered prospective for oil and gas.

CENOZOIC RESERVOIR ROCKS

Tertiary

Throughout Cenozoic time, the northwestern Gulf of Mexico basin received a massive influx of clastic sediments derived from northern and western sources that provide reservoir rocks on the lower gulf coastal plain of Texas and Louisiana and the adjacent offshore regions. Three generalized depositional facies are recognizable in a seaward direction on the basis of sandstone percentages (see Figs. I-7,I-8): continental, neritic, and deep-water bathyal (Thorsen, 1964; Norwood and Holland, 1974; Wallace and others, 1979).

In gross geometry, these depositional environments are similar to the three major facies described by Shinn (1971) as being developed simultaneously in zones which generally parallel the shoreline. His inner facies consists of continental, lagoonal, and deltaic sediments, predominantly sandstones, which were deposited near the shore and are referred to as the "massive sands" or the "deltaic plains complex." The second facies consists of alternating sandstones and shales deposited in the neritic and upper bathyal environments, while mud was deposited in the outer neritic, bathyal, and possibly abyssal environments and dominates the "deep water" facies. Because of progradation, this pattern of facies continued through time so that the sandstone-shale facies (reservoir rocks and seals) of one age are vertically stacked over older massive marine shales (source beds). The older and deeper sandstones can serve both as conduits for the upward passage of oil and gas as it is expelled from the source beds and as reservoir rocks.

Oil and gas production from Cenozoic rocks in the northern Gulf basin can be related broadly to seven depocenters: Eocene, Oligocene, Lower Miocene, Middle Miocene, Upper Miocene, Pliocene, and Late Pliocene-Pleistocene (Fig. I-9). There was a gradual northeastward shift of depocenters from south Texas to south-central Louisiana during Eocene through middle Miocene time causing the continental shelf to develop preferentially in the northeast as it prograded southward. From middle Miocene through Pleistocene, there was a prominent shift and progradation of the depocenters to the southwest across the present shelf region.

Paleocene

At the beginning of Cenozoic Era, the north-central Gulf of Mexico was covered by a shallow sea; chalk, marl, and calcareous clays were deposited in open sea marine conditions. As the interior lands to the north emerged during middle Paleocene, the fine grained surficial sediments (Cretaceous marine shales) were eroded and deposited in the Gulf as clays and silts. The later stage of the Paleocene is represented by alternating sand and shale (Rainwater, 1968). These deposits were the first influx of coarse Tertiary sediments transported into the Gulf Coast basin as a result of the Laramide Orogeny in the Rocky Mountains and the uplift of the central plains. The coarser grained Paleocene sediments were deposited under the present day upper coastal plain and the fine-grained sediments toward the Gulf. The potential for Paleocene reservoir rocks in Lease Sales 81 and 84 Planning Areas is, therefore, quite marginal.

Eocene

During Eocene, and continuing to the present day, great quantities of coarse and fine grained sand and clay were eroded, transported, and deposited in a generally subsiding Gulf Coast basin. There were alternating periods of transgressive and regressive seas in Eocene giving rise to sands, silts, and clays in the Central and Western Gulf OCS region and to clays, marls and some limestones in the eastern part of Lease Sale 81 Planning Area (Rainwater, 1968).

Eocene oil and gas production is mainly from the lower axial portions of embayments on the Texas Coastal Plain where deltaic sediments predominate (Fisher and McGowen, 1967). These delta deposits grade into bathyal facies toward the deeper parts of the Gulf basin and deltaic deposits are not thought to be present in the Lease Sale 84 Planning Area. Petroleum production from Eocene turbidite sands in six oil and gas fields on the lower south Texas Coastal Plain has been described by Berg (1981). It is possible that some Eocene turbidite sandstones deposited in deep water environments could be present under the Texas inner shelf, but these potential reservoirs would be deep.

Oligocene

Oligocene sediments were deposited on the western and northern flanks of the Gulf Coast basin as cyclic depositional units, which represent transgressive and regressive stages of deposition. These depositional cycles were caused by variations in sediment supply and subsidence. Oligocene deposits are subdivided according to depositional cycles (Tipsword and others, 1971)--the Lower Oligocene (Vicksburg) represents a transgressive phase (mainly shale and some sandstone lenses), Middle Oligocene (Frio) represents a regressive phase (sandstones interbedded with marine shales), and Upper Oligocene (Anahuac) represents transgression (marine shales and thin sandstones).

The Frio Formation is a very thick sequence of regressive sediments that were deposited rapidly in alluvial, lagoonal and inner-neritic environments (Halbouty, 1967; Martin, 1969; Tipsword and others, 1971). Non-marine sands were deposited in constantly shifting deltas and are interbedded with marine shales that were deposited during periods of local transgression. Halbouty (1967) has noted that lagoonal sand tongues and lenses in the Frio not only pinch out in an updip direction, but numerous "shale-outs" occur along strike in the Frio sands. It has generally been accepted that the area of maximum sand development paralleling the south Texas shoreline (Fig. I-9) represents a thick bar sand or barrier island environment which separates the Frio sands from thick marine shale (Halbouty, 1967). Martin (1969), however, suggests that the massive Frio sands are more closely related to thick accumulations in deltaic environments rather than barrier bar sedimentation, thus implying the possibility of numerous favorable reservoir conditions downdip beneath the Texas shelf. Oligocene turbidite sands were also deposited in nearshore, deep marine areas, such as Hackberry Embayment in southeastern Texas and southwestern Louisiana, where deltas prograded directly into deeper waters. Berg (1981) and Dramis (1981) have described oil and gas production from Oligocene channel-fill and turbidite sands along the lower Texas Coastal Plain. It is likely, therefore, that reservoir rocks in Hackberry equivalent facies and Oligocene slope deposits and deep sea fans may be present in the Texas Shelf region of Lease Sale 84 Planning Area.

Miocene

At the end of Oligocene time, the depocenters shifted northeastward into Louisiana (Fig. I-9) where the ancestral Mississippi River began to supply large quantities of sand, silt, and mud. In each Miocene depocenter (Fig. I-9), sediments were deposited on deltas and further distributed gulfward and laterally across broad shelf areas by marine currents (Shinn, 1971). The three major facies discussed earlier migrated gulfward throughout Upper Miocene and Pliocene times and represent persistent and laterally uniform sedimentary environments.

In southern Louisiana depocenters, Miocene deposits exceed 20,000 ft (6,096 m) in thickness (Rainwater, 1968) and have almost ideal source beds, reservoir rocks, structural-stratigraphic traps, and reservoir seal arrangements.

The productive trend of Miocene strata extends from east of the Mississippi River, westward across the inner shelf off western Louisiana and eastern Texas, and trends shoreward toward the Rio Grande across the South Texas OCS (Fig. II-I). Exploration objectives in the Miocene section on inner and mid-shelf areas will be directed mainly toward reservoirs located in thick sections of the sandstone-shale facies and localized principally on structural closures resulting from salt diapirism, deep-seated shale and salt uplifts, and by growth faulting. Stratigraphic traps or porosity pinch-outs may also be important objectives. Exploration for oil will most likely be concentrated in the eastern and central Louisiana segments of the Miocene trend; gas-prone tracts are exploration targets in the remainder of the trend in western Louisiana.

The Miocene trend is less prospective in Texas than in offshore Louisiana; however, the northern and central parts of the Texas OCS have important objectives. In early Miocene time, much of the Texas Coastal

Plain and Continental Shelf region was relatively stable, with a coastal-interdeltaic environment. The ancestral Brazos-Colorado river system built large deltas in the early part of Miocene when the Llano region of central Texas (Fig. I-6) was uplifted to become an important source area for sediments (Rainwater, 1967).

Lower Miocene deposits in Texas consist mainly of regressive sand tongues interbedded with marine shale, but with much less extensive sands than those in the Frio section (Tipsword and others, 1971). The Lower Miocene section is known to be as much as 5,000 ft (1,524 m) thick under the inner shelf off south Texas.

Analysis of well logs and samples from COST (Continental Offshore Stratigraphic Test) wells No. 1 and No. 2 (Fig. II-I), offshore south Texas, are reported by Khan and others (1975a, b). The Lower Miocene sediments in these wells are generally marine shales, deposited in an environment in which sand-shale sequences could have been deposited if sand had been available to this area.

Rapid subsidence and sedimentation occurred in the seaward part of the Rio Grande Embayment (Fig. I-5) through Miocene time and resulted in the construction of several deltas in south Texas and northern Mexico. The delta areas were small and transgressions and regressions were of limited extent. Favorable conditions for large accumulations of sands apparently did not exist off Texas during late Miocene and Pliocene because of a narrow shelf which greatly restricted the width of the sandstone and sandstone-shale facies (Shinn, 1971). The Upper Miocene formations in the COST wells (Khan and others, 1975a, b) show alternating sandstones and shales, having sand percentages of about 15 percent. Furthermore, because only meager volumes of sediment were supplied by the ancestral Texas rivers, the Texas stratigraphic section is thinner than its Louisiana equivalent.

Longshore sediment contributions to the Texas shelf from ancestral Mississippi River sources were either restricted or greatly limited by the topographic effect of the Sabine Arch (Figs. I-5,I-6) (Hardin, 1962; Shinn, 1971). Petroleum production has not been found yet in the Upper Miocene of the south Texas OCS. The apparent lack of high quality reservoir rocks in Miocene strata detracts from the petroleum potential in the southern part of the South Texas Shelf.

Analyses of samples from DSDP holes and seismic data indicate that the distribution of sediments in the deep Gulf of Mexico was profoundly influenced by turbidity currents and that coarse-grained turbidite sands with grain size suitable for reservoir rocks were probably deposited in the western part of the deep Gulf from Middle Miocene (or older) to Pleistocene time (Foote and Martin, 1981). Most Miocene sediments in the deep Gulf are interpreted as having their source to the west, mainly the Rio Grande embayment, based upon sediment color, grain size, thickness, and volcanic ash content. These sediments could easily have been carried by an ancestral Rio Grande across a narrow continental shelf in deep channels and submarine canyons and delivered directly into bathyal and abyssal environments during low-stands of sea level. Also, canyon systems ancestral to the present-day Alaminos Canyon could have provided conduits for clastic transport from fluvio-deltaic sytems into deeper waters of the northwestern Gulf. The coarser-grained proximal deposits will be in deeper-water parts of the continental slope east-northeast of the Rio Grande and in the northwestern part of the abyssal Gulf. The finer grained sediments were transported eastward and may interfinger with Miocene sediments transported south and southwestward from the ancestral Mississippi. Deposits of Miocene age are especially well stratified throughout the deep basin and are presumed to consist of alternating layers of sandstone and shale that could act as potential reservoir rocks and reservoir seals, respectively.

Pliocene

Pliocene strata represent a continuation of the depositional regime established in the Miocene. The area of maximum sediment accumulation lies on the middle and outer shelf off central and eastern Louisiana and stretches westward from the Mississippi Canyon into the South Marsh Island lease area (Figs. O-I,I-9). The productive trend of Pliocene strata extends in a wide belt from the east side of the Mississippi Delta westerly across the shelf into the East Texas OCS (Fig. II-1). Downdip, Pliocene strata are productive beneath producing Pleistocene reservoirs in the Plio-Pleistocene trend located mainly off western and central Louisiana.

The Pliocene trend in the central Louisiana OCS is the second most prolific trend in the Gulf of Mexico OCS, and produces oil and gas in about equal (BTU) amounts. Pliocene production offshore Texas, like that of Miocene strata, is of lesser importance than that of Louisiana mainly as a result of lesser sediment volumes delivered to the shelf by ancestral Texas rivers and the restriction of longshore contributions from the Mississippi River due to active uplift of the Sabine arch (Hardin, 1962, Shinn, 1971). The Pliocene section at the projected down-dip limit of favorable reservoir conditions is estimated to be more than 1,200 m (4,000 ft) thick off Texas and more than 2,500 m (8,200 ft) thick off Louisiana. Exploration for hydrocarbon accumulations in the Pliocene trend, both in the Louisiana and the Texas Shelf, will center on sedimentary and structural conditions similar to those controlling present production.

Pliocene and Pleistocene strata compose the upper sequence of the deep Gulf basin and represent a profound change in the general depositional character from Miocene sediments as a result of huge sediment volumes that were delivered to the east-central Gulf from northern glaciated regions in the continental interior (Martin and Foote, 1981).

In the east-central Gulf, the dominant physiographic feature is the Mississippi Fan, a broad sedimentary apron that transcends both bathyal and abyssal water depths (Fig. I-3). The Pliocene-Pleistocene sequence in the upper Mississippi Fan is characterized by relatively complex internal stratigraphy changing to relatively uniform bedding in the lower fan. Seismic data in the upper fan suggests numerous deep canyons and channels that were subsequently filled (possibly with sand), overbank deposits, facies proximal to sand sources, and slump and debris flow deposits. The middle fan appears to be a complex of interlocking channels dispersed over a large area. These channels are probably filled with sands and hemipelagic deposits. Reservoir rocks are most likely present in the eastern part of the deep Gulf as part of the upper and middle Mississippi Fan complex. Reflection characteristics suggest a preponderance of fine-grained silts and clays with few sands in the western sector of the lower fan, a greater likelihood of turbidite sand horizons interbedded with silts and clays in the southeast, and diffuse zones indicative of fine-grained debris flow deposits toward the west. The distal deposits from the Mississippi Fan were probably spread southwesterly over a large part of the deep Gulf, but are dominantly of fine-grained material and probably have less favorable reservoir-rock qualities (Foote and Martin, 1981).

Quaternary

Pleistocene

The Pleistocene sedimentary sequence represents a continuation of the Upper Miocene-Pliocene depositional environments and, although there were numerous, short transgressive and regressive sedimentary cycles, the section represents an overall regression (Powell and Woodbury, 1971). Alluvial deposits of Pleistocene age outcrop all along the rim of the northern Gulf basin, and are represented in the Texas-Louisiana Shelf by sediments deposited in continental, lagoonal, deltaic, neritic, and bathyal environments (Powell and Woodbury, 1971).

The Pleistocene depocenter lies along the shelf edge south of Louisiana (Fig. I-9) where Powell and Woodbury (1971) estimate more than 10,000 ft (3,048 m) of Middle and Late Pleistocene sediments have accumulated. Offshore wells within the depocenter have penetrated as much as 15,000 ft (4,572 m) of shallow-water Pleistocene deposits underlain by an unknown thickness of deep-water clay (Lehner, 1969). The total thickness of Pleistocene deposits in the depocenter may exceed 20,000 ft (6,096 m).

The Pleistocene sedimentary sequence of the Texas-Louisiana OCS is typified by a sizeable quantity of sand deposited under dominantly marine conditions, and is structurally affected by salt diapirs and by nondiapiric salt and shale uplifts. Overall, the sequence was deposited during a general stage of regression often interrupted by short periods of transgression. Uppermost Pleistocene deposits, generally within 600 m (2,000 ft) of the seafloor, are composed almost entirely of continental and deltaic facies and are not considered favorable for hydrocarbon production (Powell and Woodbury, 1971).

Strata of Pleistocene age contain the most basinward trend of oil and gas production in the Gulf of Mexico OCS. The trend extends westward from the Grand Isle Area south of Morgan City, Louisiana to the southern part of the Galveston Area offshore Texas (Fig. II-1) and lies generally coincident with the Pleistocene depocenter (Fig. I-9).

The Pleistocene trend off western Louisiana (East and West Cameron Areas) ranks third in hydrocarbon production (principally gas) in the Gulf of Mexico OCS. Significant accumulations of gas and condensate have been discovered in the High Island area offshore Texas since the western part of the trend was opened to leasing in 1972. The hydrocarbon potential of this province is generally regarded as being very good. Off south Texas, the Pleistocene section remains unproductive. Thickness of Pleistocene deposits beneath the South Texas Shelf ranges from less than 1,000 ft (305 m) thick along the coast to more than 5,000 ft (1,524 m) beneath the shelf edge. Test holes on and near salt structures on the upper slope off south Texas generally penetrated less than 1,000 ft (305 m) of Pleistocene deposits, mainly clays (Lehner, 1969).

Potential reservoir rocks might be expected in Pleistocene sands that may be present on the continental slope in sand-filled canyon and deep-sea fan deposits in an otherwise very fine grained sequence. Sands of reservoir quality may be present in the narrow basins and troughs between the diapiric salt and shale structures on the slope, but their lateral extent is probably limited. These narrow basins and troughs consist of three principal types: (1) remnants of submarine canyons blocked by diapiric uplift that terminated active downslope sediment transport common during stages of low sea level; (2) closed depressions formed by subsidence in response to salt and shale withdrawal and flow into surrounding diapiric uplifts; and (3) small collapse basins formed by faulting in strata arched over structural crests of diapirs (Martin and Bouma, 1982). Basinal areas between diapiric structures in the upper slope commonly contain as much as 3,500 m (12,000 ft) of sediments, most of which are muddy slump deposits with infrequent turbidite sand zones (Lehner, 1969). Despite the apparently low incidence of turbidite sands encountered in continental slope drill holes (Lehner, 1969; Woodbury and others, 1973), sands of reservoir quality could conceivably be present in the upper and, possibly, middle slope basins especially in Pleistocene strata, which accumulated when shorelines and sediment sources were close to the present shelf edge (Powell and Woodbury, 1971; Sheffield, 1978).

Prospects in the upper slope region include strata of Pliocene and Pleistocene age in the area seaward of the Mississippi Delta and of mainly Pleistocene age elsewhere. Potential reservoirs are expected in regressive wedges of neritic sand, in turbidite accumulations, and localized along zones of shelf-edge growth faults and on the flanks of salt and shale structures.

STRUCTURAL AND STRATIGRAPHIC TRAPS

Lease Sales 81 and 84 Planning Areas contain a large number of structural and stratigraphic features that could entrap oil and gas, such as: anticlines and faulted anticlines formed by deep-seated salt and shale ridges, salt and shale domes, and salt massifs; structural closures against normal faults and growth faults; and, a variety of stratigraphic traps. Stratigraphic traps probably occur in sands onlapping salt and shale domes or anticlines, in facies changes from sands to impermeable shales in updip directions, and at angular unconformities.

Continental Shelf

In the continental shelf portion of Lease Sale 81 Planning Area offshore eastern Louisiana, southern Mississippi, and Alabama, the prospective oil and gas traps are primarily in extensions of the Upper Cretaceous (Tuscaloosa) and Jurassic trends that produce onshore. Prospective traps in these trends are: the updip portion of the wedge of sediment where the sands or porous carbonates pinch out or truncate updip; anticlinal structures developed on the downthrown side of large growth faults and over deep-seated salt domes and pillows; and, very subtle fault closures.

On the continental shelf off central and western Louisiana and Texas, salt domes, shale uplifts, and regional growth faults are the most important structural elements for hydrocarbon accumulations. More than 80 percent of all oil and gas fields in the Gulf Coast region are related to salt dome intrusions in the thick Cenozoic sediments or to depositional conditions resulting from salt-dome growth throughout Cenozoic time (Halbouty, 1967).

The Gulf Coast Salt Dome Province appears to lie principally northeast of the San Marcos Arch (Fig. I-6). Salt domes abound on the Louisiana Shelf and there are salt domes under the East Texas Shelf. Diapiric structures near the coastline and on the inner shelf of the northeastern Texas OCS and offshore central and western Louisiana are generally small (less than 8 km across), isolated spinelike features that pierce several thousands of meters of Tertiary and Quaternary strata. The middle shelf off Louisiana, the Mississippi Delta, and outer shelf region of the northern Texas OCS contain large isolated salt stocks and salt piercements along intricate networks of growth faults. No salt domes or massifs are thought to be present on the shelf off southern Texas (Fig. I-6), but five or more salt domes are concentrated in a relatively small area in the updip portion of the Rio Grande Embayment (Martin, 1980). The middle shelf of the northern Texas OCS, and the middle and outer shelf of Louisiana contain a number of shale piercements, stocks and ridges formed by load-induced mobilization of underconsolidated Tertiary shale (Martin, 1973; Bruce, 1973). The shale ridges, particularly in the middle shelf of Texas, pierce and arch the sediments, resulting in elongate anticlinal features.

Figures II-3 and II-4 are generalized regional maps which show the distributions of major structural features (salt or shale domes, anticlines and faults) in the Plio-Pleistocene Trend across the outer shelf-upper slope of central Louisiana and northeastern Texas, respectively (Sheffield, 1978). Sheffield (1978) has noted at least 30 faulted anticlines and 20 piercement domes on the Louisiana Outer Shelf-Upper Slope area (Fig. II-3) produced by basinward salt (or shale) movement, withdrawal, and uplifts. This tectonic activity was the result of massive loading effect on the shelf and slope environment by Plio-Pleistocene sedimentation. Potential traps exist over and around many of these structural features. On the western Louisiana and eastern Texas Outer Shelf-Upper Slope area, Sheffield has mapped about 100 piercement and anticlinal features formed by these same processes. Based upon the density of structures per square mile in the 2 areas mapped by Sheffield (1978) and on the distribution of structures shown in Figure I-6, it is apparent that there are a large number of untested structures, perhaps 200 or more, on the outer shelf of Texas and Louisiana.

Regional systems of growth faults which generally parallel the shelf edge (Figs. II-3, II-4) have resulted from load imbalances caused by rapid sedimentation along Tertiary hinge lines (Hardin and Hardin, 1961; Sheffield, 1978). Anticlinal closures are common on the downthrown sides of many such growth faults and are sites of major hydrocarbon accumulations (Shinn, 1971). Peripheral and radial systems of growth faults associated with salt and shale piercements are common occurrences in the Gulf Coast basin (Figs. II-3,II-4). Anticlinal closures against these fault systems are prospective traps.

Continental Slope and Rise

The continental slope of the northern Gulf of Mexico represents the seaward face of the Gulf Coast basin and includes all of the relatively steeply sloping seabed from the shelf edge to the abyssal floor. The structural grain and hummocky topography of the slope are controlled primarily by salt and shale tectonics (Lehner, 1969; Garrison and Martin, 1973; Martin, 1973; Martin, 1980).

In the upper slope (Figs. II-3,II-4), the Cenozoic section is pierced and uplifted by isolated salt diapirs(Fig. I-6). The middle and lower areas of the slope are underlain by large salt domes and extremely large masses of salt. These salt domes and massifs have fairly broad crests and are covered by strata as thin as 330 ft (100 m). Some of these broad salt structures have steep flanks that plunge abruptly for many thousands of feet and are separated by narrow basins and troughs filled by as much as 18,000 ft (5,486 m) of clastic sediment. The sediments above the salt basement have an overall average thickness of about 11,200 ft (3,414 m) and are mainly Tertiary and Quaternary in age. Traps favorable for oil and gas 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 narrow basins and troughs, traps are anticipated in closures against faults both over and on the flanks of salt and shale structures, in sands truncated by diapiric salt, in onlapping sands, and at unconformities.

Stratigraphic traps are most likely present in complexly bedded strata of Pliocene to Holocene age that overlie the Miocene and older Tertiary section in the Mississippi Fan and continental rise areas of the Abyssal Gulf 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) near-horizontally bedded turbidite deposits that cover the Sigsbee Plain in the central Gulf basin. Cenozoic strata in the Mississippi Fan and in the continental rise regions of this area may be especially prone to biogenically generated methane gas.

The Sigsbee Escarpment in the north-central sector of the deep Gulf is a distinct steepening of the seafloor at the base of the continental slope. The escarpment is the expression of structurally shallow masses and lobes of Jurassic salt extruded into strata in the shallow subbottom (Fig. I-15). The bases of extruded salt masses appear to be in angular contact with Tertiary and Quaternary strata that dip basinward into the Abyssal Gulf basin (Fig. I-15). 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 from seismic reflection data to be as much as 18,000 ft (5,486 m) (Martin and Foote, 1981).

The angular contact between the Tertiary and Quaternary strata and the overlying salt may be locally favorable for providing trapping conditions. Stratigraphic traps also could be present in Cenozoic turbidite sands deposited in submarine canyon, deep-sea fan and basin 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. Seismic reflection data for the most part show no evidence of structural uplift or diapiric salt masses below the Sigsbee Escarpment extrusions layer that might provide oil and gas traps.

The northern Perdido Foldbelt area (Fig. I-18) lies in the deep Gulf of Mexico basin at the foot of the Rio Grande Slope (Fig. 0-2). The foldbelt contains a series of large, mostly buried anticlines composed of well-layered clastic strata that are folded over a core of mobile salt originally deposited in Jurassic time (Martin and Foote, 1981). Maximum widths of the folds range from 1.5 mi (2.4 km) to 3.5 mi (5.6 km), and the average length is about 30 mi (48 km). As much as 12,000 ft (3,658 m) of Cretaceous and Tertiary strata are folded and, in turn, covered by an additional 4,000 ft (1,219 m) of younger Tertiary and Quaternary sediments. Sediment thicknesses between structures range from about 16,000 ft (4,877 m) to about 21,000 ft (6,401 m) (Foote and Martin, 1981).

Folding is interpreted to have taken place principally in late Oligocene to early Miocene time, but with some later movement. The limbs of the folds are asymmetrical having steeper flanks on the landward side. The landward limbs of many of the structures are reverse-faulted. Miocene and younger beds onlap the gently dipping seaward flanks. There is no information as to whether the reverse faults contribute to or detract from the favorability of the structures. These faults and the associated fracturing of rocks could, however, provide upward 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 (1,219 m). All of these structures have excellent trapping potential in anticlinal closures and closures against faults. These folds have the potential for containing multiple oil and gas zones in the deep clastic and carbonate strata of Mesozoic age and in the shallower clastic rocks of Cenozoic age. Stratigraphic traps are prevalent in the thick sequence of onlaps in upper Tertiary beds on seaward flanks of the broad folds, and in complexly bedded fan deposits in young Quaternary strata that cover the area.

The continental rise region of the Central and Western Gulf Planning Areas is underlain by an extremely thick section of sedimentary rocks that range in age from Jurassic, or older, to Holocene; the overall thickness of the sedimentary section ranges to more than 30,000 ft (9,144 m) at the edge of the Sigsbee Escarpment. There are many broad low-relief anticlines and faults of small displacement throughout the Miocene and older sequences that could provide potential traps and migration pathways for hydrocarbons. In the deep Gulf area in general, there may not have been sufficient faulting or fracturing to allow significant amounts of oil and gas to migrate upward from deep potential source beds into shallow traps (Foote and Martin, 1981).

DISTRIBUTION OF OIL AND GAS ACCUMULATIONS

From the foregoing discussions, it is readily apparent that the producing trend of a particular age tends to coincide with the location of the depocenter of that age. Depositional environments control the generation and migration of hydrocarbons, and the combinations of reservoir rocks and seals necessary to entrap the fluids and gas for two main reasons. First, the maximum thickness of the reservoir bearing alternating sandstone and shale facies occurs in the depocenters and is likely to contain widespread, impermeable shale sections to serve as reservoir seals. Second, sufficiently high temperatures to generate hydrocarbons by thermal processes were probably present only in the older, underlying source rocks in the depocenter (Rice, 1980).

A number of well-established generalizations on the occurrence of oil and gas fields in Cenozoic strata of the Gulf Coast basin have been reported in the literature. These generalizations were used in conjunction with information on structural-stratigraphic traps, source rocks and maturation and seals and timing of hydrocarbon migration to outline the areas of geologic potential in OCS Lease Sales 81 and 84 Planning Areas discussed later in this chapter. These generalizations are:

1. Shinn (1971) reported that most hydrocarbons in the northwestern Gulf Coast basin have been trapped in the inner- and middle neritic zones of the sandstone-shale facies. Progradation of the northern Gulf margin has resulted in the migration of the outer shelf-upper slope depositional regime seaward so that a series of progressively younger bands of production trends has been established. Environments seaward of the outer shelf-upper slope zone contain progressively less sand to act as reservoirs, and landward environments contain progressively less source material. Oil is found principally landward of major flexures on hinge lines, on salt domes, in the inner- and middle neritic facies, in shallow continental facies above 3,030 m (10,000 ft). Gas is more common seaward of flexures, in traps related to growth faulting, in outer neritic sandstone facies in association with outer neritic shales, and below 3,030 m (10,000 ft).

2. Fisher and McGowen (1967) noted that oil and gas in Lower Eocene strata on the Texas Coastal Plain tend to occur in depositional environments as follows: (a) delta trend-oil; (b) strandplain trend-oil; (c) barrier bar trend-oil; (d) shelf trend-oil and gas; (e) shelf-edge trend-oil and gas; and (f) submarine fan trends-oil and gas.

3. Magara (1978) discusses the optimum sandstone percent for oil accumulations. He shows that the product of the number of sandstone reservoirs and the thickness of shales becomes maximum when the sandstone percentage is about 30 percent (more or less). This product might be understood as an indication of the chance of occurrence of hydrocarbon accumulations. Sheffield (1978) also noted that 30-percent sand sections are considered optimum in deep water facies; objective sand sections with less than 10 percent sand and more than 50 percent sand are not generally

considered too prospective. Norwood and Holland (1974) point out the use of sand-percentage maps to relate the occurrence of hydrocarbons to rock facies.

4. Caughey (1975) has described four Pleistocene depositional facies: fluvial facies consisting of massive sand in updip areas; delta plain; delta front; and, pro-delta (Fig. I-8). The fluvial facies are not important oil and gas producers because of the lack of widespread and sufficiently impermeable shale intervals to serve as seals. Delta-plain facies have sand percentages ranging from 25 percent to 40 percent, were deposited in nonmarine environments, and are gas prone. Delta-front deposits contain 10 percent to 30 percent sand, host both oil and gas, and reflect brackish-to inner-neritic environments. Delta-front deposits disappear downdip into massive prodelta shales which have less than 15-percent sand. During low sea-level stands, coarse-grained fluvial systems funneled into a series of delta lobes. The oil and gas discoveries are concentrated in arcuate bands that fringe the downdip margins of principal lobes.

5. Fertl (1976) reports that a study of formation pressure gradients in the Gulf Coast fields indicate a correlation with the size and type of hydrocarbon deposit: (a) about 90 percent of the commercial oil fields are encountered in a normal, hydropressure environment and in abnormal pressure requiring no more than 13 pounds per gallon (ppg) mud weight requirements; (b) a majority of other Gulf Coast fields occur in the transition zone between the top of abnormal pressure (pore fluid pressure gradient greater than 0.465 pounds per square inch (psi)) and the top of super pressure (pore fluid pressure gradient greater than 0.70 psi); (c) about 99 percent of the fields are found shallower than the top of super pressure (requiring more than 16 ppg mud weight requirements); and, (d) with increasingly higher

shale resistivity ratios in the super pressure zone, potential reservoirs become smaller and contain mostly gas.

AREAS OF GEOLOGIC POTENTIAL

Areas of high, moderate, and low geologic potential for the generation, accumulation, and preservation of crude oil and natural gas resources within OCS Lease Sales 81 and 84 Planning Areas (Fig. II-5) were determined from synthesis of available subsurface geological information, oil and gas production figures, engineering data, seismic-reflection profile data, and data contained in published reports and articles. Consideration was given to the principal factors favorable or detrimental to the occurrence of oil and gas resources, and to the knowledge of the history of exploration and production in this region. Constraints that might impede exploration and development on the OCS, such as environmental, technological, and economic factors, were not considered in this analysis.

Areas of high geologic potential are regions known to have a high coincidence of structural features and stratigraphic conditions that favor the widespread occurrence of petroleum resources in commercial quantities. Areas of moderate geologic potential are regions where structural and stratigraphic factors generally favor the occurrence of oil and gas resources. Areas of low geologic potential cover regions of the OCS where geologic conditions are generally unfavorable for the occurrence of petroleum resources, but where isolated, local accumulations are possible.

Central Gulf of Mexico OCS (Sale 81)

Areas of high geologic potential in the central Gulf of Mexico OCS include part of the inner continental shelf off Mississippi and Alabama, and most of the continental shelf and part of the uppermost continental slope off Louisiana (Fig. II-5).

High geologic potential for tracts on the inner shelf south of the Mississippi-Alabama coast is indicated on the basis of knowledge of the regional geologic setting of this area from geophysical and subsurface geologic data and on the basis of recent gas discoveries in Upper Jurassic strata near the mouth of Mobile Bay. Prospective targets in this area include stratigraphic traps in the Upper Jurassic section particularly the Norphlet and Smackover formations, that onlap the south flank of the Wiggins Arch.

The area of high geologic potential on the continental shelf and uppermost slope from east of the Mississippi Delta to the western boundary of the planning area encompasses the region of major petroleum production on the Gulf of Mexico OCS. The region is underlain by a thick section of intertonguing shelf sands and deepwater shales that offer optimum stratigraphic conditions for source bed and reservoir potential. The prospective section ranges in age from Early Miocene to Late Pleistocene. Major oil and gas production is from beds of Miocene age on the inner shelf and around the Mississippi Delta, from Pliocene strata in the middle shelf region and around the Delta, and from Pleistocene intervals on the outer shelf south of western and central Louisiana. The area has a substantial potential for the accumulation of major quantities of hydrocarbons in traps on numerous salt and shale structures, and in structural closures in sedimentary anticlines associated with local and regional growth faults. Most of the larger structures on the shelf have been drilled with one or more wells, but smaller, untested structures remain to be explored. Future exploration objectives in this area will evolve toward these untested structures, as well as toward structural and combination traps in strata below current production depths and toward more subtle stratigraphic traps at all levels.

The area of moderate geologic potential in the central Gulf of Mexico OCS includes part of the continental shelf east and southwest of New Orleans and most of the continental slope generally to water depths of about 2,000 m (Fig. II-5).

The continental shelf area of moderate potential east of New Orleans is underlain by a relatively thin sequence of Tertiary and Quaternary strata deposited on a massive carbonate platform section composed of Late Jurassic and Cretaceous units. Structural features in the area that offer trapping potential include a few widely spaced nonpiercement salt uplifts and regional growth fault trends that converge southeastward against the edge of the Mesozoic carbonate platform. There is potential for stratigraphic entrapment of hydrocarbons in Upper Jurassic and Lower Cretaceous shelf-edge reef deposits that trend southwestward along the boundary between the Main Pass and Viosca Knoll lease areas. Also, the possibility exists for extension of the deep Tuscaloosa (Upper Cretaceous) gas trend from northwest of New Orleans into the offshore area along and southwest of the reef trend.

In the western part of the Planning Area, a small part of the shelf is delineated as an area of moderate potential on the basis of generally unfavorable reservoir rock conditions throughout the overall Tertiary and Quaternary sequence.

The remainder of the area of moderate geologic potential includes the middle and upper continental slope and adjacent parts of the outer shelf where there is an abundance of large structures formed by flowage of Jurassic salt and Tertiary and Jurassic shales. The prospective sedimentary section flanking these structures and occupying interstructural basins on the slope is generally thick and mostly Pleistocene in age. Stratigraphic conditions such as depth of burial and presence of clean, porous reservoir sands are considerably less favorable than in the adjacent area of high potential on the shelf. Submarine canyon channel-sands and sandy turbidite deposits of local extent appear to be the principal reservoir objectives in most of the region. Considerable amounts of reservoir quality sands could have been delivered to the upper slope area during low stands of sea level during the Pleistocene. Stratigraphic conditions, thus, degrade in a downslope direction.

The area of low geologic potential for occurrence of petroleum resources in the central Gulf of Mexico OCS includes the lower continental slope region and a small area of the abyssal plain. Water depths are generally greater than 2,000 m; the foot of the continental slope lies approximately coincident with the 3,000 m isobath. Except for the southwestern part of the Walker Ridge area, the region is virtually void of structural features having more than a minor degree of trapping potential. The stratigraphic section consists principally of distal turbidite deposits and deepwater fine-grained muds that generally are not likely to contain suitable reservoir rocks; suitable reservoir rocks are locally possible, however, especially in the northeastern part of this area where large quantities of sediments may have been delivered by massive turbidite flows. In the southwestern part of the Walker Ridge Area, structurally shallow, lobate masses of Jurassic salt lie beneath a thin cover of Pleistocene sediments. The overlying sedimentary section is too thin to be considered as prospective, but some potential may exist for stratigraphic traps in deeper beds that are in angular contact with the bases of the impervious salt masses.

Western Gulf of Mexico OCS (Sale 84)

Areas of high geologic potential in the western Gulf Planning Area include large parts of the continental shelf in a belt from the northeastern part of the High Island Area southwest to the lower Texas coastline, and in an area of the outer shelf and uppermost continental slope off eastern Texas (Fig. II-5). The area includes all major oil and gas production. Principal structural features favorable for trap formation include numerous salt domes and shale structures in the inner and outermost shelf regions of the Galveston and High Island Areas, and systems of regional growth faults and shale anticlines in the inner and middle shelf regions of the OCS from the Brazos Area to the southwest. Favorable stratigraphic relationships between source beds and reservoir rocks are present throughout the area of high potential. Prospective intervals include Pliocene to Lower Miocene strata and the Upper Oligocene within the inner belt, and Pleistocene strata in the outer shelf area.

The area of moderate geologic potential encompasses much of the continental slope off Texas and western Louisiana, trends across the shelf off eastern and southern Texas, and a small area of deepwater acreage at the foot of the continental slope in the Alaminos Canyon Area (Fig. II-5).

Areas of moderate potential on the continental shelf are characterized by a relatively low incidence of trap-forming structural features and by stratigraphic conditions that generally diminish the likelihood of sand intervals suitable as reservoir rocks.

The continental slope region of moderate potential is similar to the area delineated on the slope in the central Gulf OCS. Numerous structural features, formed by movements of salt and shale, with excellent trapping potential are present across this area. Stratigraphic conditions, however, generally disfavor a high incidence of reservoir quality sands over most of the region. There is a greater likelihood of suitable reservoirs in strata on the uppermost slope, particularly adjacent to the productive area of shelf, than in the middle and lower slope region.

The area of moderate potential in the southeast quadrant of the Alaminos Canyon Area is based on the presence of a series of broad anticlines that trend northeastward into the continental slope. Seismic-reflection data across these deeply buried features disclose the potential for multiple pay zones in folded Cretaceous to Middle Miocene strata, and in pinchouts in Miocene and younger strata deposited on the flanks of the anticlines.

The areas of low geologic potential (Fig. II-5) were delineated on the basis of evidence that stratigraphic conditions in these regions generally disfavor the presence of reservoir-quality sands, and that strata overlying the salt and deformed shale basement are relatively thin. Interstructural basins on the slope off southern Texas, however, may contain localized deposits of reservoir-quality turbidite sands. Similarly, local deposits of delta-front sands may be present, and thus prospective, along the outer shelf off the mouth of the Rio Grande in the South Padre Island Area.

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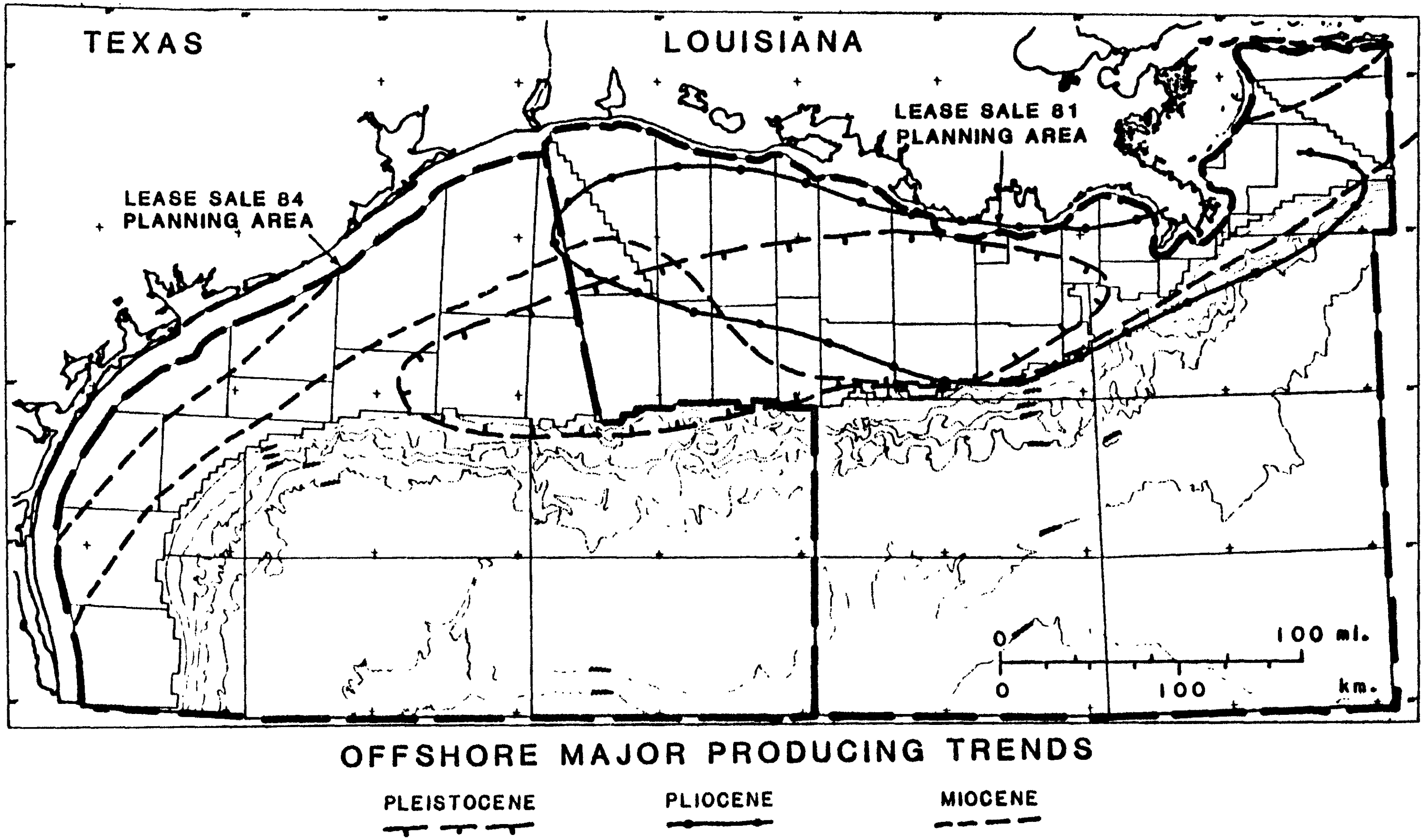

Figure II-1.--Map showing oil and gas producing trends in Cenozoic strata in Federal waters, northwestern Gulf of Mexico (after Rice, 1980).

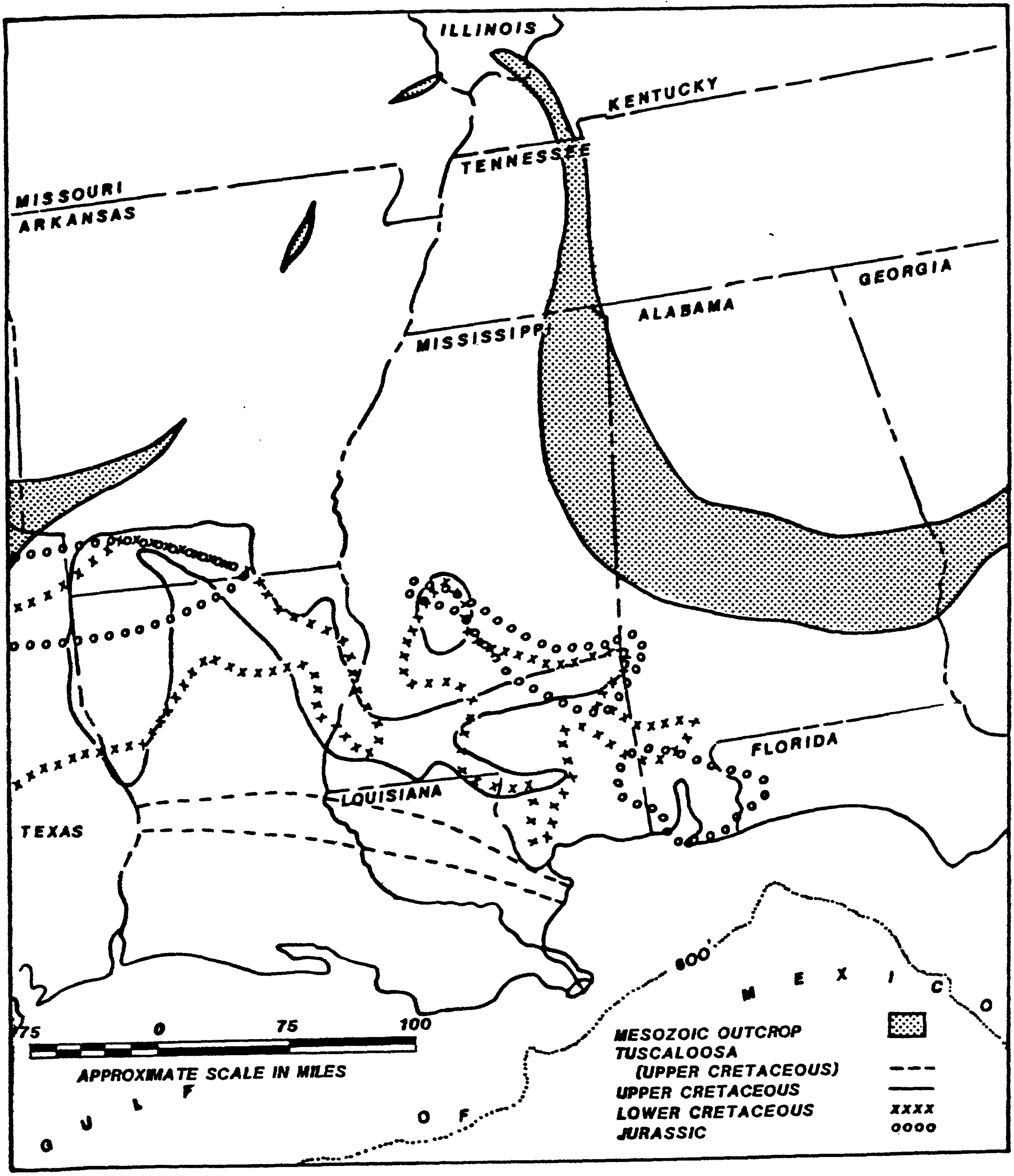

Figure II-2.--Map showing oil and gas producing trends in Mesozoic strata, East Texas-Florida (after Rainwater, 1968; Funkhouser and Bland, 1980; Foote and Martin, 1981).

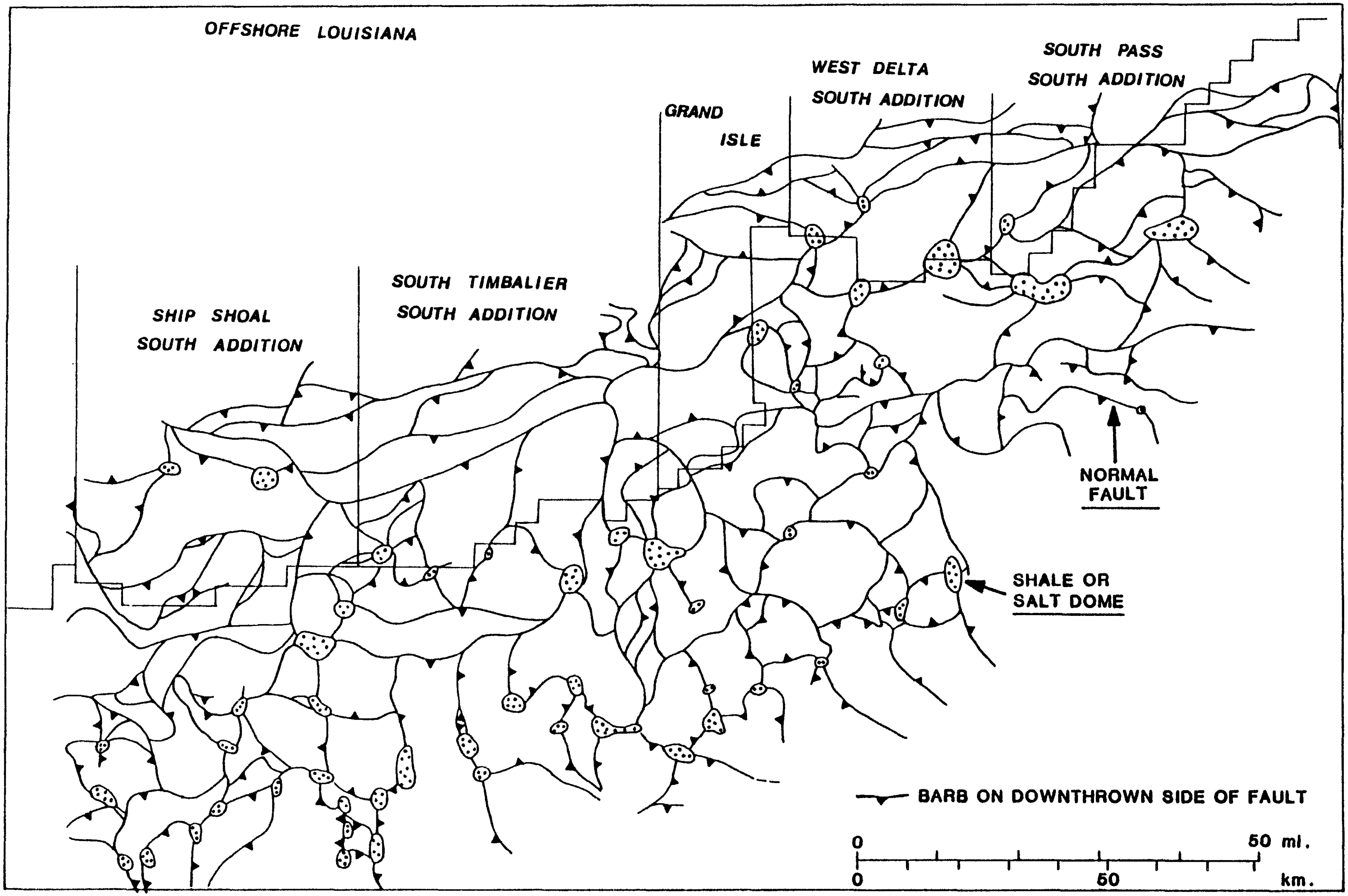

Figure II-3.--Map showing locations of major salt and shale domes and growth faults in the outer shelf and upper slope, western part of offshore central Louisiana (after Sheffield, 1978).

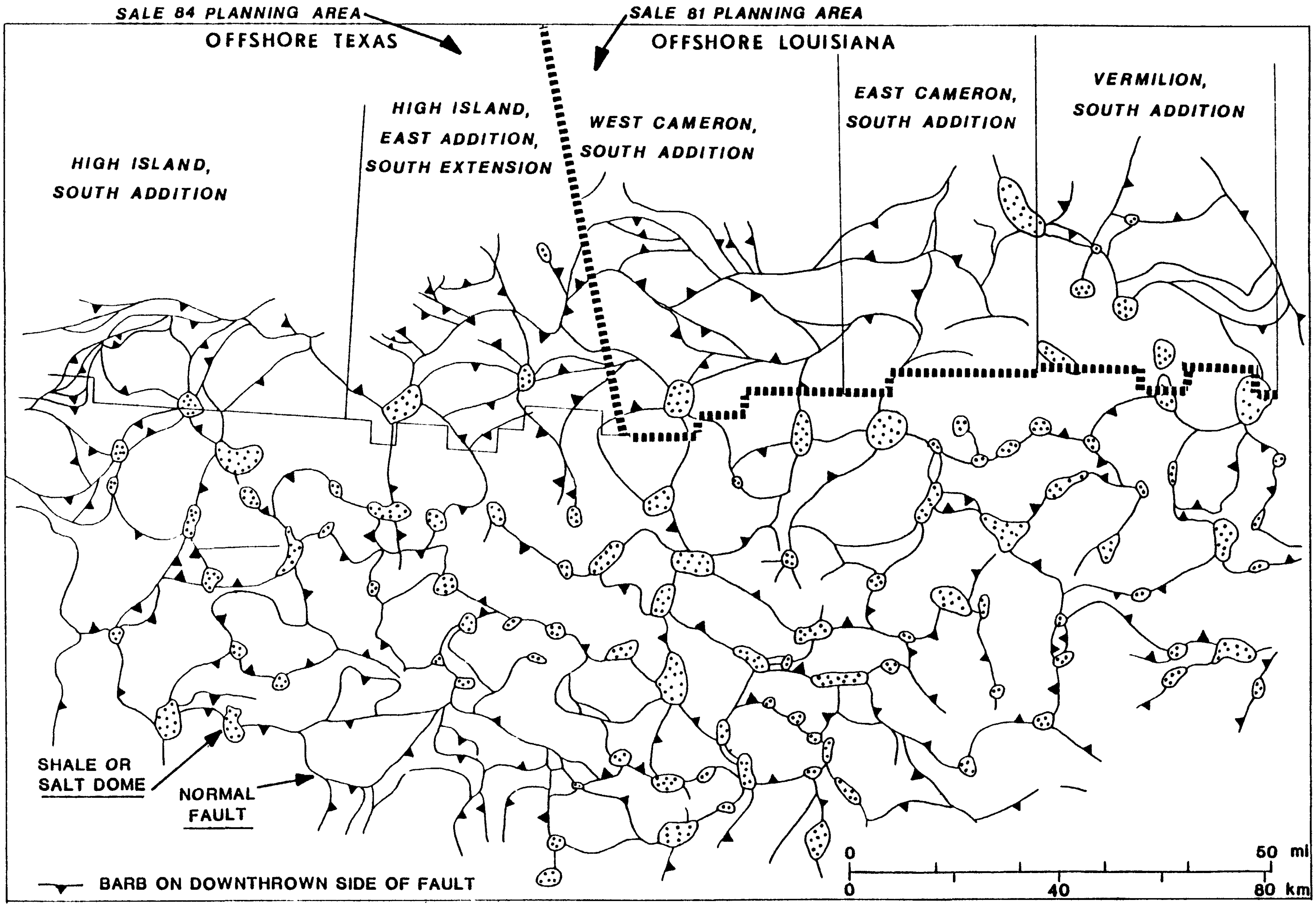

Figure II-4.--Map showing locations of major salt and shale domes and growth faults in the outer shelf and upper slope, offshore eastern Texas and western Louisiana (after Sheffield, 1978).

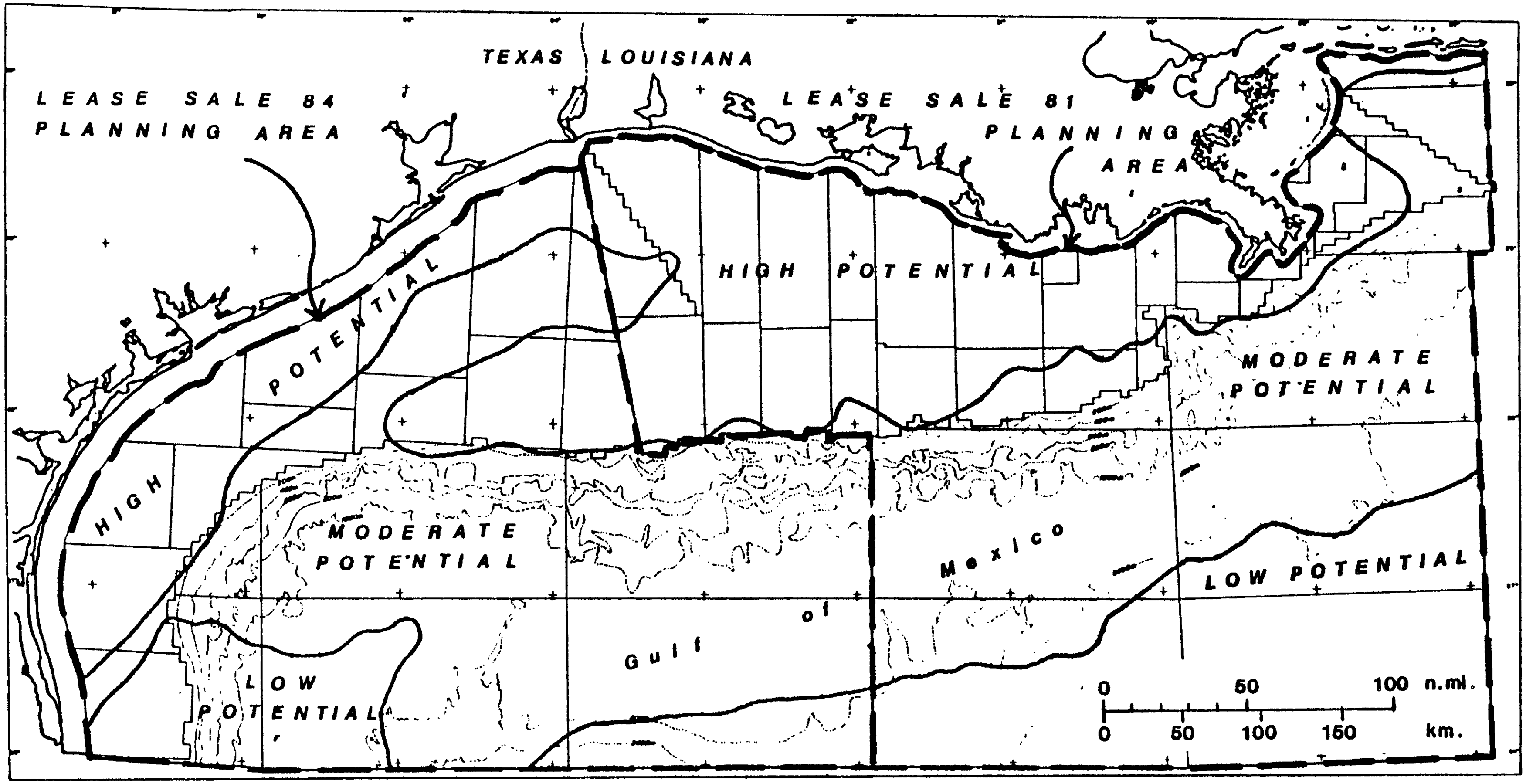

Figure II-5.-- Map of Central and Western Gulf of Mexico OCS showing areas of relative geologic potential for accumulation of hydrocarbon resources. Areas of high potential are characterized by an optimum coincidence of structural and stratigraphic conditions that favor the widespread occurrence of petroleum resources in commercial quantities. Geologic conditions in areas of moderate potential generally favor local occurrence of petroleum resources. Areas of low potential are characterized by geologic conditions generally unfavorable for the occurrence of petroleum resources.

Table II-1. Percentage of discovered in-place volumes of hydrocarbons by age, Louisiana and Texas OCS, 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

CHAPTER III

ESTIMATES OF UNDISCOVERED RECOVERABLE CRUDE OIL AND NATURAL GAS RESOURCES, PROPOSED OCS LEASE SALE 81 and 84 PLANNING AREAS

by

Abdul S. Khan

INTRODUCTION

Undiscovered recoverable resources are those quantities of crude oil and natural gas which are estimated to exist in subsurface geologic settings as commercially recoverable. Resource estimates for the Gulf of Mexico were recently assessed as a part of the study of the Nation's undiscovered recoverable conventional oil and gas resources (Dolton and others, 1981). Proposed OCS Lease Sales 81 and 84 include the continental margin seaward from the Louisiana and Texas boundaries to approximately 26°N latitude. The Louisiana Shelf, Slope, and Rise (Central Gulf Planning Area) is to be offered in OCS Lease Sale 81 and the Texas Shelf, Slope, and Rise (Western Gulf Planning Area) is to be offered in OCS Lease Sale 84.

AREA ASSESSED

For the purpose of the Dolton and others (1981) resource assessment, the Gulf of Mexico was divided into two sub-regions: 1) the western Gulf which includes the Texas-Louisiana continental margin from shoreline to 2500 m water depth, and 2) the eastern Gulf, which includes MAFLA (Mississippi, Alabama and Florida) continental margin to 2500 m water depth. Each sub-region was appraised in two water depth increments: 1) 0 - 200 m, the continental shelf province, and 2) 200 m - 2500 m, the continental slope province. The western Gulf sub-region essentially makes up the proposed OCS Lease Sale 81 and 84 Planning Areas. Lack of sufficient geological information and uncertainty concerning economics and technology have been the main reasons for not appraising the recoverable oil and gas resources of the continental rise and abyssal plain regions beyond the 2500 m water depth. Although an evaluation of the petroleum potential and estimates of undiscovered in-place oil and gas resources were made for a special study of the Maritime Boundary Region in the Gulf of Mexico (Powers, 1981), estimates of recoverable petroleum resources for this region were not calculated because of the cited uncertainties about the petroleum-reservoir properties, economics, and the technology needed to develop these deep water areas.

ASSESSMENT PROCEDURE

Estimates of undiscovered recoverable oil and gas resources for the Gulf of Mexico were made by using direct subjective probability methods as described in detail by Miller and others (1975), Dolton and others (1981), and Crovelli (1981). Volumetric yields from known producing basins, such as the Niger Delta and McKenzie Delta, were used in the analysis as analogs to determine scaling factors for the western Gulf of Mexico. Arbitrary volumetric yields from the total United States (an average, a high, and a low value) were also used as scaling factors in the analysis, as well as extrapolation of more maturely explored parts of the basin into less explored parts. Extrapolation of historic finding rates was also employed in these areas.

Each province was first assessed separately as to 1) whether it contained: any undiscovered recoverable oil; and 2) whether it contained any recoverable undiscovered non-associated natural gas. These separate events are expressed in terms of a probability on a scale of 0.0 to 1.0, called the marginal probability (MP). In a mature basin, such as the western

Gulf of Mexico where oil and gas production is already established, the marginal probabilities for oil and gas were both assessed as 1.0. On the condition that undiscovered commercial hydrocarbons exist, the volumes of undiscovered hydrocarbons were assessed at two probability levels; a low estimate at the 95th fractile (F_{95}) and a high estimate at the 5th fractile (F_5). In addition, a modal or most likely value was estimated. These conditional estimates of volumes of undiscovered oil and non-associated gas were expressed by individual subjective judgments. The associated-dissolved gas was calculated from the initial estimate of crude oil by using the gas/oil ratio (GOR) for each province (Dolton and others, 1981).

A lognormal distribution was fitted using initial low, high, and modal estimates to determine the conditional probability distribution for each province. By applying the marginal probability to the conditional probability distribution, the unconditional (risked) probability distribution of the quantity of undiscovered resource was determined.

The mean estimates of undiscovered recoverable oil and total gas (non-associated and associated-dissolved) resources for the western Gulf sub-region were allocated on a percentage basis to each province in the planning (sale) areas. The allocation percentage was calculated from the oil and total gas resource distribution for three zones of favorability - 1) area of high geologic potential, 2) moderate geologic potential, and 3) low geologic potential, based on geologic conditions and hydrocarbon richness factors in the Gulf of Mexico. The allocation percentage was applied to each province conditional estimates at F_{95} and F_5 probability and a new lognormal distribution fit was established for the shelf (seaward from the state boundary to 200 m) part and for the slope (200 m - 2500 m) part of the proposed OCS Lease Sale 81 and 84 Areas. The aggregations for the total area (shelf and slope to 2500 m) were made by a Monte Carlo technique.

CENTRAL GULF PLANNING AREA

(OCS SALE 81)

The Central Gulf Planning Area stretches east-west from the Texas-Louisiana boundary to Main Pass and Viosca Knoll area (Fig. I-1). On the continental slope, this planning area includes Green Canyon, Mississippi Canyon, Ewing Bank, and Viosca Knoll Areas, and extends seaward to approximately 26°N latitude. A deep-water area of 27,584 mi^2 (70,615 km^2) between 2500 m water depth and 26°N latitude was not included in the resource estimates.

Exploration History and Petroleum Potential

Continental Shelf

The Louisiana Continental Shelf is the most intensively drilled province in the Gulf of Mexico. The first OCS lease sale in the Gulf was held on this shelf in October 1954. Over a period of 26 years, from 1954 to 1980, approximately nine million acres (14,218 mi^2) have been leased on the Louisiana OCS -- this represents 65 percent of the total leased area (including relinquished acreage) in the Gulf of Mexico region. Over 15,000 wells have been drilled on the Louisiana OCS since 1954, indicating that the shelf has reached a mature stage of exploration. This extensive drilling has resulted in the discovery of 406 oil and gas fields in Federal waters off Louisiana. Original recoverable reserves in 369 studied fields are estimated to be 8.00 billion barrels of oil and 85.45 trillion cubic feet of total gas (Hewitt and others, 1983).

Almost all of the continental shelf, 26,497 mi^2 (67,832 km^2), of the Central Gulf Planning Area is considered a "more favorable" zone of high petroleum potential (Fig. III-1). However, a small part of the south additions of Ship Shoal and South Timbalier areas (approximately 1,991 mi^2; 5,157 km^2) in the vicinity of the Mississippi Trough is identified as a shale area of moderate oil and gas potential. As a result of almost 30 years of oil and gas exploration and drilling, most of the prospective areas (more than two thirds of the seismically mapped structures) have been tested. The remaining untested structures and possible stratigraphic traps are potential targets for future exploration on the shelf part of the Sale 81 area.

Continental Slope

Exploration and drilling on the continental slope part of the Central Gulf Planning Area has been confined to a narrow band between 200 m and 600 m water depth. This area is identified as a region of moderate geologic potential for oil and gas resources. As of December 1982, 14 oil and gas fields have been discovered in this zone. Total original recoverable reserves in 10 fields (4 fields have not been studied) are estimated at 1.73 billion barrels of oil, and 1.50 trillion cubic feet of gas (Hewitt and others, 1983). The slope (>200 m) province is still considered in the "frontier", or early stages of exploration.

Petroleum potential of the continental slope is expected to be confined to the Pleistocene section, but possibly including some Pliocene strata. The sedimentary section beneath the lower slope (water depths >600 m) consists mainly of mud and silt deposits of outer-neritic to bathyal environments. Sands deposited on the outer fringes of deltas, in submarine canyons and channels and as turbidites may be present to serve as reservoir rocks. It is estimated to have a moderate to low resource potential. Traps associated with salt domes, shale uplifts, and growth faults, described earlier, are common on the slope.

WESTERN GULF PLANNING AREA
(OCS LEASE SALE 84)

The Western Gulf Planning Area (OCS Sale 84) includes the Texas Continental Shelf seaward from the state boundary to 200 m water depth. On the continental slope, it encompasses Port Isabel, Corpus Christi, East Break and Garden Banks Areas, and extends seaward to approximately 26° latitude. The slope sale area beyond the 2500 m water depths that was not included in the resource assessments covers 4,347 mi^2 (11,128 km^2).

Exploration History and Petroleum Potential

Continental Shelf

Oil and gas exploration on the Texas OCS began in 1954; initially, exploratory drilling was confined to the inner shelf (Miocene stratigraphic trend) in High Island, Galveston and Brazos Areas. In the early seventies, the South Additions of High Island, Galveston and Brazos Areas (Plio-Pleistocene stratigraphic trend) were offered for leasing and exploration. Later, in February 1975, a Federal lease sale was held for the first time in the South Texas OCS area.

As of December 1982, over four million acres (6,406 mi^2; 16,399 km^2) were leased on the Federally owned Texas Continental Shelf, representing about 29 percent of the total acreage leased in the Gulf of Mexico since

1954. Approximately 2,139 wells have been drilled and 112 oil and gas fields have been discovered in Federal waters to December 1982. Original recoverable reserves for 102 studied fields are estimated at 0.37 billion barrels of oil and 10.88 trillion cubic feet of total gas (Hewitt and others, 1983). Two oil and gas fields have been depleted; the oil and gas reserves in 12 fields have not been studied. Resource potential of the Texas Pliocene trend (mid-shelf area) has been disappointingly low. Poor reservoir conditions and the general absence of major structures account for the optimistically, moderate resource potential (Fig. III-1).

Continental Slope

The Texas Continental Slope is the least explored area in the western Gulf of Mexico. Exploratory wells off the High Island Area in water depth greater than 200 m (East Break and Garden Bank Areas) have resulted in a few oil and gas discoveries. As of December 1982, 3 oil and gas fields on the Texas Slope (Sale 84 Area) are estimated to have original recoverable reserves of about 17.5 million barrels of oil and 311.8 billion cubic feet of total gas (Hewitt and others, 1983). The area of relatively higher potential apparently is a down-dip extension of the prolific Pleistocene trend of the adjacent shelf. The resource potential of the slope (Sale 84 Planning Area) is down-graded southward and westward into moderate and low zones. Diapiric structures, probably both salt and shale, are believed to be present in most of the Sale 84 Planning Area.

ESTIMATES OF RESOURCES

Estimates of undiscovered recoverable crude oil and natural gas for shelf and slope areas assessed for proposed OCS Lease Sales 81 and 84 are shown on Table III-1.

Estimates of resource potential in the Gulf Coast basin are restricted to 30,000 ft (9 km) depth (Dolton and others, 1981). The Gulf Coast Basin has accumulated more than 60,000 ft (18,200 m) of sediments offshore Louisiana.

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Table III-1. Summary of estimates of undiscovered recoverable oil and gas resources, areal size, and sediment volumes of Lease Offerings 81 and 84 Planning Areas, Gulf of Mexico

Assessment area	Areal size		Crude oil Billions of barrels (BBO) M.P.1/	High2/	Mean3/	Low4/	Total natural gas Trillion cubic feet (TCF) M.P.1/	High2/	Mean3/	Low4/
Lease Offering 81										
Louisiana Shelf	26,497 mi^2	67,883 km^2	1.0	4.44	2.16	0.93	1.0	49.31	26.31	13.53
Louisiana Slope	27,584 mi^2	70,615 km^2	1.0	3.10	1.50	0.57	1.0	26.46	13.58	5.81
TOTAL5/	54,081 mi^2	138,498 km^2	1.0	6.42	3.66	2.00	1.0	66.03	39.89	24.00
Lease Offering 84										
Texas Shelf	19,954 mi^2	51,082 km^2	1.0	1.43	0.64	0.27	1.0	29.94	15.52	7.88
Texas Slope	30,861 mi^2	79,004 km^2	1.0	1.83	0.89	0.33	1.0	24.46	12.49	5.14
TOTAL5/	50,815 mi^2	130,086 km^2	1.0	2.75	1.53	0.81	1.0	45.93	28.01	16.56

1/ The resources estimates are <u>unconditional</u>, that is, the marginal possibilities (M.P.), or risks, have been applied to the estimates shown.
2/ The estimates associated with a 5% probability that more than the amount shown is present.
3/ The estimate associated with the most likely amount of resource present.
4/ The estimate associated with a 95% probability that more than the amount shown is present.
5/ The conditional aggregate (such as for the total region) means are calculated from the unconditional aggregate means. They are, therefore, not necessarily the sum of the individual conditional means.

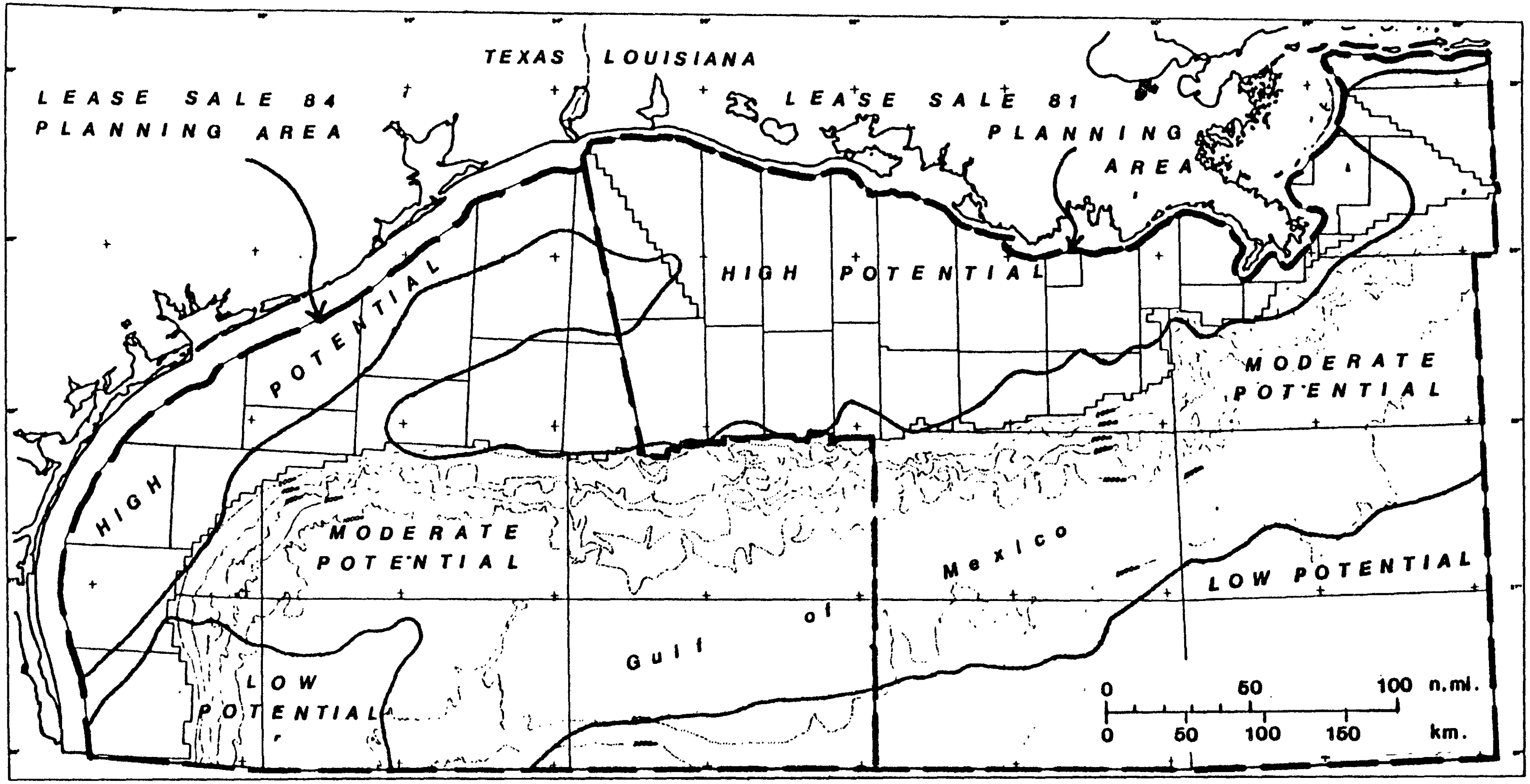

Figure III-1. Map of Central and Western Gulf of Mexico OCS showing areas of relative geologic potential for accumulation of hydrocarbon resources. Areas of <u>high</u> potential are characterized by an optimum coincidence of structural and stratigraphic conditions that favor the widespread occurrence of petroleum resources in commercial quantities. Geologic conditions in areas of <u>moderate</u> potential generally favor local occurrence of petroleum resources. Areas of <u>low</u> potential are characterized by geologic conditions generally unfavorable for the occurrence of petroleum resources.

CHAPTER IV

ENVIRONMENTAL CONSIDERATIONS FOR OCS DEVELOPMENT, LEASE SALES 81 and 84 PLANNING AREAS

by

Louis E. Garrison

INTRODUCTION

The geology of surface and near-surface sediments in the Planning Areas for Lease Sales 81 and 84 in the Gulf of Mexico is known in some detail in places, but only poorly in others. In those areas where closely spaced geophysical surveys have been made and regional tie lines provided, information on geohazards is adequate. In other areas where such data are lacking, predictions of geohazards must be made by extrapolation or by comparisons based on environmental similarities to better known areas.

This chapter summarizes in general terms what is known about the seafloor environment, the dynamic geologic processes which affect it, and the geohazards which may be encountered in developing OCS Lease Sales 81 and 84 Planning Areas.

These subjects are discussed under four headings:

- Seafloor instability
- Gas seeps and shallow gas accumulations
- Shallow faulting
- Texture of surface sediments

Information sources are from the published literature and open file government data. Although brief discussions of some of the geological processes and mechanisms are included, this is by no means an exhaustive report. Space limitations prevent the balanced treatment of these subjects that would clarify the level of our present understanding. For this, the reader must turn to the referenced literature.

SEAFLOOR INSTABILITY

The term "seafloor instability" as used here will refer to the processes of mass wasting which, through strength loss and lateral movement, transport sediments downslope at or near the bottom. They may be triggered by the over-steepening of slopes, by static loading processes such as rapid deposition of an overburden, or by the cyclic loading of storm waves or earthquake ground motion. In the northern Gulf of Mexico, these transport processes may be slumps with rotation of sediment blocks, slides with various degrees of translational motion, earth flows in which the material being moved loses all coherence, or turbidity currents with densities only slightly greater than that of sea water.

Sediment instability is more likely to occur on the continental slope than on the continental shelf due to its steeper gradients. Except for the somewhat special case of the Mississippi River Delta, the very low gradient shelf is, on the whole, a region of stability. The continental slope, on the other hand, with steeper regional gradient, rugged topography, and active diapirism displays a variety of instabilities.

Figure IV-1 and the text to follow summarize our present knowledge of stability conditions on the upper slope. Each of the areas designated will be discussed below. For the middle and lower slope regions, however, stability conditions are not as well known. Relatively few miles of high-resolution seismic profiling and almost no sediment sampling have been done. Although conditions not greatly different from those of the mapped upper slope undoubtedly extend well into the middle slope regions, the consolidation state of the sediments there is probably greater due to slower rates of deposition.

Relief features, on the other hand, are bolder, especially on the lower slope. Landslides and turbidity currents are almost certainly active in moving sediments down the more continuous canyon routes to the continental rise. Until a careful study of lower slope morphology and surface sediments has been made, we can only speculate on stability conditions there.

Upper Continental Slope

Area 1, the slope off south and central Texas lacks the abundance of diapiric intrusions that characterize the slope farther east (Figs. I-6, IV-2). The sea floor thus has little relief, and sedimentation rates in the region have been low throughout Pleistocene times, except when lowered sea levels brought deltas to the shelf edge (see Areas 2 and 3). Principal instabilities are in localized areas of creep where the upper few tens of meters of sediment are wrinkled by slow, downslope movement (Fig. IV-3). Creep rates are now known, but are not believed to be excessively high and undoubtedly vary from place to place, dependent upon sea floor gradient and the physical properties of the sediment.

The two areas designated Area 2 are submarine landslides which coincide with the shelf-edge bulges that have been associated by Curray (1960) with the low sea level Rio Grande Delta in the south, and the low sea level Brazos Delta in the north. It seems likely, therefore, that these landslides are relict, having failed when the shelf edge in those areas was loaded by the rapid deposition of material from those ice-age rivers.

Area 3 is one of the largest landslide areas identified in the northern Gulf (Fig. IV-4). It has been described by Lehner (1969) and additional morphological detail provided by Tatum (1979). Its location adjacent to the bulge of what was probably the shelf-edge Colorado River Delta indicates that this slide, like those described above is relict. Although larger and more complex, consisting of at least two limbs, it too must have been formed when the shelf edge was loaded to failure by the sediment outpourings of an ice-age stream. No studies have been made of the present state of stability of these slide areas, but there is no direct evidence that they have moved in modern times.

Area 4 includes most of the upper continental slope of the north-central Gulf. It is a region of intense diapiric activity, relatively thick surface deposits, and locally steep gradients. For these reasons, local instabilities are common. Although data concerning the physical properties of the sediments are extremely scarce (Booth and Dunlap, 1977), high-resolution geophysical surveys have yielded much useful qualitative information on geologic conditions at the seafloor (Garrison, 1979; Tatum, 1979).

Landslides are common on the steep flanks of diapiric uplifts, and around the heads of canyons or basins which are subsiding due to salt withdrawal at depth (Fig. IV-5). In many cases, initial sediment failure and landsliding have started retrogressive failure sequences that expand the slide area and reach far upslope. Present evidence indicates that most landslide debris does not travel great distances downslope before coming at least temporarily to rest in diapirically closed basins. In the complex topography of basins and highs, unimpeded pathways of great length appear to be rare.

If a coherent mass of fine grained sediment move downslope with sufficient velocity over a sufficient distance, portions of it may lose their coherence and internal structure and continue to move in something like a grain-to-grain relationship. It is then termed a debris flow. If the upper surface of such a debris flow begins to incorporate sufficient amounts of water, a high velocity current may develop in which sediment particles are held in suspension by turbulence. With densities greater than water, but with fluid characteristics, these turbidity currents move sediment far beyond the termination point of the parent debris flow.

Turbidity currents are probably common on the northern Gulf continental slope. The deposits formed when they lose velocity and sediment particles settled out are called turbidites. Turbidites are identifiable in seismic profiles by the regularity of their bedding and the horizontal attitude of their upper surfaces (Fig. IV-6). Most basins in the diapir province which have no exit on their downslope side display this type of bedding and must therefore be trapping turbidity currents. In such cases, it must be considered that bottom currents of considerable velocity periodically flow down the routes leading into these basins.

The southwestern portion of Area 5 experiences the highest rates of deposition of any continental slope area in the Gulf of Mexico. Booth and Dunlap (1977) reported a rate of 56 cm/100 yrs in the upper meter of sediment from a core taken in 336 m water depth south of the Mississippi Delta. Diapiric structures, are also present in this region, but the thicker sediment cover smooths the topography to some extent. Downslope movement of a somewhat different character than that in Area 4 affects these sediments. Rather than local slides off the flanks of diapiric hills, large areas of the clayey material are in creep (Fig. IV-7). Concentrations of arcuate faults concentrically arranged around valley heads (Fig. IV-8) indicate that downslope translation by rotating slump blocks also contributes to the transfer of large amounts of material basinward at slow rates. Some of these slumps produced sea floor scarps on the order of 20-30 high (Coleman and Garrison, 1977; Garrison and others, 1977).

The northeastern part of Area 5 is away from the influence of the modern Mississippi Delta, and depositional rates are therefore relatively low. The slope, nevertheless is gullied to some extent by small slides. At least one slide of larger dimension has been surveyed near Long. 87°40'W (Fig. IV-9). It may still be occasionally reactivated as its head has retrogressed nearly 17 km upslope to within 2 km of the present shelf break (IV-10).

Area 6, the Mississippi Canyon, contains instabilities of two general types. The presently exposed walls of the canyon, although not steep by most standards, have slopes as great as 4.0° (Ferebee and Bryant, 1979). This is sufficient to cause local slumps and slides, with more extensive areas of creep.

The debris which now fills the valley is several hundred meters thick (Coleman and others, 1983). Its base consists of material that slumped from the walls during original valley formation sometime after 27,000 years B.P., covered by beds of probable deltaic origin whose ages are between about 20,000 and 10,000 years B.P. (Fig. IV-11). Since 10,000 years B.P., or well into the rise of Holocene sea level, pelagic deposits up to 100 m or more in thickness have capped the valley fill and formed the flat surface of the present sea floor (Fig. IV-12). The seaward slope of this surface is generally less than 0.5°. This may promote a downslope creep in these latest deposits, but this has not been established by actual measurement. Although extensive studies of the stability of the canyon fill have been conducted in recent years by industry interests, the data remain proprietary for the most part.

The Mississippi Delta

Area 7, the shallow portion of the submerged Mississippi Delta, has received intensive study from both public and private sectors due to the multitude of engineering structures that dot its surface, the miles of pipeline that lace them together, and the gassy, undercompacted sediments that comprise the foundation material. Coleman and others (1980) have described a variety of failure features that may be considered hazardous in this very dynamic environment (Fig. IV-13).

Rates of deposition of the dominantly clayey sediment may be locally as high as 1 meter/year (Coleman and Garrison, 1977). Under these conditions of static loading in which insufficient time is available for compaction, sediment failure occurs when the imposed load reaches a critical level. Recent research by the USGS on the catastrophic effects of storm waves on these weak deltaic deposits has shown the cyclic loading of wave-pressure fluctuations can also be a direct cause of sediment failure (Dunlap and others, 1979; Williams and others, 1981).

Sediment failure in the Delta region is usually followed by the displacement of the failed material in a downslope direction. Although slopes are extremely low, generally less than 0.5°, these lateral movements develop depressions and gullies of considerable length, sometimes in excess of 10 km (Prior and Coleman, 1980). The seaward ends of these chutes are regions of deposition, where the lobes of successive mudflows overlap one another to form a broad flat surface, elevated slightly above the project slope of the delta front. It is assumed that mudflows are episodic and related to times of sediment failure in the upslope areas. However well the mudflow morphology of the Mississippi Delta has been mapped (Coleman and others, 1980), the result is but a single snapshot of a dynamic process. It is not known whether a single failure causes sediment to be moved down the entire length of a mudflow chute, or whether successive failures move the debris along the short bursts. The frequency of mudflow movement has not been observed, nor has the velocity of any mudflow been measured. It is well established, however, that well-head installations in failure features are damaged, and that pipelines are commonly sheared during storms at the points where they intersect mudflow chutes.

GAS SEEPS AND SHALLOW GAS ACCUMULATIONS

Gas seeps and shallow gas accumulations in the near-surface sediments are reported in abundance throughout most of the shelf-depth areas of the northern Gulf of Mexico. Figure IV-14 shows the locations of most of the occurrences reported in the literature, but they are no doubt only a fraction of the actual number. For the "Serendipity Gas Seep" area alone, Watkins and Worzel (1978) estimate more than 19,000 seeps within a 6000 sq km area. Such numbers, however, are almost meaningless because many individual outlets seeping gas into the water column must be ephemeral and exist only long enough to relieve an overpressured accumulation, or until their seep route bridges over. Only those seeps rising along fault planes from deeper reservoirs may be semi-permanent.

Opinions are divided on the principal origin of the hydrocarbon gases in marine waters and near-surface sediments in the northern Gulf of Mexico. Brooks and others (1979) believe that most such gas is biogenic, that is, it is the result of microbial activity within the upper few tens of meters of sediment. On the other hand, Reitsema and others (1978) analyzed sea water at shelf locations from Galveston to Grand Isle and concluded that "the amount of light hydrocarbons of thermal origin is considerable". It is likely that these hydrocarbons come to the surface through fault systems, or through upturned beds (Fig. IV-15).

These views are actually not incompatible, because gaseous hydrocarbons of thermal origins become mixed with biogenic methane in passing through the shallow sediments, and both sources contribute abundantly to the light hydrocarbons in solution in the Gulf waters.

The occurrence of gas of either origin, however, may under certain conditions be a hazard. Violent blowouts have resulted from drilling into high-pressure accumulations only a few hundred meters below the mud line (Fig. IV-16). These gas pockets can be identified and avoided by using high-resolution acoustic profilers in pre-drilling site surveys (Fig. IV-17). Biogenic gas also can create hazardous conditions in areas of rapid deposition, such as on active deltas. If methane is generated in sediment pore waters in amounts that exceed saturation and gas bubbles are formed, the resulting increase of pore pressure may lower sediment shear strengths to the point of failure. Such a process is thought to have been the cause of pipeline ruptures and platform failures around the Mississippi Delta.

SHALLOW FAULTING

Although several generations of tectonic maps depict regional faulting trends in the northern Gulf of Mexico (Lafayette Geol. Soc., 1973; Martin, 1978), no adequate compilation of shallow faulting throughout the region is available. Berryhill and Trippet (1980) have mapped shallow faulting for the south Texas Continental Shelf Area, and Berryhill has also mapped the shallow faults on part of the Louisiana shelf as well (Berryhill, this report). For the remainder of the shelf region, data in considerable amounts but scattered localities exist in the form of high-resolution surveys in individual lease blocks for OCS sales. These data, however, have not been compiled.

In general, it can be said that shallow faulting, i.e., the small faults which offset mainly Holocene deposits, follow approximately along the trend of depth contours over the Texas-Louisiana Shelf and Upper Slope. Departures from these trends are caused by near-surface diapiric penetrations. Relief faults and crestal graben related to the uplift of shallow beds surround each of these structures with its own shallow fault pattern (Fig. IV-18).

Shallow faulting on the continental slope is poorly known, but it is probably safe to assume that regional trends do not exist in areas much below the shelf break. Some regional growth faults and growth fault trends are accompanied locally by shallow antithetic faulting, but these have not been compiled or mapped.

Except for these, shallow faulting on the continental slope is also associated with individual diapiric intrusions (Fig. IV-19). Because of the thinner sediment cover and larger volume diapiric pillars, fault offsets and fault scarps may be much greater than those on the shelf. These fault displacements may frequently be the start of landslides as well.

TEXTURE OF SURFACE SEDIMENTS

The textural distribution of surface sediments on the continental margin in the northwest Gulf of Mexico has been synthesized from several sources and compiled by the Bureau of Land Management's New Orleans OCS office as a visual aid for proposed lease sales. Figure IV-20 was adapted from that map. For more detailed information within limited areas, see Berryhill and Trippet (1980) and Berryhill, this report.

The grain-size distribution patterns shown in Figure 20 can be summarized as follows:

1) Clay and silt are the most abundant sizes.
2) Sand dominates the nearshore regions except off the mouths of active passes.
3) The largest mid-shelf sandy area lies in the central shelf off Texas, with a secondary sandy shelf area east of the Mississippi Delta.
4) Very little information is available on the texture of continental slope sediments. From a few observations and by inference, it can be said that sand is found principally in basins which serve or once served as turbidity current routes to the lower slope.
5) Except for the effluents of the Mississippi River, little or no present day river-borne coarse detritus passes the bays and lagoons to be added to modern shelf deposits, although the fine-grained suspended load from all the Gulf coast rivers is swept along by currents and deposited over the inner shelf. The middle and outer shelf surface is essentially a relict coastal plain whose materials were reworked by the waves and currents of the rising Holocene seas and to some extent by the present oceanographic regime. A thin blanket of very fine grained Holocene sediments covers the continental slope and rise (Fig. IV-21).

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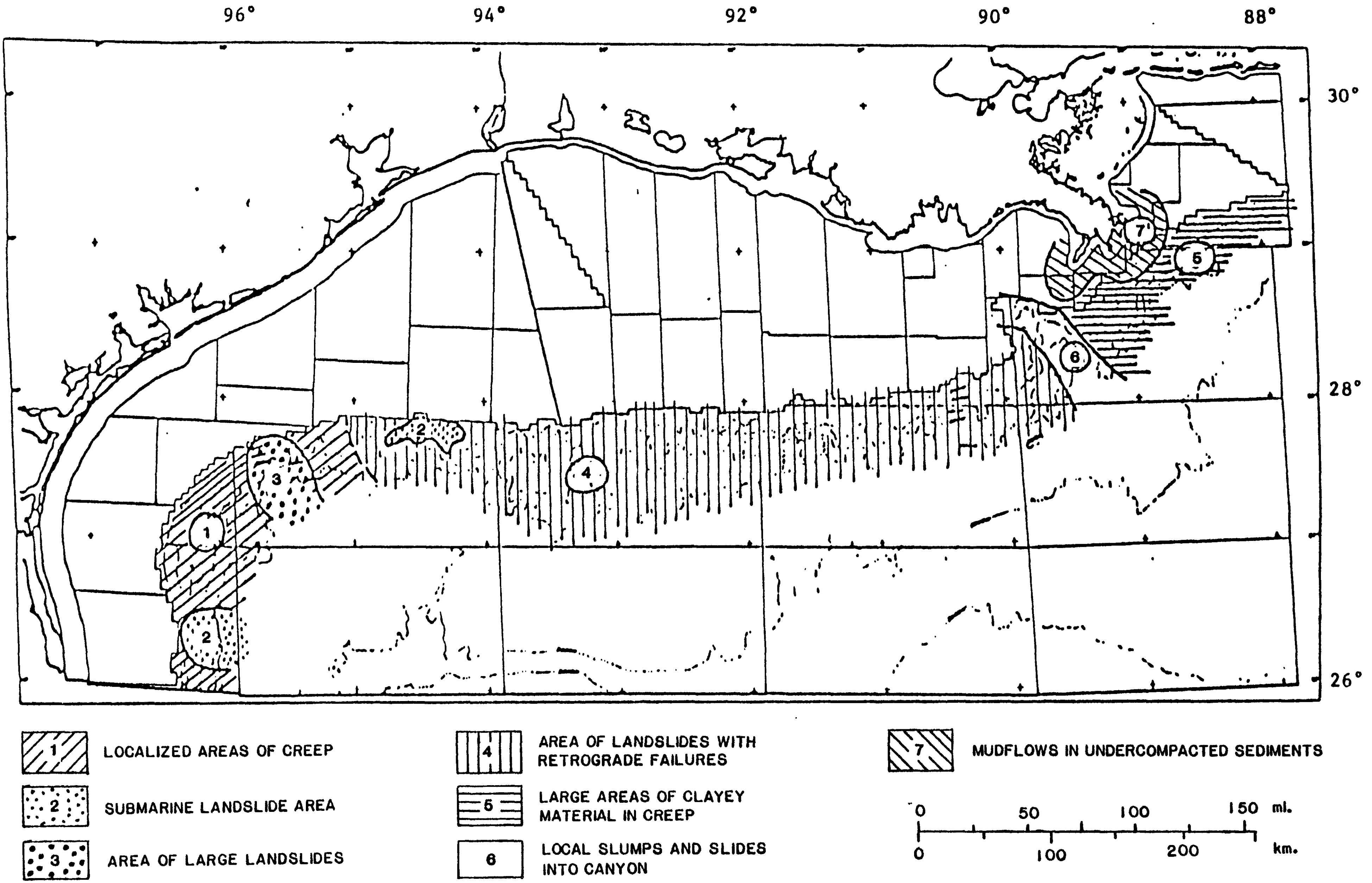

Figure IV-1. Sea floor instability in the northwestern Gulf of Mexico.

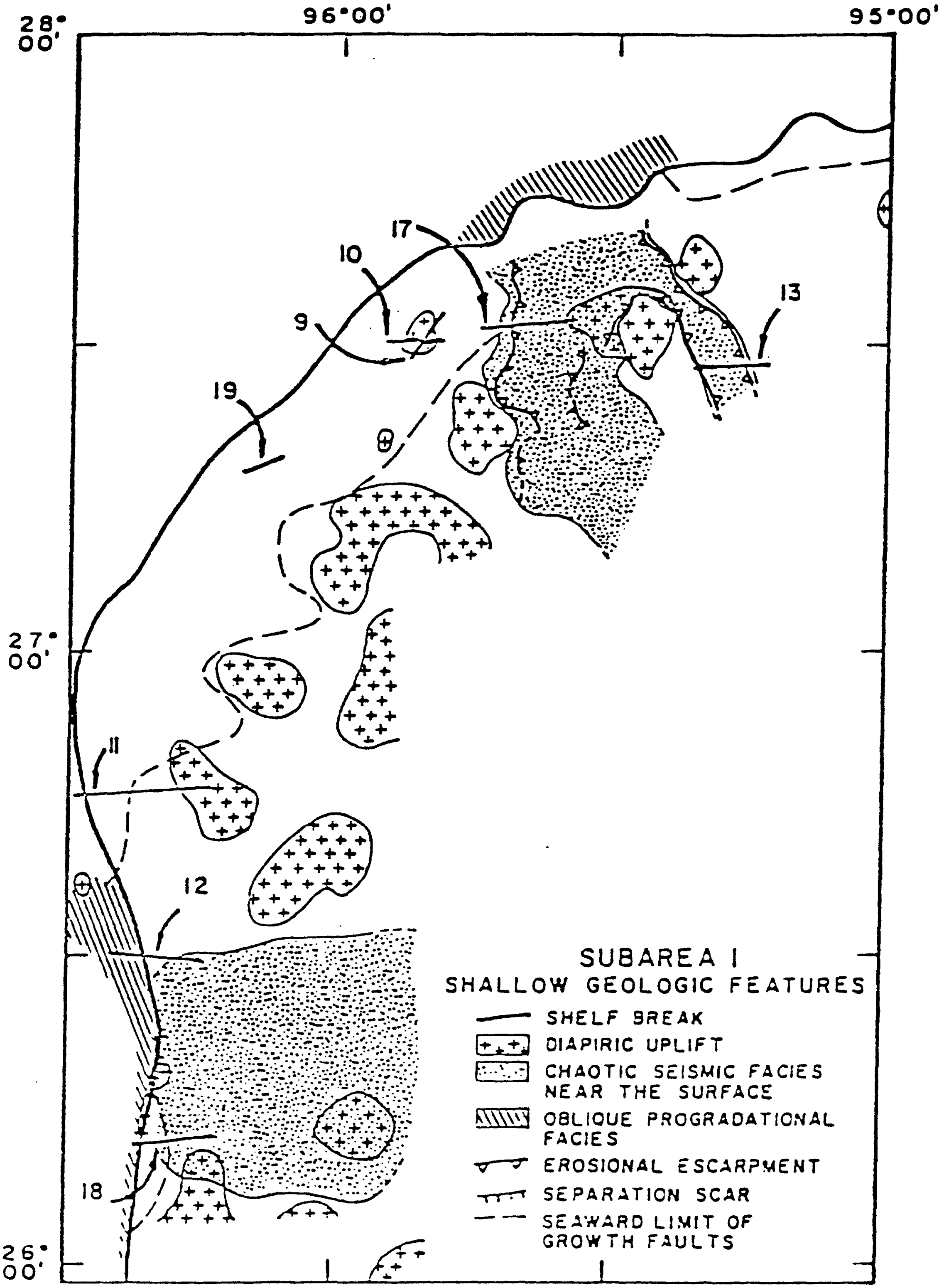

Figure IV-2. Shallow geologic features on the upper continental slope off south Texas. (From Tatum, 1979).

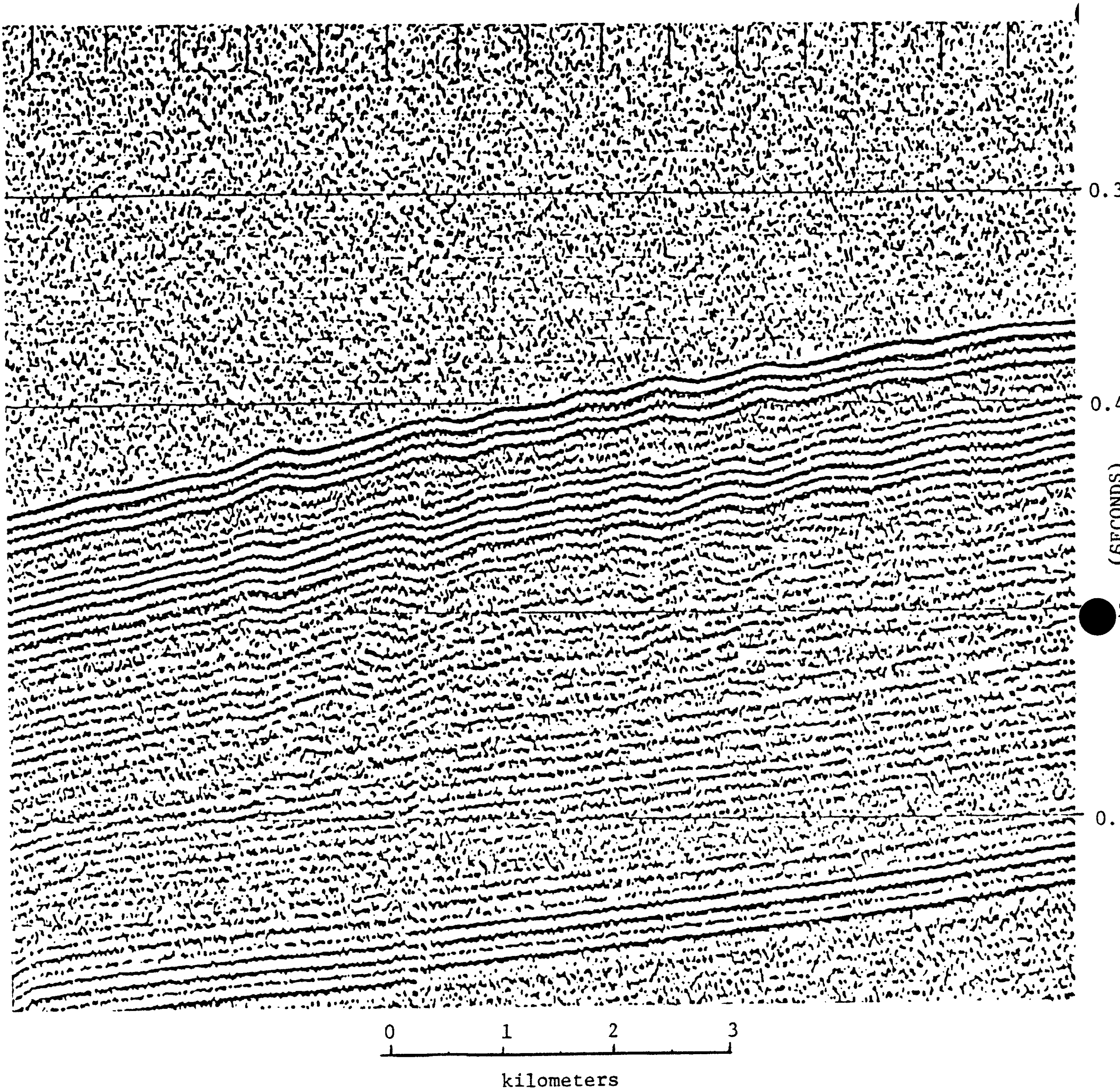

Figure IV-3. Creep folds on the upper continental slope off south Texas. (WB Line 15, Garrison, 1979).

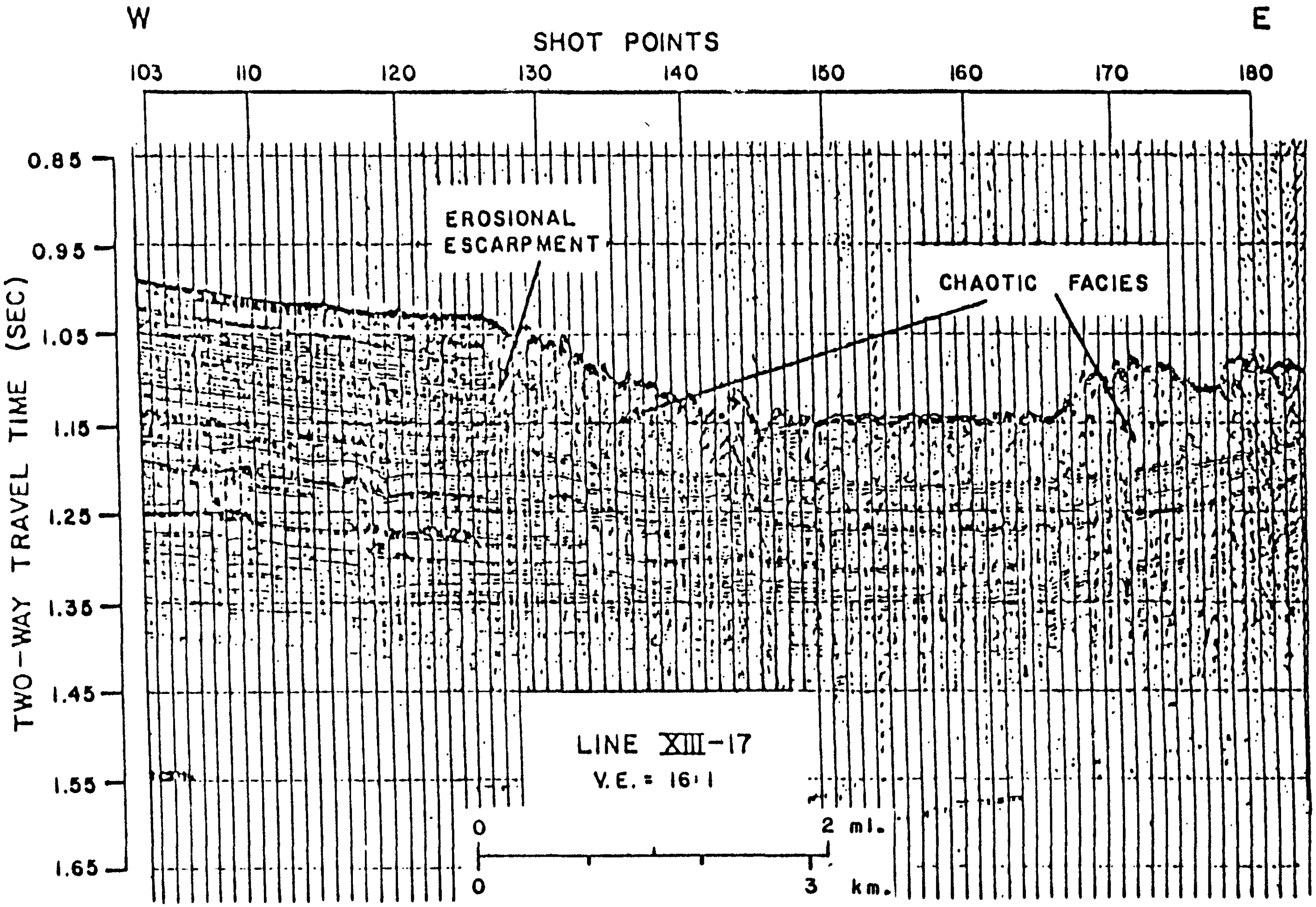

Figure IV-4. East-Breaks Area landslide. Sparker profile from Tatum (1979).

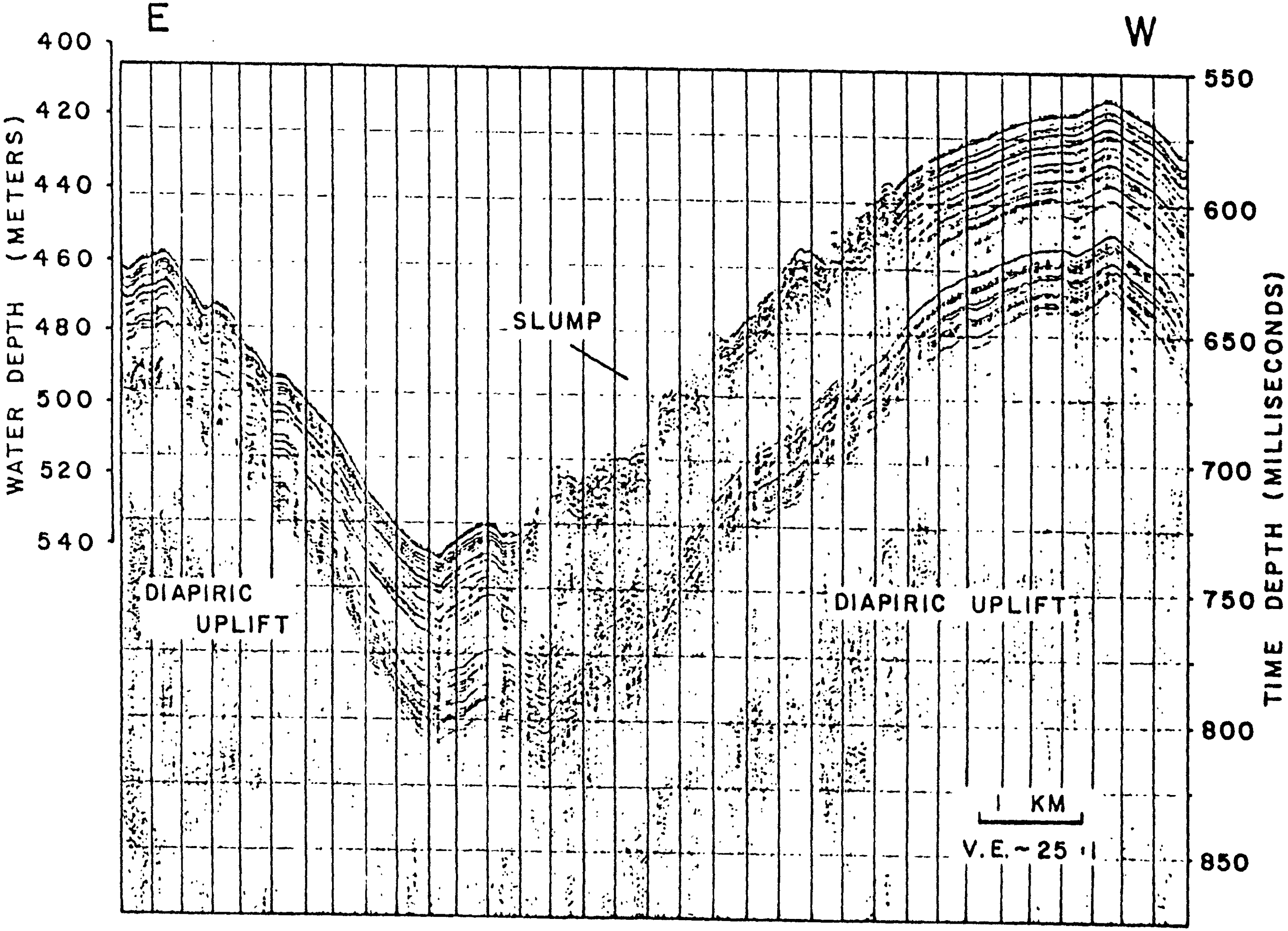

Figure IV-5. Slumping off flank of a rising diapir. (From Bouma and Martin, 1980).

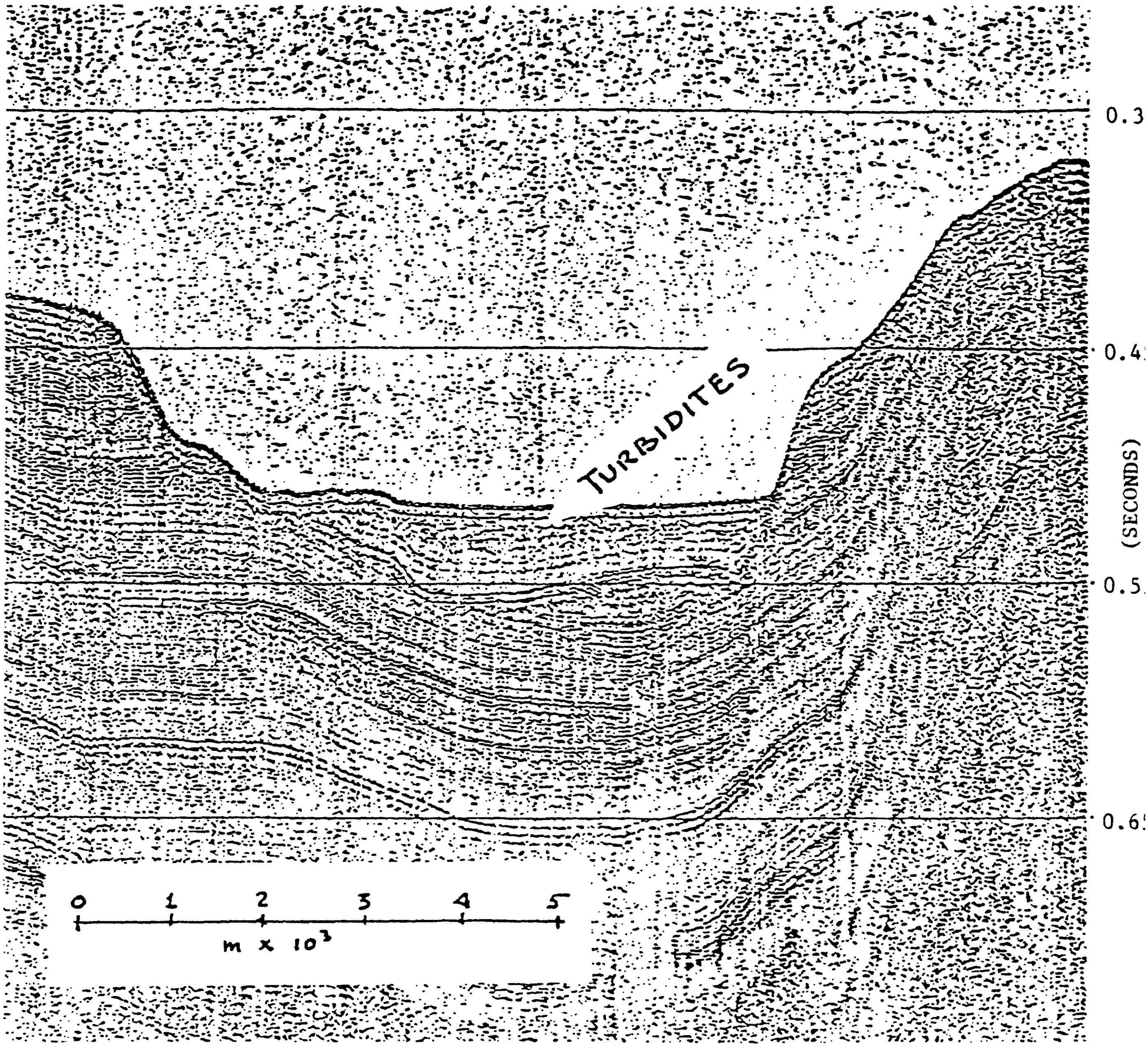

Figure IV-6. Turbidity current deposits in continental slope basin. WB Line 110, Garrison, 1979.

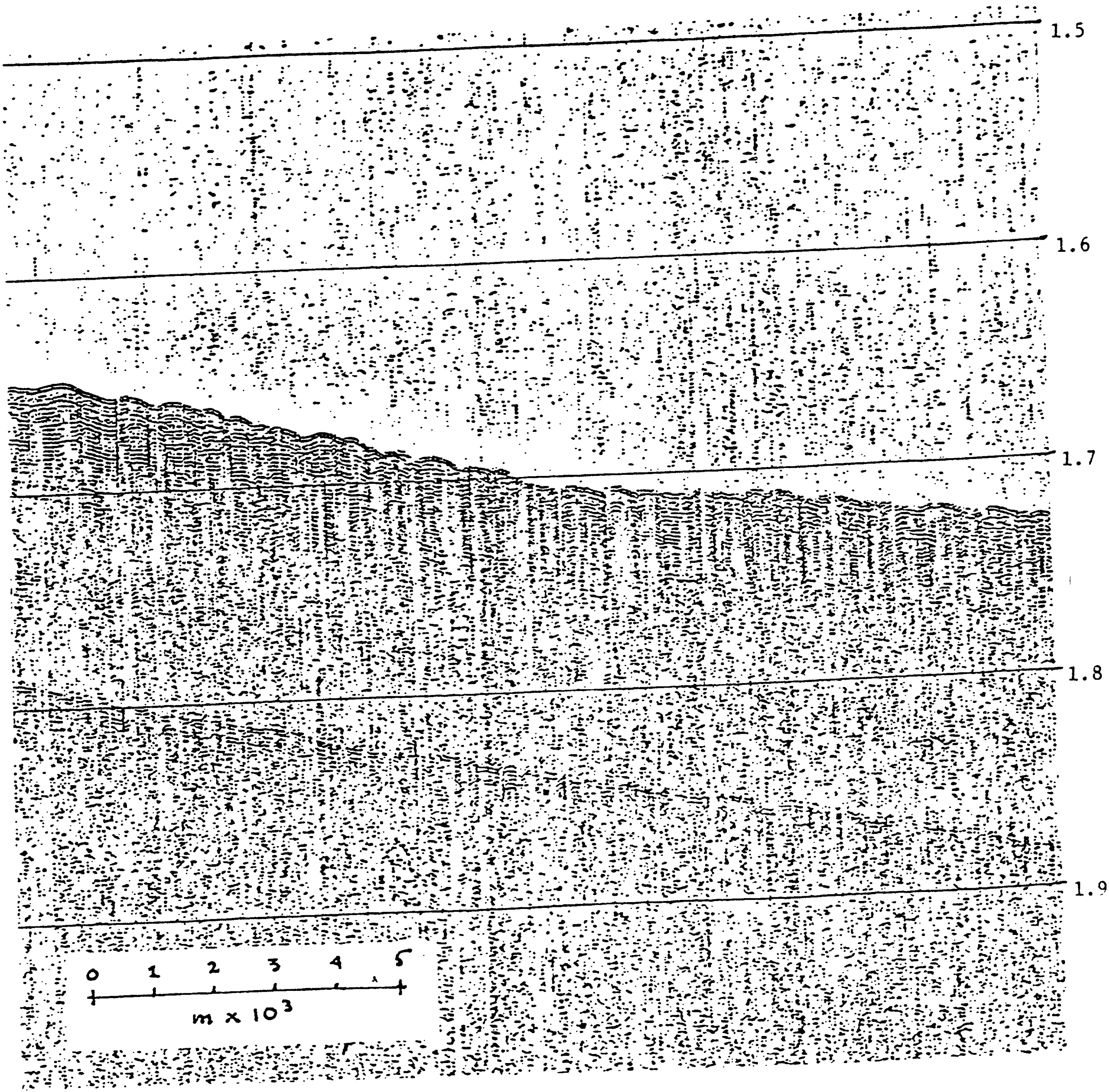

Figure IV-7. Downslope creep in upper sediment layers, Mississippi Canyon Area (WB Line 152, Garrison, 1979).

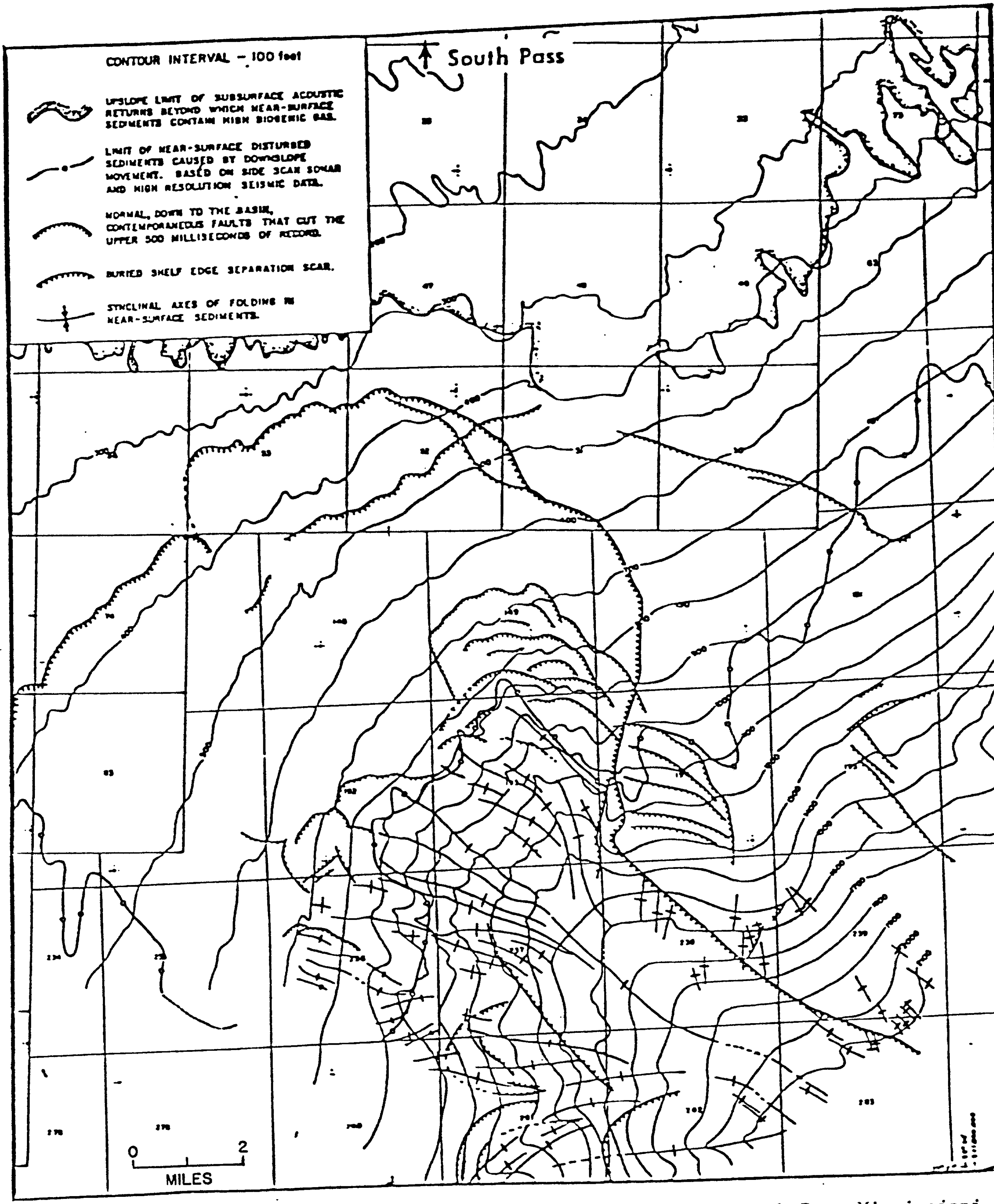

Figure IV-8. Shallow faulting peripheral to head of valley, South Pass-Mississippi Canyon Area. From Coleman and others, 1983.

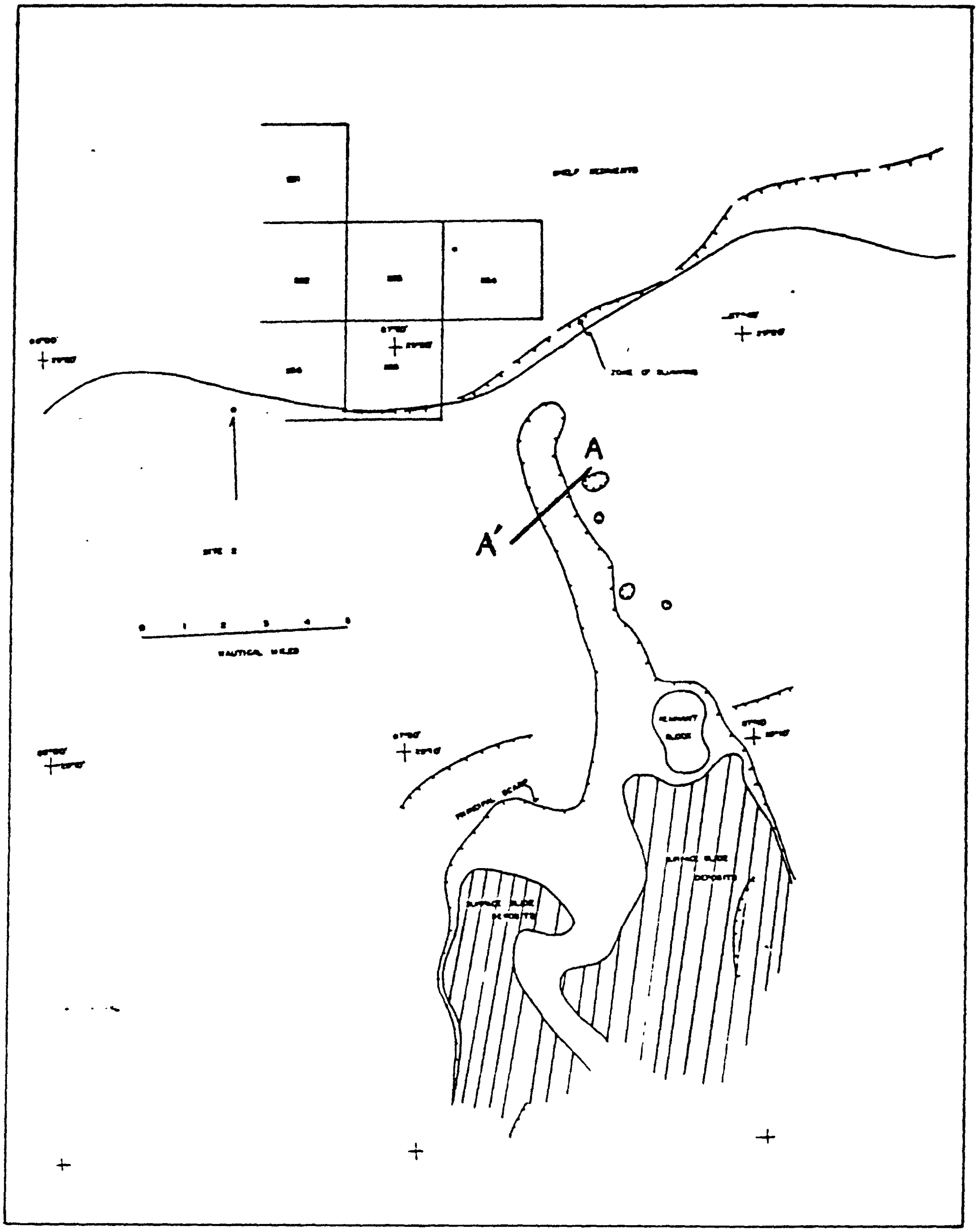

Figure IV-9. "Site 2" landslide, Viosca Knoll-Destin Dome area. See profile Figure 10.

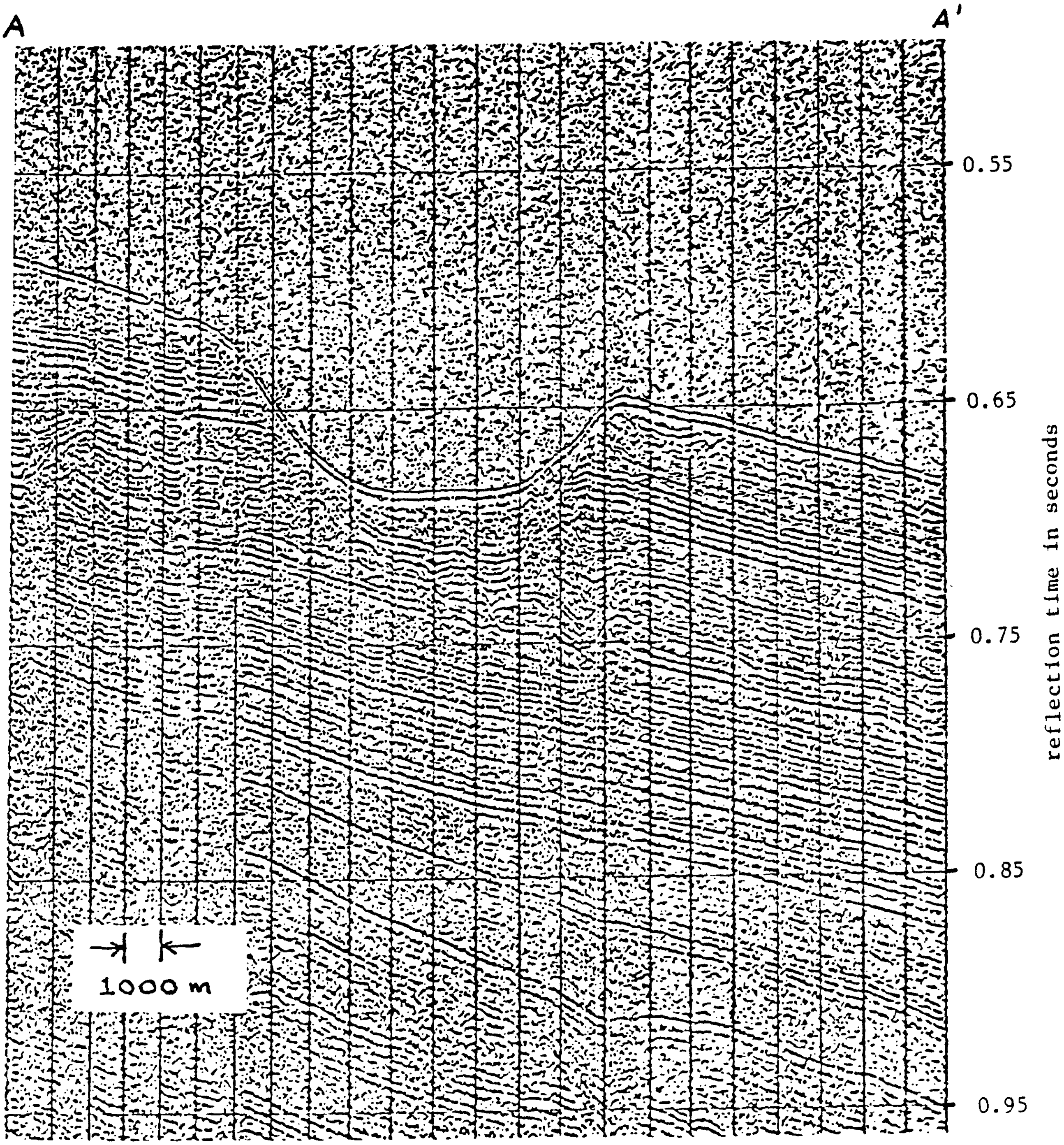

Figure IV-10. Sparker profile across "Site 2" landslide gulley (Garrison, 1979).

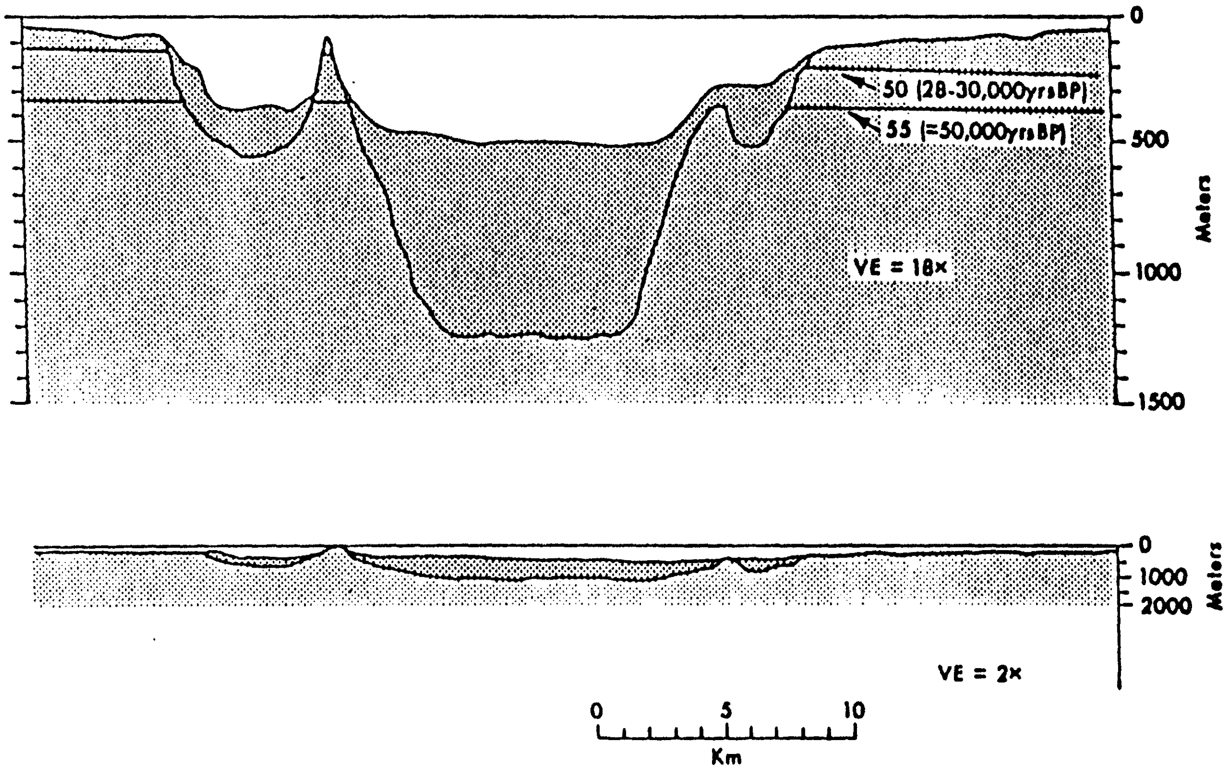

Figure IV-11. Cross-section of Mississippi Canyon showing ages of beds cut by canyon erosion. From Coleman and others, 1983.

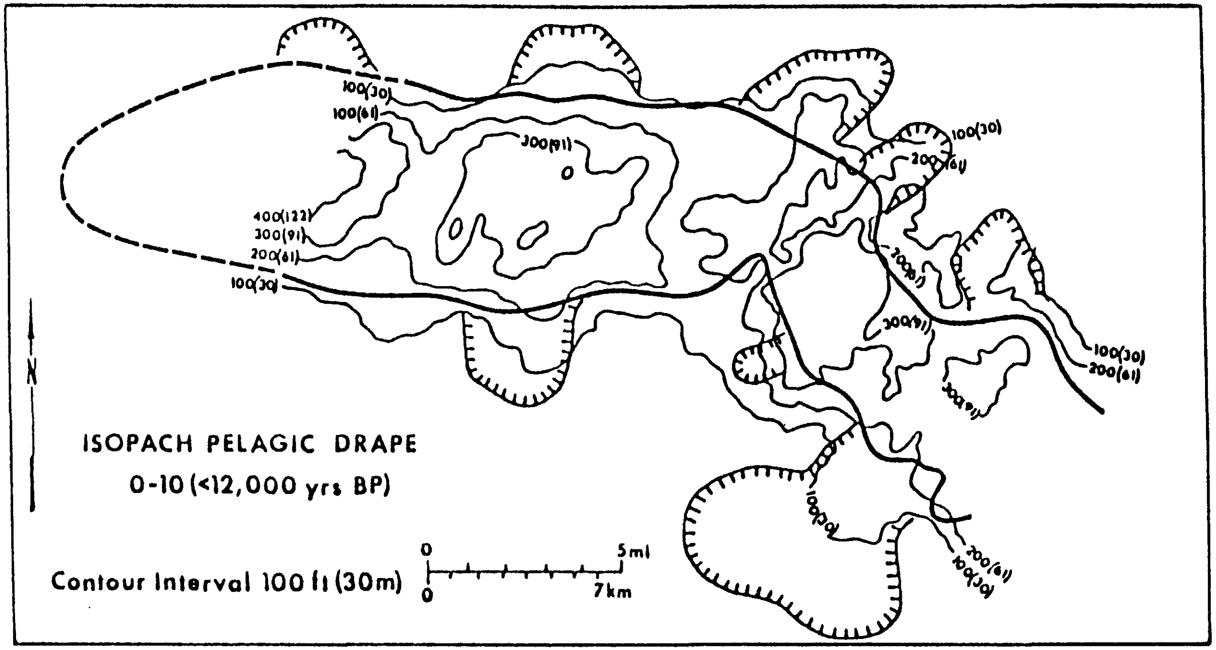

Figure IV-12. Thickness of uppermost sediment unit, Mississippi Canyon. From Coleman and others, 1983.

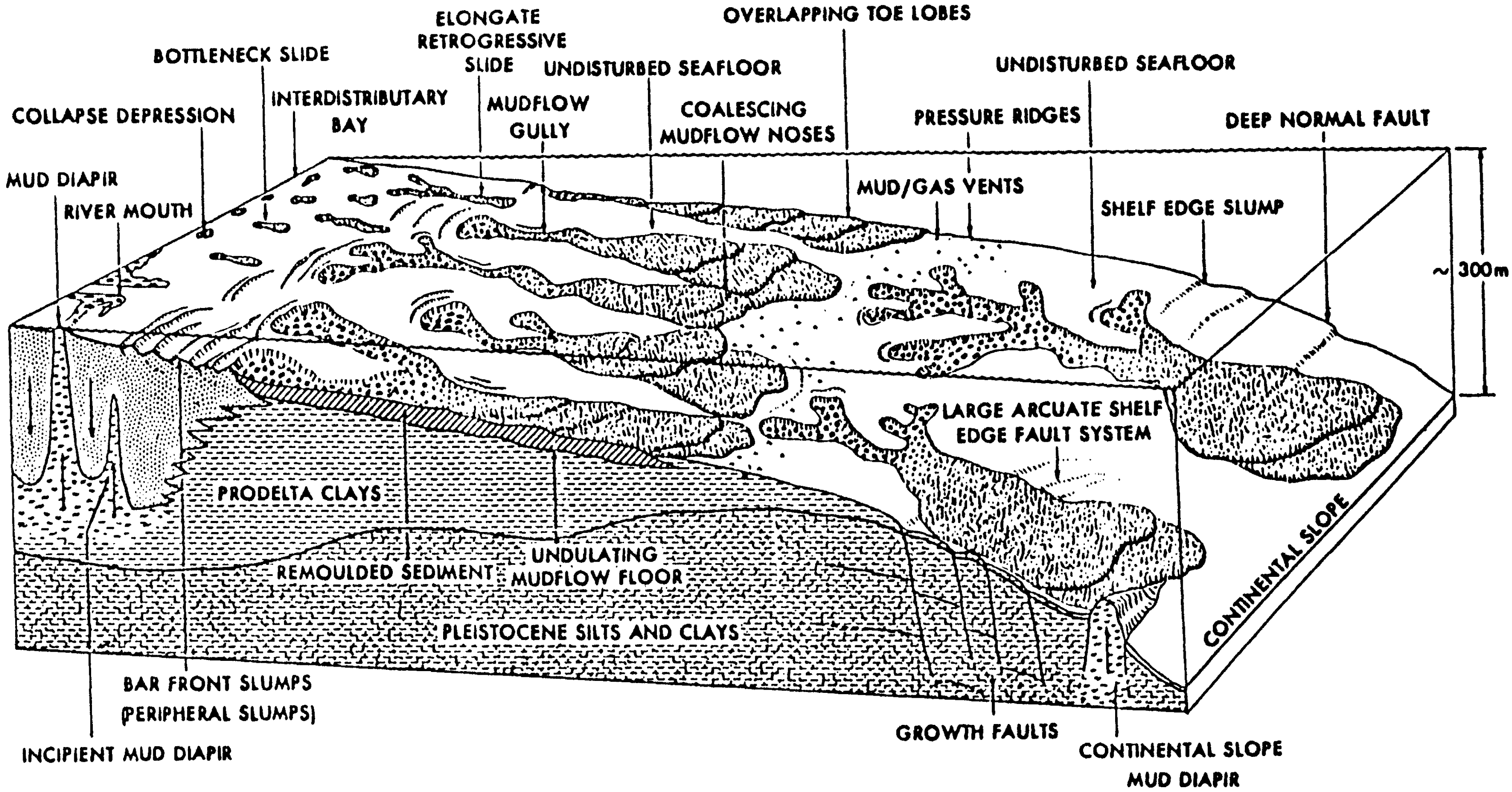

Figure IV-13. Schematic block diagram showing the relationship of the various types of subaqueous sediment instabilities. (From Coleman and others, 1980).

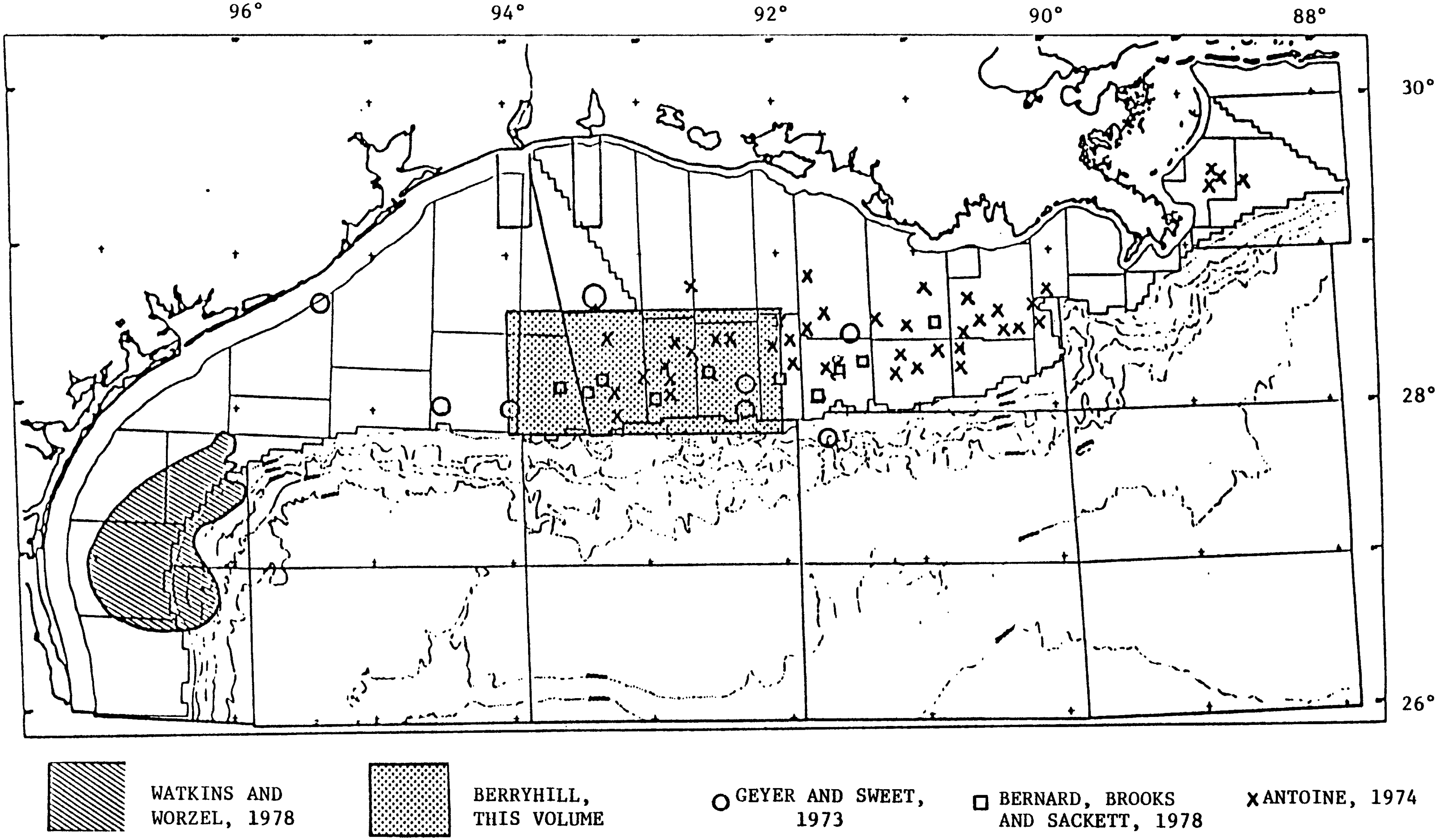

Figure IV-14. Locations of reported gas seeps and shallow gas accumulations, northwest Gulf of Mexico.

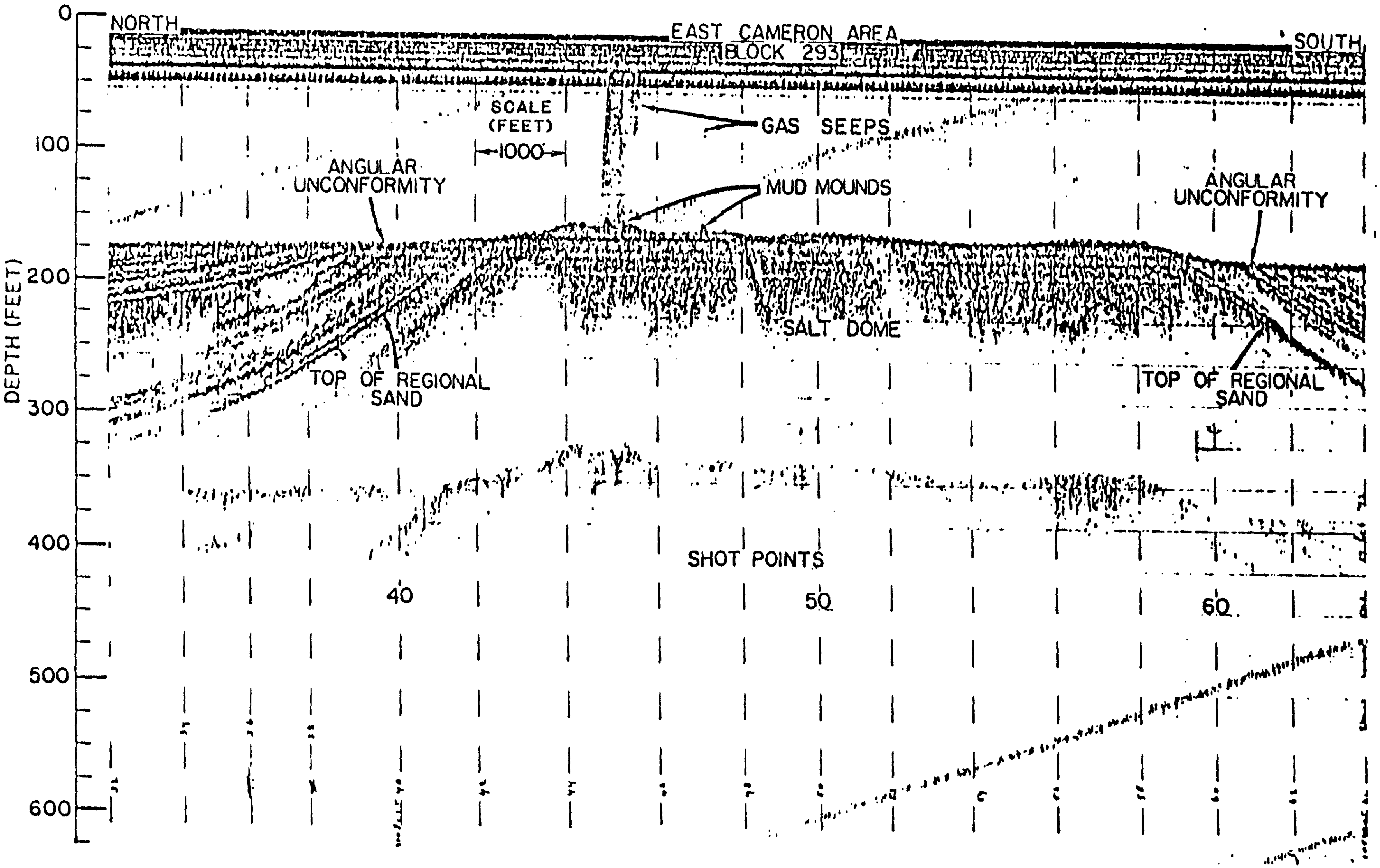

Figure IV-15. Gas seeps around a salt dome, East Cameron Blk. 293. 3.5 kHz profile from Roemer and Bryant (1977).

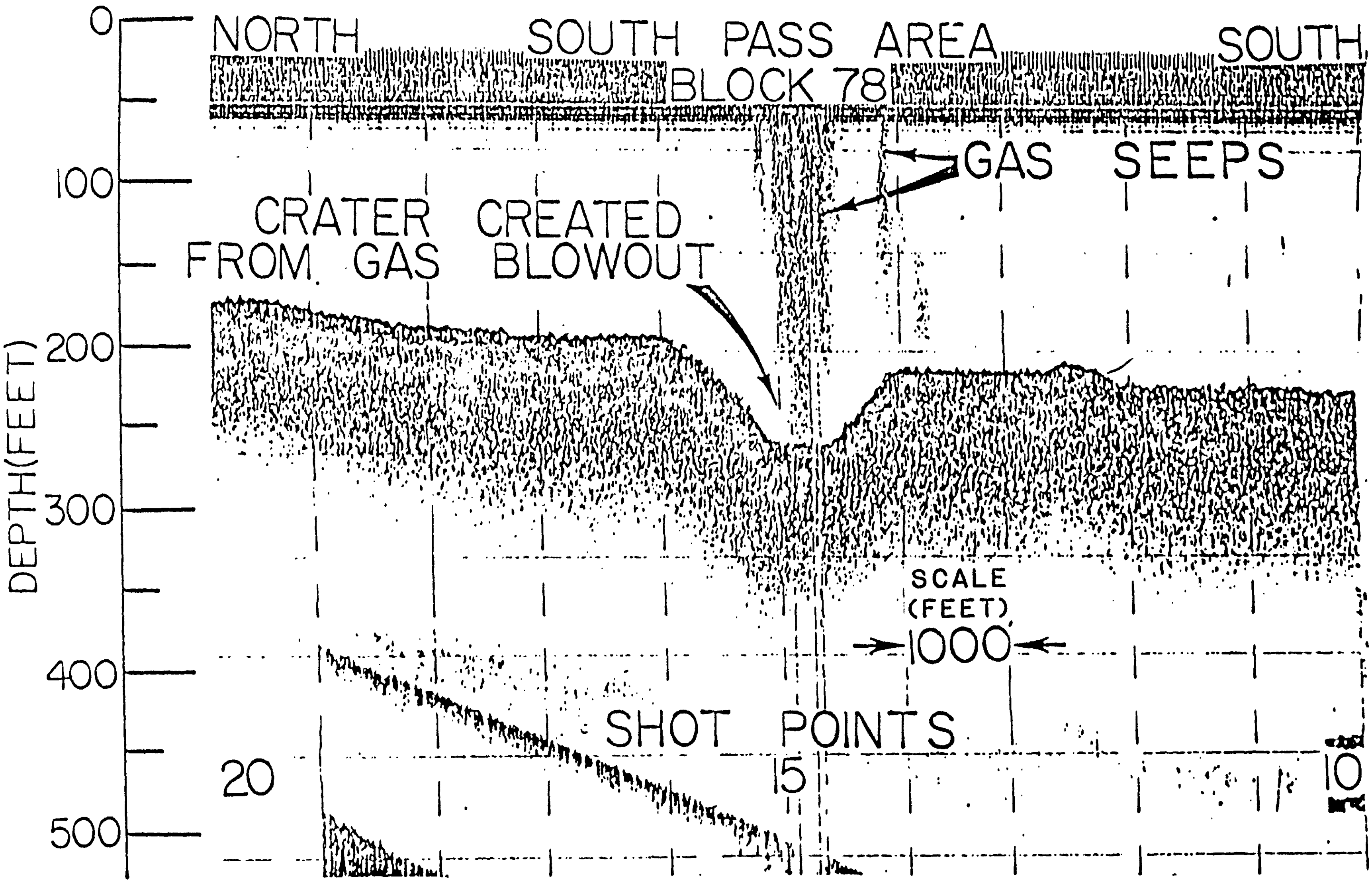

Figure IV-16. Blow-out crater, South Pass Block 78. 3.5 kHz profile from Roemer and Bryant (1977).

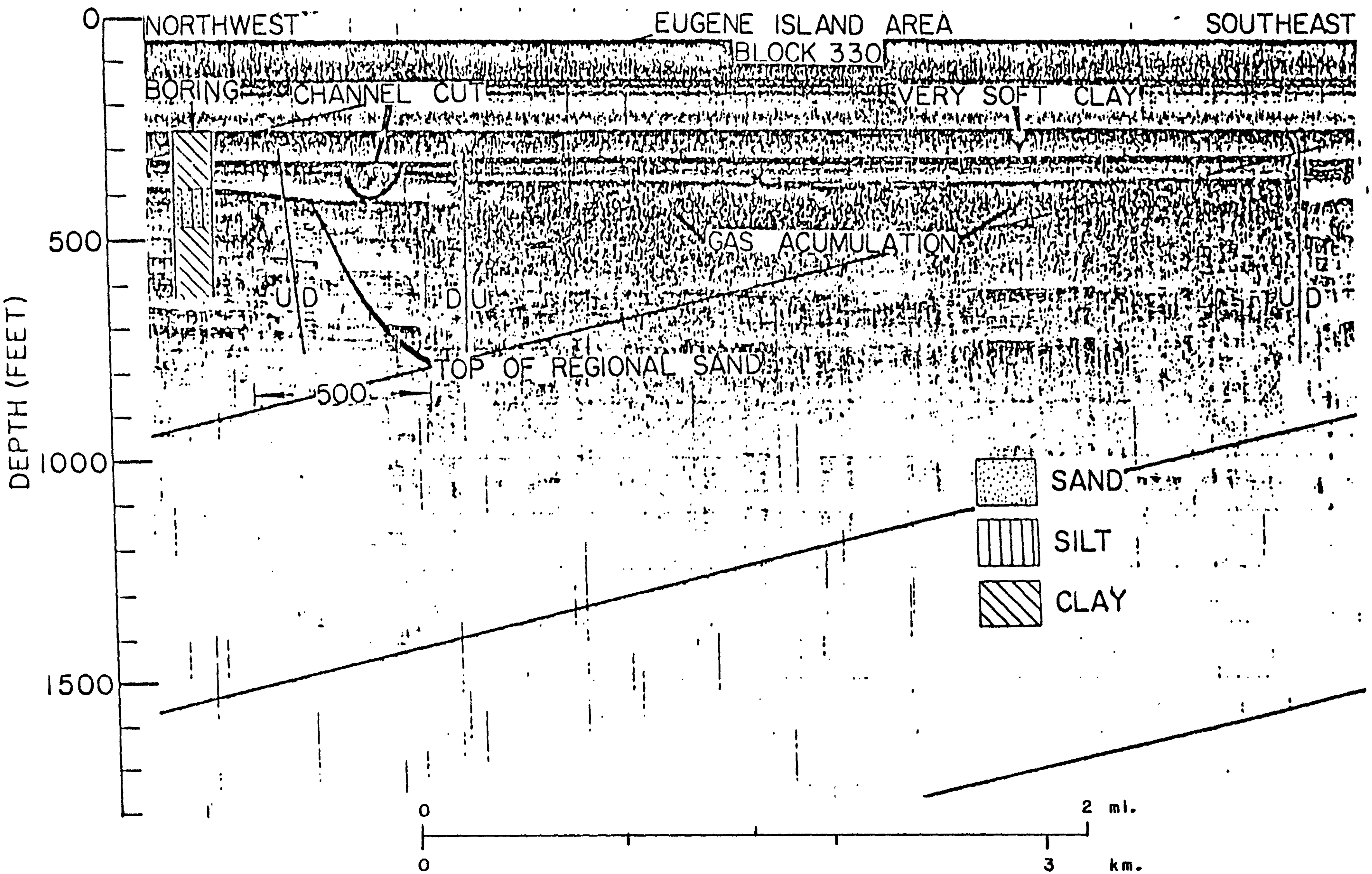

Figure IV-17. Accumulation of gas in shallow sediments. Air gun profile from Roemer and Bryant (1977).

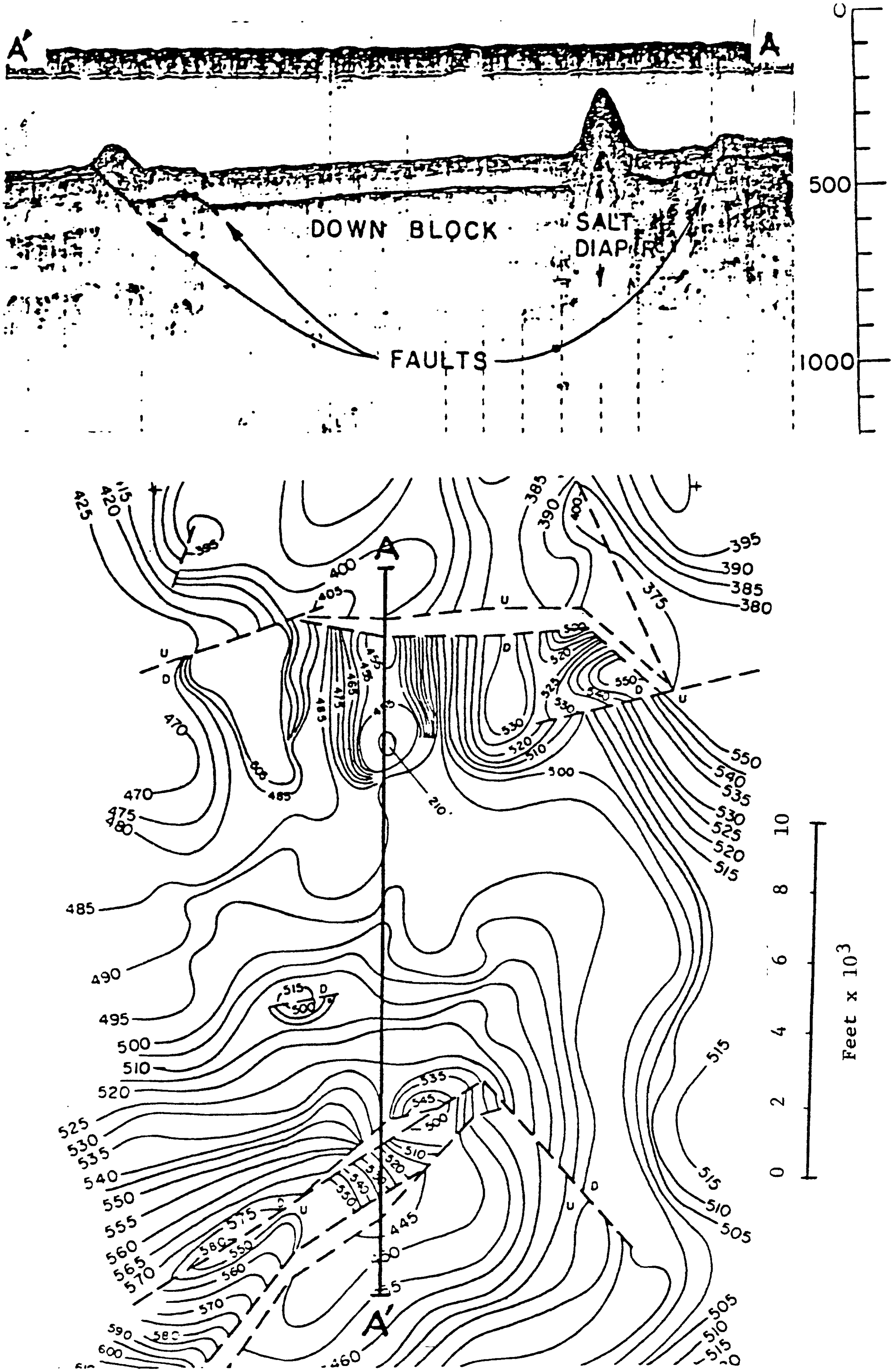

Figure IV-18. Shallow faulting around diapiric structure. Contours are in feet, interval between water surface and seismic marker in subsurface (From Antoine, 1974).

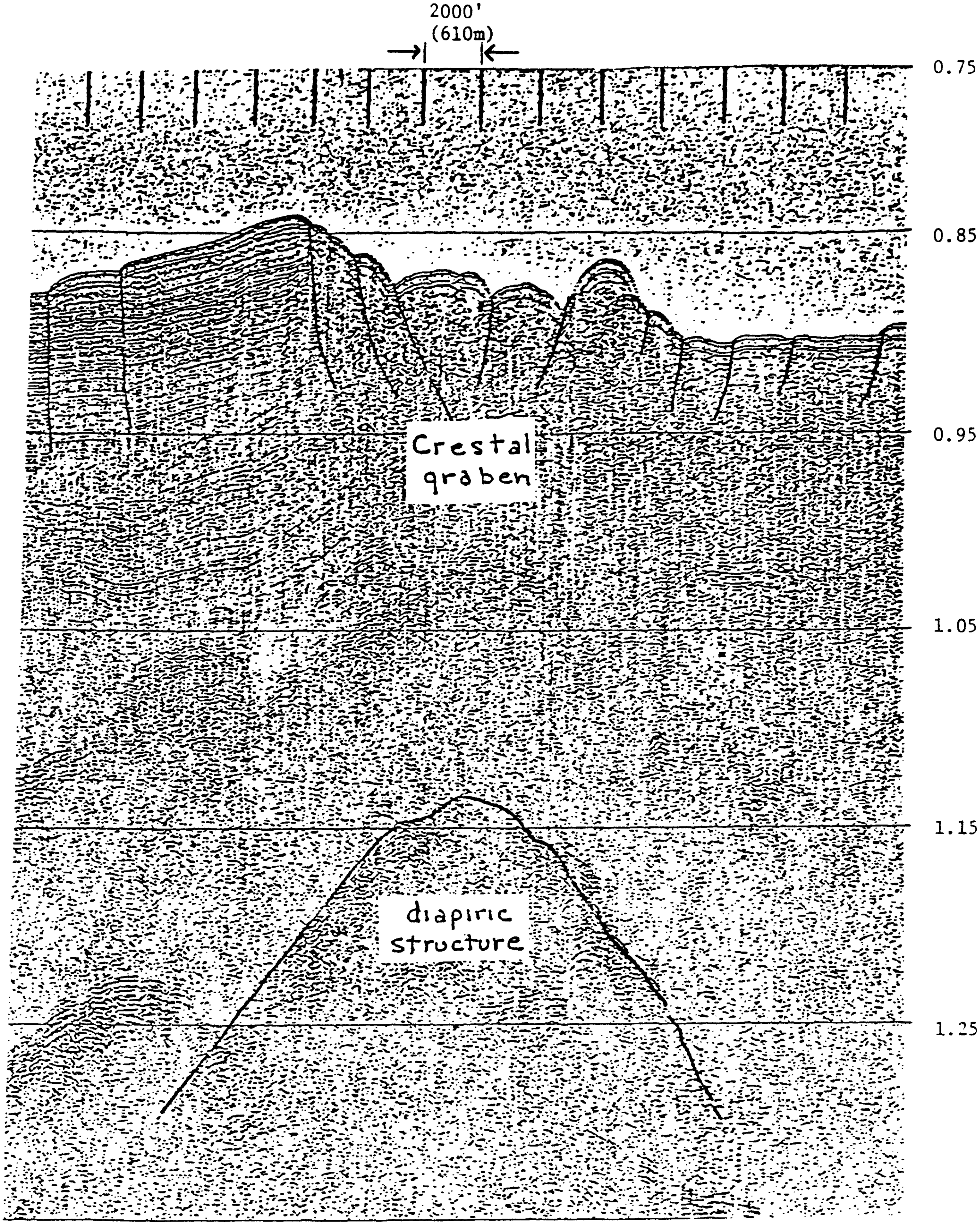

Figure IV-19. Collapse faulting over diapiric structure.

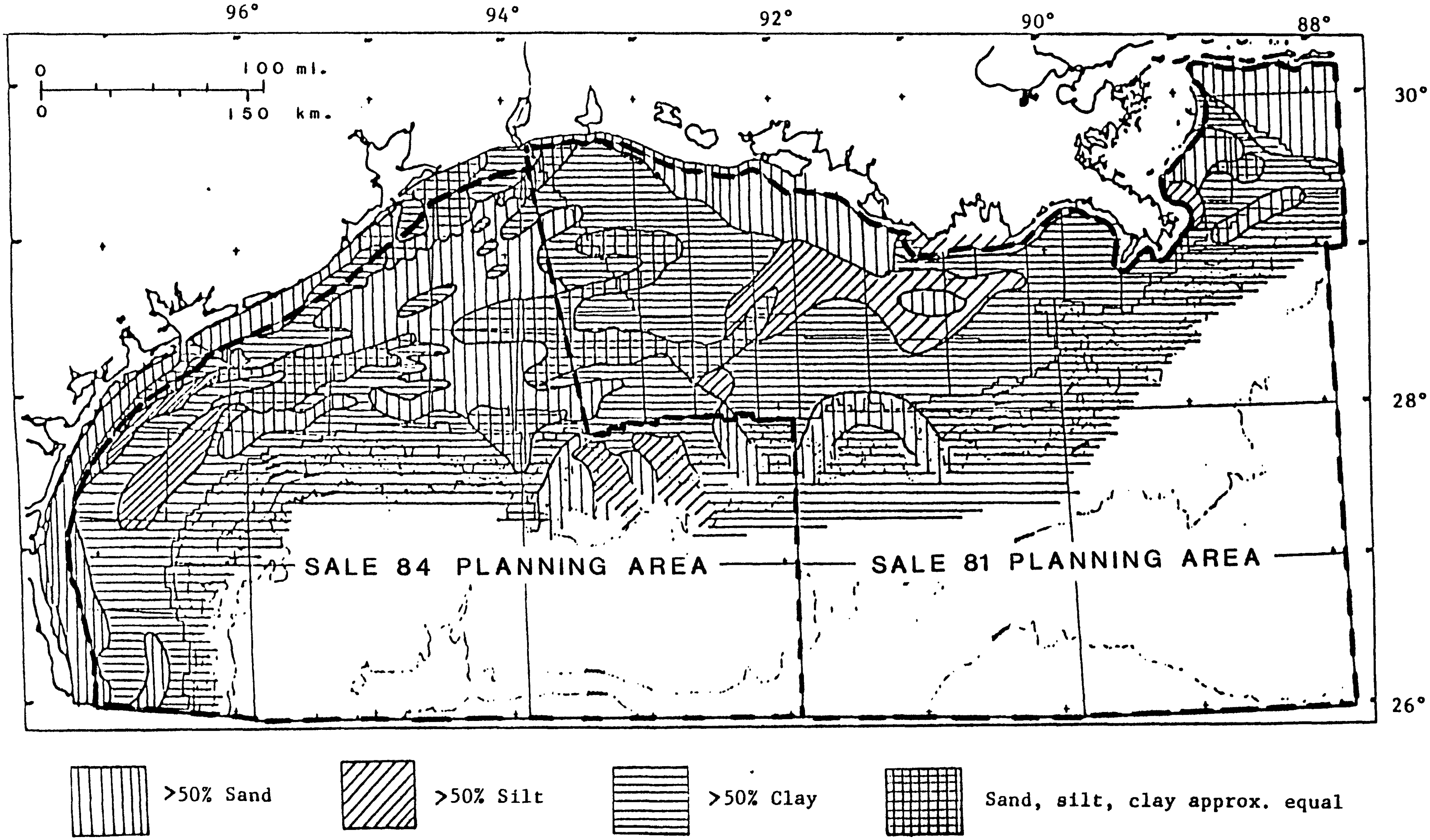

Figure IV-20. Textural distribution of surface sediments. (Adapted from BLM, New Orleans OCS Office, Visual No. 3).

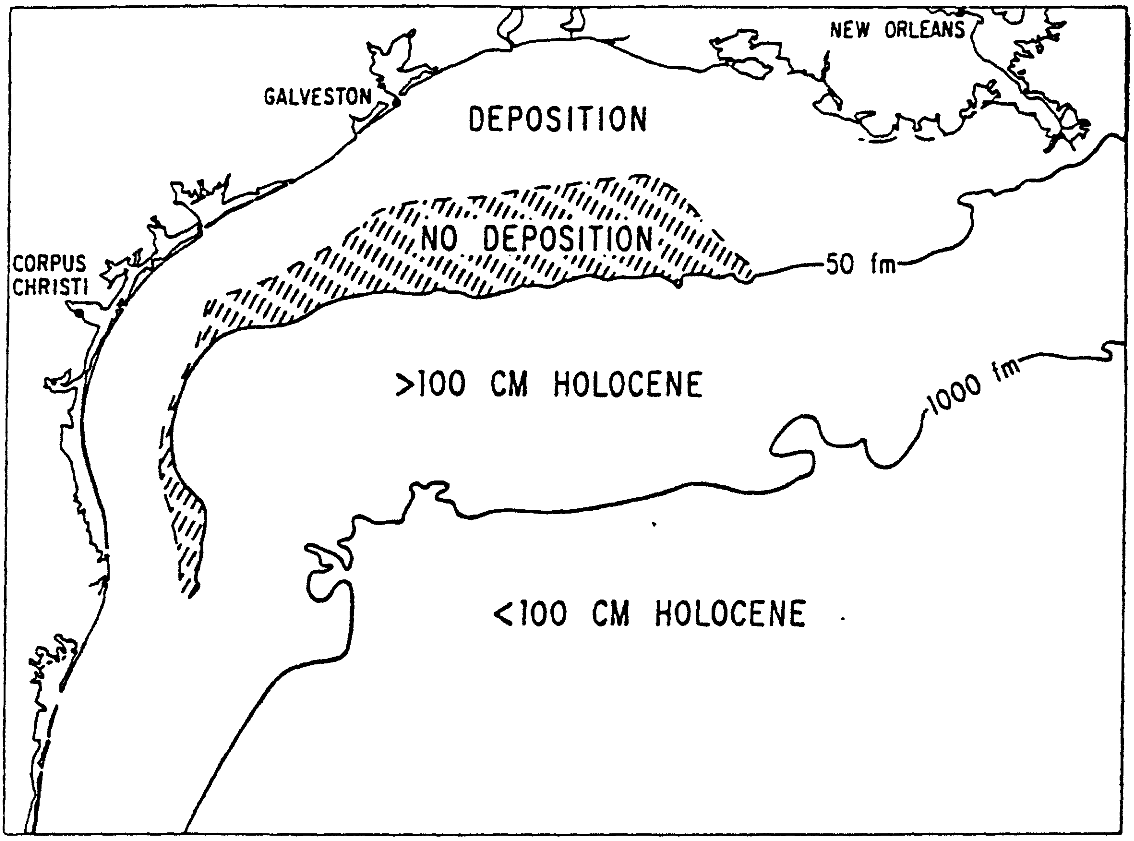

Figure IV-21. Holocene deposition in the northwestern Gulf of Mexico (after Phleger, 1967).

CHAPTER V

UNCONVENTIONAL ENERGY RESOURCES: OCS LEASE SALES 81 and 84 PLANNING AREAS

by

R. Q. Foote, L. M. Massingill and R. H. Wells

GEOPRESSURED-GEOTHERMAL ENERGY RESOURCES

Some Tertiary strata in the northwestern Gulf of Mexico basin 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, 1969). 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.

Studies of geopressured-geothermal energy resources have been under Government energy agency sponsorship since 1975. Since its inception, the program has focused on geologic (resource) assessment studies in the Gulf Coast and, more recently, on test wells. The objectives of the program are to determine if the resource has potential, now or in the future, as an economic, reliable, and environmentally acceptable energy source. The results of the geologic studies since the start of the program have been to reduce the potential of recoverable resources with each succeeding estimate, but conservative estimates are still large, as will be discussed in a later section. The well program is used to identify sites with promising reservoirs and to test these reservoirs by drilling design wells or using wells of opportunity. Ten wells of opportunity and four design wells had been tested or were being drilled in 1981. Westhusing (1981) reported that there were insufficient data to access the resource, but the volumes of gases and the heat, pressures, and deliverable volumes of fluids from the aquifers have not been as high as desired or estimated. Additional long term flow tests of wells dispersed over the favorable resource areas are needed to continue the resource appraisal (Westhusing, 1981).

Dissolved methane is the only important source of geopressured-geothermal energy available in the offshore area. Problems associated with transmission to shore of electrical power and the limited requirement for the use of the electrical power or the limited direct heat applications at offshore installations generated from the thermal and hydraulic energy of geopressured-geothermal water restricts the potential use of these resources. However, conventional oil and gas production installations (platforms) and natural gas pipelines for transmission to shore are in place in most of these areas and the extraction of dissolved methane from water bearing geopressured (and normally pressured) sandstone reservoirs might be a technically and economically viable alternative to well-plugging and platform removal when the conventional reservoirs are depleted (Wallace, 1979a).

Geology of Geopressured Zones

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). These wedges of sediments are characterized in the chapter on Petroleum Geology as 1) massive sandstone in which sandstones equal or exceed 40 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. During burial, each of these sequences contained water from the depositional environment (continental, estuarine, or marine) which was trapped between the mineral grains. Water was expelled from the sediments as the porosity was reduced during further burial and compaction processes. As the sediment overburden increased, more water was squeezed out, and the volume of sediments was reduced even more. Pressure on the retained waters from the sedimentary overburden increased until normal hydrostatic pressure was significantly exceeded and geopressure existed. 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, therefore, support a part of the weight of the overlying sediments.

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 (Dickinson, 1953). Wallace and others (1979a,b) 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 retained locally in massive sandstone facies.

Fluid pressures higher than normal are more commonly associated with alternating sandstone and shale facies than with massive shale facies (Bebout and others, 1975). Fluid pressure in alternating sand and shale facies may be high because expulsion of fluids is restricted or retarded by relatively impermeable barriers, particularly growth faults. 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, 1979a). He has 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 zones for the Texas and Louisiana Gulf Coastal Plain and Continental Shelf areas has been published by Wallace and others (1979b, Map No. 3) as part of the Geothermal Research Program, U.S. Geological Survey. As a general rule, the top of the geopressured zone becomes shallower and occurs in progressively younger rocks in a seaward direction.

Trends and Prospects

Onshore

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, 1969). 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. V-1). 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 (1975); Bebout and others (1976); Loucks and others (1977); Bebout and others (1978); and Loucks (1979).

Studies of the geopressured-geothermal resource potential onshore Louisiana include the lower Tertiary strata on the Coastal Plain and the deep Cretaceous strata extending generally east-west across the central part of the state. In one of the original studies of Tertiary strata on the Louisiana Coastal Plain, sixty-three potential areas of interest were identified (Bernard, 1977). A northwest-southeast trend of high energy content across central Louisiana coincides with the location of the deep Tuscaloosa gas trend described earlier in the chapter on Petroleum Geology. The Louisiana Department of Natural Resources has studied the geopressured-geothermal resource potential of the Tuscaloosa Formation in the False River Field, Louisiana (Bland, 1979). Their tests of the formation waters confirmed the theoretical amount of methane, approximately 100 cubic feet per barrel of water, predicted for the formation temperature and pressures.

Offshore

A preliminary investigation of the high energy content areas occurring on the continental shelf of the Gulf of Mexico has resulted in the designation of five prospective areas (Wallace and others, 1979a); they note that other prospects probably exist. Their prospective areas are: Brazos South-Mustang Island East Prospect and Brazos Prospect offshore Texas; Cameron Prospect, Eugene Island Prospect, and South Timbalier Prospect, offshore Louisiana (Fig. V-I).

The South Timbalier Prospect extends over an area of about 460 mi^2 (1191 km^2). More than 1300 net ft (396 net m) of sandstone has been penetrated in the depth interval between the occurrence of geopressure and 17,000 ft (5182 m) in the deepest well in this area. Geopressured reservoirs have pressure gradients ranging from 0.65 to 0.86 psi/ft (14.7 to 19.4 kPa/m), temperatures ranging from 200°F (94°C) to 291°F (144°C), and salinities ranging from 43,200 to an average high of 183,400 mg/L dissolved solids NaCl. Maximum mud weights of 17.1 pounds per gallon (ppg) have been used to drill the geopressured formations, indicating the presence of fluid-pressure gradients up to about 0.88 psi/ft (19.9 kPa/m). The maximum observed BHT measurement recorded on a well-log heading was 279°F (137°C), corresponding to a corrected formation temperature of 303°F (151°C).

The Eugene Island Prospect encompasses an estimated 200 mi^2 (518 km^2) area of potential interest. Geopressured reservoirs are characterized by pressure gradients of 0.6 to 0.9 psi/ft (13.5 to 20.4 kPa/m), temperatures ranging from less than 248°F (120°C) to 298°F (148°C), and salinities as dissolved solids NaCl ranging from 61,300 to an average high of 156,111 mg/L. Maximum mud weights of 17.7 ppg were used in drilling through 750 net ft (229 net m) or more of geopressured sandstone which usually occurs at a depth of about 12,500 ft (3310 m). A maximum recorded BHT of 277°F (136°C), 304°F (151°C) corrected, was measured.

The Cameron Prospect occupies parts of High Island and High Island East Addition Areas, offshore Texas, and West Cameron, East Cameron, and Vermillion Areas, offshore Louisiana. About 1900 mi^2 (4921 km^2) are included in the area which is an offshore continuation of a well-developed onshore geopressured sandstone trend. More than 1100 net ft (335 net m) of sandstone is commonly penetrated in this area; the highest temperatrue recorded was 320°F (160°C), or 344°F (173°C) corrected. The depth to the top of the geopressured zone varies from less than 10,000 ft (3048 m) to more than 14,000 ft (4267 m). Mud weights range to 18.3 ppg which is equivalent to a fluid-pressure gradient of more than 0.9 psi/ft (20.4 kPa/m. Fluid pressure gradients range from about 0.54 (12.2 kPa/m) to more than 0.9 psi/ft (20.4 kPa/m), temperatures range from less than 248°F (120°C) to 344°F (173°C), and salinities as dissolved solids NaCl range from 38,800 to 99,500 mg/L.

The Brazos Area appears to be limited to a 140 mi^2 (363 km^2) area of maximum sandstone development; sandstone sequences attain a net thickness of 750 ft (229 m). The top of the geopressured zone is encountered at a depth of between 7500 and 8500 ft (2286 and 2591 m). Temperatures vary from less than 248°F (128°C) to 281°F (138°C), salinities vary from an average of 81,636 to an average of 142,331 mg/L, and mud weights ranged from 13.8 to 16.6 ppg.

The Brazos South-Mustang Island East Area has more than 2000 net ft (610 net m) of geopressured sandstone in parts of an area of approximately 200 mi^2 (518 km^2). The extent of this area is not well defined because of insufficent well control. The depth to the top of the geopressured zone is relatively shallow occurring at less than 5000 ft (1525 m), but also as deep as 11,000 ft (3658 m). Temperatures range from less than 212°F (100°C) at shallow depths to 305°F (152°C) at 12,000 to 13,000 ft (3658 to 3962 m). Mud weights range from 10.7 ppg to 18.1 ppg. Salinities in the geopressured reservoirs, as dissolved solids NaCl, range from an average low of 29,900 mg/L to an average high of 127,800 mg/L.

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. The prospective area does not extend to the mid-shelf area because interpretations of seismic data and well logs by Khan and others (1975a,b) suggest that the thickness and lateral extent of sandstones will not meet the minimum requirements for geopressured-geothermal prospects in the vicinity of the COST wells (Fig. II-I).

Sands favorable for geopressured-geothermal prospects could possibly have been deposited in Miocene, Pliocene, and Pleistocene ages on the outer shelf and slope. These 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 in the lower continental slope, rise, and abyssal Gulf. However, the samples and cores are from shallow depths, and geopressured zones may be present in deeper strata. Certainly, the deeper water parts of the OCS Lease Sales 81 and 84 Planning Areas with buried massive shale facies must be considered as possible geopressured zones.

Summary

Estimates of the geopressure-geothermal energy contained in pore waters in the northern Gulf of Mexico basin were reported by Wallace and others (1979b). His estimates are for the accessible fluid resource base which is the energy in geopressured water reachable by production drilling without regard to the amount recoverable or the cost of recovery. Dissolved methane is equal to 5700 trillion cubic feet which represents 35 percent of the estimated thermal and thermal-equivalent geopressured-geothermal energy contained in the water of sandstones to a depth of 22,500 ft (6.86 km) in the basin. Of this dissolved methane, 32 percent (1824 trillion cubic feet) is estimated to occur in Texas, 22 percent (1254 trillion cubic feet) in Louisiana and 46 percent (2622 trillion cubic feet) beneath the Federal OCS area. The Louisiana Shelf has 65 percent (1704.3 trillion cubic feet) and the Texas Shelf has 35 percent (917.7 trillion cubic feet) of the dissolved methane estimated to be in Federal waters.

Five areas of high energy concentration are located on the Texas-Louisiana Shelf. A map published by Wallace and others (1979b, Map 3) shows variations in concentration of dissolved methane, but not all areas of high concentration are expected to become development prospects when examined on a detailed site-specific basis.

Similar estimates for the continental slope and rise areas of OCS Lease Sale 81 and 84 Planning Areas have not been prepared because geological, hydrogeological, and other critical data to complete a resource appraisal have not been assimilated and interpreted.

The technical and economic viability of producing water for methane extraction upon depletion of conventional oil and gas reservoirs may warrant consideration in the future.

UNCONVENTIONAL GAS RESOURCES: GAS FROM GAS/WATER

Natural gas is a mixture of hydrocarbons occurring as: (1) a "gas cap" in contact with oil above an oil deposit which is, in turn, in contact with and above formation waters within a reservoir; (2) gas dissolved in solution with the crude oil within a reservoir (associated gas); or, (3) as dry gas that is not associated with or in contact with crude oil in a reservoir. On the other hand, unconventional gas (which is mostly methane) is found: (1) dissolved in formation waters (solution gas); (2) dispersed as mobile-immobile free-gas in reservoirs, and (3) concentrated as mobile free-gas in non-commercial quantities. Unconventional gas is present in hydropressured and geopressured reservoirs in all sedimentary basins producing conventional petroleum. The Gulf Coast basin probably has the largest concentration of unconventional gas resources in the United States. Because of the widespread occurrences and the expected size of these deposits, unconventional gas resources are an asset for the Nation. The economic value of the gas resources is, however, highly dependent upon the degree of concentration, the reliability with which this can be predicted, commodity prices, and other factors.

Unconventional gas from brines (solution gas) is not yet ready for widespread commercial extraction. There are individual reservoirs, however, which are already producing, as described later. Also, there are a limited number of watered-out reservoirs that are producing gas in commercial quantities. As more information becomes available, it should become more evident as to what role, if any, unconventional gas resources will play in the transition of the Nation from conventional oil and gas to other energy resources.

The different types of occurrences of unconditional gas are:

1. Solution gas in reservoir waters. The dissolved gas content of formation waters increases with increased temperature and pressure and decreased salinity. After reservoir pressure has been reduced below the saturation pressure, gas will evolve from solution throughout the reservoir. If gas saturation has increased to the point where it can flow (equilibrium saturation has been reached), free-gas will then begin to flow toward the well-bore.
2. Free-gas (and dissolved gas) in watered-out reservoirs. In some water drive reservoirs in the Gulf Coast basin, the hydrocarbon/water interface rises faster around the well-bore as fluids are produced, leaving gas trapped elsewhere in the reservoir. Production tests have shown that some of this trapped gas can be mobilized and produced by withdrawing large quantities of formation waters (e.g., the water invaded region is depressured). Approximately one dozen U.S. patents detail methods for extraction of this gas.
3. Reservoirs with mobile free gas in non-commercial quantities. Mobile gas which is present in non-commercial quantities in stringer (i.e. thin) sandstones near aquifers is defined as unconventional gas. Geopressured or hydropressured reservoirs containing water with dissolved gas and associated with a non-commercial origin stringer gas sand may be a prospective target for production tests.

Industry Activities

Several major oil and gas companies have, or are conducting, research and production test programs on unconventional gas from gas/water and water systems in the Gulf Coast. The nature, locations and extent of this work is known only where the companies have released information to the public. A summary of some of the industry efforts is provided below.

Exxon Company U.S.A. has three offshore wells (one in Grand Isle Block 16 and two in West Delta Block 73) that yield methane from waters in hydropressured reservoirs that is produced for injection into deeper conventional oil reservoirs as part of a water-flood program (Winsauer, 1979). The aquifers are sands at a depth of about 4950 ft which produce waters at or near saturation (10-15 scf/Bbl of water at 135°F, sodium chloride concentrations of 100,000 ppm, and bottom-hole pressure of 2000 psi). The produced methane is sold to a pipeline company and provides sufficient revenue to reduce the water-flood costs to $0.05 per barrel of injected water.

Exxon is producing substantial quantities of gas trapped in watered-out, water-drive gas reservoirs in south Texas (Chesney and others, 1981). Their method in the North Alazan field, Kleberg County, involves pumping large quantities of water from the water-invaded region of a hydropressured reservoir. This causes the reservoir to depressure and release trapped gas (by cusping of the regenerated gas cap around the well bore).

The Gas Research Institute is sponsoring research at the Texas Bureau of Economic Geology and the Louisiana Geological Survey to evaluate Gulf Coast reservoirs containing solution gas, free-gas in thin reservoirs, gas trapped in watered-out reservoirs, and associated aquifer cases (mobile-immobile-solution gas). The objectives of this research are to determine reservoir performance, analyze and predict production, and to approximate the gas-in place modeled systems. The results of these studies should be applicable to preparing future estimates of unconventional gas resources.

Resource Estimates

The Federal Energy Regulatory Commission's Supply-Technical Advisory Task Force on nonconventional natural gas resources dissolved in water produced a report in March 1979 that provides the first estimate of this resource in the Gulf Coast area. The total dissolved methane resource base in the 2,000-19,000 ft depth interval beneath onshore and offshore south Louisiana, including both hydropressured and geopressured sandstone aquifers, is estimated to be 3,264 trillion cubic feet. This figure does not include the resource base beneath the Texas onshore-offshore area, aquifers deeper than 19,000 ft, the amount of dissolved methane in shale waters, gas in non-commercial reservoirs, or gas in watered-out reservoirs. The total resource base for all unconventional gas is very high. However, only a small part of resource base is recoverable with existing technology. Also, commodity prices are too low now for extraction to be profitable, except in special circumstances.

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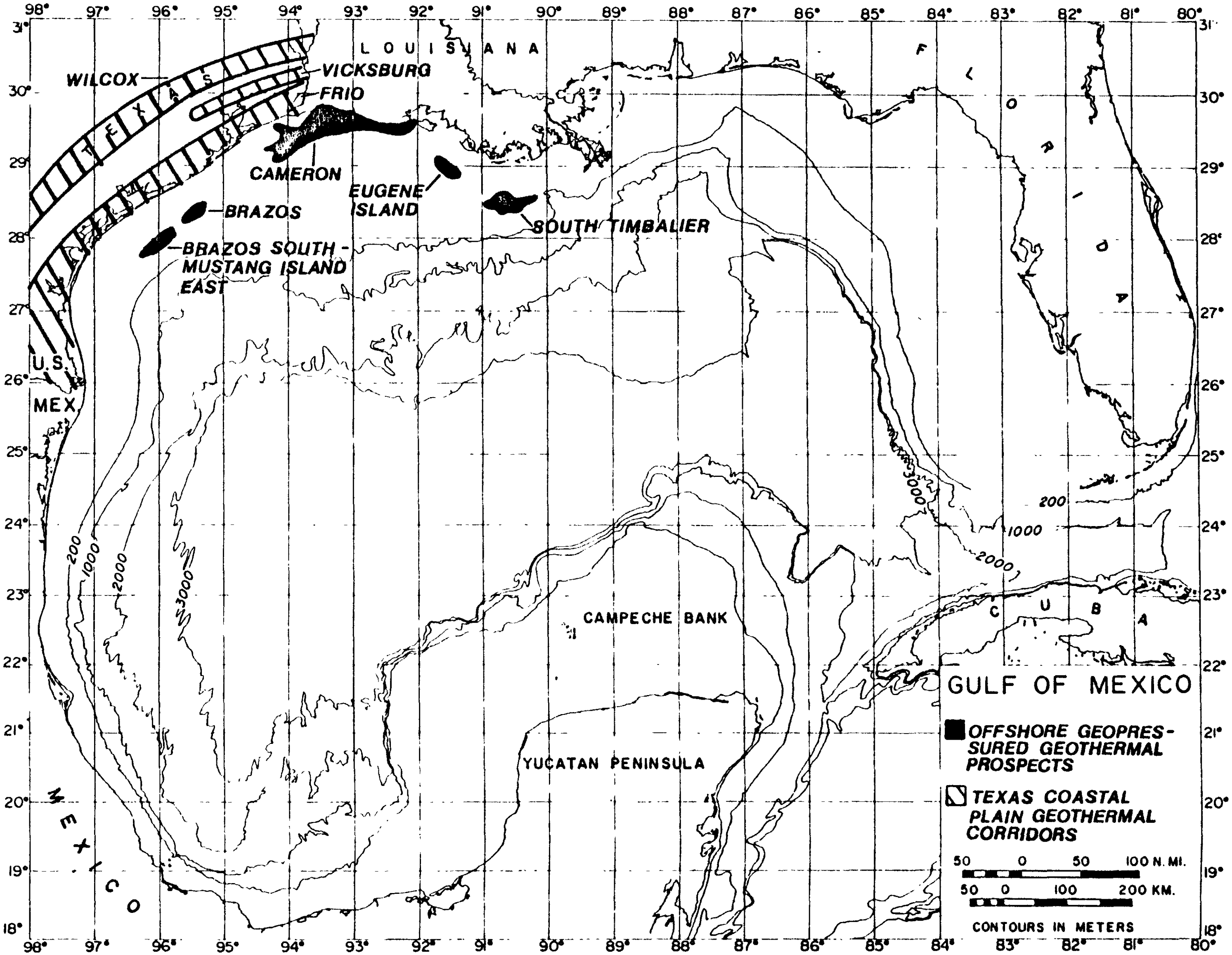

Figure V-1.--Map showing locations of Texas Coastal Plain geothermal corridors and geopressured-geothermal prospects in the continental shelf, northwestern Gulf of Mexico (from Bebout and others, 1978; Wallace, 1979a).

APPENDIX

ENVIRONMENTAL GEOLOGY SUMMARIES

by Henry L. Berryhill, Jr.

INTRODUCTION

Since late 1974, systematic geological studies with emphasis on environmental aspects and geohazards have been conducted in the northwest Gulf of Mexico in cooperation with the Bureau of Land Management. The studies have been done in yearly increments under MOU's between BLM and USGS, Corpus Christi, Texas, and the maps and reports specified have been delivered to the BLM on a yearly basis. Two areas have been studied: the Pleistocene Trend Area off southwest Louisiana, and the south Texas Outer Continental Shelf. The location of the two areas is shown by the index map, Figure A-1.

PLEISTOCENE TREND AREA: SOUTHWEST LOUISIANA SHELF AND SLOPE

Geographically, the area studied is seaward of the shoreline of east Texas and Louisiana. Dimensions are 200 km east-west and 220 km north-south, prescribing a total area of 44,000 km^2 bounded east to west by the 92° and 94° longitude lines and on the south by the 27° north latitude line. The geophysical data used for the geologic synthesis were collected using standard marine surveying techniques which included precision depth recording and high-resolution seismic-reflection profiling. Two types of high-resolution systems were used: 3.5 kHz profiler recorded at 0.24 sec. sweep and 400 joule minisparker recorded at 0.5 sec. sweep. Survey traverses were spaced in a 4.5 x 4.5 km east-west and north-south grid to provide a uniform and evenly spaced net of data over the area. Navigation fixes were taken every 152 m along each traverse. The total amount of profiles used in the study is 22,400 km each of the 3.5 kHz and the minisparker data.

Physiographically, the northern three-fourths of the area is a segment of the continental shelf. The southern fourth is underlain by the upper continental slope where the gradient of the seafloor increases toward the deeper parts of the Gulf. Water depths locally reach 700 m along the southern part of the study area.

Geologically, the regional setting is the submerged continental terrace and includes the main Pleistocene depocenter in the northwest Gulf of Mexico, commonly referred to in petroleum exploration as the "Pleistocene Trend". Thickness of the Pleistocene sequence, as constructed from drill hole data, exceeds 3,500 m (Woodbury and others, 1973). Sea level fluctuations during low stands accompanied by rapid sedimentation along the outer shelf and salt diapirism have caused progradation and structural evolution of the shelf edge and upper slope. The geologic characteristics of the outer shelf and upper slope molded by these processes, in combination with the increase in sea floor gradient at the edge of the shelf, are potentially unstable and must be considered in appraising sites for petroleum production platforms and pipelines. Furthermore, an understanding of the magnitude of these processes and of the shape, size, and stratigraphic relations of the sedimentary bodies deposited is fundamental to deciphering the geologic history of the continental margin. In turn, understanding the geologic history and the spatial relations of the sedimentary units that have undergone progressive structural modification is essential for assessing resource potential.

To provide the type of information needed, the data have been compiled topically to highlight the pertinent geologic features. The topics are: 1) thickness of Holocene sediments; 2) location and depth of buried stream channels; 3) distribution of gas at shallow depth plus location of gas seeps; 4) location of faults and identification of recently active faults;

5) extent of surficial and shallow deformation by sliding, and 6) extent and chronology of deformation caused by diapirism.

Status of Information

Following data collection, interpretation, and compilation, reports have been delivered to the BLM on a yearly basis as Administrative Reports. The list below indicates the scientific reports prepared and delivered since the beginning of the study in 1979.

<u>1980</u>

1. A set of maps at a scale of 1:100,000 compiled on a lease block grid covering the 6 topics listed above plus a bathymetric base. The area covered by the maps is approximately the southern third of the total area and straddles the edge of the continental shelf. Relative to the named series of National Ocean Survey's 1° x 2° bathymetric charts covering the northern Gulf of Mexico, the area covered by the interpretative maps prepared in 1980 is the southern half of the Bouma Bank sheet and the northern half of the Garden Banks sheet. Because of the relatively large scale used, the area was divided into 8 subareas. A total of 48 maps make up the set delivered to the BLM in the summer of 1980. Accompanying the maps was a 100-page interpretative text.
2. Berryhill, H. L., 1980, Ancient Mississippi River Submarine Canyon: Clue to Sedimentary Processes in Shelf Edge Migration, Abstracts with Programs, Geol. Soc. Amer. Annual Mtg., Atlanta, p. 386.
3. Tripett, A. R., 1980, Geology of the East and West Flower Garden Banks: Admin. Rept. to BLM publishd as Special Information Bulletin.
4. Trippet, A. R., 1980. East and West Flower Garden Banks: 3 topical overlay maps transmitted to BLM as Administrative Report.

<u>1981</u>

1. A set of topical maps in Atlas format at a scale of 1:250,000 were delivered to the BLM in May 1981 as an Administrative Report in compliance with the MOU agreement. The maps are being prepared by BLM for release as Open-File Report 82-02 in a set entitled, "Geology of the Continental Shelf Edge and Upper Continental Slope of Southwest Louisiana." The maps, to be printed in color, include a text for each topical sheet plus segments of seismic profiles as examples of salient geologic features pertinent to identifying potential geohazards. In addition to the 6 topical sheets, the set includes a bathymetry map and a seventh sheet entitled, "Geologic Features Expressed Topographically on the Sea Floor." Each map includes the lease block grid. The maps are designed to be used as overlays so that cause and effect relationships will be apparent.
2. A set of preliminary topical maps (7) at a scale of 1:250,000 covering the entire area: the northern half of Bouma Bank, all of the Port Arthur 1° x 2° map; as well as the area completed in 1980, incorporated so that regional relations would be presented on a single map for the entire area. These maps were delivered to BLM in the summer of 1981 as Administrative Reports in preliminary form so that the information would be available for use in the EIS preparation process.
3. Berryhill, H. L., 1981, Ancient Buried Submarine Trough, Northwest Gulf of Mexico: Geo-Marine Letters, v. 1, no. 2, p. 105-110.
4. Trippet, A. R., 1981, Interaction Between Diapirism and Sediment Loading at the Shelf-Slope Boundary, Northwest Gulf of Mexico: Geo-Marine Letters, v. 1, no. 2, p. 111-114.

1982

Work is in the last stage on the final reports for the Pleistocene Trend study. The material will be transmitted to the BLM by September 30, 1982. Included will be sets of topical maps (36) with texts for the Port Arthur, Bouma Bank and Garden Banks 1° x 2° sheets. The maps follow the Atlas format agreed upon by USGS and BLM. In addition to the standard 6 topics specified by the cooperative arrangement, the following supplementary topical sheets have been prepared: 1) up-to-date plot of all producing petroleum fields; 2) shelf-edge features documenting positions of ancient shorelines during late Quaternary low stands of sea level; 3) a structure contour map drawn on the erosional surface that represents the probably early Wisconsinan erosion surface (3 and 4 document rates and extent of post Wisconsin tectonic deformation); and 5) isopach maps of post Wisconsinan sediment thickness to document rates of sedimentation along the shelf edge.

Summary

The mass and detail of information for the Pleistocene Trend area included in the interpretative maps and reports prepared and delivered to the BLM since 1979 by cooperative agreement are not compatible with the format restrictions of this report. The highlights are generalized on the maps shown by Figures A-2 through A-9.

1) Distribution of Holocene Sediments (Fig. A-2) - Unconsolidated Holocene sediments are unevenly distributed and represent three shelf subfacies of deposition: inner shelf fan material of intermixed sand and mud carried westward from the Missisippi River delta complex since sea level reached its present position; shelf edge sediments that represent the early Holocene transgressive; plus overlying sediments that have been carried westward from the Mississippi River by shelf edge currents; and

large sandy patches over the northwestern part of the area that are in part relict and in part reworked fluvial and deltaic sediments. The east-west orientation of these sediments suggests that they accumulated initially along temporary shorelines during the Holocene rise of sea level. The shelf-edge sediments are offset by faults indicating recent shelf-edge movement.

2) Buried Stream Channels (Figs. A-3;A-4) - The two youngest sets of buried stream channels were mapped. The older of the two sets, thought to represent the early Wisconsinan low stand of level, are shown by figure 3; the youngest set thought to represent the late Wisconsinan withdrawal, by Figure 4. Depositional structure and texture are highly variable in sediments filling old stream channels. Commonly, these variations occur over short distances, both laterally and with depth, causing equally abrupt changes in cohesiveness and bearing strength. Also, sediments in buried channels may contain sufficient organic material to generate significant amounts of biogenic gas.

3) Diapirism (Fig. A-5) - Diapiric structures dominate the shelf edge and continental slope. No data exist for estimating rates and frequency of diapiric movement. Empirical evidence based on the stratigraphy and relative configuration of up-turned strata around the diapirs indicates local uplift of as much as 145 m during and since the late Pleistocene. The numerous fault scarps on and around the diapiric hills plus local displacement of erosional terraces strongly indicate relatively recent movement.

4) Active faults (Fig. A-6) - Faulting has been extensive and reflects both diapirism and adjustments to sediment loading as predominant structural stresses along the shelf edge and beyond. Most of the faults either reach the sea floor or terminate just below it. Scarps along some of

the faults document relatively recent movement; offset of the youngest sediments confirms that gravity and tectonic adjustments within the submerged continental margin are a continuing process. The chronology of fault movement revealed by the acoustical profiles shows progressively greater offset of reflectors at depth along most of the faults, indicating repeated movement over a substantial period of time.

5) Surficial and Shallow Deformation (Figs. A-7;A-8) - Surficial slides recorded on the profiles are restricted and are confined to the shelf edge and upper slope. The slides which indicate movment of relatively thin layers of sediment along the sea floor are located either on the brow of late Pleistocene deltas or on the flanks of diapiric hills. Buried slides are extensive and make up a significant amount of the ancient shelf edge deltas. Surface deformation such as shallow compressional folding, tensional faulting and sea-floor collapse is most common on and around diapiric structures.

6) Gas at Shallow Depth (Fig. A-9) - The acoustical response of the sediments suggests that gas of probable biogenic origin is widely distributed. The gas is associated most commonly with buried stream channels, buried ancient estuarine and bay deposits and with the faulted diapiric structures, but is not confined to these features.

Natural gas seeps are numerous (Fig. A-9). Evidence of seepage was recorded on the seismic profiles as plumes in the water and as mud mounds on the sea floor; 305 seeps were recorded, mainly on the outer shelf and along the shelf edge and upper slope where ancient deltaic sediments are extensive. Seepage of gas around some of the diapiric structures and along several of the larger faults may be of thermogenic origin.

Amounts of gas are not known, but site-specific studies should be made where shallow gas is indicated.

SOUTH TEXAS OUTER CONTINENTAL SHELF

The field studies for the work off South Texas began in October 1974. Results of the studies were reported to the BLM as a series of reports delivered on a yearly basis. The last year of operation on STOCS was FY 1978 and the final product was a series of 1:250,000 scale topical atlas maps prepared in three sets: Port Isabel, Corpus Christi, and Beeville. The total of 18 maps in the three sets were published by USGS in the Miscellaneous Investigations Map Series and released in 1980/81. Topics included in each atlas set were: 1) Water Circulation and Rates of Sedimentation; 2) Nature of Shallow Subsurface Sediments and Biogeology; 3) Post-Wisconsinan Sedimentation Patterns and Faulting; 4) Trace-Metal Content and Texture of Surficial Bottom Sediments; 5) Paleogeography of the Shelf During the Wisconsinan Low Stand of Sea Level; and 6) Structure of the Continental Terrace (faults, diapirs, slides).

A listing of the maps and reports generated by the environmental studies off south Texas follows. Except for item no. 57 published in 1982, the reports listed were submitted to the BLM in the period 1976-1981 for use in the petroleum leasing program in the northwest Gulf of Mexico. No additional data have been collected on the South Texas OCS since 1978.

Gulf of Mexico, Environmental Geology/Geohazards Project
South Texas Outer Continental Shelf, 1975-1980:
A listing of reports generated

1. Berryhill, H. L., Jr., and others (4), 1976, Environmental studies South Texas Outer Continental Shelf, 1975: geology: NTIS Pub. no. PB 251-341, 353 p., 116 figs.

2. Berryhill, H. L., Jr., Holmes, C. W., and Martin, R. E., 1976, (abs.) Distribution and thickness of the Holocene sequence, South Texas OCS: Geol. Soc. Amer., South-Central Sec. Program (Houston).

3. Berryhill, H. L., Jr., Holmes, C. W., and Martin, R. E., 1976, (abs.) Late Pleistocene and Holocene evolution of the South Texas OCS: Amer. Assoc. Pet. Geologist, New Orleans: AAPG Bull. v. 60, no. 4. p. 649.

4. Berryhill, H. L., Jr., 1976, Marine Geology, South Texas Outer Continental Shelf: a process approach: Proceedings volume, Oceans '76, Marine Tech. Soc., Sept., 9 p., 3 figs. (18D-1 - 18D-9).

5. Berryhill, H. L., Jr., 1977, Environmental Studies, South Texas Outer Continental Shelf, 1975: Atlas and integrated Summary: prepared for release by the BLM, 301 p., 117 figs., 14 tables.

6. Berryhill, H. L., Jr., 1977, Integrated Environmental Studies, South Texas Outer Continental Shelf: Proceedings vol., Offshore Tech. Conference, Houston, May, 11 p., 3 figs., 2 tables. (Paper no. 2754).

7. Berryhill, H. L., Jr., and others (4), 1977, Environmental Studies, South Texas Outer Continental Shelf, 1976: Geology: Formal report to the BLM for release by NTIS. Approved by Director for release by NTIS.

8. Berryhill, H. L., Jr. with Shideler, G. L., 1977, Maps showing sea-floor sediment texture on the South Texas inner shelf, Corpus Christi Bay to Baffin Bay: U.S. Geol. Survey Miscell. Field Studies Map, MF-901.

9. Berryhill, H. L., Jr., Holmes, C. W., McGowen, J. H., and Morton, R. A., 1978, Marine Geologic Studies, Texas Coastal Zone: Proceedings Volume, Coastal Zone '78 Conference, San Francisco, March 1978, 16 p., 6 figs.

10. Berryhill, H. L., Jr., 1978, South Texas Continental Shelf and Continental Slope: Late Pleistocene/Holocene evolution and sea-floor stability (an outline and notes relative to geologic hazards on the sea floor) <u>in</u> Bouma, Berryhill, Warme, Coleman, Sangrey, Walker, and Suhayda, <u>Offshore Geologic Hazards</u>, Short Course given at Rice University, May, 1978.

11. Berryhill, H. L. Jr., 1978, Origin of discrete sand layers and mobility of sea floor-sediments, in Berryhill and others, 1978, Environmental Studies, South Texas OCS- 1977: Geology, p. 145-169 (for release by NTIS).

12. Berryhill, H. L. Jr., 1980, Environmental Geology of continental margin off central and south Texas in Atlas Format (abs.): Technical Program Summaries and Abstracts, American Association Petroleum Geologists, annual meeting, Houston, Texas, April 1-4 1979.

13. Berryhill, H. L., Jr., 1980, Post Wisconsin sedimentation patterns and tectonism: topical map in Berryhill and Trippet, eds. and compilers, Offshore Environmental Geology Atlas of the Port Isabel 2° Sheet, Texas (1:250,000); 7 topical maps. In press.

14. Berryhill, H. L., Jr., 1980, Paleogeography of the Continental Shelf during the low stand of sea level, Wisconsin Glacial Epoch: topical map in Berryhill and Trippet, eds. and compilers, Offshore Environmental Geology Atlas of the Port Isabel 2° Sheet, Texas (1:250,000); 7 topical maps. In press.

15. Berryhill, H. L., Jr., 1980, Structure of the Continental Terrace: topical map in Berryhill and Trippet, eds. and compilers, Offshore Environmental Geology Atlas, Port Isabel 2° Sheet, Texas (1:250,000); 7 topical maps.

16. Berryhill, H. L., Jr., 1980, Post Wisconsin sedimentation patterns and tectonism: topical map in Berryhill and Trippet, eds. and compilers, Offshore Environmental Geology Atlas of the Corpus Christi 2° Sheet, Texas (1:250,000); 7 topical maps. In press.

17. Berryhill, H. L. Jr., 1980, Paleogeography of the Continental Shelf during the low stand of sea level, Wisconsin Glacial Epoch: topical map in Berryhill and Trippet, eds. and compilers, Offshore Environmental Geology Atlas of the Corpus Christi 2° Sheet, Texas (1:250,000: 7 topical maps. In press.

18. Berryhill, H. L., Jr., 1980, Structure of the Continental Terrace: topical map in Berryhill and Trippet, eds. and compilers, Offshore Environmental Geology Atlas of the Corpus Christi 2° Sheet, Texas (1:250,000); 7 topical maps. In press.

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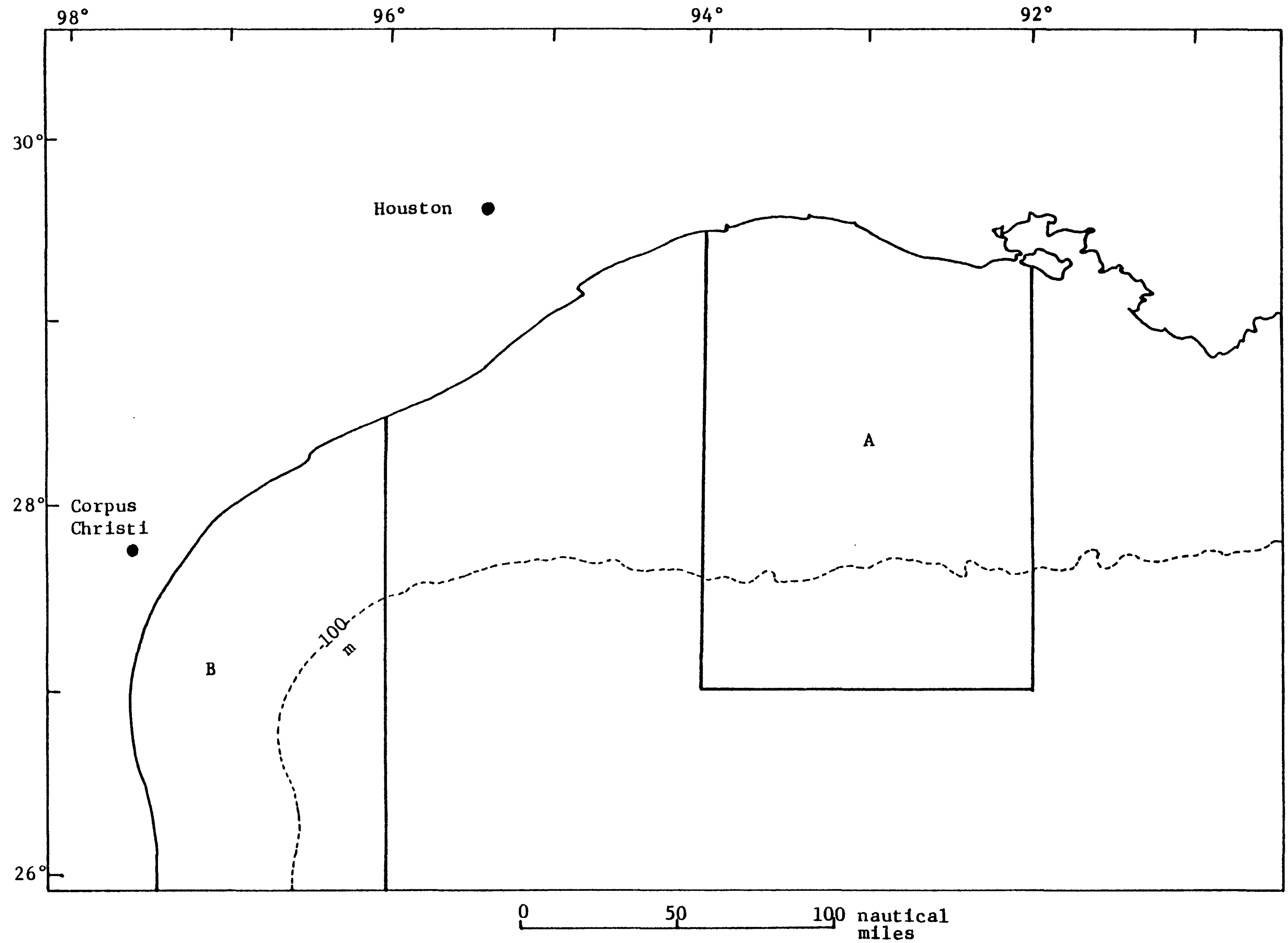

Figure 1. Index map of northwest Gulf of Mexico showing the two areas studied in cooperation with the Bureau of Land Management: A - Pleistocene trend off southwest Louisiana; and B - the South Texas OCS.

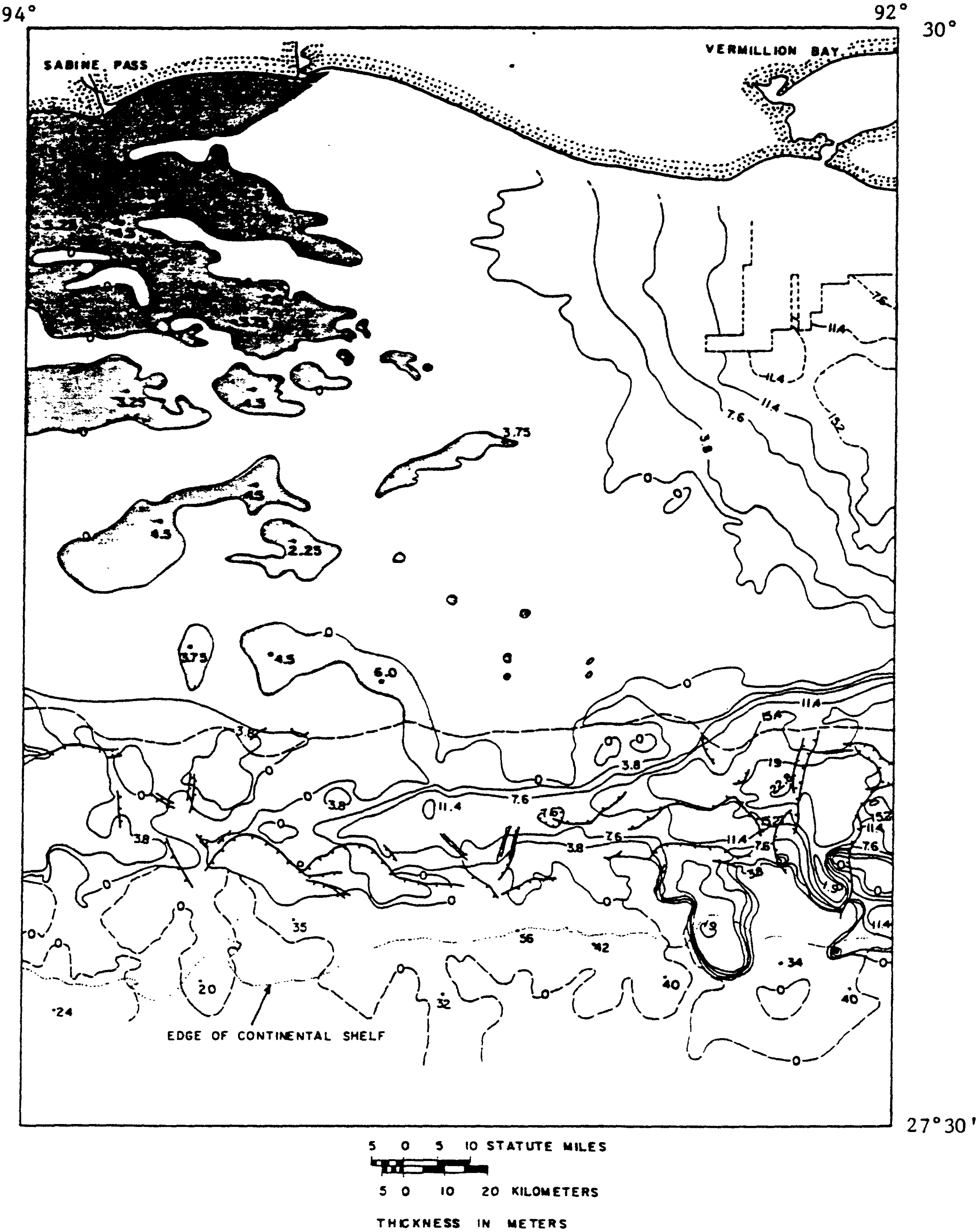

Figure 2. Distribution and thickness of Holocene sediments. Stippling indicates fluvial and deltaic sediments reworked during the Holocene transgression.

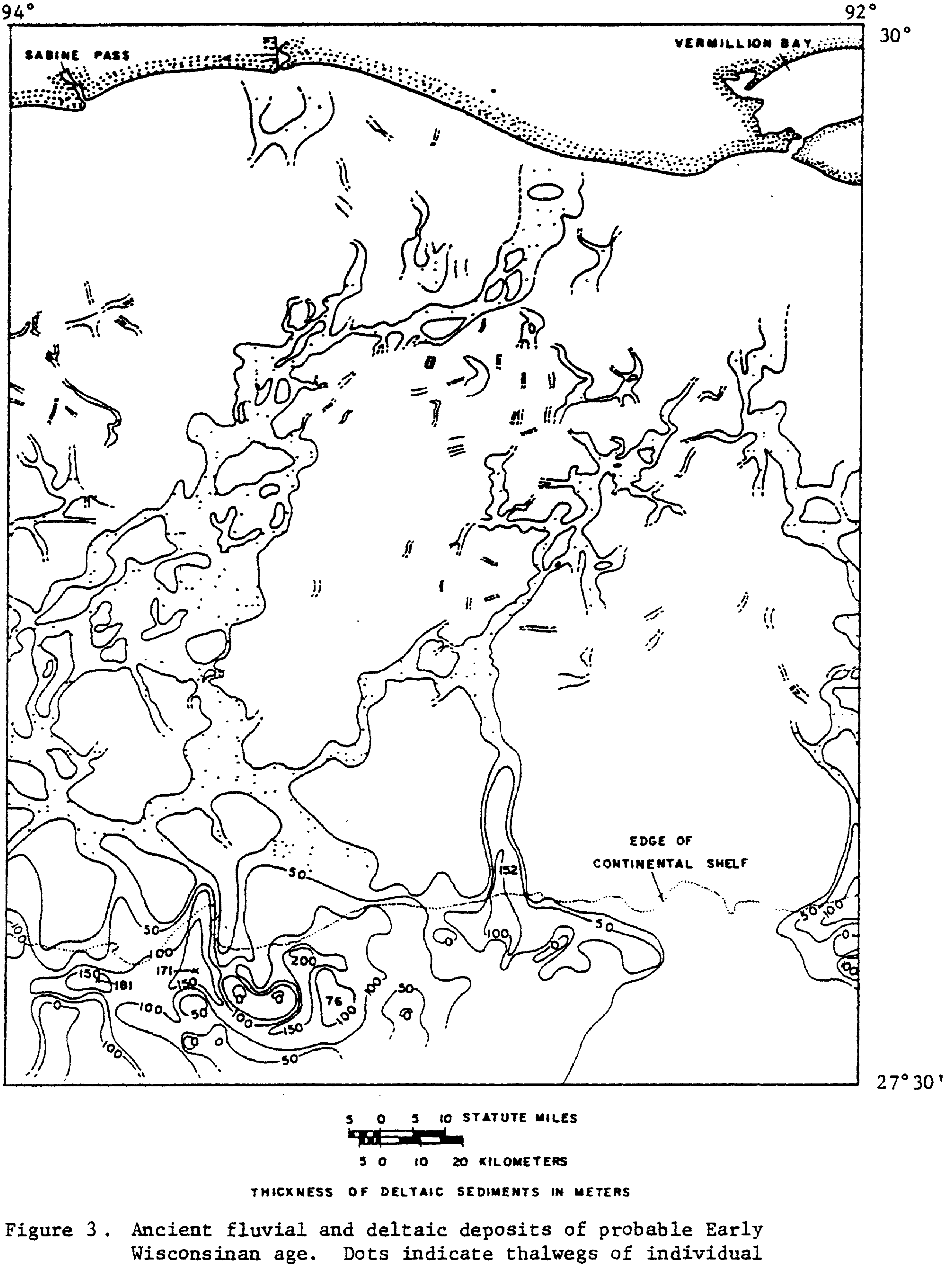

Figure 3. Ancient fluvial and deltaic deposits of probable Early Wisconsinan age. Dots indicate thalwegs of individual streams.

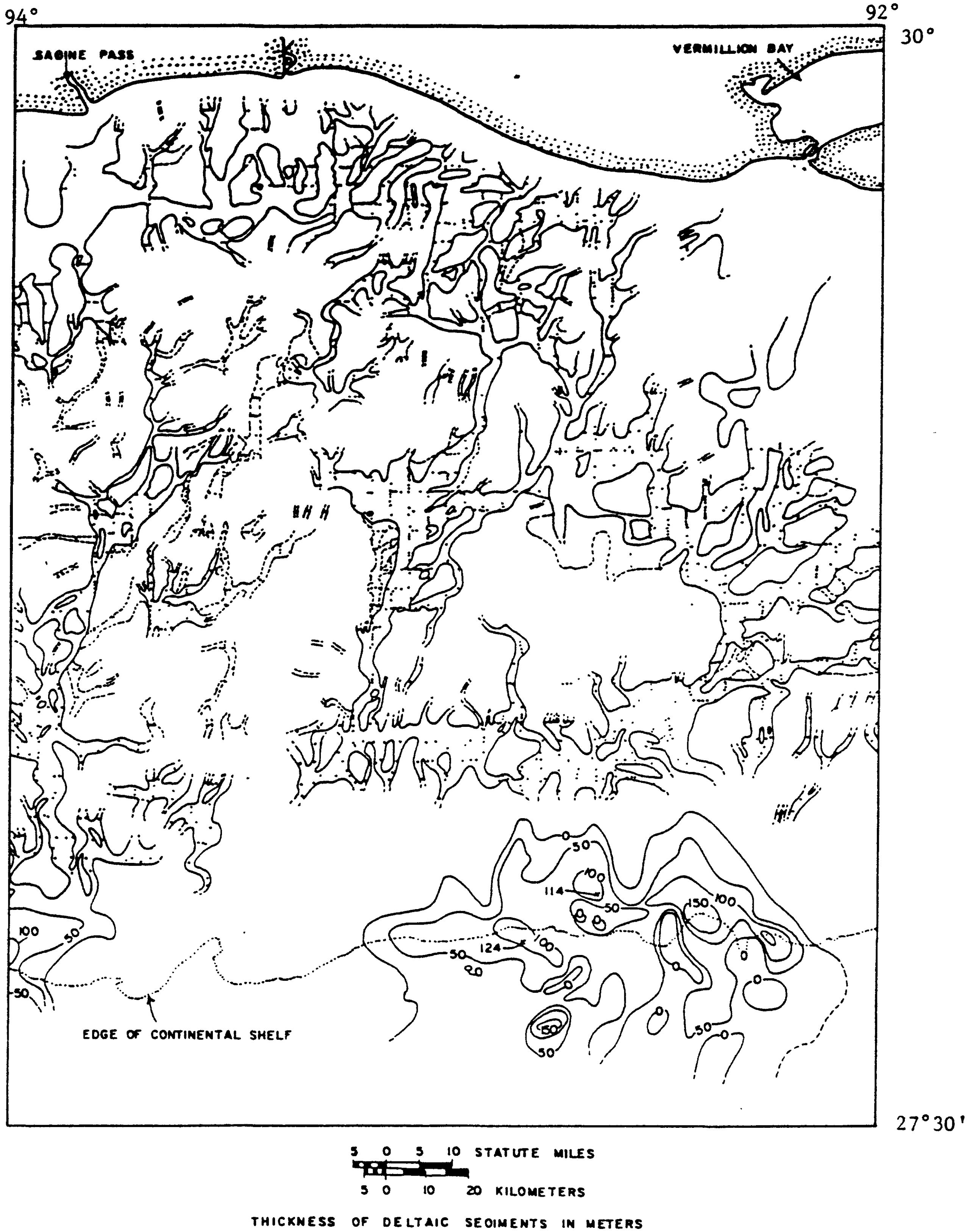

Figure 4. Ancient fluvial and deltaic deposits of pobable Late Wisconsinan age. Dots indicate thalwegs of individual streams.

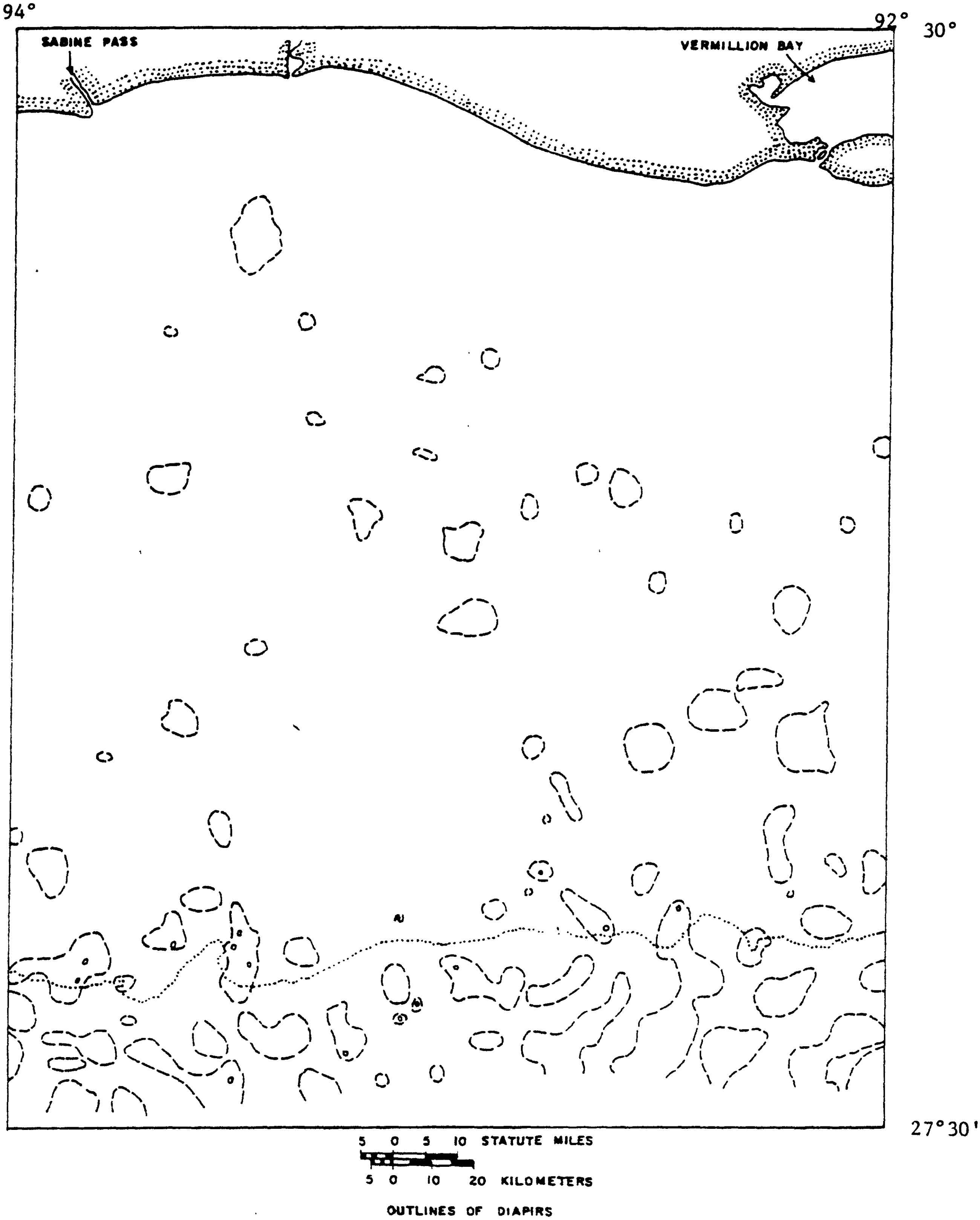

Figure 5. Extent of diapiric deformation. Dashed lines indicate periphery of domal structures created by rising diapirs. Dotted line marks edge of continental shelf.

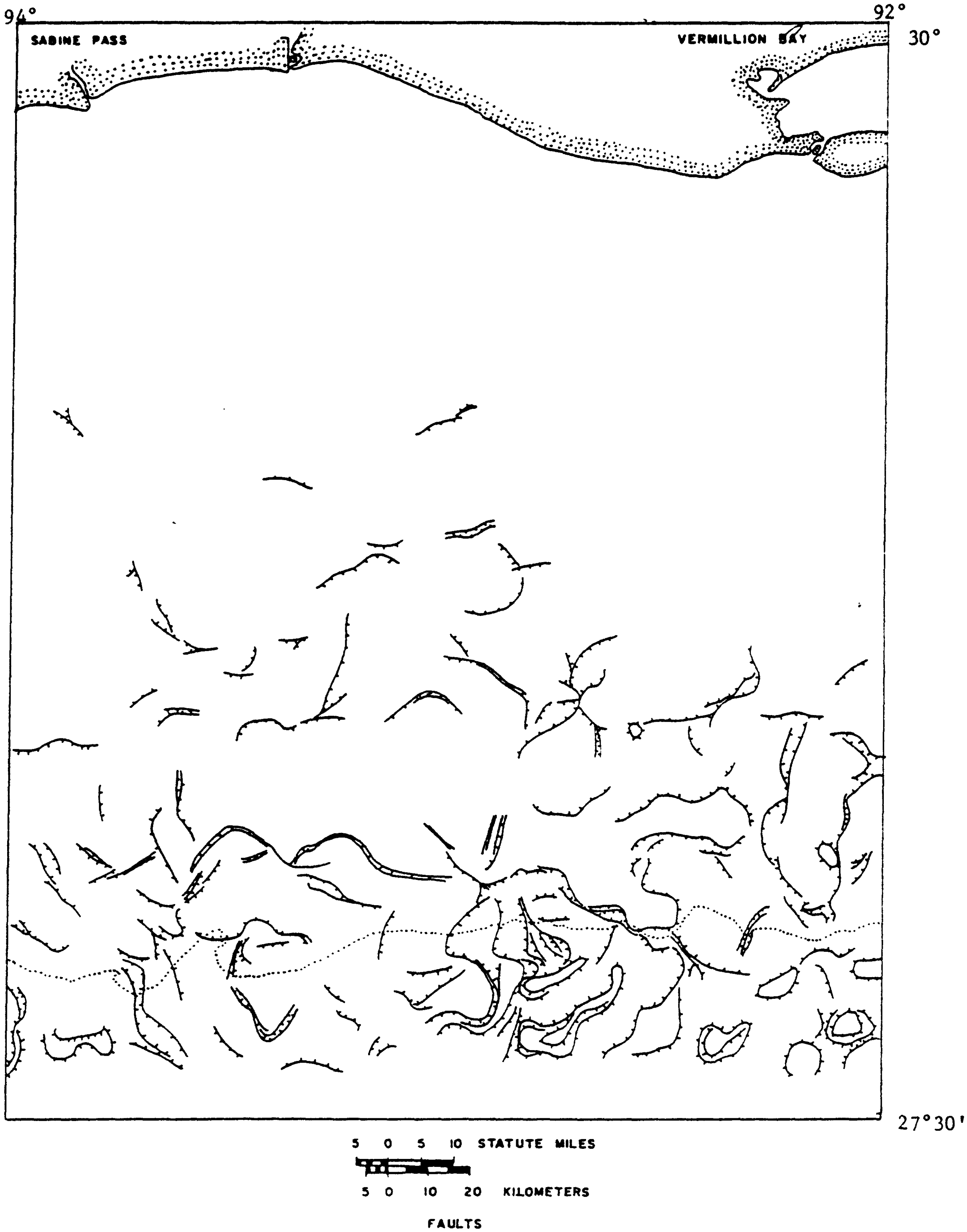

Figure 6. Major faults that either offset the sea floor or terminate within 4 m of the sea floor. Hachure is on downthrown side. Dotted line marks edge of continental shelf.

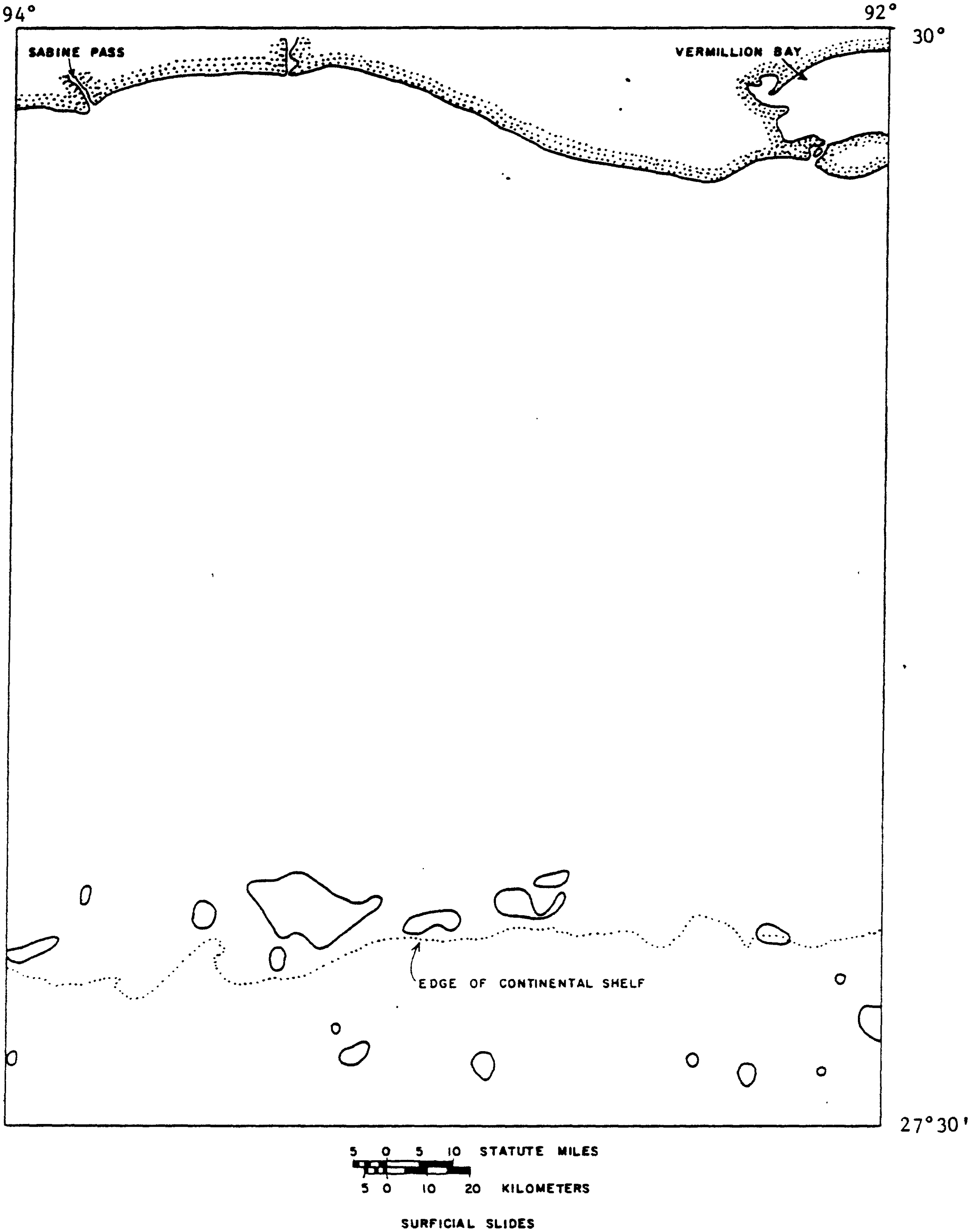

Figure 7. Size and distribution of surficial sediment slides.

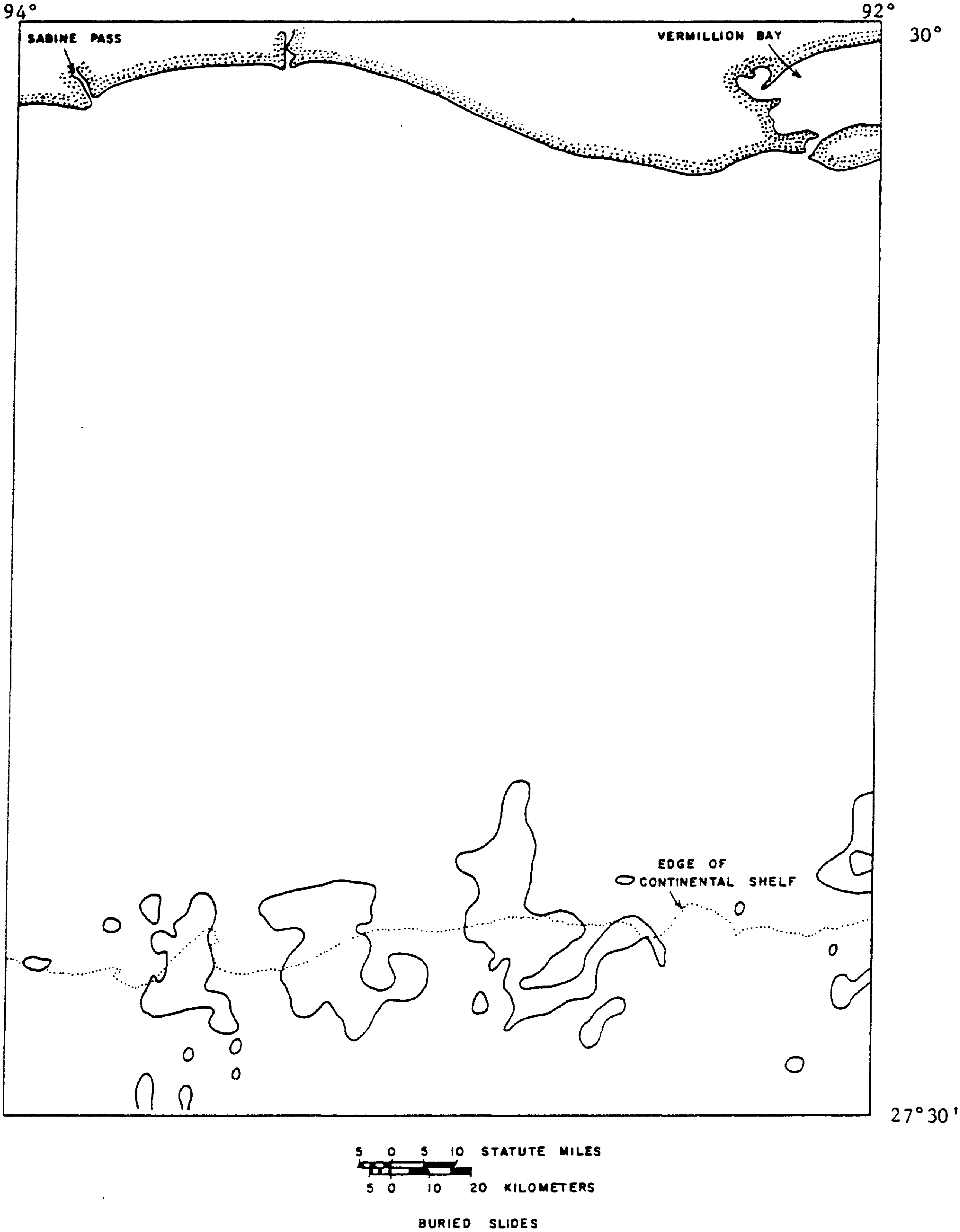

Figure 8. Extent of buried sediment slides covered by undeformed sediments of 50 m thickness or less.

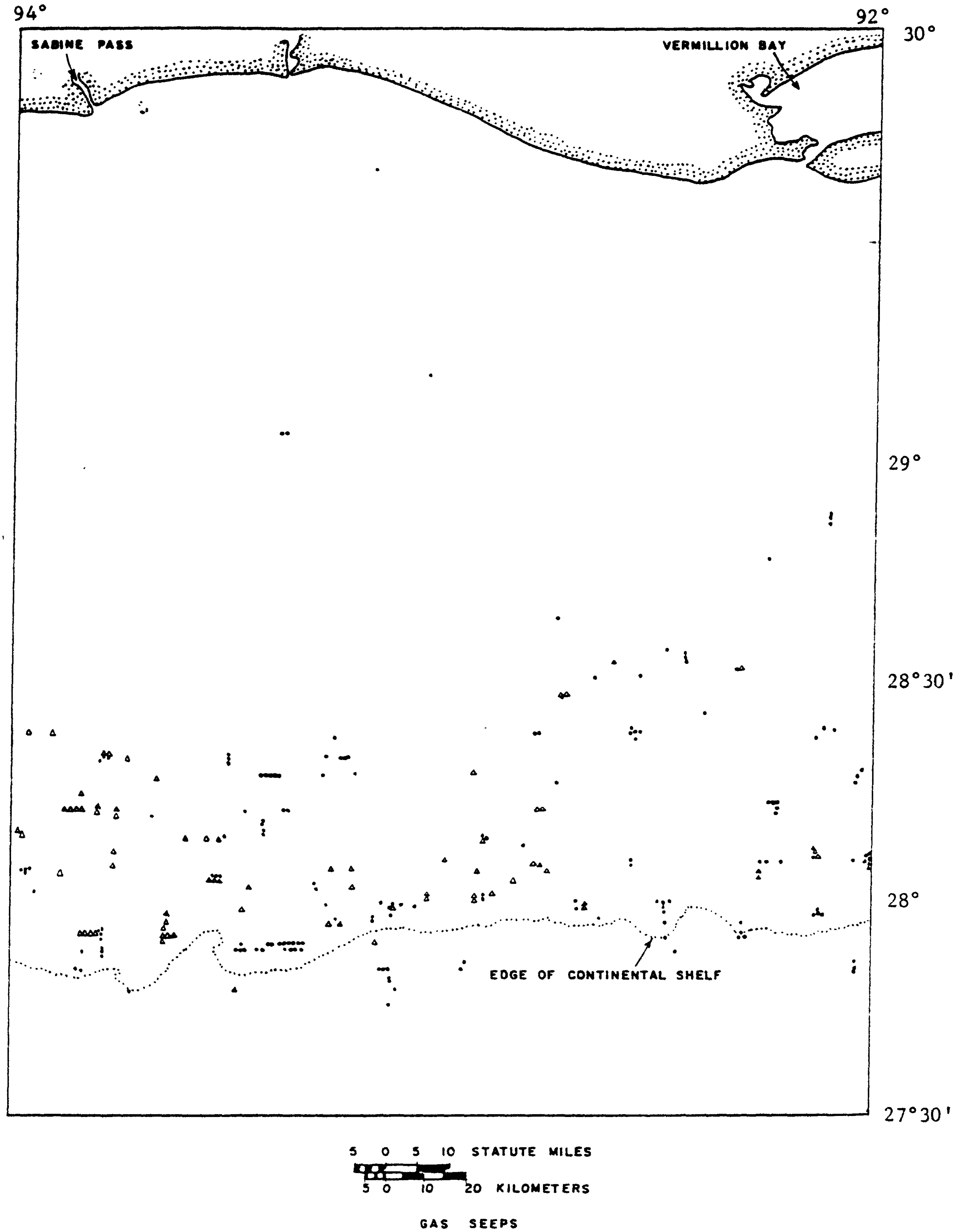

Figure 9. Location of gas seeps. Dots represent gas in the water at the time of seismic surveys; triangles represent mud mounds on the sea floor built by escaping gas.