ENVIRONMENTAL INFORMATION ON HURRICANES, DEEP WATER TECHNOLOGY, AND MISSISSIPPI DELTA MUDSLIDES IN THE GULF OF MEXICO

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MANAGER'S NOTE

The reprint of the Open File Report 80-02 is available through the Minerals Management Service (MMS). The component of the Service responsible for this report is the former New Orleans Outer Continental Shelf Office (OCS), Environmental Assessment Division of the Bureau of Land Management (BLM). On May 10, 1982, following the first printing of the report, a departmental realignment occurred, resulting in the transfer of the New Orleans OCS Office, from the Bureau of Land Management to Minerals Management Service.

This document will make reference to both agencies as is appropriate. Credit for preparation of the original report is given the Bureau of Land Management, while subsequent printings are available through the Minerals Management Service.

John L. Rankin
Acting Minerals Manager
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SUBAQUEOUS SEDIMENT INSTABILITIES IN THE OFFSHORE MISSISSIPPI RIVER DELTA

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Introduction

The Mississippi River delta has stimulated a wide variety of geological, hydrological, and geomorphological research. However, much of this research has been concentrated on the subaerial platform of the delta (Figure 1). The offshore area of the modern delta has not been adequately described. This text and the accompanying maps have been prepared to provide the regional framework and a characterization of associated near-surface sediment instabilities of the offshore Mississippi River delta shelf and upper slope.

In the 1950's, offshore exploration began actively in the shallow-water areas off the delta, and data from soil foundation borings and hydrographic surveys were utilized to develop the first regional assessment of the geological setting (Fisk, et al., 1954; Fisk and McClelland, 1959; Shepard, 1955). In the 1960's, research scientists of the Coastal Studies Institute, Louisiana State University, began conducting systematic research studies of the hydrodynamic aspects of the lower delta, sedimentation processes and patterns, and the geologic framework (Morgan, 1961; Morgan, et al., 1963; Coleman and Gagliano, 1964; Coleman and Wright, 1975; Wright and Coleman, 1974). In 1969, during Hurricane Camille, two offshore platforms were destroyed and one was severely damaged by submarine landslides (Sterling and Strohbeck, 1973; Bea, et al., 1975). After this hurricane, a considerable amount of research on the offshore region of the Mississippi delta was initiated by the petroleum industry, consulting firms, governmental agencies, and universities. The major published papers (to 1979) that resulted from this effort are listed at the end of the text.

In 1974, the U.S. Geological Survey (USGS), Corpus Christi, Texas; the Coastal Studies Institute, Louisiana State University (LSU); and Texas A&M University began a series of cooperative research projects in the outer continental shelf off the delta to: a) establish the regional geologic framework of the delta; b) map the distribution and describe the variety of types of subaqueous instabilities; c) characterize the soil properties and their behavior under various stresses; and d) determine the mechanisms responsible for the subaqueous sediment failures. This effort is continuing to the present, and many publications have resulted (see references). The maps accompanying this text were prepared to set the regional near-surface framework of the delta so that more detailed analysis of site-specific areas could then be undertaken.

The text describes the type of data contained on each map and illustrated via seismic and side-scan sonar records the types of features mapped. No attempt will be made to document the causative mechanisms, magnitude, intensity or frequency of movement, or engineering problems caused by sediment movement. Such information has been previously published (see references).

Types and sources of data. The maps depicting the various aspects of the near-surface marine geology of the delta region were prepared primarily from high-resolution geophysical and side-scan sonar surveys, which were supplemented by many bottom samples and soil foundation borings. Most of the geophysical surveys utilized high-frequency (~ 110 kHz) acoustic sources for bathymetry, 3.5- to 12-kHz-frequency sources for near-surface (less than 200 feet) subbottom penetration, and lower frequency (50-100 kHz) sparkers or other acoustic sources for deeper subsurface penetration (generally on the order of 500-800 feet). Most of the geophysical data were acquired in an analog format rather than in a digital format. The presence of biochemically produced methane gas in bubble phase within the sediments precluded obtaining good records in some parts of the delta platform. Generally, these areas were found in water less than 200 feet deep. The gas in the sediments also caused problems in converting velocity data to depth for measuring thickness of units. However, because of the shallow penetration of most of the systems utilized (generally less than 700 feet), errors are probably not significant and are generally less than 10%. A two-way travel time of 5,000 ft/sec was used for all conversions of velocity to depth.

The side-scan sonar data were acquired with both standard systems such as EG and G, Edo, and Klein, and a digital system, the EG and G SMS 960. Approximately 35% of the total data was acquired with the SMS 960. SMS 960 data are processed for corrections of ship speed and slant range and thus represent

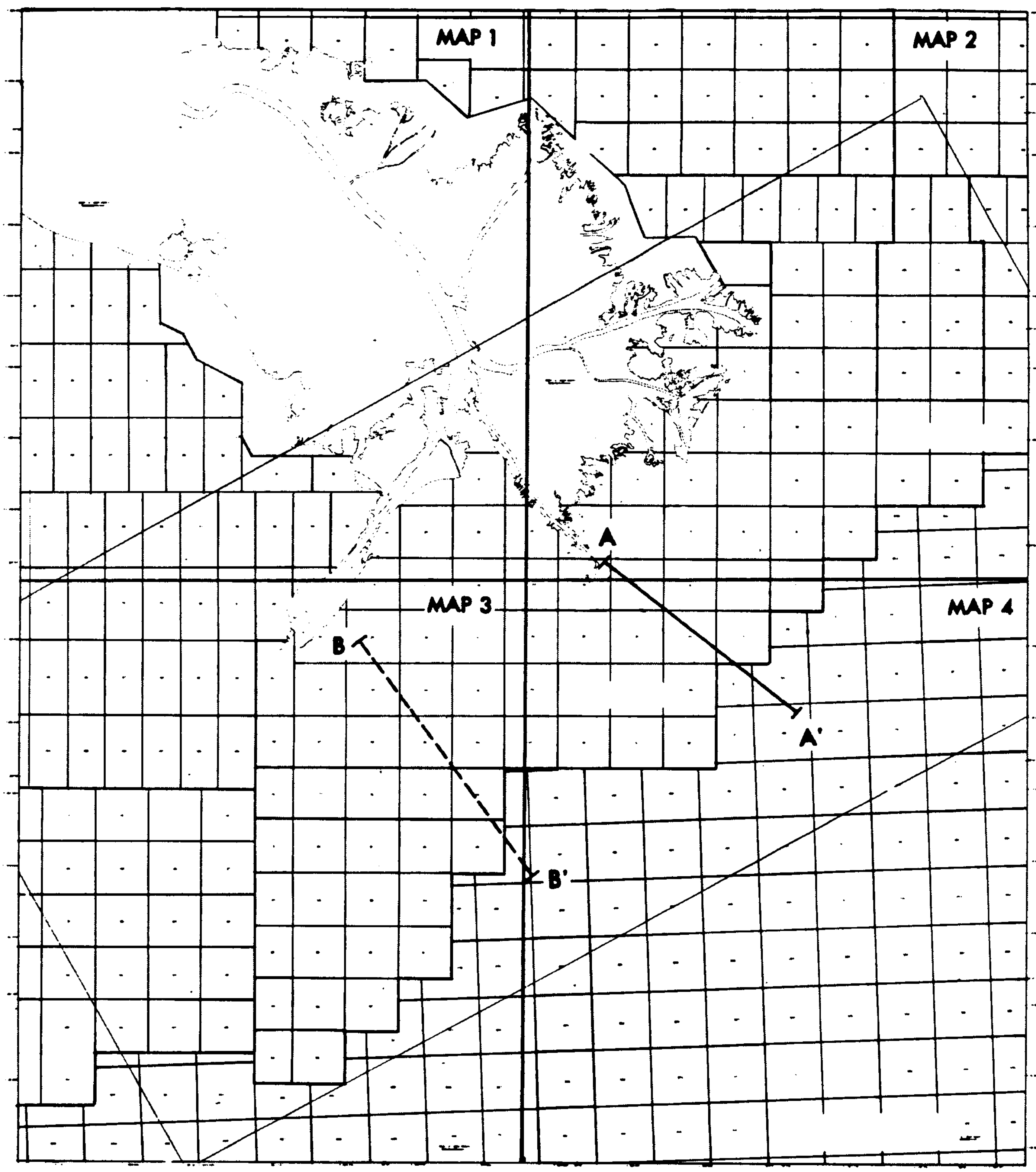

Figure 1 Profiles A–A' and B–B' are illustrated in figure 3.

an almost undistorted acoustic view of seafloor features. Conventional side-scan sonar data were distorted in both ship speed and slant range, and manual corrections were applied to these data during the mapping of the bottom features. The range settings on the data varied from 150 m (495 feet) to 200 m (660 feet), giving overall swath widths of 990 and 1,320 feet, respectively. Track line spacing ranged from 840 to 1,200 feet; thus, all side-scan data contained overlapping coverage of the bottom, eliminating the need for interpretation between lines. In the accompanying maps, corrections for setback distance on the tow fish cable have been applied. The original side-scan sonar data were acquired at scales of 1:1,500 to 1:2,000, were mapped at a scale of 1:12,000, and were photographically reduced to the scale of the maps presented (1:48,000) (Open File Report 80-01). The data in the present report were further reduced to a scale of 1:100,000.

Navigation systems utilized during the surveys varied, but most of the data were acquired by utilizing Loran C, transponder ranging systems, or auto-tape. At a mapping scale of 1:12,000, all the systems appeared to be accurate enough to eliminate significant positioning errors. Checks on cross-tie lines generally indicated that errors were less than 100 feet; such small errors would show up at the mapping scale as less than 0.1 inch and after reduction would be less than 0.025 inch.

Of the total data acquired, some 70% were obtained from the U.S. Geological Survey and run specifically for this project. Additional data were acquired from various petroleum company block surveys.

Acknowledgments

Although these maps are a direct product of the Mississippi Delta Project, a joint research program between LSU and the USGS, they are, in a broader sense, a result of the cooperation of government agencies, academic institutions, and the offshore petroleum industry.

We extend our thanks to members of the USGS in Metairie, Louisiana, who supplied the major part of the data for this study, especially to Dick Scrivener and Bill Sweet of that office, who assisted greatly in the project, and to U.S. Bureau of Land Management personnel in New Orleans where Jack Rebman and Doug Elvers were most helpful. Special thanks go to the many oil company geologists, engineers, and consulting firms who, through the contributions of data and interpretations, helped to fill in some of the blank areas in our coverage.

Mississippi River Delta Setting

The Mississippi, the largest river system in North America, drains an area of 1.3×10^6 square miles. Average water discharge of the river at its delta is 542,500 cu. ft/sec, and average maximum and minimum discharges are 2,100,000 and 101,070 cu. ft/sec, respectively. The annual sediment discharge is estimated at 680 million tons. The bedload consists of 90% fine sand, and the suspended load is characterized by 65% clay and 35% silt and very fine sand. Thus, the Mississippi River carries a substantial sediment load annually, and a high percentage consists of fine-grained clay and silt transported as suspended load. The coarser material is deposited at or near the distributary mouths because of rapid effluent deceleration and saltwater entrainment as the plume leaves the distributary. The fine-grained sediment is kept in suspension and spreads laterally far beyond the immediate mouths of the distributaries. During the 1973 flood, a highly turbid plume extended 12-15 miles from the mouth of South Pass, depositing fine-grained sediment derived from the river beyond the edge of the continental shelf in water depths approaching 1,000 feet.

Deposition of the widely disseminated fine-grained sediments builds a platform fronting the delta that consists of clay that was rapidly deposited, that has an extremely high water content, and that, because of abundant fine-grained organic matter, which is rapidly degraded by bacteria, includes large accumulations of sedimentary gases (primarily methane and carbon dioxide). Understanding the processes of building a fine-grained, unstable delta platform is essential in deciphering the complex types of subaqueous mass movements that take place in this region.

The modern bird-foot or Belize delta is the youngest of the delta lobes of the Mississippi River; radiocarbon dates indicate that it formed within the past 600-800 years (Fisk, et al., 1954). The area of the subaerial bird-foot delta is 530 sq. mi., compared with an average areal extent of 3,000 sq. mi. of the older delta lobes (each of which had an active life of 800-1,200 years). The confinement of the modern delta to a small area has been compensated for by expansion of its vertical thickness. The average thickness of the older delta lobes is 60 feet, whereas the average thickness of the Balize delta is 300-350 feet. Seaward progradation rates of the distributary mouths vary from in excess of 300 ft/yr to less than 150 ft/yr, depending on the specific distributary monitored. Sedimentation rates seaward of the river mouth are extremely high, averaging 2-4 ft/yr. During periods of high flood, accumulation of 10-15 feet of sediment over a 4-month period has been measured. In adjacent interdistributary bays, accumulation rates rarely exceed a few inches per year, and in some places, the bay bottom is being eroded. In offshore waters in front of the delta, accumulation rates vary considerably, from a few inches per year in 150-foot water depths to fractions of an inch per year in water depths approaching 600 feet.

Offshore slopes of the entire delta front are extremely low, rarely exceeding 1.5°, and in the interdistributary bays, bottom slopes are generally less than 0.5° and are rarely greater than 0.2°. In water depths of 30-250 feet, bottom slopes range from 0.7° to 1.5°, and in depths of 250-500 feet, the slopes are less than 1°. At the shelf break, which generally is in water depths of 500-650 feet, the slopes increase slightly, averaging 1.7° to 2.2°. In general, hydrographic maps indicate irregular topography; the bottom is characterized by many radial submarine gullies in water 30-250 feet deep and by broad, flat terraces seaward to water depths as great as 600 feet. These submarine gullies were first described and illustrated from the Mississippi delta by Shepard (1955). At the shelf edge and on the upper continental slope, abrupt scarps are found on the seafloor; some localized scarps are as high as 150 feet, and slopes approach 2.5° to 3.0°.

Subsidence in the Mississippi River delta is highly variable and complex. Regional subsidence caused by basement tectonics and regional loading by older Pleistocene and Tertiary sequences is extremely hard to document because of complexities caused by eustatic sea level changes. Even though sea level has risen some 250-300 feet during the past 15,000 years, sediment influx by the Mississippi River has maintained a progradational nature and deltaic deposits have formed on the shelf off the modern delta. Many radiocarbon dates from borings in the delta, however, seem to indicate regional subsidence ranges of 0.1-0.3 feet per century. Although this rate is rapid compared with those of many passive margin coasts, it probably has had little effect on the sedimentation patterns and structural framework of the Holocene and late Pleistocene deposits off the delta. This range of regional subsidence rates computed from the delta is in general agreement with the present published rates of other areas in the Gulf coast geosynclinal system. Of greater significance in the modern delta is the response of the weak plastic sediments to rapid sedimentary loading. Consolidation by dewatering, degassing, and underlying sediment flowage beneath rapidly localized loading can be significant. In the region of the immediate river mouths, where denser bar sands prograde over weak underlying clays, local subsidence rates can be as high as 0.5 ft/yr, an extremely rapid subsidence rate. Other lines of evidence, mainly historic village sites and old bathymetric maps, show rates that range from 0.1 to 0.2 ft/yr. The high rates of sedimentation and rapid formation of bubble-phase gas cause even more complex relationships in localized consolidation history. The rapid deposition, as much as a foot or more during a month or so, does not allow pore fluids to migrate through the rather low permeability clays and silts, and thus the pore fluids remain trapped. As sediments accumulate, loading increases, and the pore fluids begin to bear the weight of the overlying load; pore-fluid pressures begin to increase over hydrostatic pressures. Although the process of formation of sedimentary gas into the bubble or free-gas stage is complex and poorly understood, it probably plays a role in the overpressuring of the sediments. Measurements in situ in shallow buried delta sediments (less than 80 feet) show excess pore pressures have been found to approach geostatic pressures. Excess pore pressures play a major role in the compactional history and in the measurement of engineering characteristics of these sediments.

The Mississippi River has had pronounced influence on the development of the northern Gulf of Mexico throughout a long period of geologic time. During the Tertiary, large volumes of sediment brought down by the river created many depocenters along the northern Gulf coast. In more recent geologic times, changing sea levels associated with the advance and retreat of inland glaciers during the ice ages have strongly influenced the near-surface sedimentary patterns off the coast of Louisiana. During the Pleistocene, some 2.8 million years in duration, sea level fluctuated several times; most authorities agree on at least four or five major low sea level stands and four or five high-level stands. At the lower sea level stands, the ocean stood some 500-600 feet below present level. The last major lowering of sea level was approximately 30,000-35,000 years ago. During the subsequent rise in ocean level, a major sand unit, generally referred to as the "Strand Plain" sand, was deposited. This event is easily recognized in high-resolution seismic records, as it forms a major erosional unconformity. In borings, this unit is represented as a slightly carbonate-cemented, mediumgrained sand body containing large amounts of shell and capped by a Lithothamnian algal-cemented shell and coral deposit. In the vicinity of South Pass, this horizon is found 750-1,000 feet below sea level. The deposits overlying this unit consist primarily of marine and prodelta clay and silty clay containing thin silt partings. This sequence averages some 200-250 feet in thickness. Approximately 22,000-25,000 years ago, the river shifted its course to the west and probably began dumping sediments down the axis of the Mississippi River Canyon, and a thin shell unit was deposited over most of the shelf off the modern river delta. The clays that cap this shelf horizon are generally red and carry an eastern Gulf mineral suite, high in kaolinite. These sediments were derived from small streams such as the Pearl and Mobile Rivers.

Approximately 12,000-15,000 years before present, sea level again fell to 250-300 feet below its present elevation, and the red clays were capped by a thin sandy shell horizon that has been dated and correlated across much of the shelf off the modern delta. In some instances, the unit forms an erosional unconformity and can easily be identified on the seismic lines. The presence of such a widespread shell horizon on the shelf represents a relatively long period of nondeposition of clastic material. The Mississippi was probably still delivering its sediment load down the canyon or to a site west of the canyon. Sediment representing Mississippi River deposition 12,000-7,000 years ago has not been found in the borings off the modern delta. This evidence seems to confirm debouching of river sediments down the canyon into deeper waters of the continental slope.

Some 7,000 years ago, sea level had reached nearly its present level or was only slightly lower than it is now. The Mississippi River was forming a delta out on the shallow shelf off central Louisiana. During the period 7,000 years ago to the present, the river built and abandoned several delta lobes that presently form the broad expanse of coastal wetlands of Louisiana. The modern or bird-foot delta began its progradation some 600-800 years ago. During this time, the thick sequence of prodelta clays accumulated on the shelf off the modern delta.

The major characteristics of the Mississippi River delta and its continental shelf that influence the stability of marine bottom sediments include: 1) high rates of sedimentation, which result in excessive sedimentary loading; 2) deposition of dense sand and silt over weak plastic clay, causing differential loading of the underlying sediments; 3) high water contents, generally low strengths, and underconsolidation of the deltaic deposits; 4) biochemical degradation of organic material in the deposits, which results in formation of large quantities of in situ sedimentary gases; and 5) annual passage of winter storms or hurricanes, which result in cyclic wave-loading processes.

Explanation of Maps

There are eight maps accompanying the text in a separate packet. These maps have been produced at a scale of 1:100,000. Maps 1-7 are reduced from plates accompanying BLM Open File Report 80-01, and Map 8 is an original plate covering the same basic area that was prepared for Section II of this report.

The Bureau of Land Management, the U.S. Geological Survey, and the U.S. Fish and Wildlife Service are attempting to prepare new regional mapping in the Gulf coast area to a standard base map scale of 1:100,000. These eight maps are the BLM's first productions at that series scale.

Each of Maps 1-7 were reduced photographically from 4 maps of a scale 1:48,000 to achieve the desired 1:100,000 scale. The value of the 1:100,000 maps can be noted for their ease of handling and display. The visual quality of Maps 7 and 8 has also been enhanced through the use of color to identify major components of the seafloor morphology.

The reduction by over one-half of the original scale was drastic, yet there has been no loss of detail in the reduction process, and no information was deleted on the reduced scale maps. Lawrence R. Handley, of the BLM, was in charge of production of these maps and the drafting of Maps 1-7 and compilation of information for Map 8.

The land area on each of the maps is dated and can be compared for gain or loss of surface area for the corresponding map dates. The 1874 and 1956 land areas are taken from the BLM Open File Report 80-01, while the more recent 1971 land area is derived from a U.S. Geological Survey aerial photograph mosaic of the Mississippi delta. The outline of the 1971 land area has been generalized to provide easy comparison with the earlier land areas.

Date of lease or operator status is valid for July 1, 1980, and should be used as a generalized guide for the area. Official lease information must be taken from the BLM New Orleans Outer Continental Shelf Office lease files. Likewise, the platform and pipeline information should be used as a general guide showing current development of major facilities.

Reference guides on the maps consist of longitude and latitude, Lambert and UTM coordinates, and interior cross ticks. Lease block boundaries and block numbers are shown for easy reference; however, for clarity of the grid information and block numbers, Map 8 can best serve as a reference.

Map 1. Survey Lines (1 map, 1:100,000)

This map shows the distribution of survey lines utilized to produce the various interpretive maps. Each survey consisted of a Precision Depth Recorder, a high-frequency subbottom profiler (3.5-12 kHz), a lower frequency sparker or boomer (50-100 Hz), and side-scan sonar sensors. Because of the dynamic changes that take place in the delta during only a few years, it was decided to utilize as short a time span as possible for mapping the various geological features. Most of the data shown on the map were collected during the period October 1977 through March 1979. Some of the deeper water regional survey grids shown, however, were collected in 1975 and 1976. Change in this area is thought to be much slower; thus, the features depicted have probably experienced little modification.

The coverage is not uniform across the entire survey area, as shown in Figure 2. Some 10,880 miles of data was collected, interpreted, and mapped over a 774 square mile area, or some 98 lease blocks. In the area designated as "Complete Coverage," survey track lines were spaced so that complete overlapping coverage was obtained on side-scan sonar records. Survey lines were spaced in this area at distances of 840-1,200 feet. The label "Incomplete Coverage" in Figure 2 indicates those areas where complete overlap of side-scan sonar images was not available and interpretations had to be made. Areas outside the coverage area may have some widely spaced regional data that were available for interpretation.

The quality of the data utilized was, overall, excellent; very little was excluded because of inferiority. Navigation throughout the region surveyed was quite good, and the lines showed generally less than 100 feet of error.

Map 2. Bathymetry 1874 (1 map, 1:100,000)

Sediment accumulation rates are an important aspect of interpreting the frequency of sediment mass movements, and the delta region, because of the importance of navigation at the mouths of South West and South passes, has been the subject of many surveys. During the project, an attempt was made to collect as many of the older maps as possible. Although a good many maps are available, only a few cover the entire region offshore of the Mississippi River delta.

Map 2, showing the bathymetry in 1874, was drafted from several maps that span the period 1872 to 1874. Copies of the original soundings were obtained from Hydrographic Office Map 94 and corrected for changes in

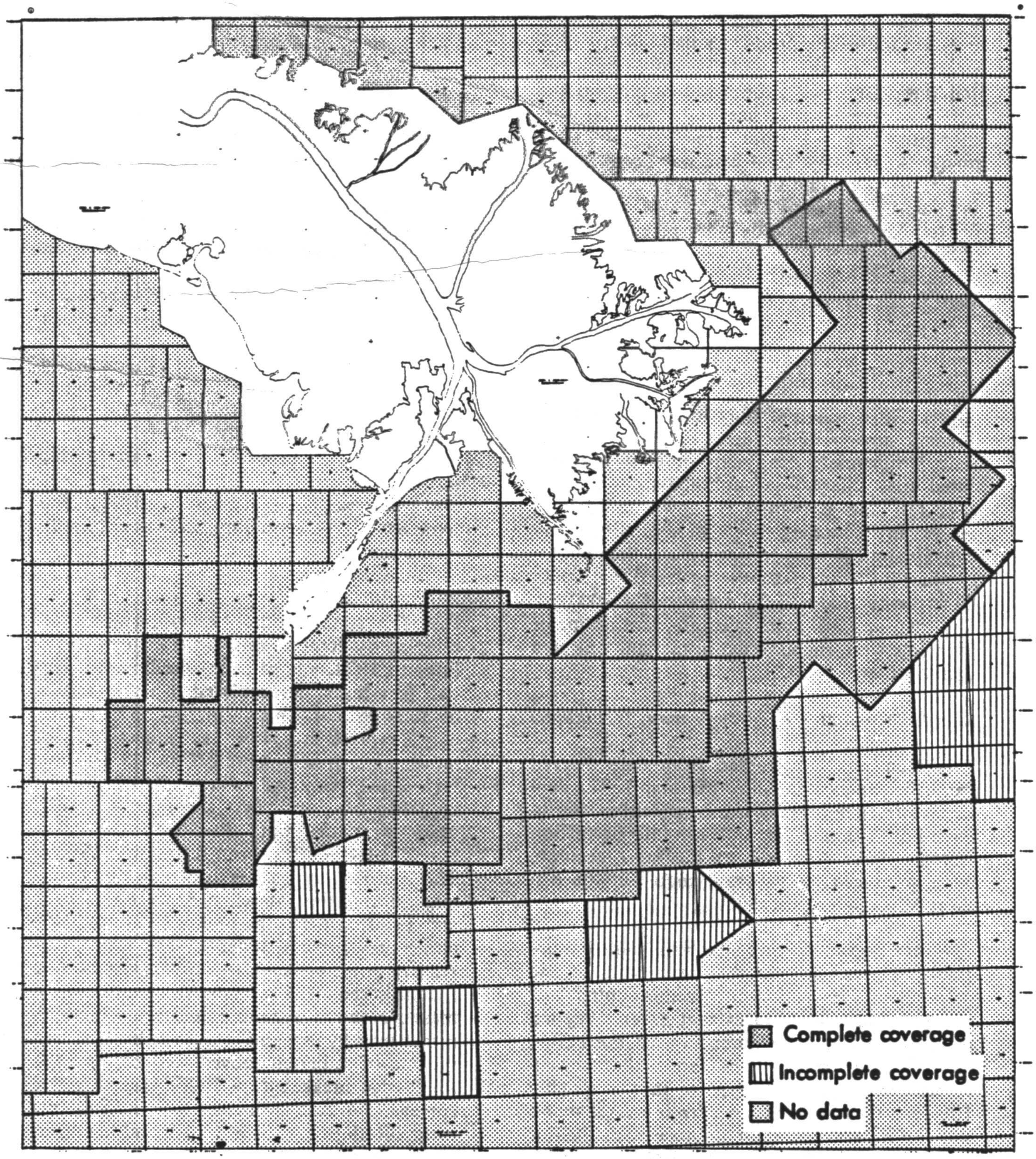

Figure 2 Survey data coverage. "Complete coverage" indicates total overlapping side-scan sonar imagery areas; "incomplete coverage" designates areas where survey lines were spaced more than 2,000 feet apart, requiring considerable interpretation; "no data" indicates those areas having no survey coverage or areas where survey grids were so widely spaced that spatial interpretation was impossible.

base line since 1874, and the soundings were then contoured to produce a bathymetry map. Distribution of the soundings was quite good, and the offshore location was carefully worked out by triangulation methods, which were supported by sextant readings between points. Apparently, great care was taken in producing the sounding sheets, and the accuracy of the map is quite good. Therefore, Map 2 is useful for comparisons with more recent maps to obtain accumulation rates.

Map 3. Bathymetry 1940 (1 map, 1:100,000)

In 1940, the U.S. Coast and Geodetic Survey made a series of detailed sounding grids across the modern delta to update the existing coast charts. This was probably one of the most detailed surveys of the delta region up to that time. Unfortunately, no map, other than an updated coast chart, was published from the survey. For the bathymetry shown in Map 3, the original sounding sheets were obtained, and individual areas were contoured and then photographically reduced to the scale of 1:48,000, then further reduced to a scale of 1:100,000. The map appears quite accurate, and no major problems were encountered in merging one area with another.

Map 4. Bathymetry 1977-79 (1 map, 1:100,000)

This map was constructed from data derived from the survey lines shown in Map 1. The density of track lines, the use of precision depth-recording fathometers, and accurate navigation systems make this one of the most accurate maps produced of the bathymetry in the offshore Mississippi River delta.

The map shows the irregular and gullied topography present in the shallower parts of the delta region (20- to 250-foot water depths) and a few broad, flat terraces that extend beyond these water depths. Comparison of the bathymetry of the older maps shows that considerable change has taken place in the roughly 100-year time span covered by the three maps. This information, when combined with shallow seismic data, can be used effectively to date the movement of some of the instabilities on a gross scale and to obtain sediment-accumulation rates. By utilizing maps showing bathymetry at smaller time intervals in selected areas where data are available, the frequency and magnitude of movement or accumulation can be much better documented.

Data extracted from Maps 2-4 can be utilized to draw regional cross sections that show the magnitude of mass movement that can take place during a relatively short time. Figure 3 illustrates two such cross sections off South Pass, Mississippi River delta. The locations of these cross sections are shown in Figure 1. In profile A-A', large amounts of sediment can be seen to have accumulated in present-day water depths of 300-500 feet. The accumulation of such large quantities of sediment in these water depths cannot be accounted for by settlement out of the water column and thus represents deposition by subaqueous mass movement. In profile A-A' (Figure 3) off South Pass, some 100 feet of sediment has accumulated in 400 feet of water during the 100-year span. In addition, the shelf edge break in slope has built seaward or prograded some 8,000 feet, a truly dynamic type of sedimentation.

Profile B-B' (Figure 3), which is west of South Pass, shows still another type of phenomenon revealed by comparisons of the historic maps. Prior to 1874, a large mass of sediment, some 110 feet thick, accumulated in water depths of 300-400 feet. This accumulation undoubtedly represents large subaqueous mass movements of sediments off an old distributary called "Grand Pass" (see Map 2), which branched off South Pass and built a distributary west of South Pass into East Bay from the late 1700's through the early 1900's. This distributary pass is discernible on many maps during this interval (1838, 1872, 1898, and 1900). During the period 1874 to 1940, either erosion or sediment failure resulted in removal of this sediment. The authors feel that this sediment probably was removed by mass-movement sediment-failure mechanisms rather than by erosional currents. If so, a large volume of sediment moved well beyond the shelf edge break before 1940. Deeper water surveys are not available to confirm this interpretation. Since 1940, sediment has again begun to accumulate in these water depths by mass-movement processes.

Another use of the historic bathymetric maps is to construct sediment isopach maps. By overlaying two bathymetric maps, the amount

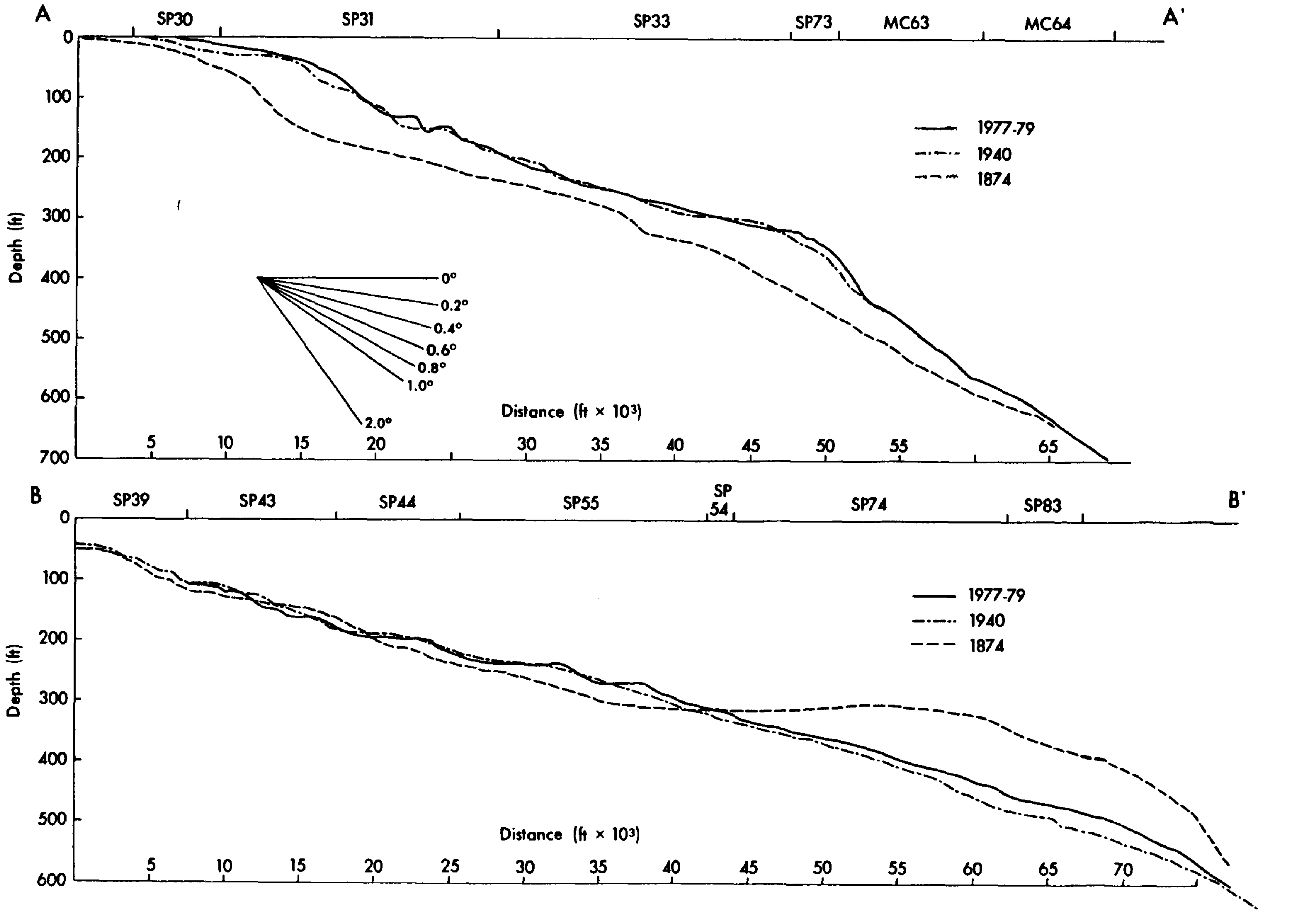

Figure 3 Cross sections showing bathymetric changes between 1874 and 1979. Locations of profiles shown in Figure 1.

of change can be determined over some grid spacing, and the magnitude of change in a spatial context can be determined. Figure 4 shows three such maps prepared for South Pass Blocks 33, 49, 73, and Mississippi Canyon 63. They show the magnitude of change during the period 1874 to 1977-79, 1874 to 1940, and 1940 to 1977-79. In these blocks, considerable change over large spatial areas has taken place during a short time. During the period 1874-1979, two areas of accumulation can be seen, one major area in the northeastern corner of the map and a smaller one along the western margin of the map. As much as 120 feet of sediment has accumulated during the 105-year period in water that is presently 350-400 feet deep. During the time interval 1874-1940, the major part of this accumulation took place in the northeast, and only slight amounts of sediment accumulated along the western boundary. During the period 1940-1979, the area in the northeast received only small additions of sediments, while a major accumulation of sediment was delivered to only the western boundary of the area shown on the map. It is anticipated that large-scale maps of the entire delta will be digitized and that isopach maps across the whole delta will be constructed.

Even more specific information on accumulation rates can be obtained in those few areas that have been mapped more frequently. Figure 5 illustrates such examples in South Pass Block 30. On the earliest map, 1875, points of reference are chosen, on this map one point each in a topographic gully and on the adjacent ridge. When these points are then transferred to each subsequent map, a profile can be drawn that shows the changing water depths or accumulation or loss of sediment that has taken place during some interval of time. Two gully-ridge examples are shown. The years of available maps are shown on the left-hand margin. Water depth changes (or accumulation rates) on the ridges indicate nearly continuous shoaling or accumulation with time. The average rate is approximately 2 ft/yr. For the area and water depth off South Pass, this figure agrees with other types of measurements. In the gullies, however, note that periods of rapid infilling were followed by periods of sediment loss. Accumulation rates were as much as 16 ft/yr. Usually the sediment loss takes place in less than a year's time. This episodic infilling and evacuation of the gullies indicates the frequency of mass-movement processes. Comparison of many such sites around the delta indicates that gully evacuation (or subaqueous mass movements) takes place primarily when the gully totally infills and is nearly level with the adjacent ridge. Sediment failure usually follows major floods on the river. Sediment in the gully fill has accumulated extremely rapidly and therefore possesses high pore water pressures and requires little stress to cause failure. Thus, apparently, once a landslide gully forms, it maintains episodic activity for long periods of time, whereas, adjacent ridges maintain stability during the same time interval. Examination of many areas for which many maps exist indicates that across the delta, initiation of new gullies correlates primarily with extreme floods and is not an annual event.

Thus, the historic maps are extremely useful not only for obtaining sediment-accumulation rates but also for obtaining information on frequency of movements and causative mechanisms and predictions of downslope movement of sediment.

Map 5. Seafloor Morphology (1 map, 1:100,000)

Map 5 shows the distribution of a wide variety of subaqueous landslide features and other seafloor irregularities, as mapped solely from side-scan sonar data. It includes those bottom features present during the period late 1977 through 1979. Because of the dynamic nature of the mass-movement processes, additional changes will undoubtedly take place; thus, this map will serve as a basis for determining such changes when future surveys are conducted.

In addition, this map serves to evaluate the distribution of features across the whole delta front and provide a regional view of the morphological variations in the sediment instabilities. Figure 6 illustrates schematically the relationship of the variety of sediment instabilities as they are found from a distributary mouth, offshore to the shelf edge and upper slope. Rather than try to describe the features and the causative mechanisms fully, the following text will simply illustrate the types of features mapped and how they appear on side-scan sonar and seismic records. Reference to the published literature should be made to obtain more details about specific features. Before significant differences in patterns can be documented, considerable time and effort will be required to study the vast quantity of data already acquired. This study is planned for the future, but immediate publication of the maps was deemed essential.

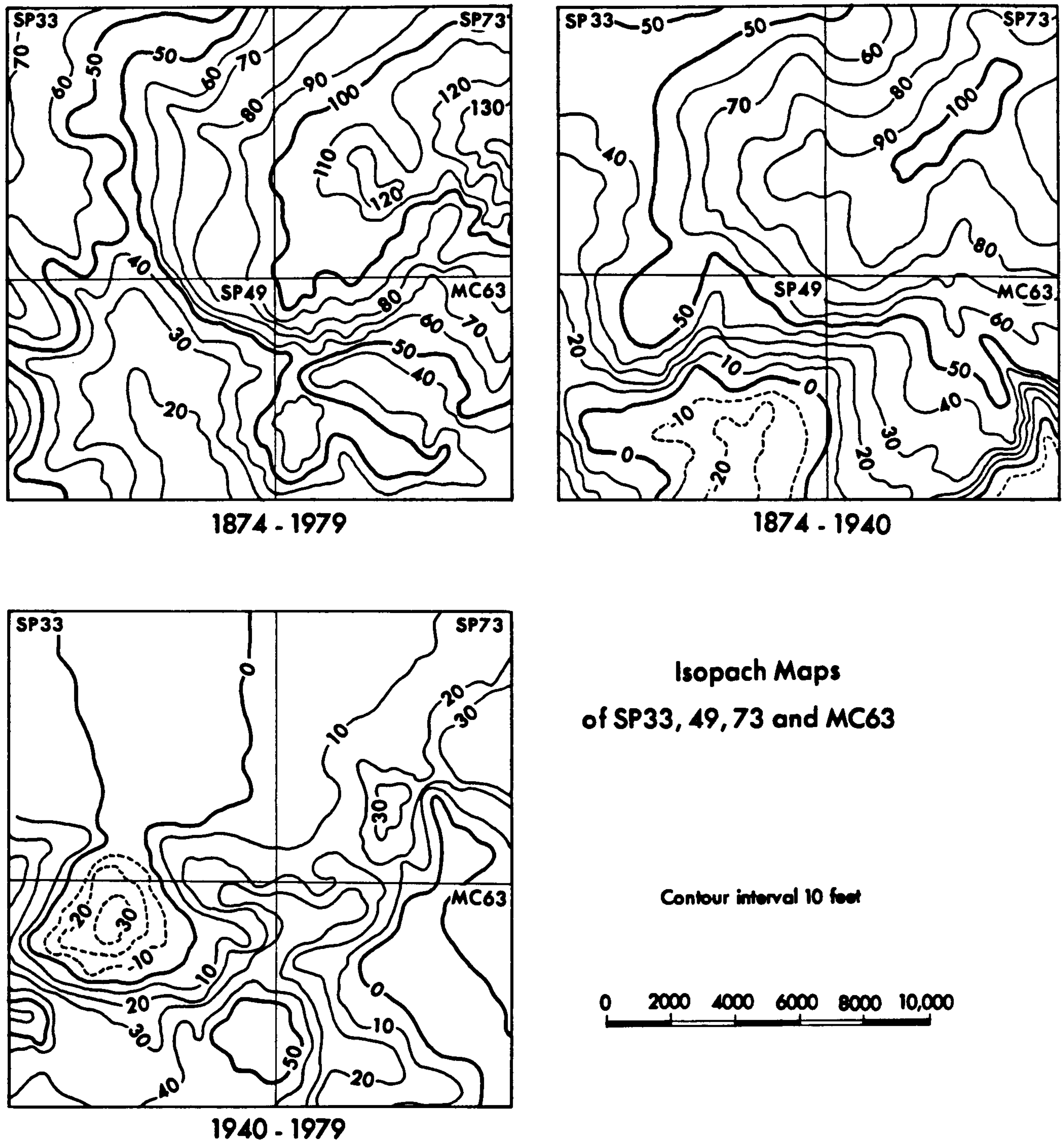

Figure 4 Sediment isopach maps of South Pass Blocks 33, 49, 73, and Mississippi Canyon Block 63 for the intervals 1874-1979, 1874-1940, and 1940-1979.

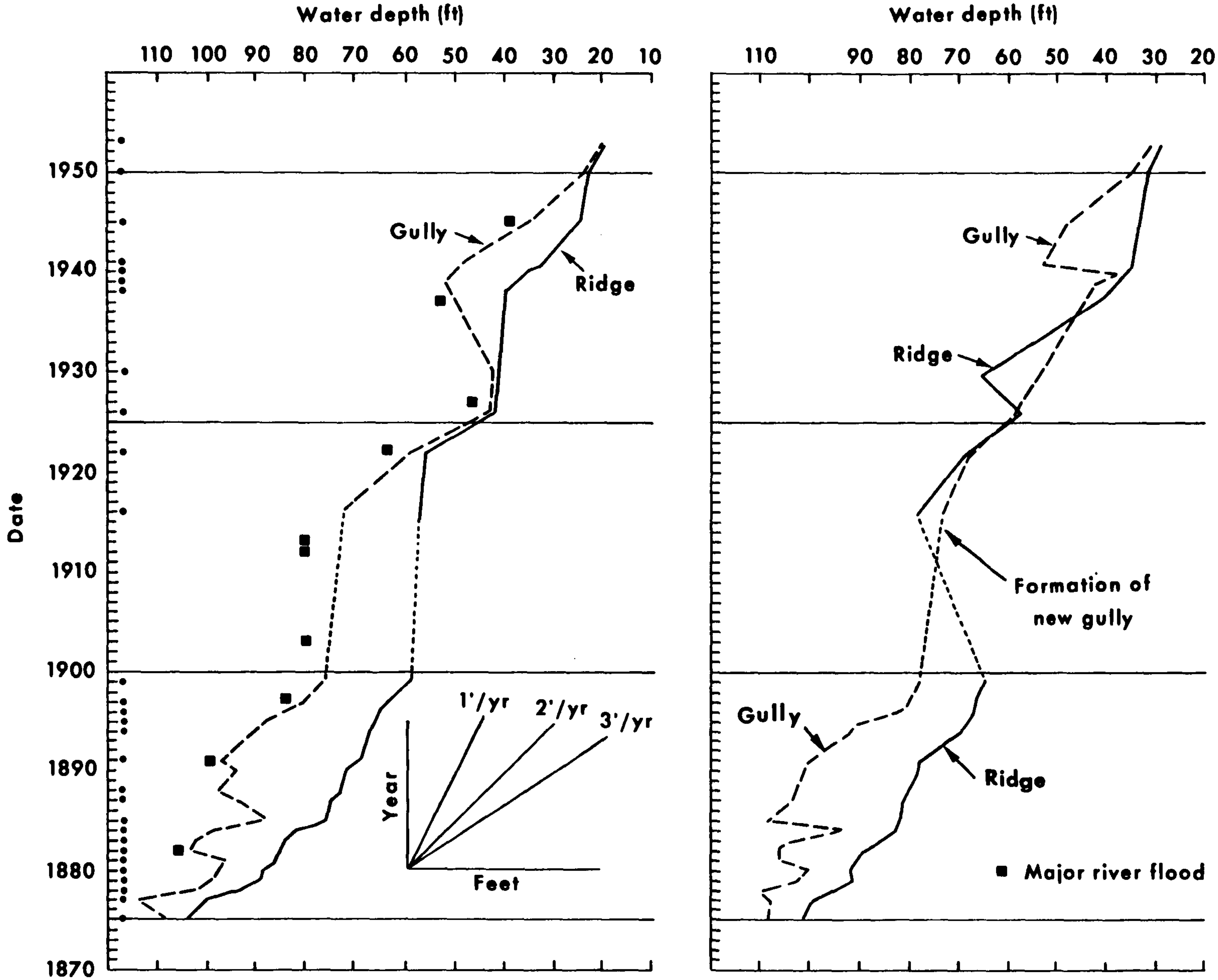

Figure 5 Sediment accumulation in mudflow gullies and adjacent ridges in South Pass Block 30 during the period 1874-1953. A dot denotes that a map is available for that time period.

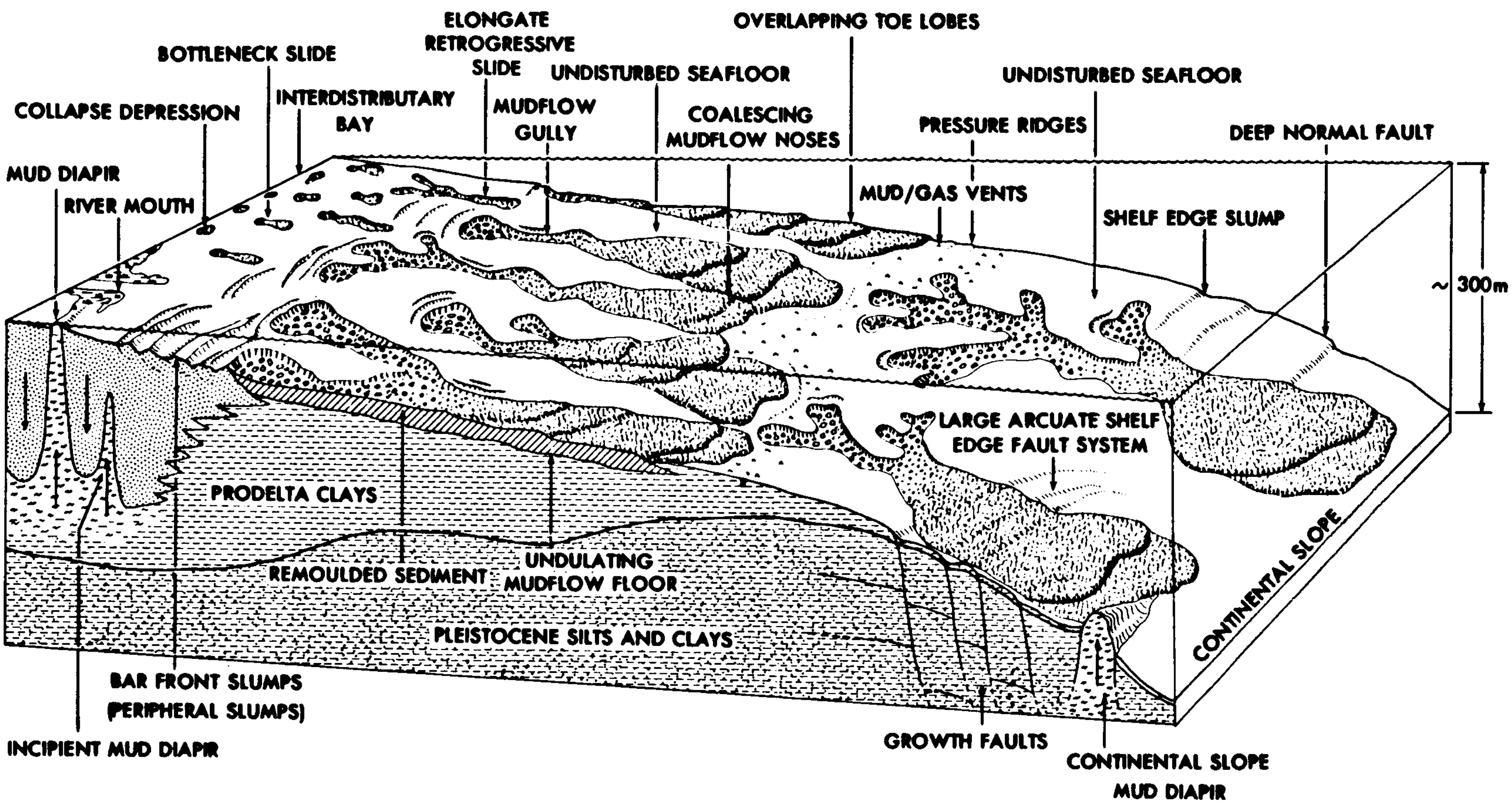

Figure 6 Schematic block diagram showing the relationship of the various types of subaqueous sediment instabilities.

1. *Collapse depressions and bottleneck slides.* Collapse depressions and bottleneck slides are present primarily in the shallow water areas of the interdistributary bays and slightly beyond the bays to water depths of 30-50 feet. They are most commonly associated with slopes ranging from <0.1° to 0.4° and show a spectrum from small rounded collapse features on lower slopes to more elongate bottleneck slides on the steeper slopes. In areas where they are most common, sedimentation rates are slower than rates elsewhere in the delta. Collapse depressions are relatively small in relation to other mass-movement features in the delta; however, they are extremely numerous within any given area. The features range in diameter from 120 feet to more than 500 feet and have length/width ratios of 1.0 to 1.5. Typically the depressions are bounded by curved or near-circular escarpments as much as 9 feet high, within which the bottom is depressed and filled with irregular blocks or clasts of sediment. Side-scan sonar records clearly show that such bowl-shaped areas, bounded by scarps, have been displaced vertically and represent distinct depressions of the seafloor. Figure 7 illustrates schematically the morphology of these features. The depressed central area of the collapsed feature has irregular and hummocky topography. On the upslope margin, crown cracks often extend into the adjacent stable sediments, and on the downslope side is a shallow-angle reverse slope; in a few depressions, a slightly raised rim of sediment is observed, indicating a tendency for downslope translatory movement. On fathometer profiles and on high-frequency seismic data, the depressed floors of the feature often show floor of the feature is, on many records, the area where several seafloor multiples exist, giving some indication that the sediments flooring the depression have slightly higher densities than the adjacent sediments. Similarly, side-scan sonar records show very high return of energy from the depression floors, especially in the areas between the hummocky blocks.

On slightly steeper slopes within the interdistributary regions and on slopes 0.2° to 0.4° are features that are referred to as bottleneck slides (see Figure 8). These features are similar morphologically to collapse depressions, but the boundary scarps do not form a totally closed perimeter around the instability. Rather, they have narrow openings at the downslope margin of the failure, through which remolded debris is discharged over surrounding intact slopes. At the narrow openings of the source area where the depositional toe begins, transverse tensional cracks are common. The areas of displaced debris are arranged as distinct undulatory depositional lobes, which may have clearly identifiable sharp edges or may grade out imperceptibly downslope as thin fans. Bottleneck slides range in length from 500 or so to 2,000 feet and have length to width ratios of 1.5 to 3.0. Figure 8 is a schematic diagram showing the major morphological features associated with this instability.

Figure 9 is a side-scan sonar mosaic constructed from several track lines showing the characteristics of several collapse depressions and a small bottleneck slide. The collapse depressions are labeled A on the illustration. They range in width from 80 to 1,200 feet

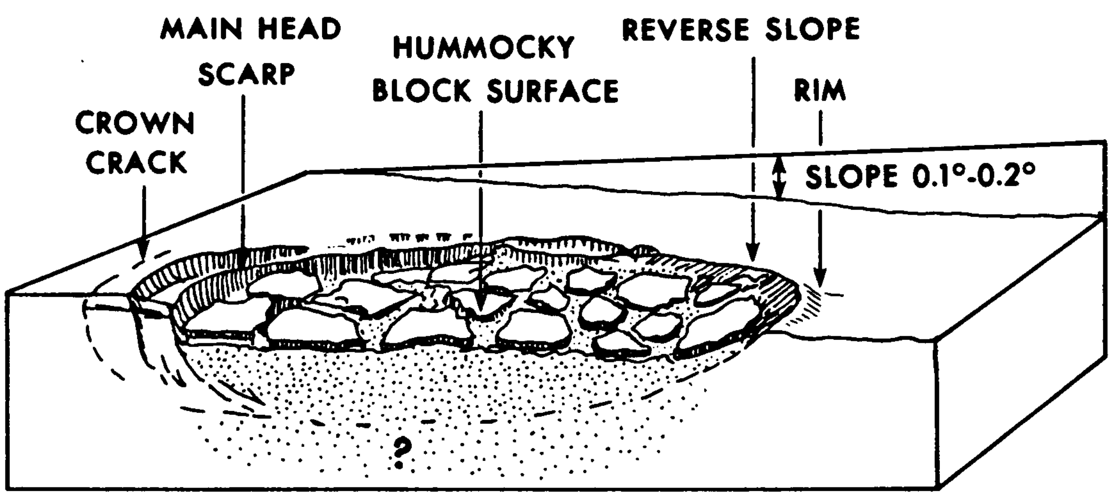

Figure 7 Schematic diagram illustrating the morphology of collapse depressions. Stippled area represents disturbed sediments whose depth is unknown.

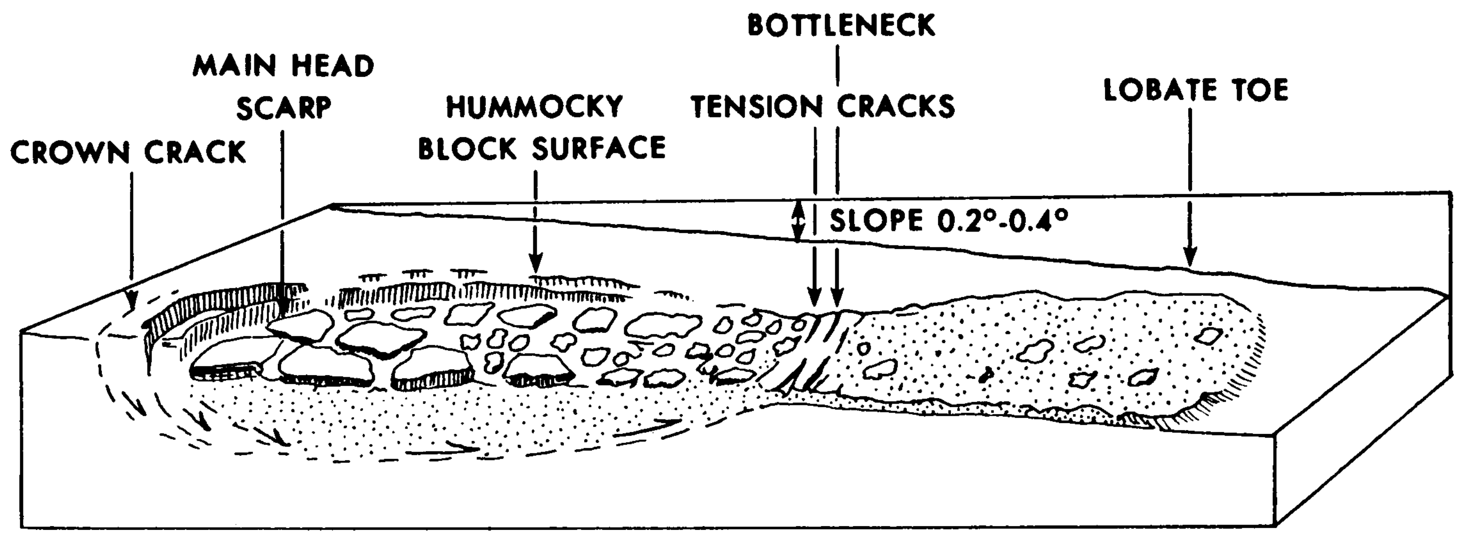

Figure 8 **Schematic diagram illustrating the morphology of bottleneck slides. Stippled areas represent disturbed sediment.**

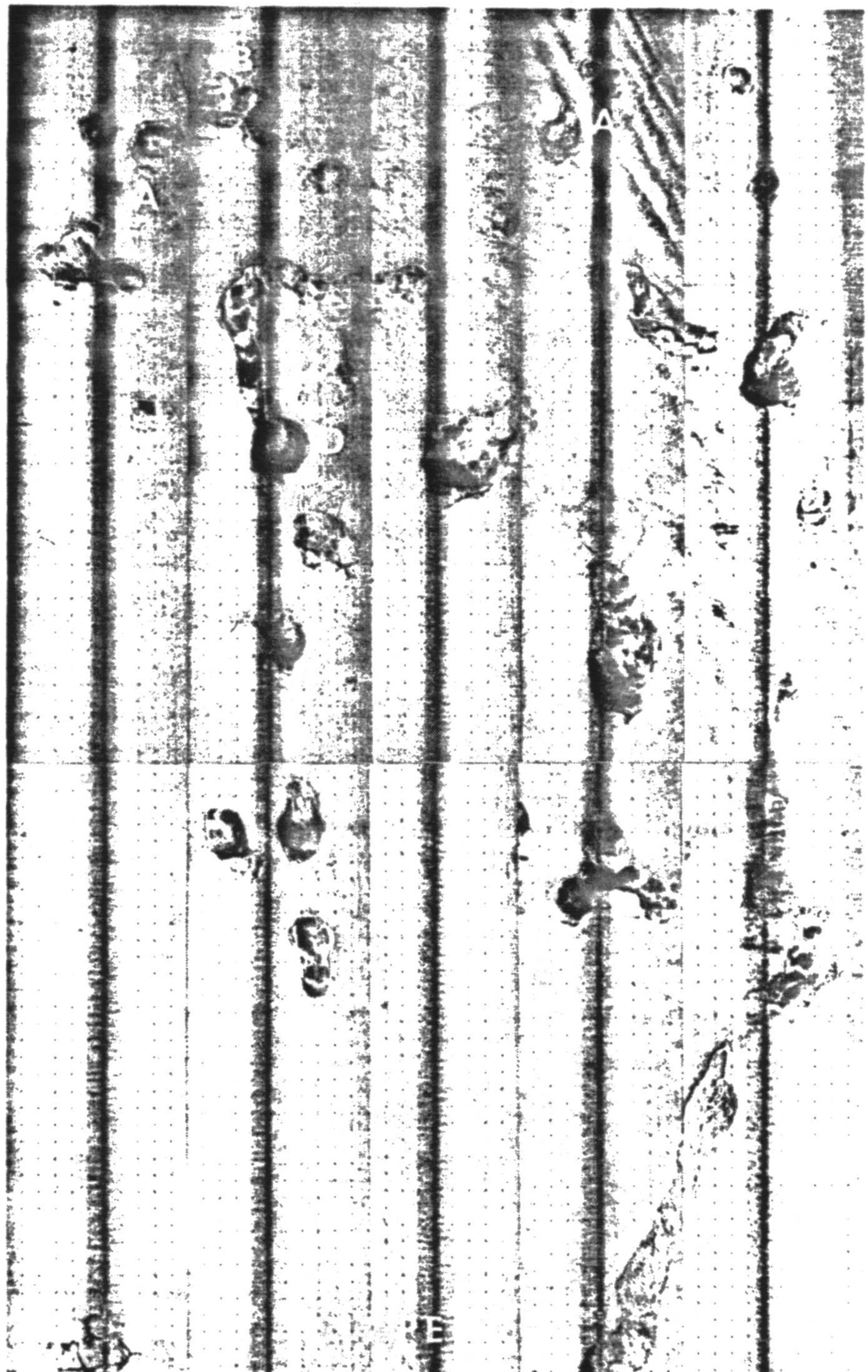

Figure 9 Side-scan sonar mosiac, illustrating several collapse depressions and a bottleneck slide. The grids are 82 feet (25 m) apart, and the mosaic covers a region 0.8 x 1.4 mi. A, collapse depressions; B, crown cracks; C, bottleneck slide; D, depositional lobe of bottleneck slide.

and have depressed floors that range from 2 to 10 feet below the surrounding seafloor. Note the irregular and hummocky topography associated with these features. Note also the strong reflections of the acoustic signal that are often seen in the features, attesting to the slightly higher density of the material that occupies the areas between the erratic blocks. Small crown cracks surrounding the major features are labeled B in the illustration. Many of these depressions have scarps that are only a foot or so high. Figure 10 illustrates an enlarged part of the mosaic shown in Figure 9, and, because of the larger scale, most of the details described above are clearly shown.

A bottleneck slide shown in Figure 9 (C) has a length of 3,600 feet. Note the similarity of the source areas for this feature and for the collapse depressions. The bottleneck slide, however, has a large depositional lobe, labeled D in the illustration. This lobe occupies an area of approximately 6×10^5 square feet. Seismic data across the depositional lobe indicates that the thickness is generally less than 5 feet, and the feature forms a raised mound on the seafloor.

2. *Peripheral rotational slides.* Downslope movement of large sediment masses often begins high on the upper delta-front slope, near the distributary mouths of the river. Bottom slopes

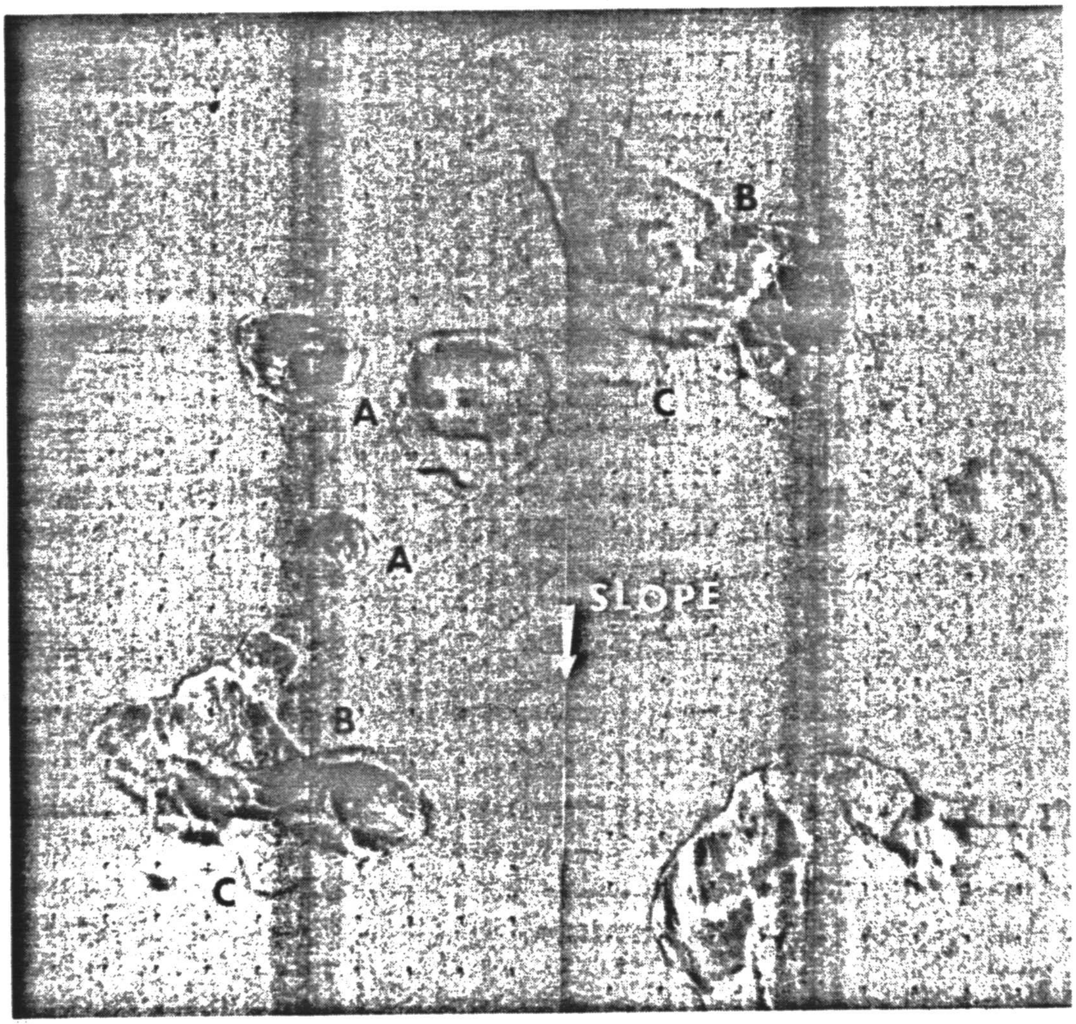

Figure 10 Enlarged part of side-scan sonar mosaic (fig. 9) showing some of the details of the collapse depression. A, circular collapse depressions; B, more elongate and irregularly shaped collapse depressions; C, crown cracks associated with the edges of the collapse depressions.

immediately at the mouths of the distributaries range from 0.2° to 1.0°, but in many places, major scarps having distinctive curved or curvilinear plan views scar these gentle slopes. The localized scarps range in height from 10 to 20 feet and have slopes of 1° to 4°. In many areas, they give the bar front a stairstepped appearance in profile view. Tensional crown cracks are commonly present upslope from the major scarps, and mud vents are associated with many of the scarps. The surface of the slump block normally has extensive hummocky and irregular bottom topography and displaced clasts of sediment. The rotational nature of the downthrown block can be recognized by the reverse slope often seen in fathometer profiles.

Figure 11 shows in schematic form the most common characteristics of this sediment instability. Because it is formed in the extremely shallow waters off the distributary mouth bar, only a few lines cover this type of feature.

The morphology shown in Figure 11 is indicative of rotational sliding over slightly curved shear planes that are concave upward. The shear planes undoubtedly turn into bedding planes downslope and result in downslope translatory motion of the sliding mass. The average depth to the shear plane is approximately 80-110 feet. Although movement rates are hard to document in detail, repeated surveys indicate that blocks moved downslope more than 1 mile in a 1 year period.

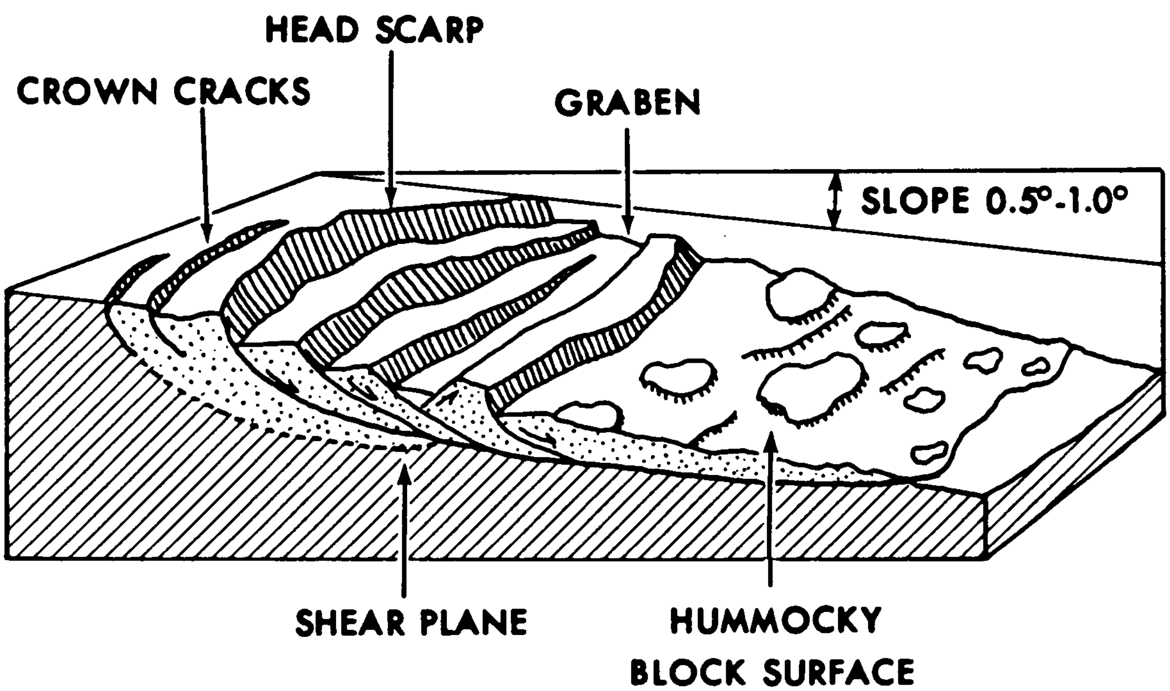

Figure 11 Schematic diagram illustrating the morphology of rotational peripheral slides. Stippled areas represent disturbed sediment.

Figure 12 is a conventional side-scan sonar record showing several stairstepped peripheral slides. Note that the scarps of the shear planes are not entirely linear features, but are composed of many small arcuate slides reminiscent of subaerial rotational land slumps. Figure 13 is a high-resolution seismic line run across several of these slides. Note that the slides show the rotation typical of concave-upward slide planes, although the seismic signal does not penetrate deep enough to show the curved nature of these shears. The slope of the bottom in this region is approximately 0.45°.

3. *Mudflow gullies.* Extending radially seaward from each of the distributaries in water depths of 20-300 feet are major elongate systems of sediment instabilities referred to as delta-front gullies or mudflow gullies. The features were first described on hydrographic maps by Shepard in 1955, and the 1977-79 bathymetry (Map 4) illustrates these features. Side-scan sonar records and high-resolution seismic data show that these valleys or gullies emerge from within an extremely disturbed area of slumped topography high on the delta. Each gully has a clearly recognizable area of rotational instability or shear slumps at its upslope margin. This feature is the most common type of sediment instability fronting the Mississippi River delta.

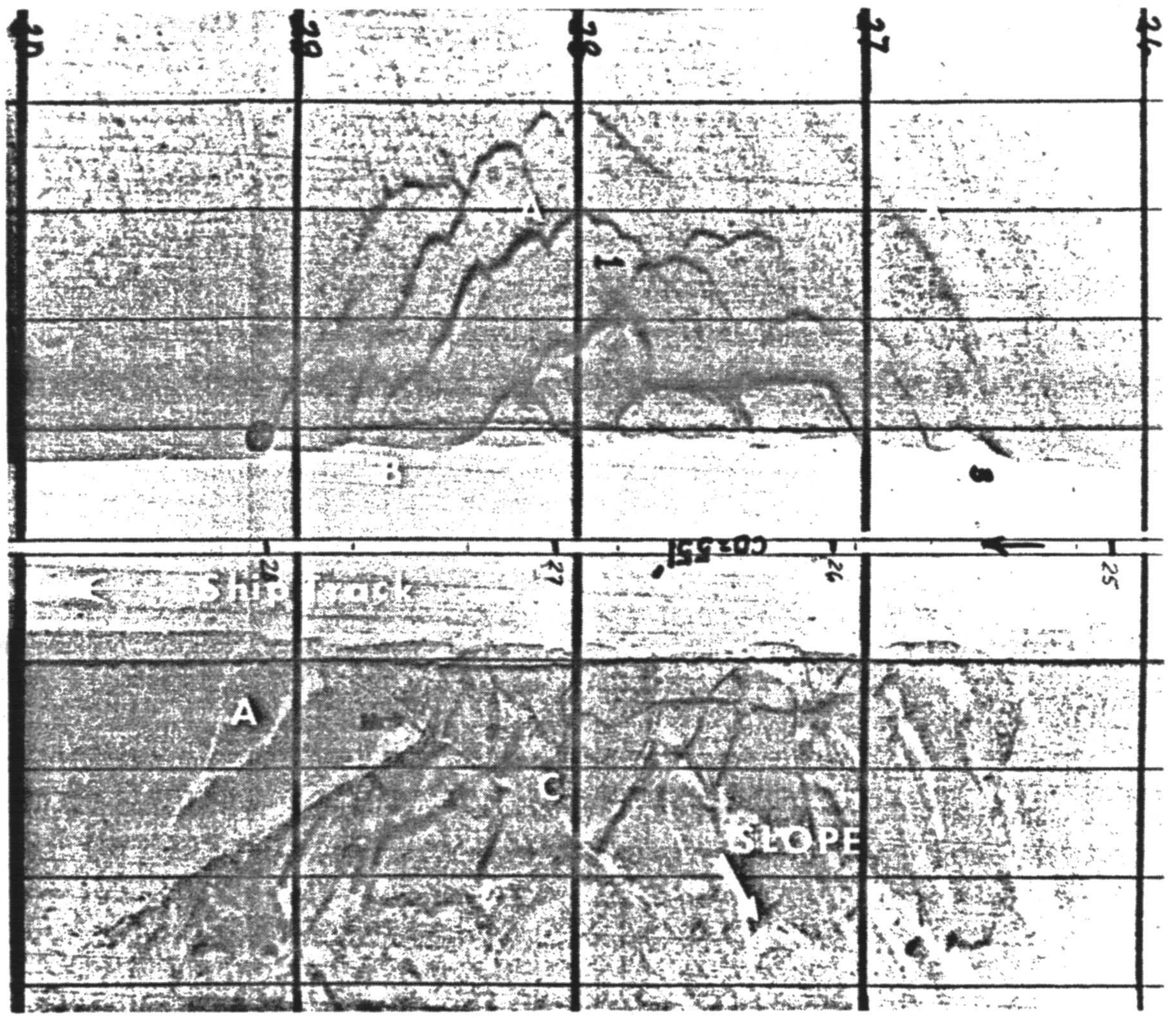

Figure 12 **Conventional side-scan sonar record, showing several rotational slides. Navigation fixes are 500 feet apart, and lateral timing lines are 82 feet apart. A, shear planes showing up as scarps on the sea floor; B, rotated block; C, shrimp trawler's drag mark.**

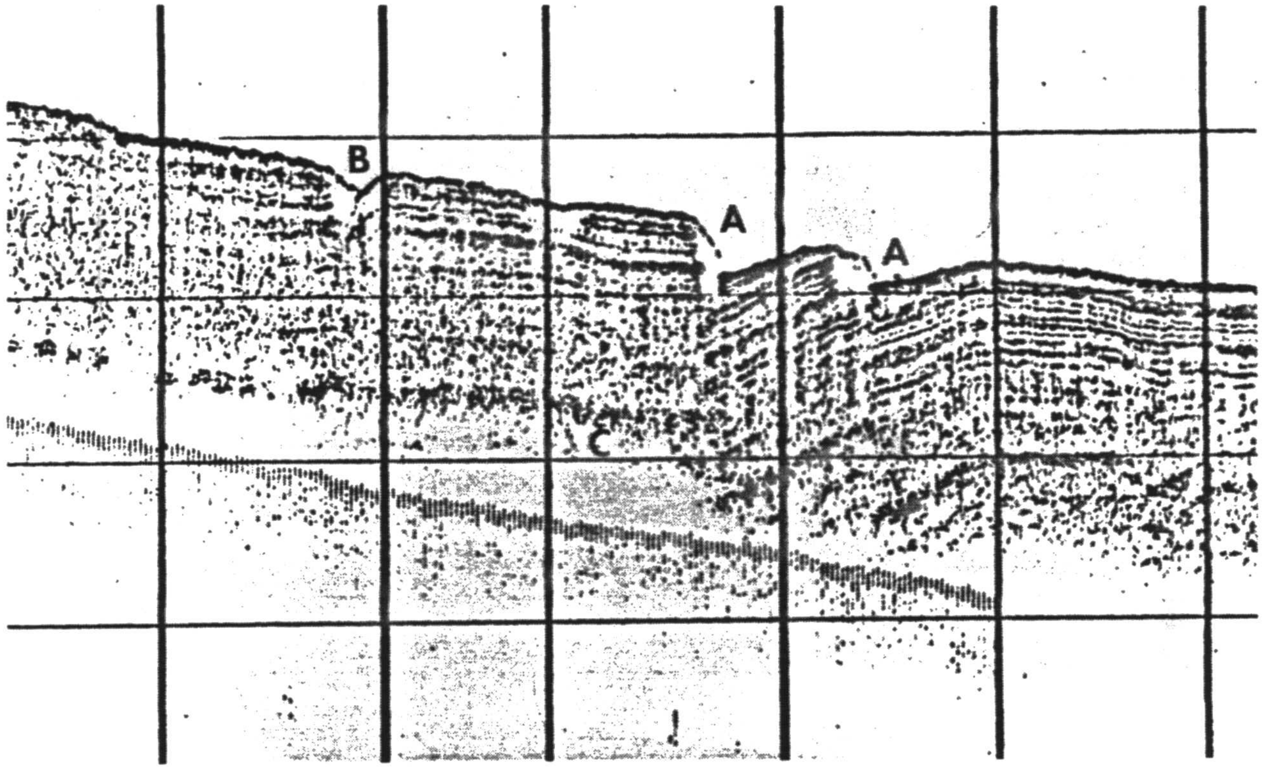

Figure 13 High-resolution seismic line run across several peripheral slides. Navigation fixes are 500 feet apart, and timing lines are 31.5 feet apart. A, rotational slides; B, newly forming rotational slide upslope; C, note the offset in this reflection horizon.

Each mudflow gully possesses a long, sinuous, narrow chute or channel that links a depressed, hummocky source area on the upslope margin to composite overlapping depositional mudflow lobes on the seaward end. Figure 14 schematically illustrates the major morphologic characteristics of these features. Each instability is bounded on its upslope side by a bowl-shaped depression that serves as the source area. Often, multiple head scarps and crown cracks can be seen on the side-scan sonar records, indicating upslope retrogression. Within the bowl-shaped depression, hummocky, irregular, distinctive blocks of various sizes and arrangement can be discerned. Downslope from the bowl-shaped source area is an essentially elongate narrow chute. These chutes or gullies are bound by very sharp linear escarpments that are arranged parallel or subparallel to one another. The area enclosed by the scarps is downthrown and is composed of irregular chaotic topography of blocks of debris of varying sizes. Commonly, the blocks within the chute area are smaller toward the central axis of the gully. The gully floors are 10 to as much as 60 feet below the adjacent intact bottom. The slopes along the sides of the gullies range from less than 1° to as high as 19°. Most of the gullies extend downslope approximately at right angles to the depth contours and may be more than 4-6 miles long.

In plan view, these features are rarely straight, quite commonly are markedly sinuous, and have alternating narrow constrictions or chutes and wider bulbous sections. Figure 15 is a side-scan sonar mosaic constructed from lines run across a zone of mudflow gullies. The area covered by the mosaic

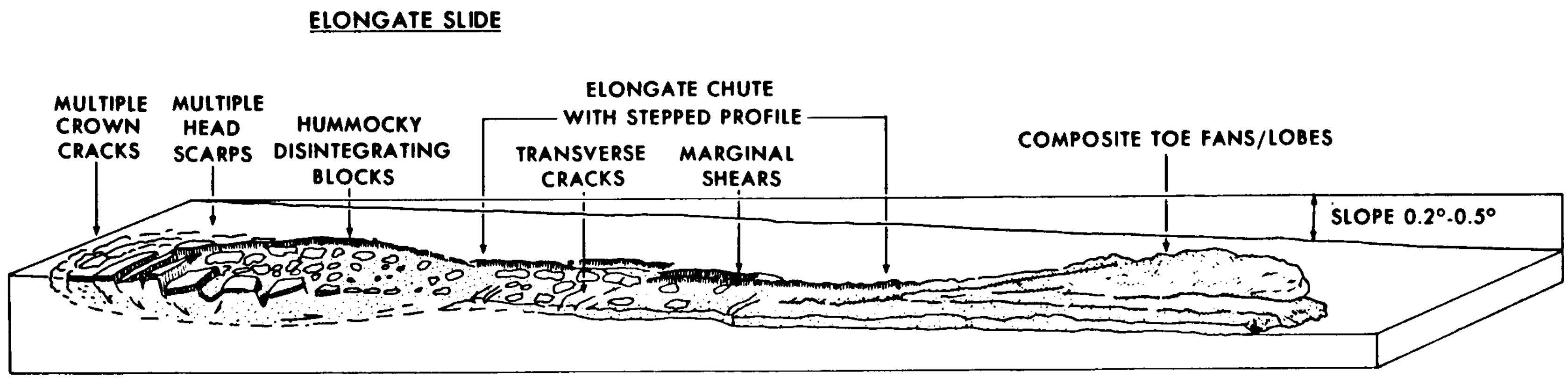

Figure 14 **Schematic diagram illustrating the morphology of mudflow gullies and depositional mudflow lobes. Stippled areas represent disturbed sediment.**

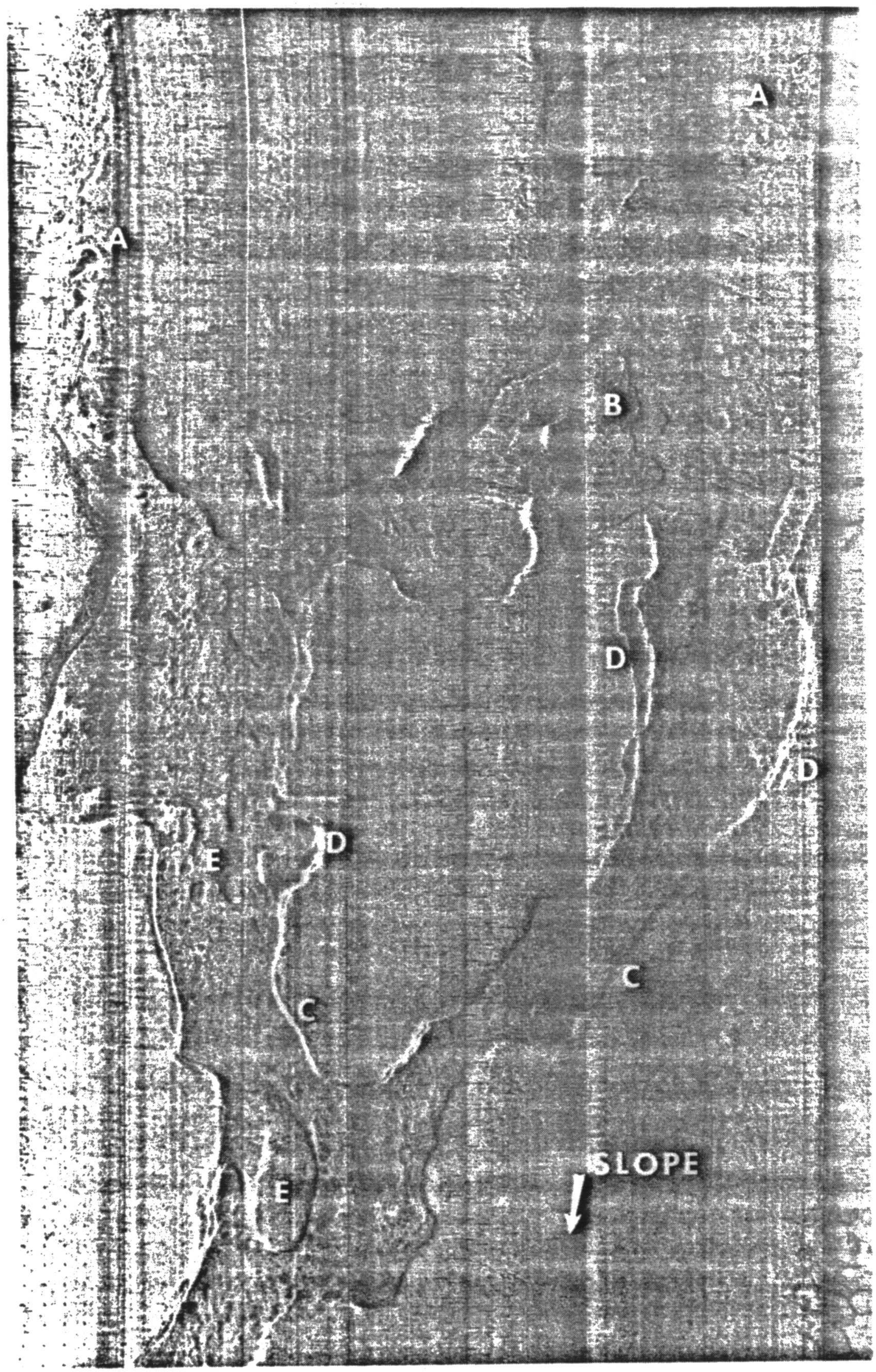

Figure 15 Side-scan sonar mosaic showing several landslide gullies. Grid is 82 x 82 feet, and the mosaic is 0.7 x 1.1 mi. Water depths are approximately 70 feet at the top of the figure and 110 feet at the lower end. A, source area; B, retrogressive gully; C, narrow incised gully; D. sidewall-instability slides; E, large erratic blocks in gully floor.

is 0.7 mile by 1.1 miles. Three major elongate gully systems are shown, beginning with blocky source areas (A) bounded by scarps. The source area geometry is very irregular; considerable differences exist in block size and orientation. One gully has retrogressed upslope and has eaten into an adjacent well-established gully (B). The narrow gullies are relatively deeply incised (C), and evidence of sidewall instability is indicated by the small slumps along the gully margin (D) and by the alternations of bulbous source areas and narrow chute regions. The widths of the individual gullies range from 60 to 500 feet at the narrow points to 1,200-1,800 feet at the widest. The floors of the gullies are characterized by large erratic blocks of different sizes (E) found in complexly fractured remolded debris. At the downslope ends of the gullies, extreme widths of as much as 1 mile can be found.

In many areas, particularly in shallow water, adjacent gullies coalesce to form branching tributary systems, and commonly their junctions are discordant and are marked by accumulation of lobes of debris discharges from a tributary into the main channel. The debris often spills out of the channel and forms ridges or natural levees along the channel margin. Figure 16 is a high-resolution seismic line run across a mudflow gully (A), showing the overbank spillover of debris and formation of topographic ridges or natural levees (B). The material undoubtedly must be quite viscous for this feature to form. The buildup of such features often gives the gully a perched topographic expression, as shown on Figure 16. The spillover material along the gully shown in Figure 16 is approximately 6 feet thick, and the topographic levee has relief on the order of 10 feet and a width of 150 feet. Such spillover features commonly form where a tributary channel enters a major gully, where the gully has tight sinuous bends, or where a narrow gully has been blocked by large piles of debris and blocks.

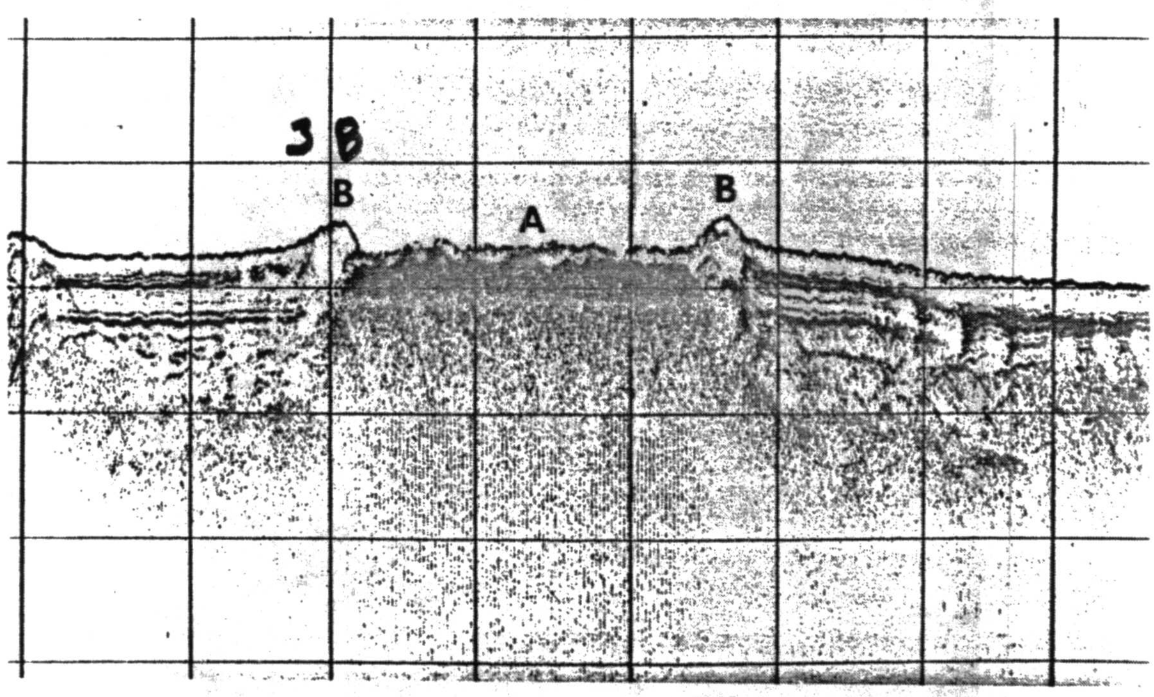

Figure 16 High-resolution seismic record run across a gully where remolded debris has been ejected out of the valley onto the adjacent slopes, forming natural levees. Navigation fixes are 500 feet apart, and timing lines are 31.5 feet apart. A, mudflow gully floor; B, topographic overbank natural levees.

The sidewalls of the mudflow gullies are subject to instability; this slumping can produce contrasting forms and is probably responsible for localized widening along an individual gully system. Figure 17 is a side-scan sonar mosaic showing extremely narrow gullies (approximately 100 feet wide), which are characterized by many elongate crack systems parallel or subparallel to the main boundary scarps, suggesting linear block faulting toward the gully floor. These crack systems are labeled A on Figure 17. In the bowl-shaped areas, arcuate scarps representing shallow rotational slide slumping are more common, resulting in the

tion seismic line run at right angles to the axis of a narrow gully. Several rotational slides (A) on both sides of the channel can be discerned. As the blocks slump down into the gully, they are carried downslope during the next episodic movement of the debris in the gully. Note the offset of reflection horizons and the stairstepped topographic expression of this instability.

The formation of elongate chutes of this type is very similar to the morphology associated with subaerial debris flows and some types of subaerial mudflows. The chutes or chan-

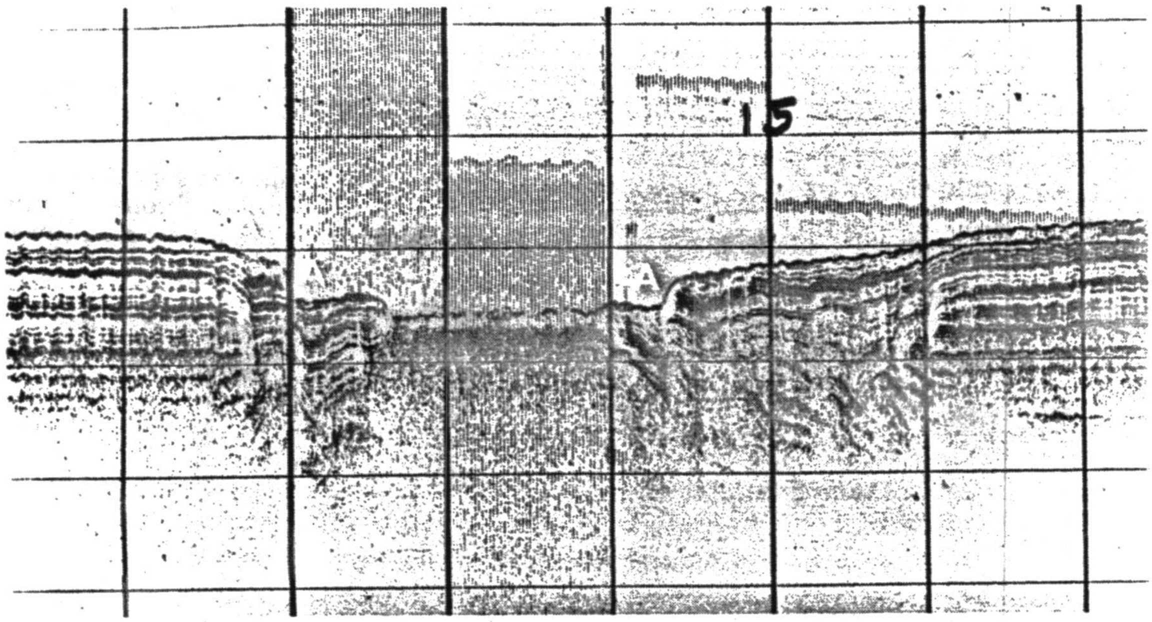

Figure 18 **High-resolution seismic line run across a mudflow gully that shows numerous sidewall rotational slides (A). Gully is approximately 1,200 feet wide and has a relief of 25 feet. Navigation fixes are 500 feet apart, and timing lines are 31.5 feet apart.**

zones and constitute transport conduits for disturbed and remolded sediments, together with displaced blocks of various sizes. Sediments are remolded as a direct consequence of disturbance of the sediment-water-gas system that accompanies slumping and represents fluidization/liquefaction mechanisms. The mechanism of transport is probably characterized as slurry flow, which can be a type of plug flow in which rigid plugs move over and within a zone of liquefied mud. The presence of partially disintegrated rafted blocks suggests laminar or plug flow rather than turbulent flow.

4. *Mudflow lobes.* At the seaward or downslope ends of the mudflow gullies, extensive areas of irregular bottom topography are composed of discharged blocky disturbed debris. In plain view, this discharged debris is arranged into widespread overlapping lobes or fans. This morphological feature is illustrated schematically in Figure 14.

Each lobe is composed of two major morphological features: an almost flat or gently inclined surface (less than 0.5°) and an abrupt distal scarp representing the downslope "nose" of the displaced debris. The seaward scarps range in height from only a few feet to more than 75 feet, and have slopes as great as 7° to 10°. In plan view, the scarps are generally curved and adjacent lobes are separated from one another by major reentrants. Because of the large number of gullies that front the present delta of the Mississippi River, the displaced debris from adjacent gullies may coalesce, providing an almost continuous sinuous frontal scarp that may extend peripheral to the delta 15-20 miles. Detailed mapping, however, shows that the depositional areas are composed of multiple overlapping lobes, each having its own distinctive seaward nose, and are due to episodic discharge from the gullies farther upslope.

The more recent the emplacement of a lobe, the more irregular and blocky the surface topography; in older depositional lobes, the topography is commonly characterized by small-scale pressure ridges arranged as sinuous parallel ridges and hollows, and in places contains many small mud volcanoes and gas vents produced by the localized sedimentary loading.

Figure 19 is a side-scan sonar mosaic (4,800 x 6,800 feet) of a depositional mudflow lobe emanating from an upslope mudflow gully off

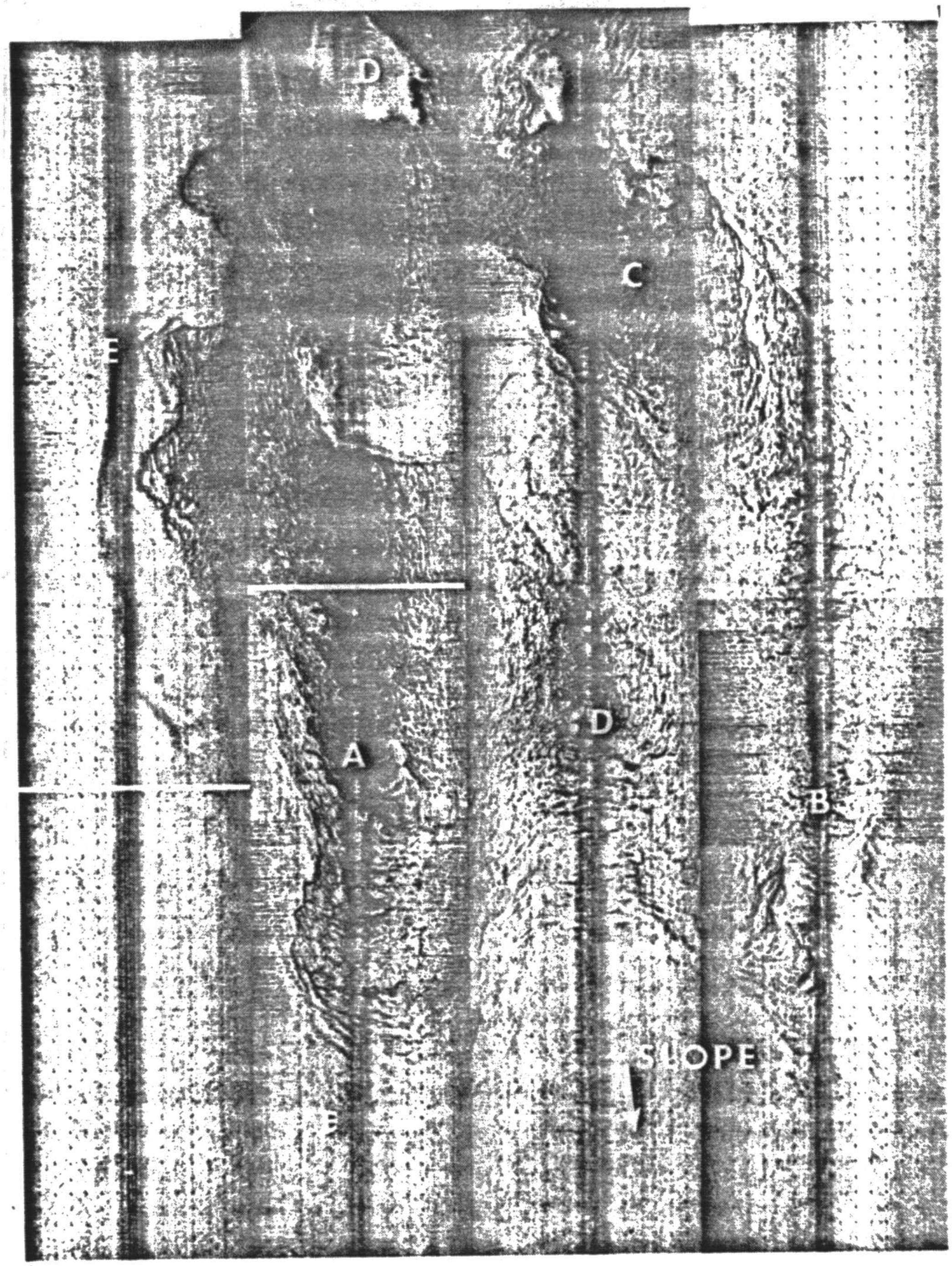

Figure 19 Side-scan sonar mosaic showing multiple overlapping mudflow depositional lobes. The grid tick marks are 82 feet apart. A, B, C, mudflow lobes; D, erratic blocks; E, pressure ridges.

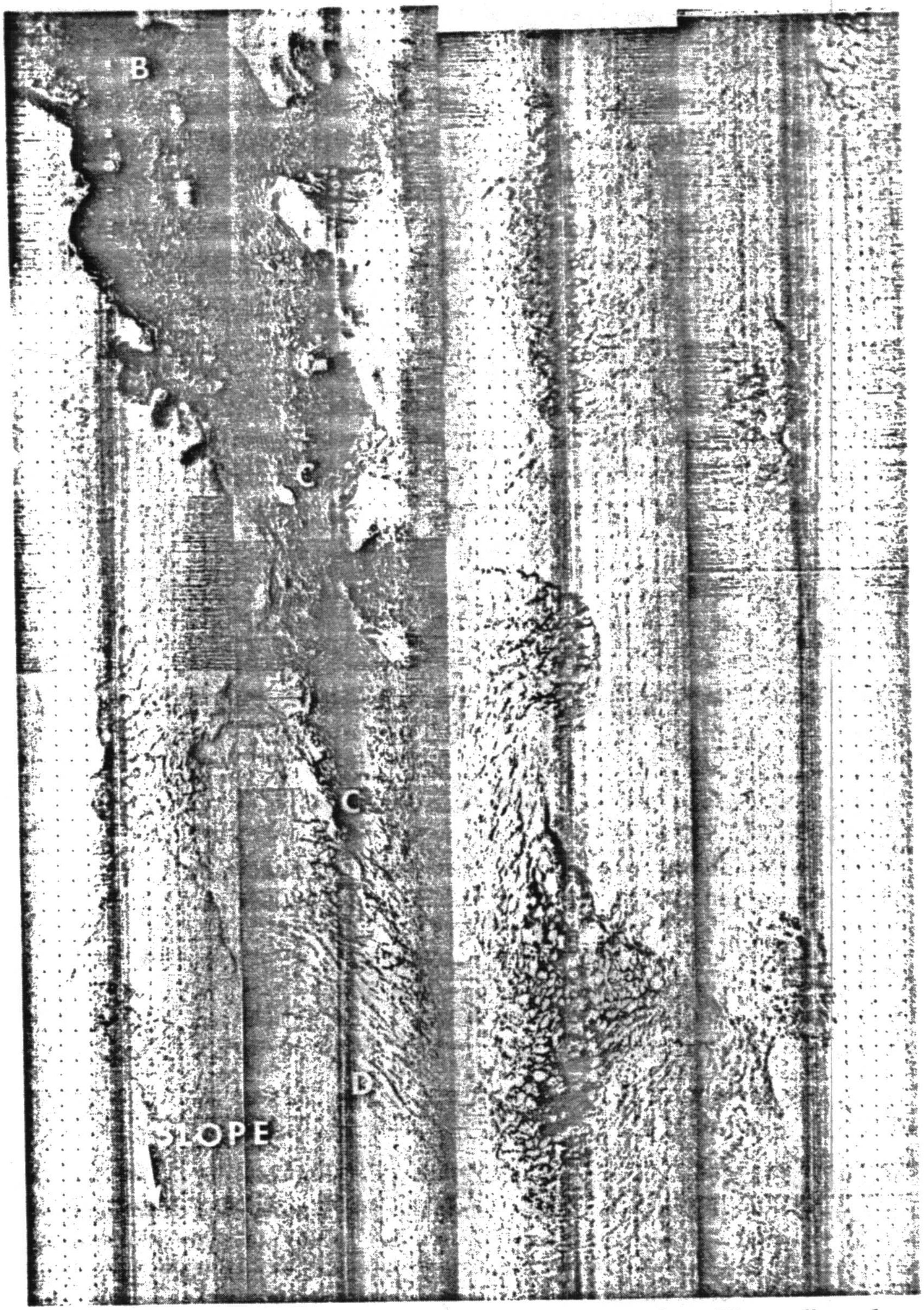

Figure 20 Side-scan sonar mosaic showing lower part of mudflow gully and a single large elongate mudflow depositional lobe. Grid tick marks are 82 feet apart, and mosaic covers an area 1.0 mi by 1.4 mi. A, mudflow depositional lobe; B, mudflow gully; C, large erratic blocks; D, pressure ridges.

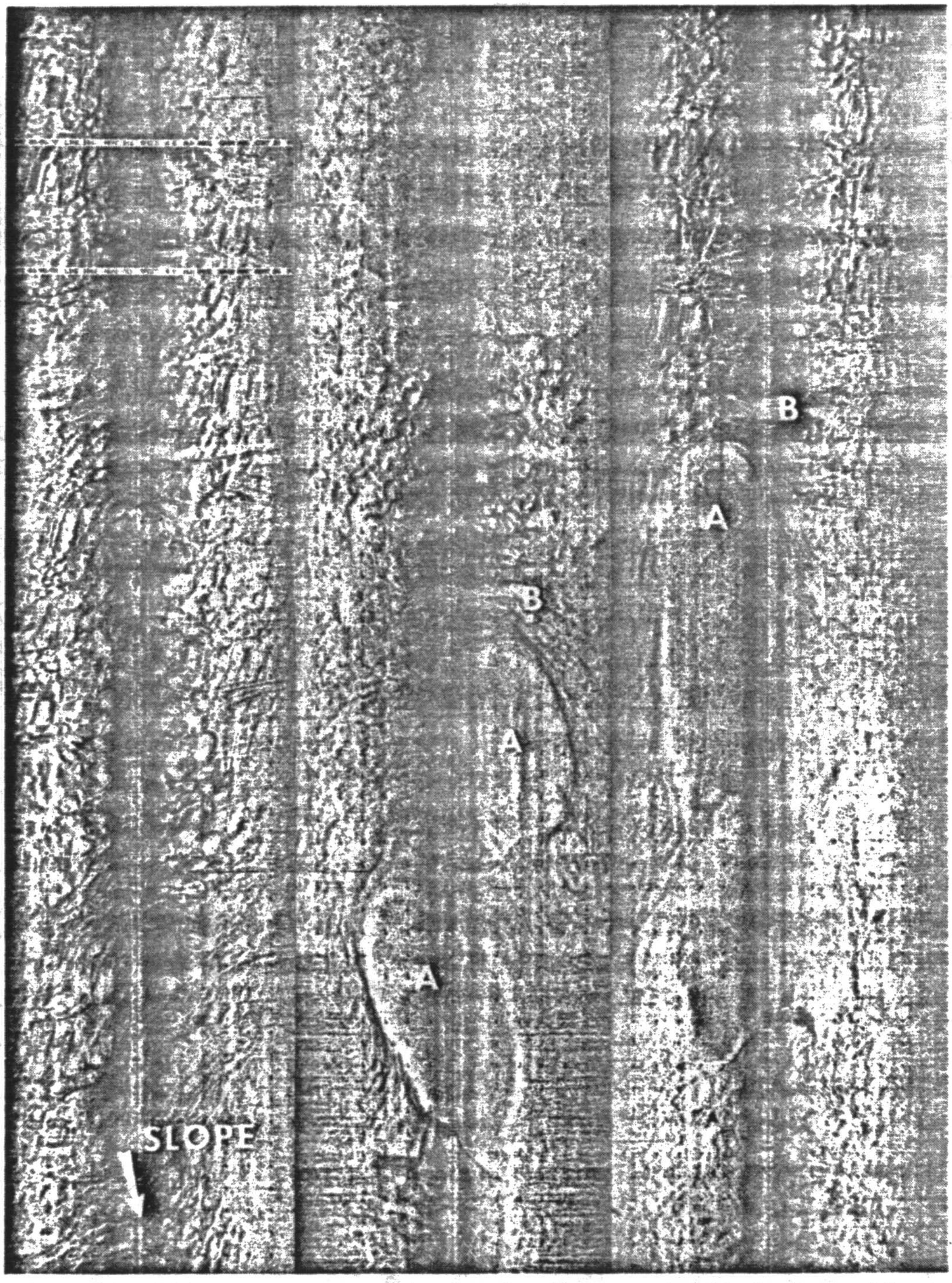

Figure 21 Side-scan sonar mosaic showing large erratic blocks in mudflow lobe. Grid tick marks are 82 feet apart, and the mosaic covers an area 0.7 mi by 0.9 mi. A, large erratic blocks; B, flow lines around blocks.

South Pass, Mississippi River delta. Notice that at least three overlapping lobes (A, B, and C) compose this feature. The discharged debris consists of extremely erratic large blocks, most of which are about 100 feet or so in diameter. Larger blocks (D, Figure 19) are often incorporated in the depositional lobes and may be 500-1,000 feet in diameter. Flow lines are very apparent within the discharged material and indicate differential rates of flow during the movement. Around the peripheral edges of many flows are convective pressure ridges (E, Figure 19) and many small slumps, mud vents, and mud volcanoes. The average thickness of these lobes is 30-40 feet; however, high variation exists from the eastern to the western margin of the delta. Figure 19 shows broad overlapping lobes that are most characteristic of the region around Southwest Pass and off South Pass. Eastward, toward Pass A Loutre, long narrow mudflow lobes are much more common. Figure 20 illustrates a side-scan sonar mosaic of this type of mudflow. Internal morphology (erratic blocks, pressure ridges, etc.) is similar, but the lobe is much more linear and does not tend to spread laterally as much as the previous example. In some places, individual narrow lobes will move downslope for 2-2½ miles. The lobe depicted in Figure 20 has formed an individual feature approximately 5,500 feet long while maintaining a width of only 1,500 or so feet. Note the presence of the many large blocks both within the mudflow gully and in the mudflow lobe.

In the southern and eastern parts of the delta, the upper parts of the mudflows are commonly characterized by many large erratic blocks of various sizes and shapes. Figure 21 illustrates several of these blocks (A) in a region containing a major mudflow lobe. The side-scan sonar mosaic is taken from data run in Main Pass Block 152, where mudflow lobes are very common. The individual blocks range from 500 to 1,500 feet in length and have smooth undisturbed topography on their surface. Figure 21 shows that flow lines (B) wrap around the blocks. Figure 22 is a high-resolution seismic line run across a single block in a region characterized by many blocks on mudflows. The block in the central part of the seismic line is approximately 1,200 feet wide. As can be seen, the block is elevated some 15 feet above the debris floor and shows only minor distortions of reflection events. Approximately 20 feet in the subsurface, few reflections can be seen. Whether

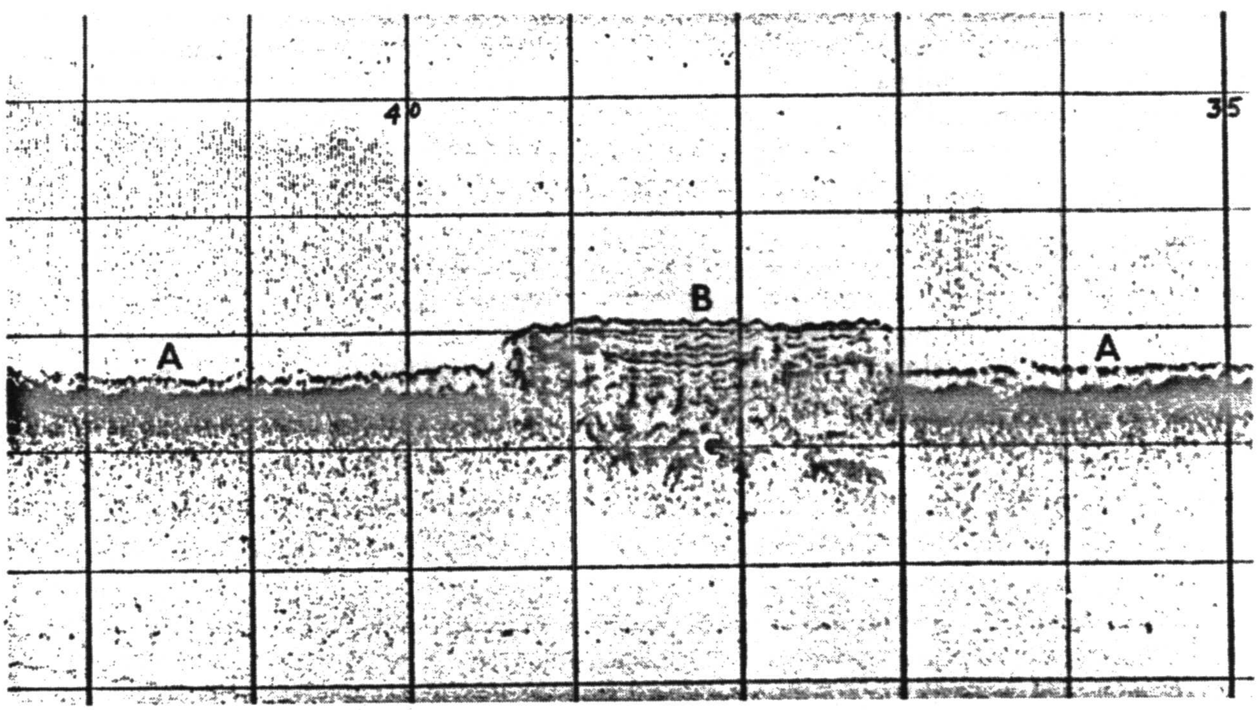

Figure 22 **High-resolution seismic line run across large erratic block in mudflow lobe. Navigation fixes are 500 feet apart, and time-line intervals represent 31.5 feet.**

these blocks represent stable areas of the seafloor or whether they are moving downslope with the debris is uncertain; however, several lines of evidence tend to indicate that the blocks are moving. For example, seismic lines such as the one illustrated in Figure 22 tend to point to instability of these blocks and to indicate that they represent large clasts that are moved downslope during the period of active movement. Soil foundation borings drilled through such blocks tend to show a crustal type of shear-strength profile where the strength from the surface builds up to some level and then abruptly decreases to extremely low values at the cutback.

Episodic failures in the mudflow gullies result in overlapping mudflow depositional lobes, eventually piling up mudflow deposits to a thickness as great as 200-300 feet. Once the mudflow movement has ceased, normal sedimentation out of suspension and sediment introduced by the eruption of mud volcanoes then forms a mantle over the mudflow deposit. This results in a capping of acoustically stratified sediments over an amorphous or nonacoustically stratified mudflow deposit. When another mudflow movement takes place, it overrides and covers previously existing deposits. This overlapping nature of mudflow deposits is illustrated in Figures 23 A and B. Figure 23 A is a high-resolution seismic line run parallel to the axis of mudflow movement; it shows two overlapping lobes (1 and 2) separated by a thin zone of acoustically stratified layers (a). Each of the lobes is 30-40 feet thick. Figure 23 B is a high-resolution seismic line run perpendicular to the axis of mudflow movement. Several overlapping lobes (1, 2, 3, and 4) interfinger with acoustic stratified sediment (a, b, and c). Note that each mudflow at this site is rather thin, ranging from 20 to 40 feet, but because of the aggradation of mudflows, the disturbed section is some 90 feet thick.

The mudflow lobes advance downslope at varying rates but probably move rapidly but episodically. Although no actual instantaneous rates have been measured, repeated surveys have shown as much as 3,000 ft/yr seaward advance of some mudflows. Downslope movement is probably also accompanied by oversteepening of the frontal slope, which produces surficial rotational sliding and could account for some of the large chaotic blocks associated with the seafloor scarp. Movement undoubtedly ceases when the forward momentum is checked by degassing and drainage of internal water or by the lower slope angles of the stable shelf across which the mudflow progrades. At the downslope margins and to a lesser extent at the lateral margins, the mudflows encounter passive pressure from preexisting shelf sediments, and this causes some upthrusting and creation of pressure ridges. Within the area of deposition, and in some places for large distances downslope beyond it, the effects of rapid sedimentary loading cause localized pore water/gas pressures to increase and to be released by mud and gas vents.

5. *Slightly disturbed seafloor and mud volcanoes and vents.* Around the periphery of the seaward-coalescing mudflows a band or rim of disturbed seafloor is often found, characterized by slightly irregular topography and zones of mud volcanoes and mud vents. Generally this layer is less than 10-15 feet thick and is characterized by an amorphous unit on the seafloor overlying acoustically well-stratified deposits. Figure 24 illustrates a subbottom profile and side-scan sonar image run across such a region. The main mudflow lobe is upslope, to the left of the diagram, and the amorphous unit extends some 6,000 feet seaward. Note on the side-scan sonar image that the bottom sediments are characterized by many mud volcanoes and slightly irregular topography. Mud volcanoes in these zones can be extremely large; the bases of the volcanoes commonly attain diameters of 90-150 feet and heights of as much as 20-25 feet.

6. *Erosional furrows.* In two regions off the delta are found zones of erosional furrows. These two areas are off South Pass and off Pass A Loutre. In both areas, the linear furrows radiate into topographic lows or large valley reentrants. Figure 25 is a side-scan sonar mosaic (6,150 x 8,900 feet) of a region off South Pass that illustrates these furrows. Individual furrows can be followed downslope for distances of as much as three miles and are generally oriented at right angles to the depth contours. Those off South Pass are in water depths of 400-1,300 feet and undoubtedly continue downslope, but side-scan sonar data are lacking. The furrows are 30-80 feet wide and have depths ranging from 3-9 feet. Their origin is uncertain, but they are probably the result of scour by bottom currents. Other investigators have reported such features in areas of high tidal currents or in the deep sea and in association with density currents.

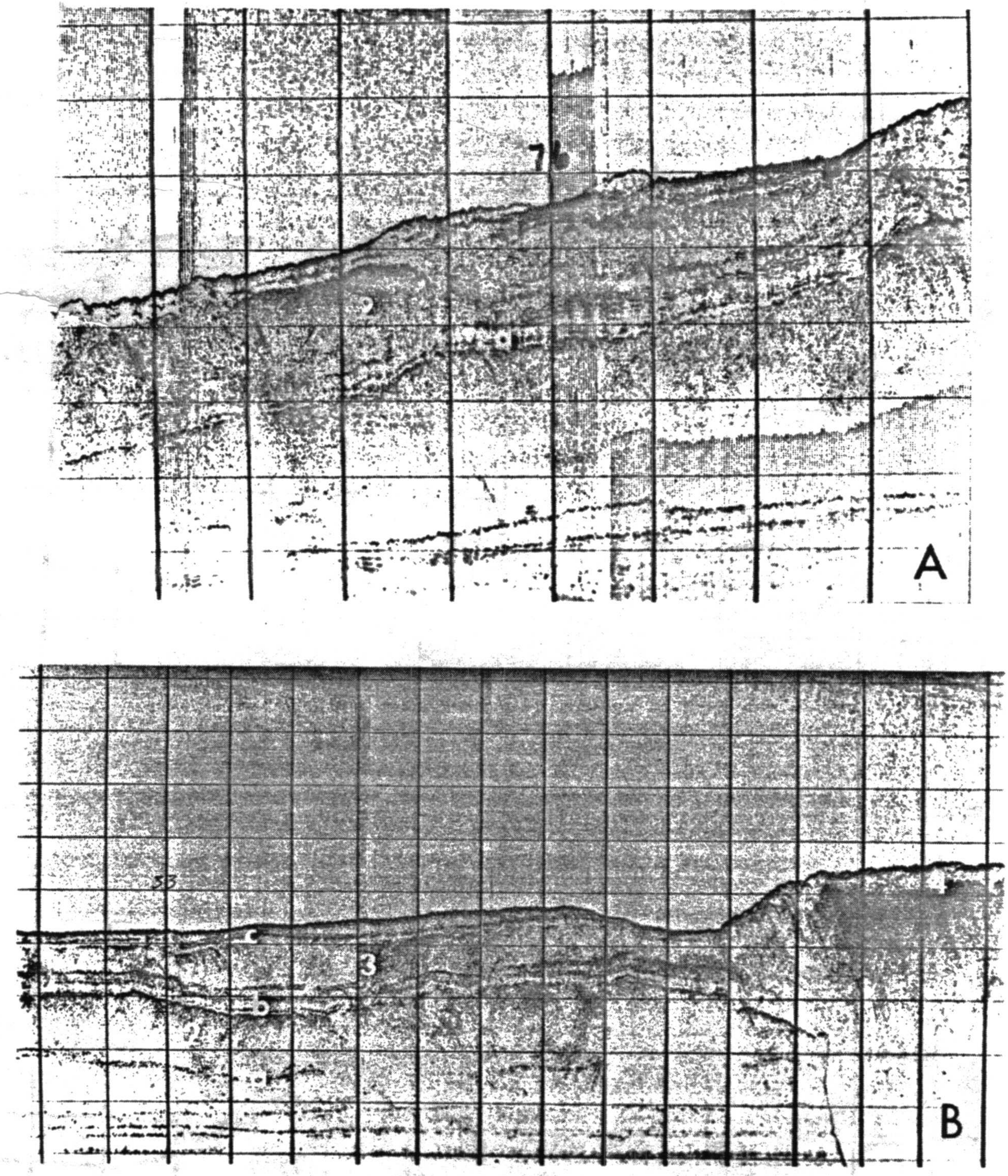

Figure 23 A and B High-resolution seismic records run across mudflow depositional lobes. Navigation fixes 500 feet apart and timing-line interval 31.5 feet. A, seismic section run parallel to axis of mudflow movement; 1, 2, mudflow lobes; A, acoustically stratified sediments; B, seismic section run perpendicular to axis of mudflow movement; 1, 2, 3, 4, mudflow lobes; a, b, c, acoustically stratified sediments.

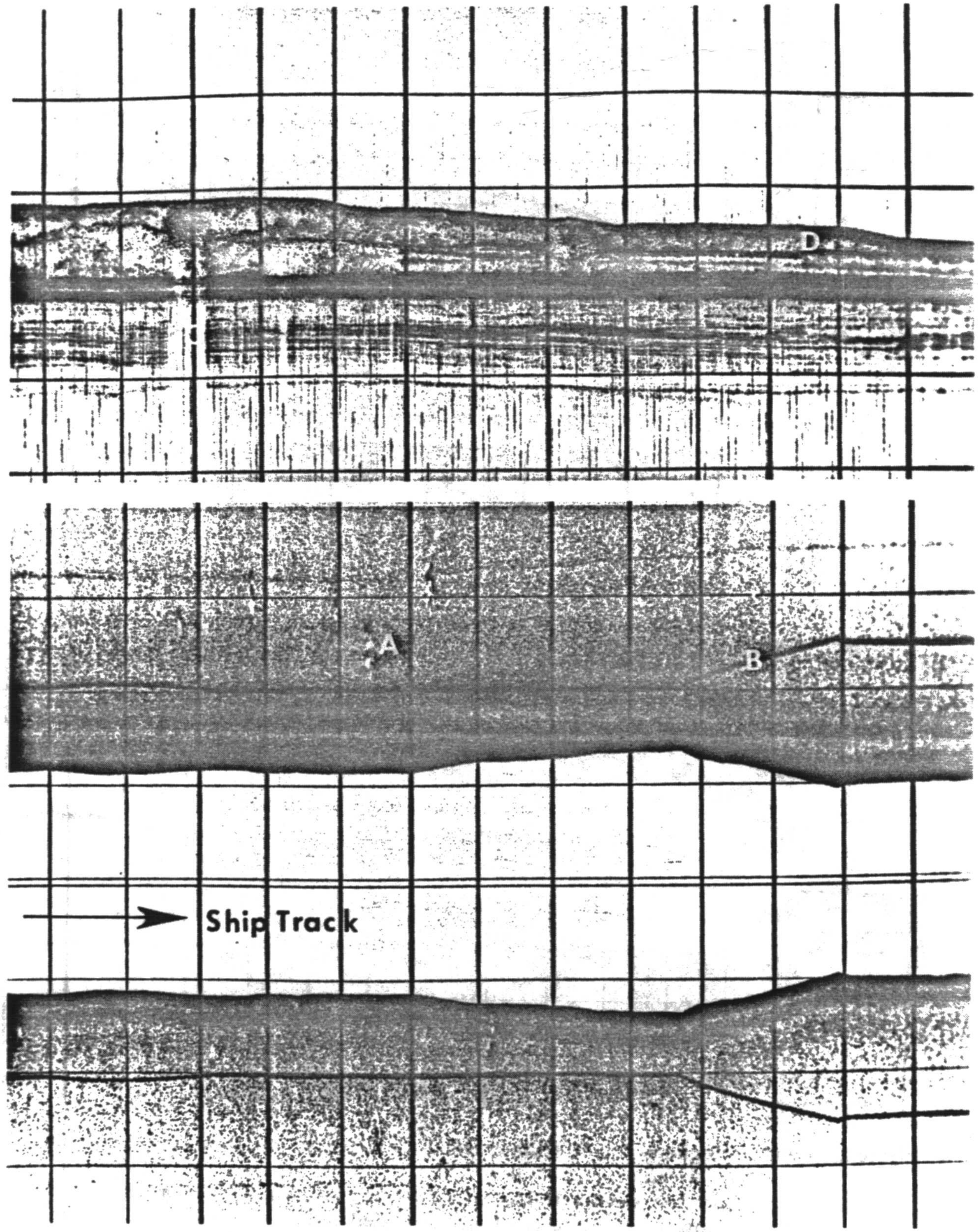

Figure 24 Side-scan sonar image and high-resolution seismic line run across seaward end of mudflow lobe. Side-scan sonar image: Navigation fixes are 500 feet apart, and timing lines are 82 feet apart. A, mud volcanoes; B, tow fish cable length change. High-resolution seismic profile: Navigation fixes are 500 feet apart, and timing lines are 31.5 feet apart. C, acoustic void caused by gas in overlying sediment; D, thin apron emanating off mudflow to right of diagram.

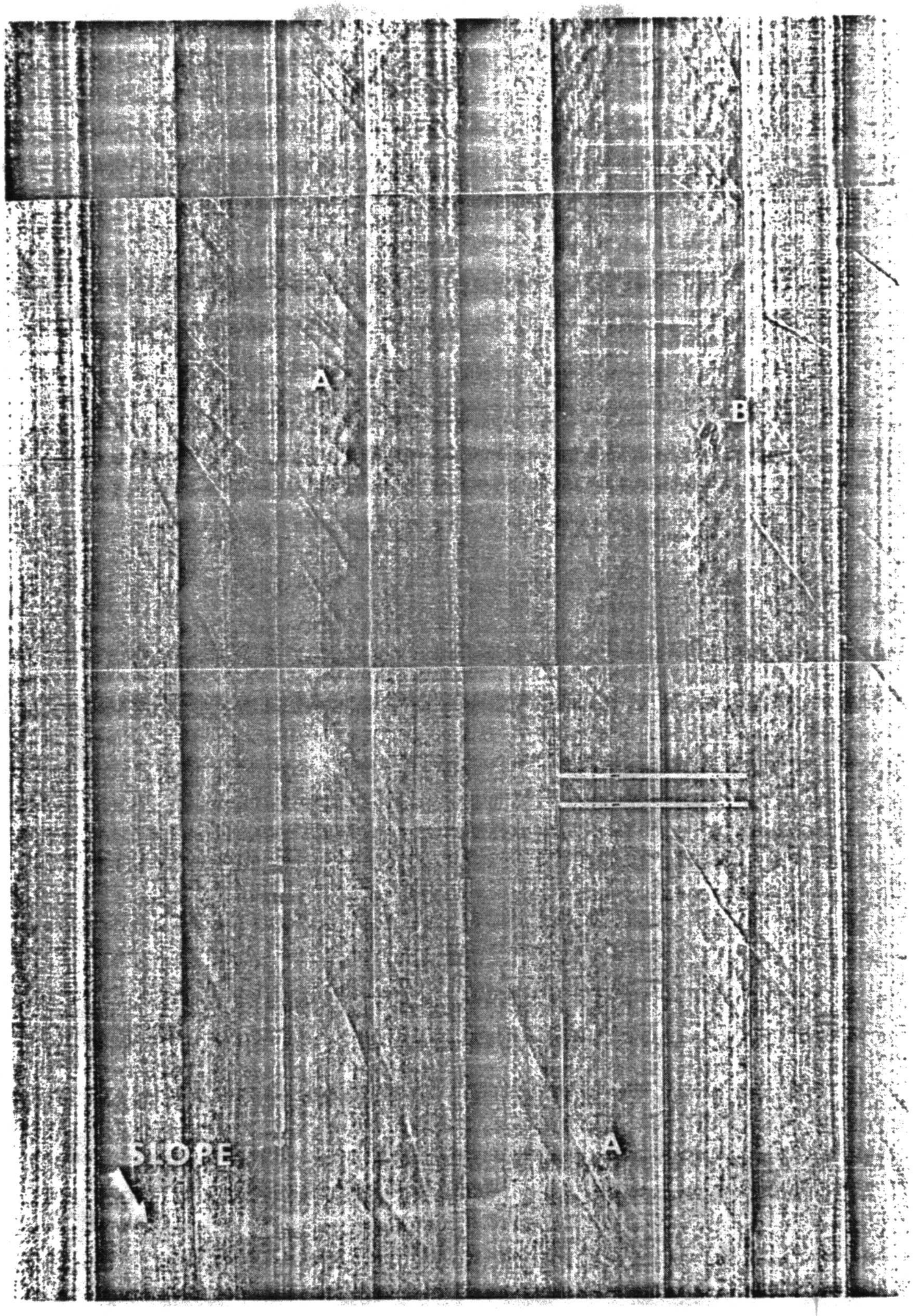

Figure 25 Side-scan sonar mosaic illustrating erosional furrows on the sea floor off South Pass. Mosaic covers an area of 6,150 by 8,900 feet, and grid tick marks are 82 feet apart. A, erosional furrows; B, drill-site location.

Figure 26 is an enlargement of a part of the side-scan sonar record shown in Figure 25, showing the details of some of the furrows.

7. *Reefs.* Along the south and southeast margin of the salt dome in South Pass Blocks 60-67, an extensive cemented reefal system crops out. This unit undoubtedly began its growth during a period of lowered sea level and maintained upward growth as sea level rose. At present, the reef does not appear to be living, but it does protrude above the muddy sediments and provides a rough topographic bottom. Figure 27 is a side-scan sonar mosaic (1.1 x 1.1 mile) illustrating a part of the outcropping reef.

Map 6. Isopach Map of Disturbed Sediment (1 map, 1:100,000)

Map 6 shows the distribution of the thickness of the disturbed sediment based upon measurements from high-resolution seismic data, primarily boomer records. The upslope

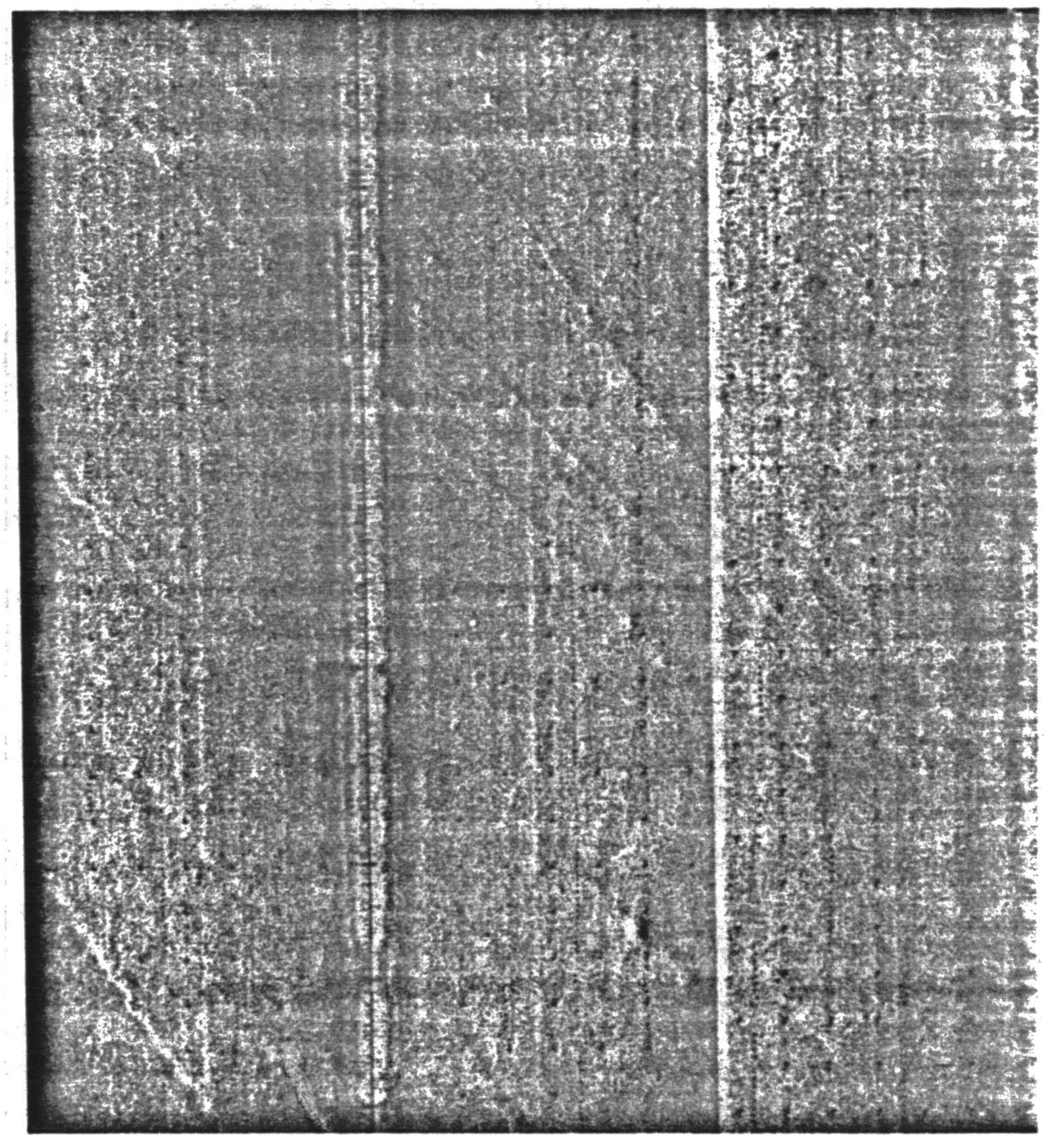

Figure 26 Enlargement of a part of the mosaic shown in figure 25 to illustrate the details of the erosional furrows. Grid tick marks are 85 feet apart.

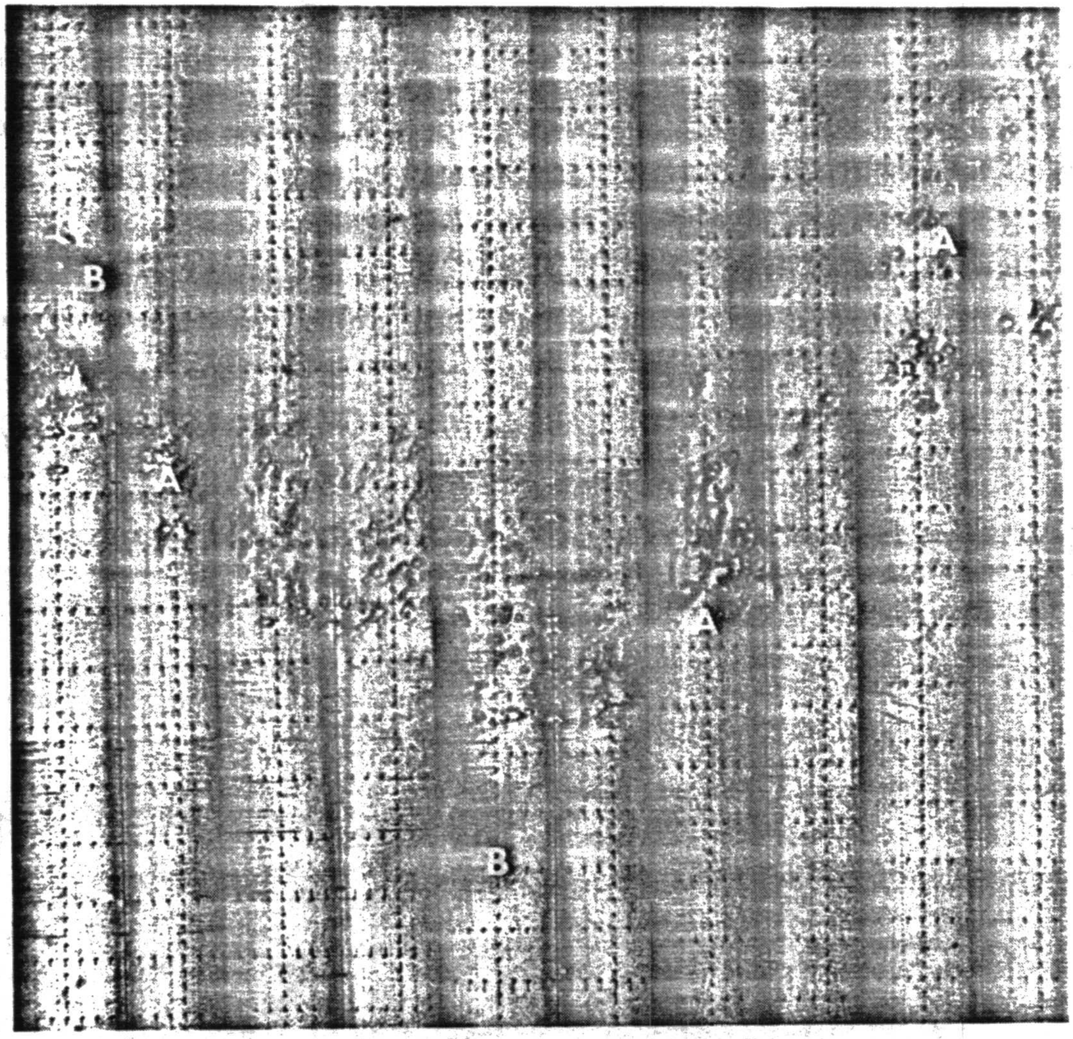

Figure 27 Side-scan sonar record showing distribution of reef around the southern rim of a salt dome (Blocks SP 60-67). A, outcropping reef; B, petroleum-production platform. Grid marks are 82 feet apart. Mosaic covers an area 1.1 x 1.1 mi.

termination of the isopach lines is governed by the data quality. Methane gas in bubble phase within the sediments scatters and absorbs the energy and results in a lack of acoustic returns beyond a certain point upslope. Unfortunately, this is generally the area where the thickest sequence of disturbed sediments occurs. However, the map does give a rather regional view of the extent of sediments disturbed by downslope mass-movement processes.

The thinner parts of the disturbed sediments (sediment thicknesses less than 20 feet) are extremely difficult to measure because of the relatively low slope angles and the broad extent of such areas. The accuracy is probably not as great in these areas as in the regions where thicker sequences form distinct mudflow lobes.

The thickness was measured directly from each record and is based on a two-way travel time of 5,000 ft/sec. Gas in the sediment undoubtedly causes much slower velocities in some areas, and therefore it is believed that the isopachs represent maximum thicknesses. Figure 28 is a part of a boomer record showing the base of the disturbed sediments, which was typical of the type of measurements made. A prepared acetate scale was moved along the record until an even increment of ten feet of sediment was encountered and the shot point location was noted on the base map, including corrections for setback distance from the navigation antennae.

Map 7. Geologic Structure - Shallow Subsurface (1 map, 1:100,000)

In addition to the surface types of sediment instabilities, buried mass-movement features exist but do not show on side-scan sonar records. The high-resolution seismic records show a wide range of various types of disturbance features that extend below the surface and down to depths below seismic penetration. Map 7 shows the distribution of these features as interpreted from each seismic line.

The following examples are shown on this map:

1. *Gas line.* Biochemically produced methane gas generated in the sediments and existing in a bubble stage is extremely efficient in scattering and absorbing acoustic energy. Subbottom acoustic returns are no longer received at some point when the amount of gas, the bubble density, or the thickness of gas-saturated sediments attains a certain value. At present, the intensity of these variables is unknown, and all that can be determined is that returning acoustic energy is rapidly lost and no signals are received. This point on each seismic line was mapped and is marked on Map 7.

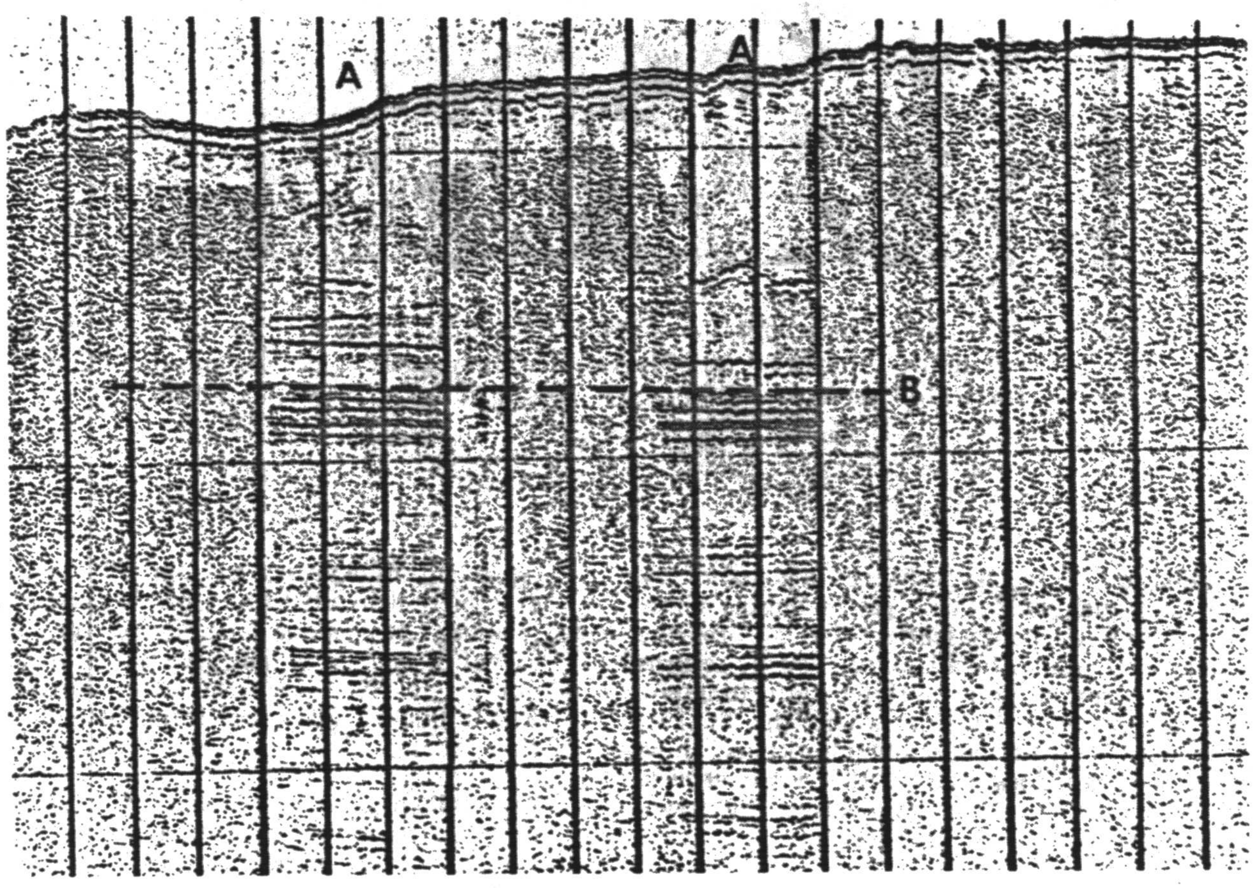

Figure 28 **High-resolution seismic record illustrating seismic window (A). The horizon labeled B represents the base of disturbed sediments. Navigation fixes are 500 feet apart, and timing lines are 125 feet apart.**

Figure 29 shows an example of a boomer record in which such a change in returning acoustic energy is evident. By utilizing this point on each data line, zones of no acoustic returns can be mapped. It is highly probable that only small amounts of gas in the sediments can significantly degrade the seismic signal. In a few areas where the mudflows are thin or in areas that have degassed (for example, in some of the collapse depressions or mudflow gullies), small seismic windows can be seen. Figure 28 illustrates several of these isolated windows.

2. *Line of 0 disturbance.* By utilizing the side-scan sonar and subbottom high-resolution records, an interpretation of the seaward extent of disturbed sediment can be made. This line, shown on several of the maps, is an interpretation and attempts to show that seaward of the line no evidence of downslope mass movement can be discerned. Because of the formation of a thin broad apron seaward of most mudflow lobe scarps, this line is highly interpretive and could show major differences, if mapped by several different personnel. The authors attempted to work together on the data sets to arrive at a common point on which to draw this line.

3. *Faults.* In the deeper waters of the outer continental shelf surrounding the modern bird-foot delta are found a wide variety of contemporaneous slumps and faults, the distribution of which is shown on Map 7. In many areas, the edge of the continental shelf is crenulated; the crenulations normally coincide with many intersecting arcuate rotational slumps and faults. Many of these features are presently active, as they cut the seafloor, but the rate of movement is normally not known because of lack of borings, stratigraphic control, and radiometric dating.

One of the most common types of fault at the edge of the shelf and on the upper continental slope off the Mississippi River delta are

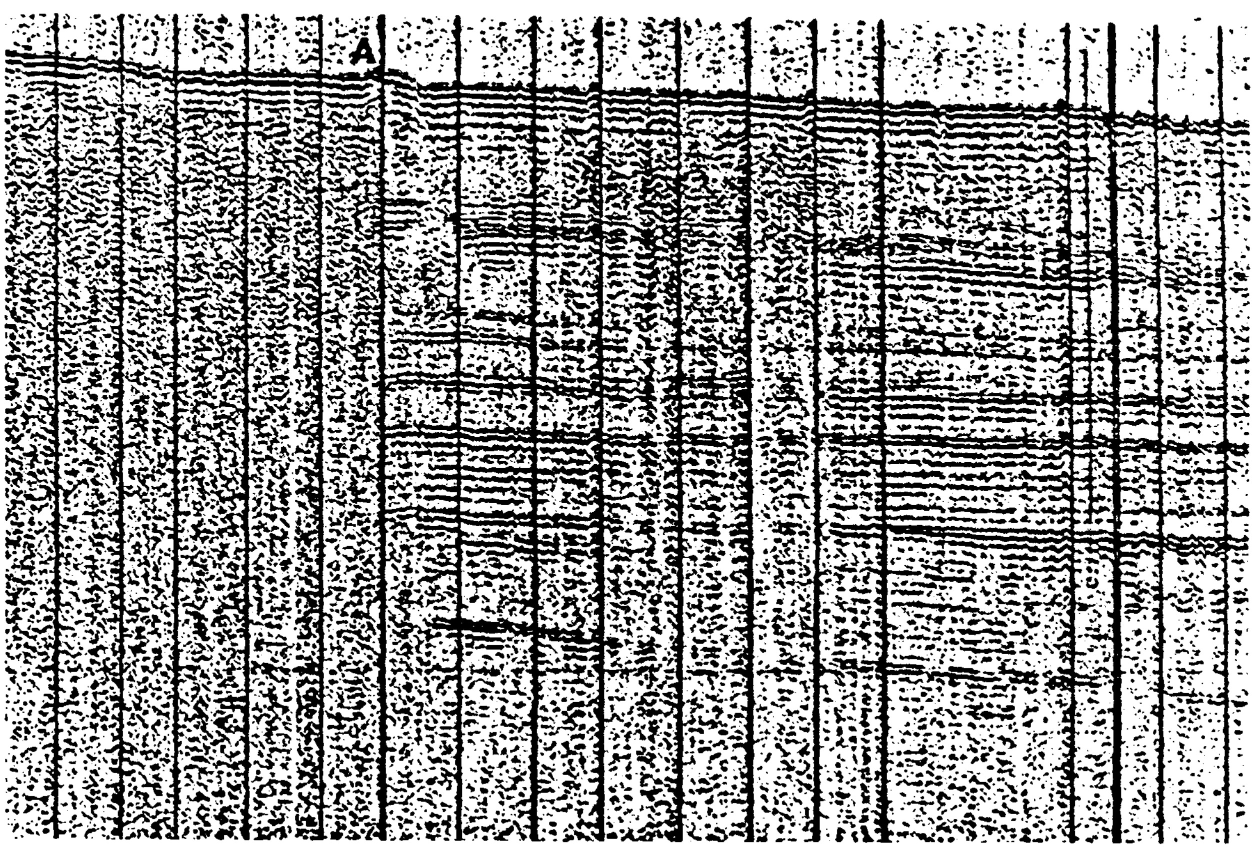

Figure 29 **High-resolution seismic record illustrating the effect of gas in sediments on seismic signals. Navigation fixes are 500 feet apart, and timing lines are 125 feet apart. Mosaic covers an area 1.1 x 1.1 mi.**

large down-to-the-basin fault systems that are forming contemporaneously with present-day deposition. In most places, faults formed in late Pleistocene times, and movement along the fault plane has been continuous to the present. Many of these faults cut the present seafloor and result in large scarps that attain heights of 40-100 feet. In faults that show no surface expression, sedimentation has kept pace with movement along the fault. These types of faults are generally referred to as contemporaneous faults, or, in common terms of the Gulf coast petroleum geologist, growth faults. On such faults, movement is continuous through long periods of time, and accumulation of sediment on the downthrown side is contemporaneous with movement. Offset of individual beds in the subsurface increases as depth increases along the fault. Higher sediment accumulation rates are found on the downthrown side of the fault than in a similar bed on the upthrown side of the fault. Figure 30 illustrates a high-resolution seismic section across such a fault system slightly beyond the edge of the continental shelf off the Mississippi River delta. The increase in offset with depth and the higher accumulation on the downthrown side of the fault are well illustrated in this example.

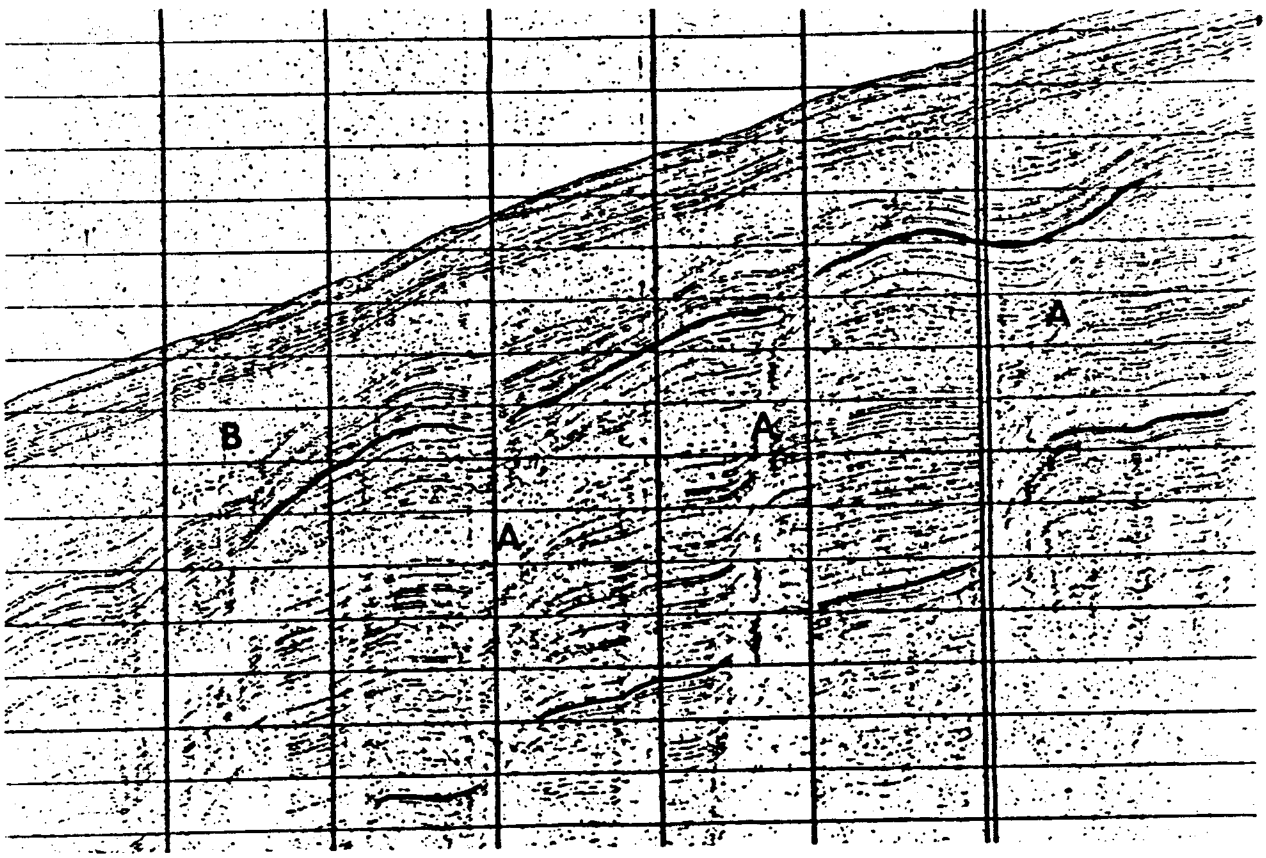

Figure 30 **High-resolution seismic record run across several contemporaneous faults (A) near the shelf edge off South Pass. Note that offset of marker beds increases as depth increases along a given fault. The mudflow unit (B) also appears to increase in thickness as it crosses this zone of faults. Navigation fixes are 50 feet apart, and timing lines represent 25-foot increments.**

Figure 31 shows another seismic section run across a contemporaneous fault and illustrates the presence of a thickened section of mudflow material as it has moved across the fault trace. This type of mudflow is one mechanism for adding a thicker sedimentary sequence to the downthrown sides of the fault. Normal sedimentation settling out of the water column in these water depths would be measured in fractions of an inch per century, but because of the presence of mass movement of sediment by mudflows, considerable volumes of sediment can be added to the sedimentary column. As the surface mudflows cross the faults, sediment accumulates rapidly across the fault scarp on the downthrown side. Thus, a greater volume of mudflow accumulates on this side, adding weight to this side of the fault and probably playing a role in maintaining the continuing movement along these faults.

The presence of these faults generally south of South Pass and the subsequent downslope movement associated with the faults have resulted in the creation of a large reentrant in the bathymetric contours. This topographic valley (Map 4) has a width of approximately 5-7 miles and relief of 500 feet from the ridge crest to the bottom of the valley.

4. *Folds.* In the vicinity of the contemporaneous faults, folding of the sediments is a common feature. This folding is highly evident on

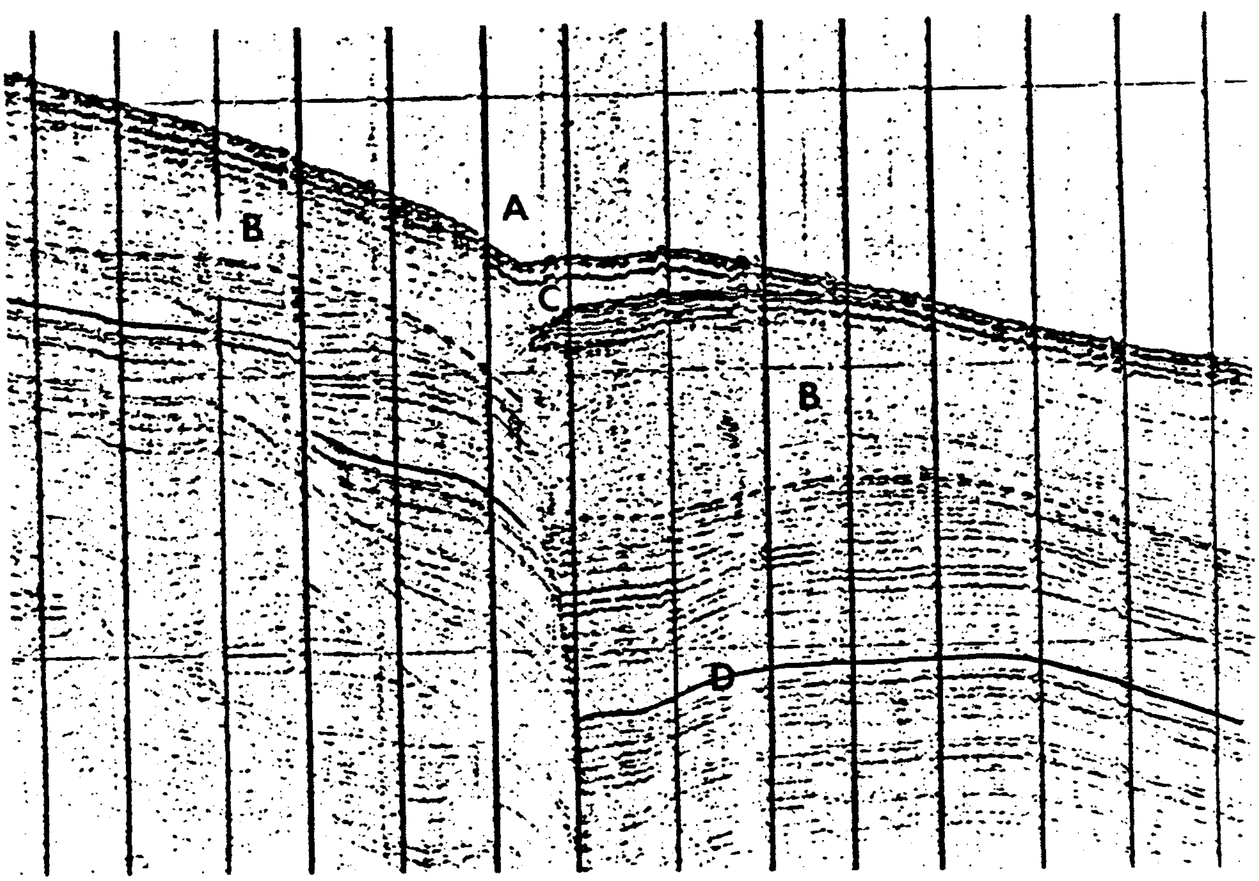

Figure 31 High-resolution seismic record run across a contemporary fault (A) showing the increased thickness of a mudflow (B) as it crosses the fault. Note the small zone of mudflow material (C) accumulating on the fault scarp on the sea floor. Marker horizons (D) also show greater displacement at greater depth. Navigation fixes are 500 feet apart, and timing intervals are 125 feet apart.

the seismic data, and even has seafloor expression on some bathymetric profiles. In general, the folding exists in the upper 500 feet of the sedimentary column. The axes of the synclinal troughs are depicted on Map 7. The folding is generally asymmetrical; the folds are broad anticlines and exceptionally tight syclinal troughs. Relief between the crest of the fold and trough is variable but averages 20-40 feet. Wavelengths of the folds are also variable, but most tend to be on the order of 1,200-2,500 feet. Figure 32 is a boomer record illustrating this type of sediment instability. The exact mechanism producing these folds, their rate of formation, and their present state of activity are unknown. However, the association of the folds with the zone of growth faulting tends to indicate that compressional forces play a major role in their formation. Folds in the sediment can also form, as downslope creep of sediments is laterally confined.

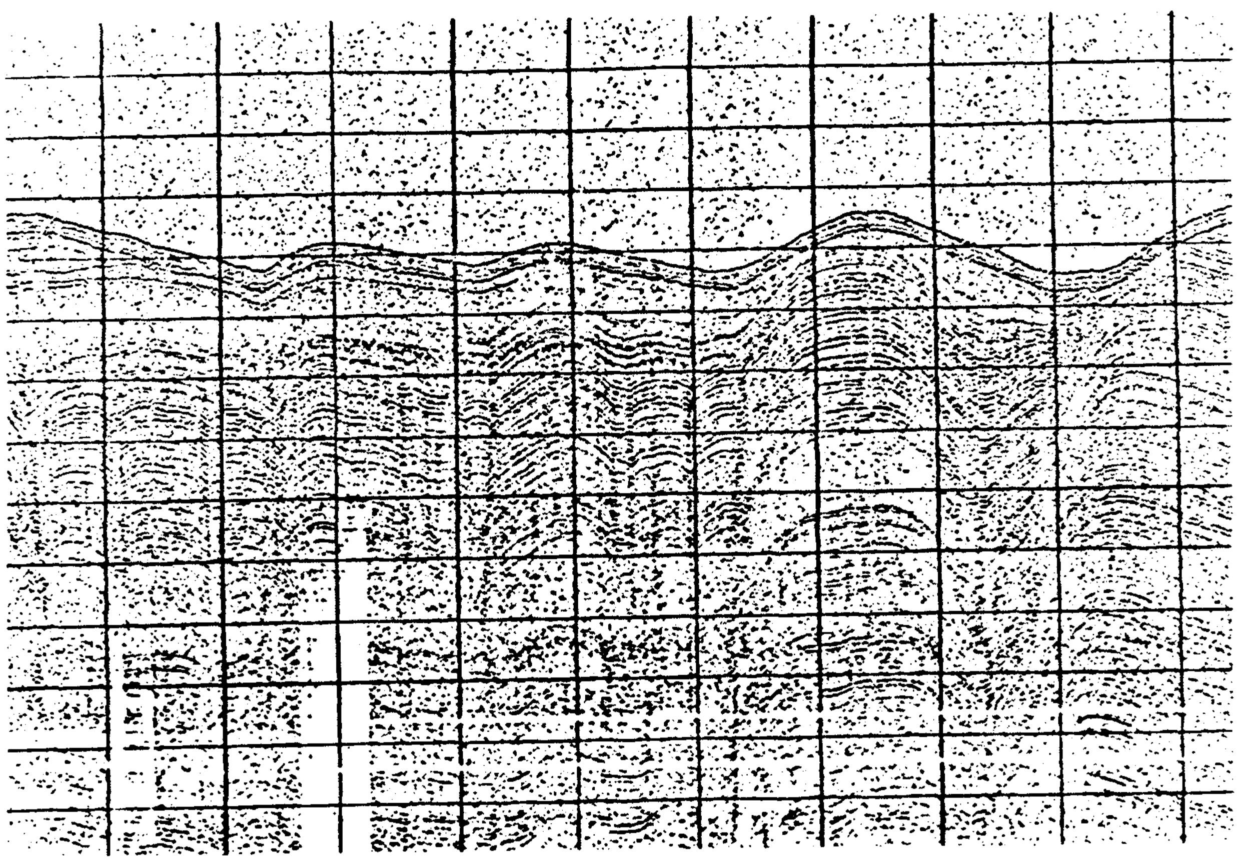

Figure 32 High-resolution seismic record run across a series of folds off South Pass. Note the tight synclines and broad anticlines. Navigation fixes are 1,000 feet apart, and timing-line intervals represent 25 feet.

5. *Shelf-edge separation scar.* Off the central part of the delta is a large buried shelf-edge truncation or separation scar. Figures 33 and 34 illustrate the major characteristics of this feature along high-resolution seismic lines. As can be seen, reflections are abruptly truncated (a, Figure 33; A, Figure 34) and then, an infilling of strata shows relatively high dip angles. These infilled sediments have been termed an "accretion unit." The steepest dips are 6° to 8° and, as infilling proceeded, dip angles decreased to 3° or less. This feature probably represents a massive failure at the shelf edge during late Pleistocene times at a lower sea-level stand. After failure, the topographic trough was rapidly filled, forming the steep inclined bedding near the scarp and less inclined bedding away from the scarp. The failure took place either during the Illinoian Glacial Stage (120,000 years B.P.) or the Wisconsin Stage (35,000 years B.P.). The scale of this feature is extremely large, and the basal shear plane cuts down into the sediment for thicknesses as great as 1,200 feet. Seismic tracing of reflection events from dated horizons in borings tends to give some evidence that the failure did not take place until the late Wisconsin low sea-level stand (approximately 20,000-35,000 years B.P.) and that the infilling had been completed by the last

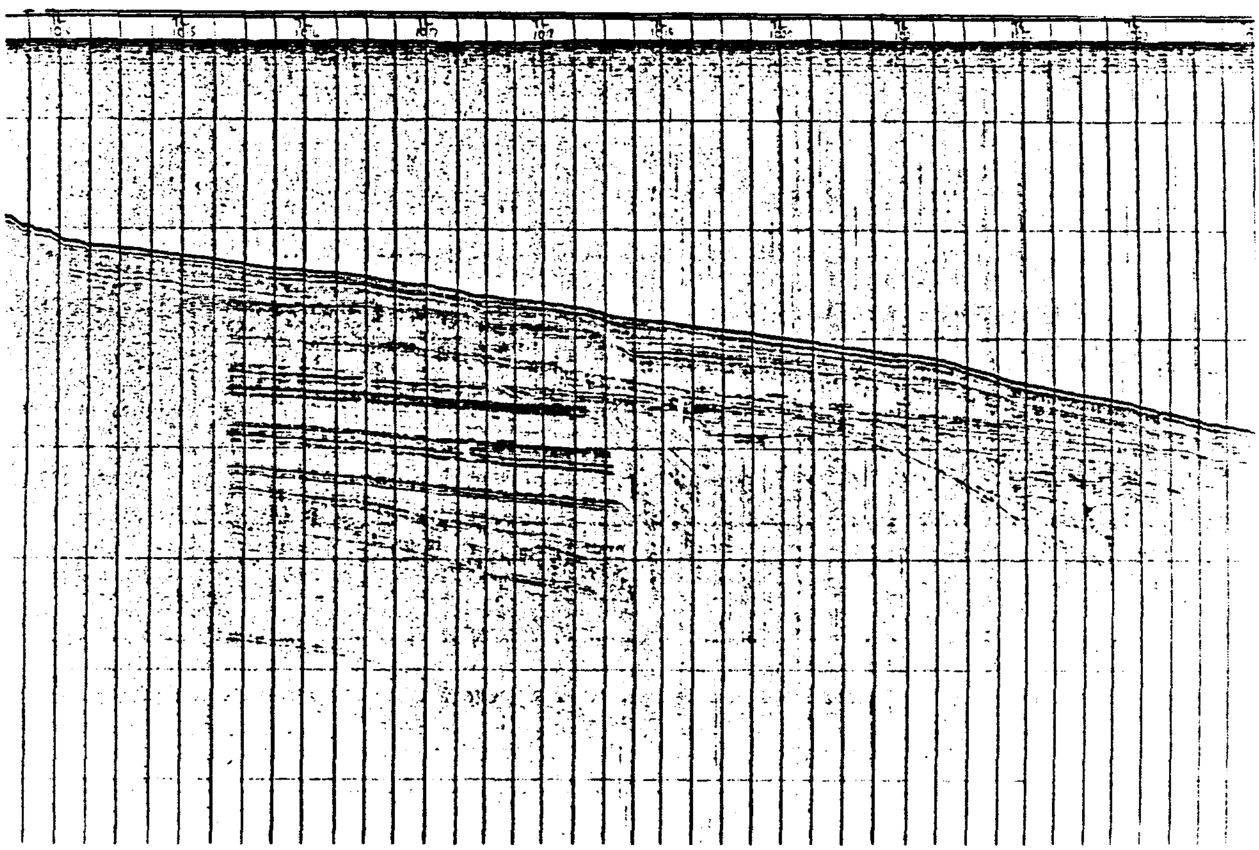

Figure 33 High-resolution boomer record run across the shelf-edge separation scar. Navigation fixes are 500 feet apart, and timing-line interval is 125 feet. a, failure scar; b, steeply inclined infilling bedding; c, marker horizon correlated seismically to borings and dated at 35,000 years B.P.; d, erosional unconformity and marker horizon seismically traced to boring and dated at 15,500 years B.P.; e, effects of gas in sediment causing no acoustic reflections; f, buried mudflow that has taken place since 1874, according to bathymetric map comparisons.

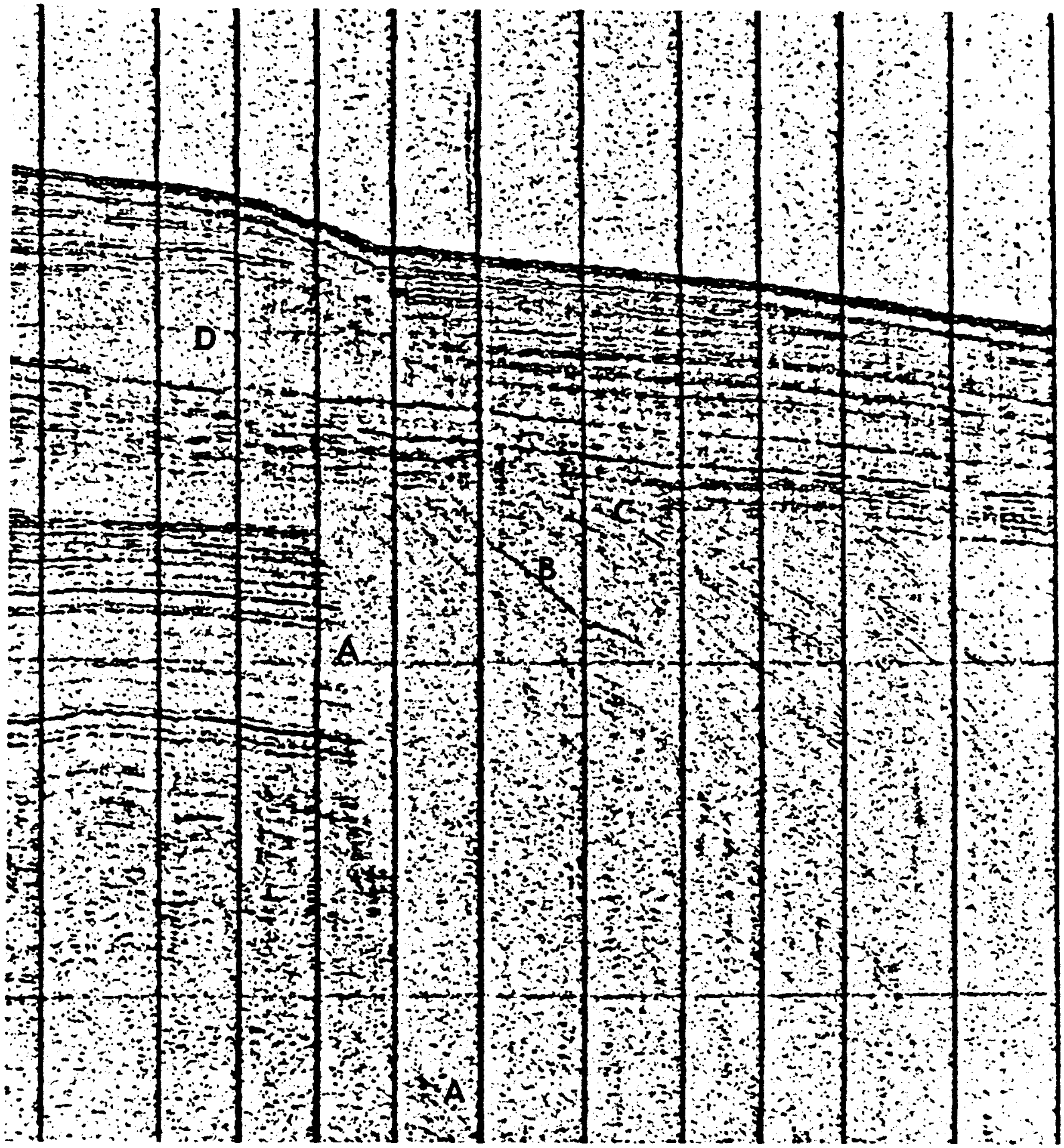

Figure 34 Detailed high-resolution seismic line run across shelf-edge separation scar. Navigation fixes are 500 feet apart, and time-line intervals represent 125 feet. A, shear plane of failure; B, steeply dipping infilled sediment; C, erosional unconformity (approximately 15,000 years B.P); D, modern mudflow depostional lobe.

stand of sea level (15,000 years B.P.), at which time erosional truncation removed some of the sediment, producing a major erosional unconformity. Dated horizons in several borings, averaging 15,000 years B.P. in age, have been seismically traced across the infilled trough.

6. *Diapirs.* Shallow-seated diapiric structures, primarily salt domes, are found offshore of the modern Mississippi River delta. Some of these features intrude to the near surface, strongly affecting and arching the overlying sediments. Figure 35 illustrates a high-resolution seismic section across such a salt structure in South Pass Blocks 60-67 region. Note that many of the seismic reflections have been distorted and arched upward on the sides of the dome. Mudflow deposits have accumulated around the sides of some domes, being diverted around a topographic high. Other domes have little or no topographic expression today, and the mudflow has accumulated over the top of the dome.

Map 8. Pipelines, Platforms, and Lease Status (1 map, 1:100,000)

This map, with the same basic coverage as the other maps, presents the major development in the offshore Mississippi River delta. The pipelines shown are only those licensed by the Bureau of Land Management, and are the major transportation lines in particular, connecting offshore platforms and well concentrations with the mainland. Shorter feeder and connecting pipelines are far too numerous to show. The platforms, also, are only those considered to be the major platforms of the area, i.e., they are the larger platforms, having one side at least 50 feet in length (USCG,

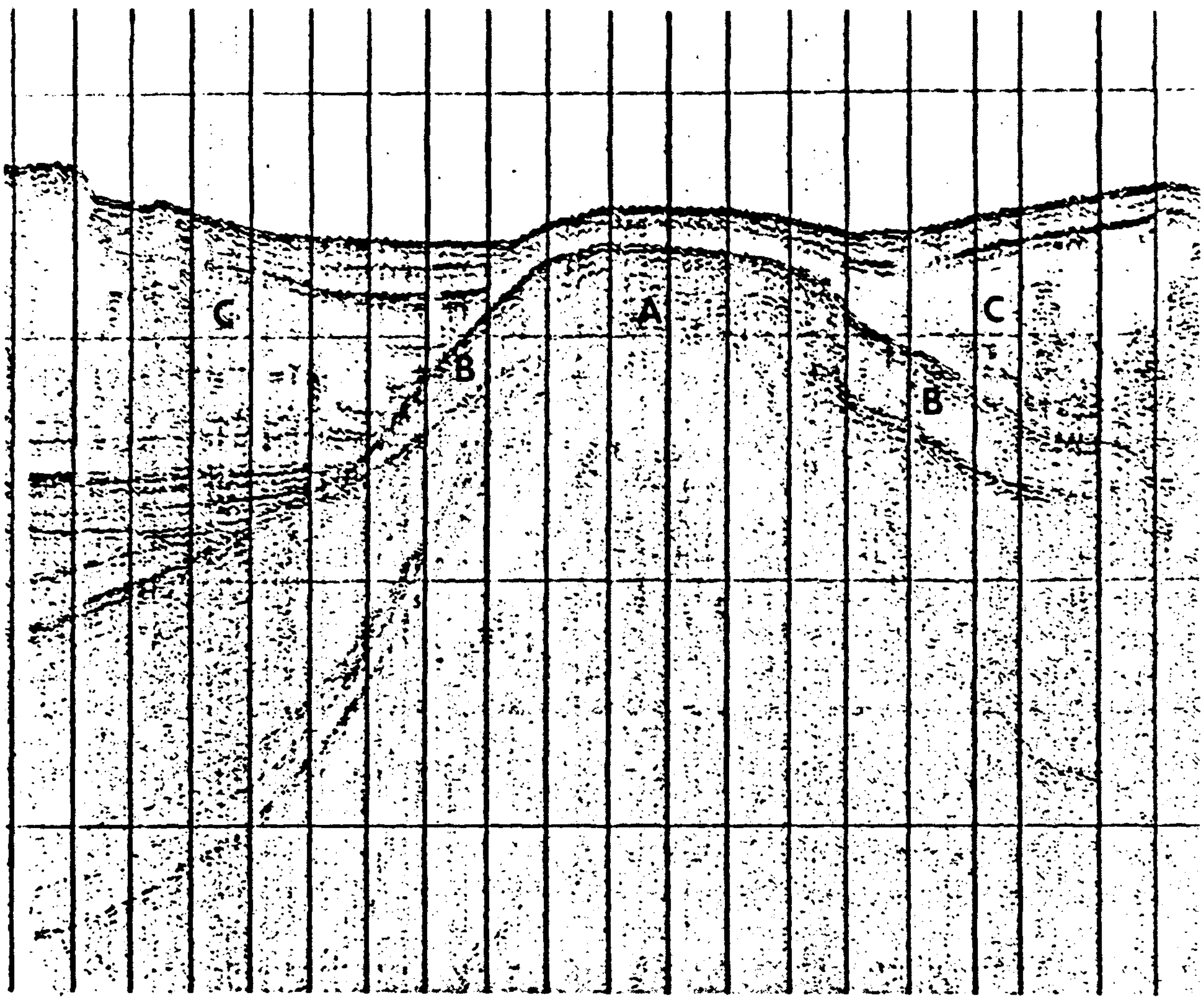

Figure 35 High-resolution boomer record run across shallow-seated salt dome (A) in SP 60-67. Note the steep dips along the sides of the dome (B) and the mudflow lobes (C) that have formed around the sides of the dome. Navigation fixes are 500 feet apart, and timing lines are 125 feet apart.

June 1, 1979). The lease status is shown for those blocks that are active and for those that have expired leases. The present principal lessee(s) are shown for each block. No attempt has been made to subdivide those blocks that contain multiple areas leased.

Of note on Map 8 is the general paucity of large platforms and pipelines throughout this active seafloor area. However, there are 14 large platforms and 3 oil transmission pipelines within or near mudflow lobes, gullies, and collapsed depressions.

A primary intent of this map is to apply the geohazards of Maps 6 and 7 to the further establishments of platforms and pipelines in the offshore delta. Utilization of this map in the planning and licensing of platforms and pipelines may warn and even avert the loss or damage to offshore structures, as happened in 1969 during Hurricane Camille (see BLM Open File Report 80-01, p. 46) when three platforms were lost or damaged due to seafloor mudslides.

Likewise, the set of maps has been used to determine the necessity of cultural resource surveys within certain lease blocks. For instance, BLM is not recommending cultural surveys for tracts 75 and 83 in South Pass Area, South and East Additions, because of the depth of recent sedimentation and mudflow disturbances (see Draft Environmental Impact Statement for Proposed Sales A66 & 66).

Summary

The maps and text are intended to serve primarily as a regional overview of the subaqueous sediment instabilities that exist on the shelf off the modern Mississippi River delta. Previous literature tended to be confined to small areas off the delta, and it was difficult to assess the magnitude of each of the types of failures. The mapping of the data shows many types of sediment instabilities around the periphery of the delta; these vary considerably in magnitude, frequency of occurrence, and the driving mechanisms responsible for their formation. Because of this regional overview of the types and distribution of the subaqueous sediment failures, detailed surveys in individual lease blocks can be better evaluated for changes in bottom features.

The maps show that a variety of sediment failures take place in the deepwater areas at the shelf margin and on the upper slope. However, only small areas of this region were mapped in detail, and little is known about the frequency of movement. It is intended, as a continuing effort, to update this set of maps in the deeper water areas as more data are accumulated in the next few years.

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SECTION II

OIL AND GAS DEVELOPMENT IN THE MISSISSIPPI DELTA MUDSLIDE AREA: RECOGNITION OF A GEOHAZARD

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Introduction

For five decades the continental margin of the U.S. in the Gulf of Mexico has been a major exploration focus for a large segment of the oil industry. However, the capability to find and produce large quantities of petroleum from the seafloor adjacent to the continents has been an unending development.

Interest in oil development began in the 1920's along the Texas and Louisiana coasts as geophysical exploration showed that sizable onshore fields continued under the adjacent offshore seafloor. However, the shallow offshore waters were not enticing to prospectors at this time. Of greater priority was development of drilling engineering onshore where the fields were substantial; the water-logged soil had the consistency of tomato paste and low load-bearing capabilities, pilings sank out of sight in the unconsolidated sediments, and large wooden mats rotted, broke up, or sank. The development of the submersible drilling barge in 1933 provided a major breakthrough for drilling in the lakes, swamps, and marshes onshore, just as 14 years later the use of mobile floating platforms would allow petroleum drilling offshore.

In 1933, the first attempt was made to drill a well in the Gulf of Mexico. The drilling was done from a solid platform of timber pilings in 3.7 m (12 feet) of water about 915 m (3,000 feet) from shore. This hole in the offshore Creole field was dry. The first successful well in the Gulf was drilled in 1937, 1,830 m (6,000 feet) offshore in the Creole field in 4 m (14 feet) of water using a platform of timber pilings (Londenburg, 1972).

By 1941 only ten wells had been drilled off the Louisiana coast, all in the Creole field; only nine more were drilled through 1946, largely because crews spent as much time worrying about German submarines as drilling for oil (Londenburg, 1972).

A few months after the end of World War II, the state of Louisiana held its first offshore lease sale, auctioning off the drilling rights to thousands of acres of offshore state land (Londenburg, 1972). The federal government, seeking additional petroleum resources for the country, began hearings in 1945 to determine whether the state or federal government should control offshore oil and gas leases and development. On September 28, 1945, President Harry S. Truman issued a proclamation declaring that the U.S. should exercise " . . . jurisdiction over the natural resources of the subsoil and seabed on the continental shelf by the contiguous nation is reasonable and just . . . the continental shelf may be regarded as an extension of the land mass of the coastal nation and thus naturally appurtenant to it" (U.S. President (1945-1953: Truman), 1945).

The U.S. Supreme Court did not decide until 1954 where the boundaries lay between state and federal jurisdiction; that demarcation line was revised again in 1975 between the state of Louisiana and federal waters and is in litigation at present.

In October 1947, Kerr-McGee successfully drilled a well in 5.4 m (18 feet) of water 19.3 km (12 miles) from land using a mobile platform. Not only did the well produce, but it was impressive because the operation took little more time from rigging-up to completion than onshore drilling.

Geophysical exploration proceeded at a feverish rate in the late 1940's (Figure 1). For example, in 1948 explorations indicated " . . . the existence of upwards of 90 salt domes and other structures within the (31.4 mile) zone of the Louisiana coast" (Williams, 1948, 154). Efforts were primarily confined to the shallow areas of the continental shelf, gradually pushing to greater distances from shore. By 1955 the offshore frontier had been extended to 80 km (50 miles) with more than 40 platforms in operation. By 1973 exploration for new prospects had progressed to the edge of the continental shelf (Figure 2); 409 offshore fields had been located in the Gulf of Mexico and 14,600 wells had been drilled offshore. Today, major production technology is well developed for the continental shelves while exploration is concentrating on the continental slope and rise. The oil and gas industry agrees that it " . . . must look to the continental shelves and closely adjoining deeper waters for most of the hydrocarbon to be obtained from beneath the seas" (Weeks, 1965, 127).

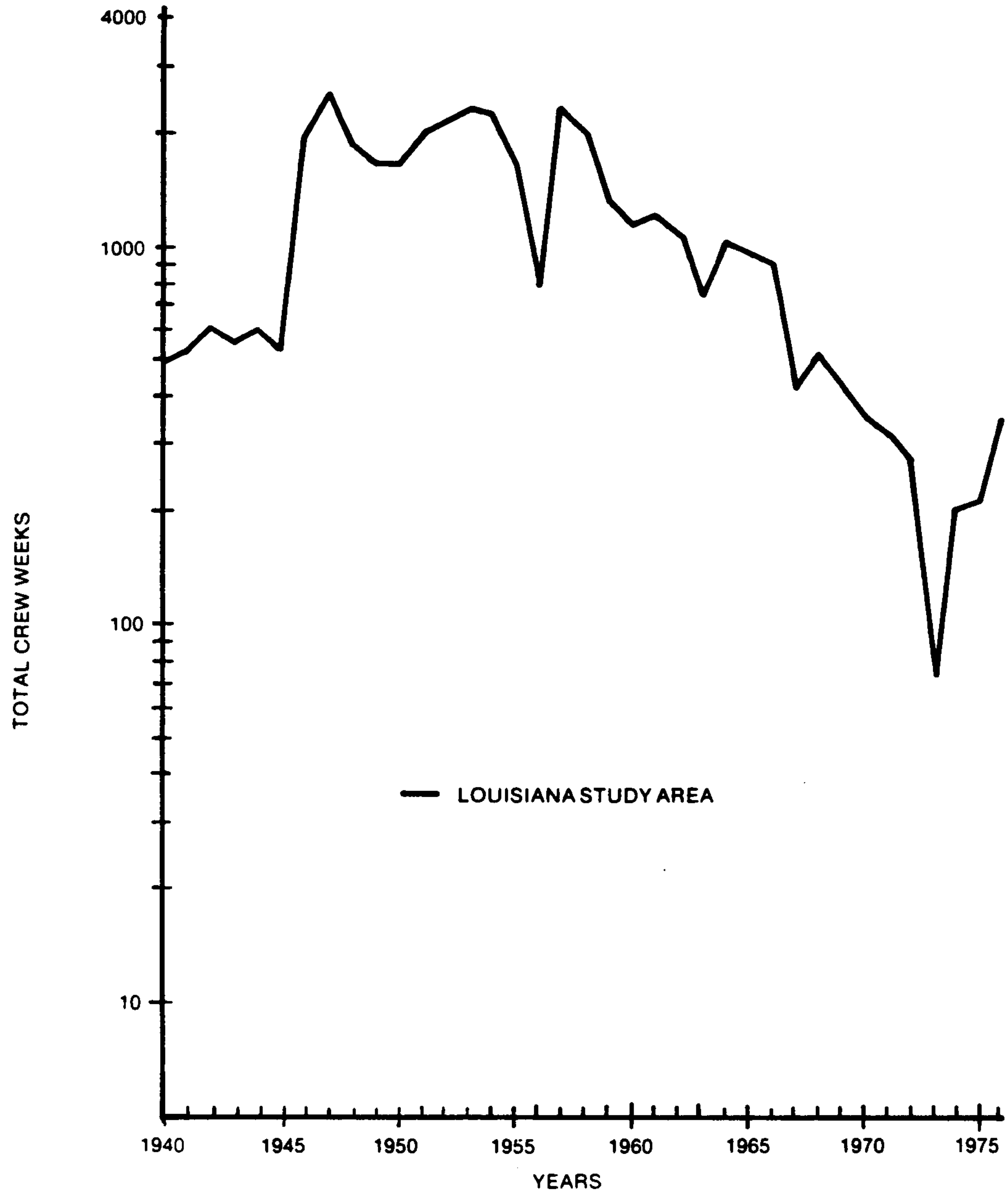


FIGURE 1 GEOPHYSICAL EXPLORATION ACTIVITIES, 1940 - 1976

SOURCES: NATIONAL OIL SCOUTS' & LANDMEN'S ASSOCIATION YEARBOOK. 1941. 1942.
INTERNATIONAL OIL SCOUTS' ASSOCIATION, 1938 - 1974.

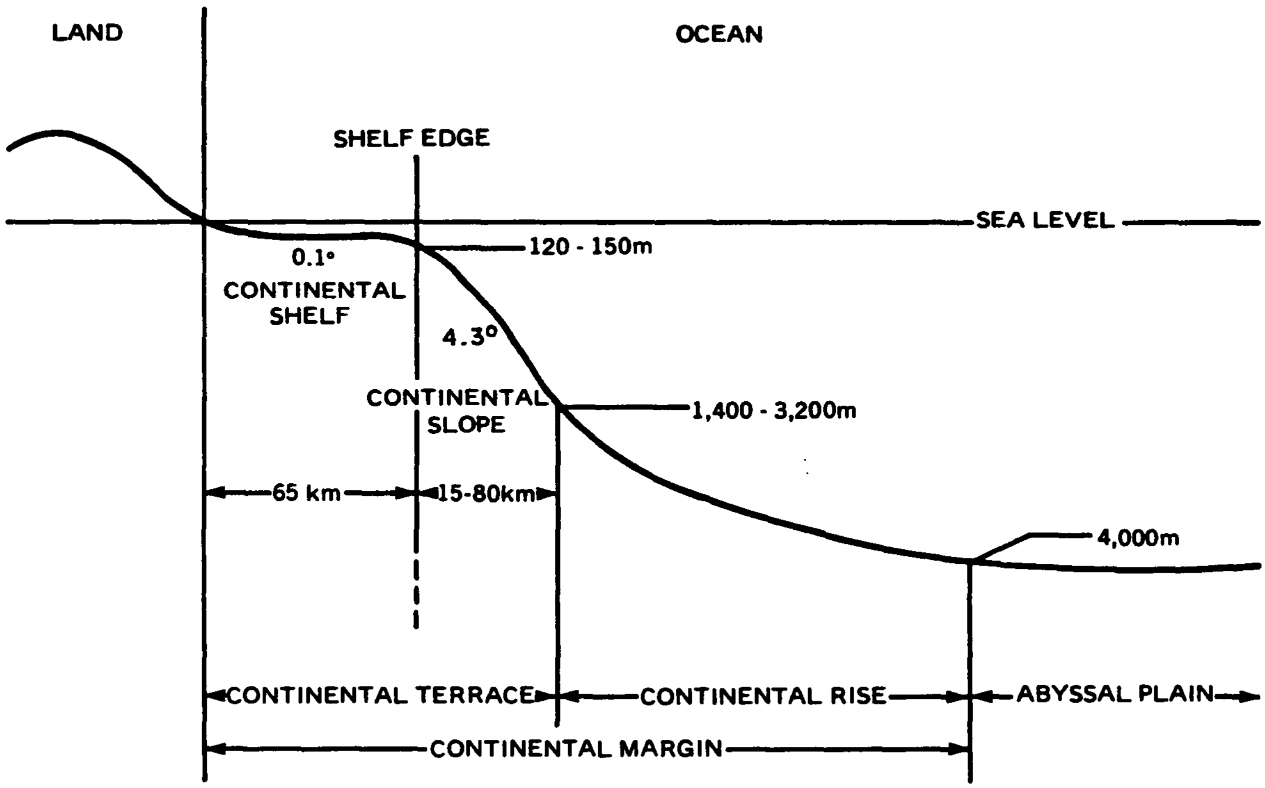


FIGURE 2.

GENERALIZED PROFILE OF THE CONTINENTAL MARGIN.
NUMBERS SHOWN ARE AVERAGES.

Production from offshore wells increased each year, reaching a peak in 1970 (Figures 3 and 4). Even though the greatest proportion of the fields had been found by 1970, exploration, drilling, and the state and federal leasing programs continued to escalate. In 1973 the number of offshore tracts in the Gulf of Mexico leased by the Bureau of Land Management (BLM) was 1,797, increasing to 3,109 tracts in 1979. Figure 5 shows the general increase in acres leased by BLM since the late 1960's. The cumulative acreage leased in the BLM oil and gas lease sales has increased to 12,537,976.606 acres.

Although most of the leased offshore tracts are located in less than 200 m (656 feet) of water, lease tracts have been offered on the continental slope with a water depth greater than 200 m (656 feet). In Figure 6 note also, the increasing number of trancts offered in water deeper than 400 m (1,312 feet). The Shell Cognac platform was placed on the continental slope with a water depth greater than 329 m (1,080 feet), and Chevron has drilled a discovery well in water over 335 m (1,100 feet) deep. The problems encountered increases proportionally as you go farther offshore and into deeper water. Costs increase for exploration, drilling and development; maintenance costs increase due to greater surface area corrosion and longer supply lines. (See Section IV on deepwater technology for problem identification and technological developments for the deeper continental shelf and slope areas.) The weather also poses problems of high winds and waves; in particular, the hurricanes in the Gulf of Mexico become a major problem to technology, structures, lives, and production. (See Section III on hurricane development, distribution, and their offshore influence. Refer also, to the accompanying hurricane map.)

Prior to 1950, oil produced offshore was transported by barge to coastal facilities. Only one 14-km (8.4 miles) pipeline existed before a major pipeline laying episode commenced in 1951. By the mid-1950's, more than 1,450 km (900 miles) of pipelines had been laid; by 1973 more than 6,400 km (4,000 miles) of pipeline, and in 1979 there were 10,779 km (6,704 miles) of pipeline on the Gulf of Mexico seafloor (Figure 7).

Today, several pipelines over 160 km (100 miles) long have been laid with one pipeline over 482 km (300 miles). The increased miles of pipelines laid on the seafloor and the geohazards encountered has required the solving of many technological problems, such as route surveying methods and data interpretation, welding, flexible joints, flotation prevention, and ditching pipelines in shallow water or shipping channels.

Development Offshore of the Mississippi Delta

In 1948 the first wells were drilled in the West Delta area, with major field development beginning in the West Delta, South Pass, and Main Pass lease block areas in the mid-1950's (Figure 8). Today, 37% of the 3,500 production structures for oil and gas in the Gulf of Mexico are located in the Main Pass, South Pass, and West Delta areas.

The earliest development in the offshore delta (area covered by Map 8) occurred in 1950 within shallow state waters in what later became the very productive South Pass 24 field. Not until 1955 did exploration and development extend this same field into federal waters (Block 37). In May of the same year, the first major drilling and production platform was located by the Shell Oil Company in South Pass Block 42.

In Figures 9 and 10, it is notable that major platforms have been located in increasingly deeper water as a function of time. Engineering, surveying, and exploration technologies have advanced over the past three decades, specifically to increase production, maintain safety, and develop new fields farther offshore on the OCS.

However, a comparison of Figures 9 and 10 shows that development in the area around the Mississippi River delta has proceeded into deeper water at a more rapid rate than development for the rest of the Gulf. For instance, South Pass Area has three structures constructed in water depth greater than 182 m (600 feet). Of the ten deepest structures in the Gulf, six are in the offshore Mississippi River delta area. Figure 11 illustrates the general increase of platform height over the past two decades.

Coincidental to production and platform development has been the need for pipelines to transport the oil and/or gas to nearshore and

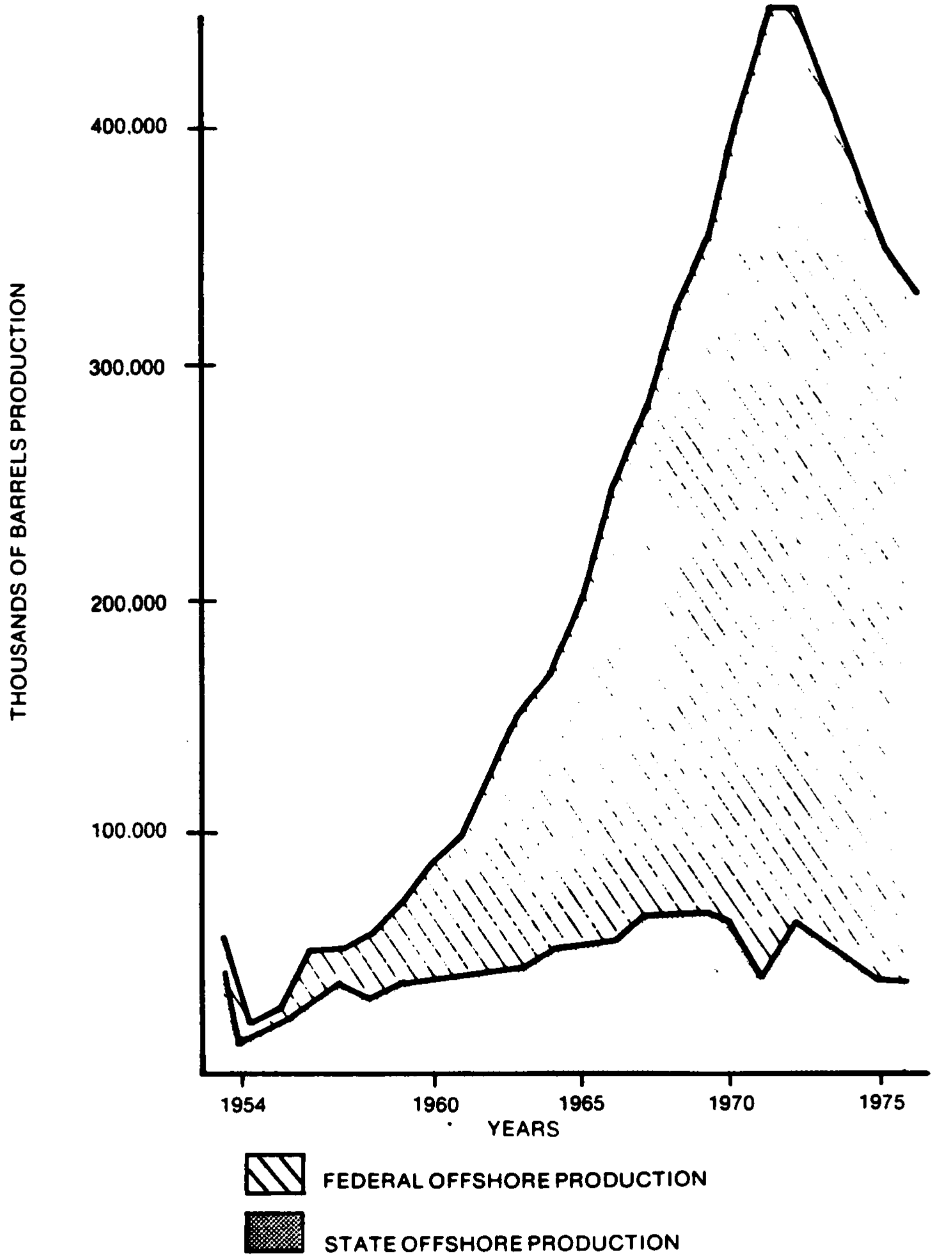


FIGURE 3 LOUISIANA OFFSHORE OIL AND CONDENSATE PRODUCTION — STATE AND FEDERAL OCS

SOURCE: AMERICAN PETROLEUM INSTITUTE, 1979, P.13.

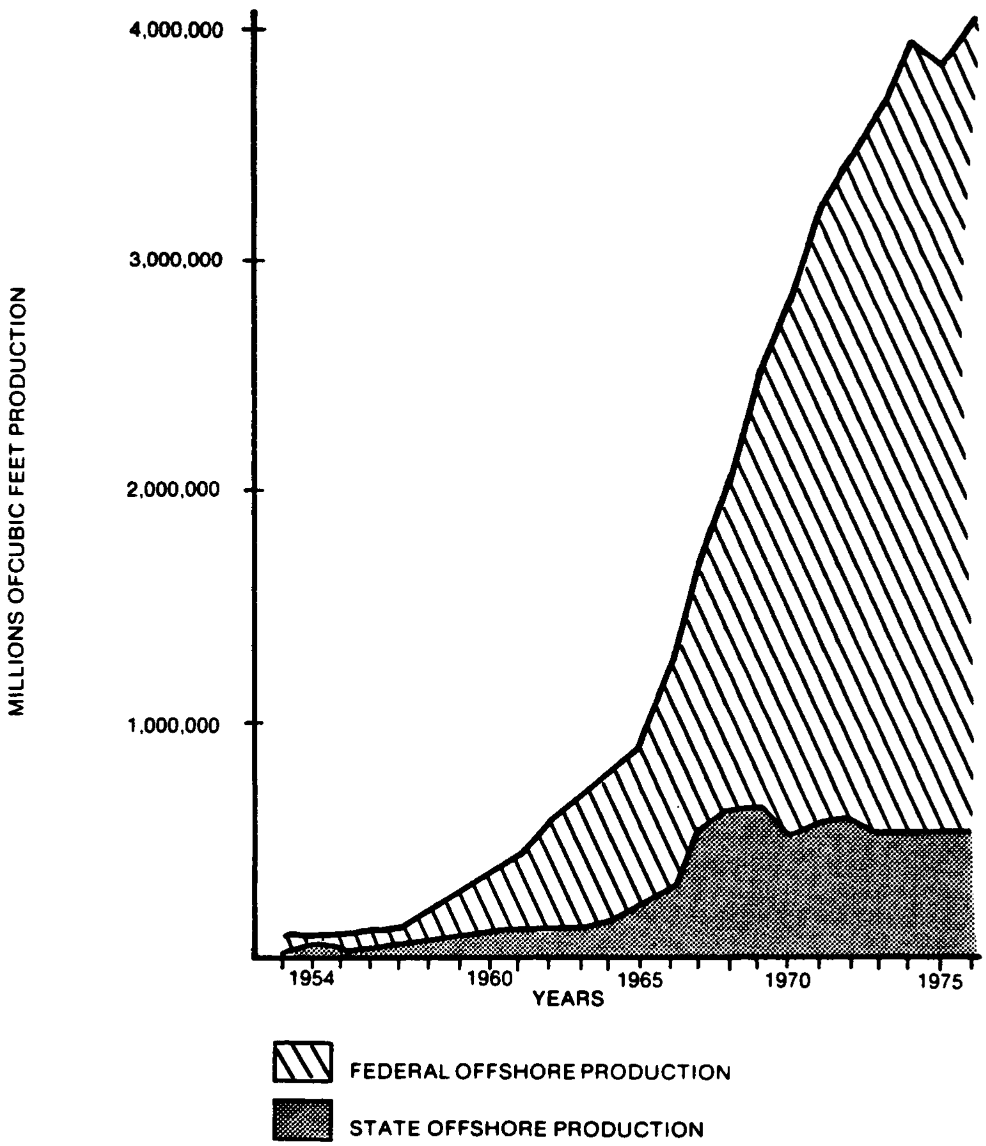


FIGURE 4 LOUISIANA OFFSHORE GAS PRODUCTION — STATE AND FEDERAL OCS

SOURCE: AMERICAN PETROLEUM INSTITUTE, 1979, P 13

FIGURE 5

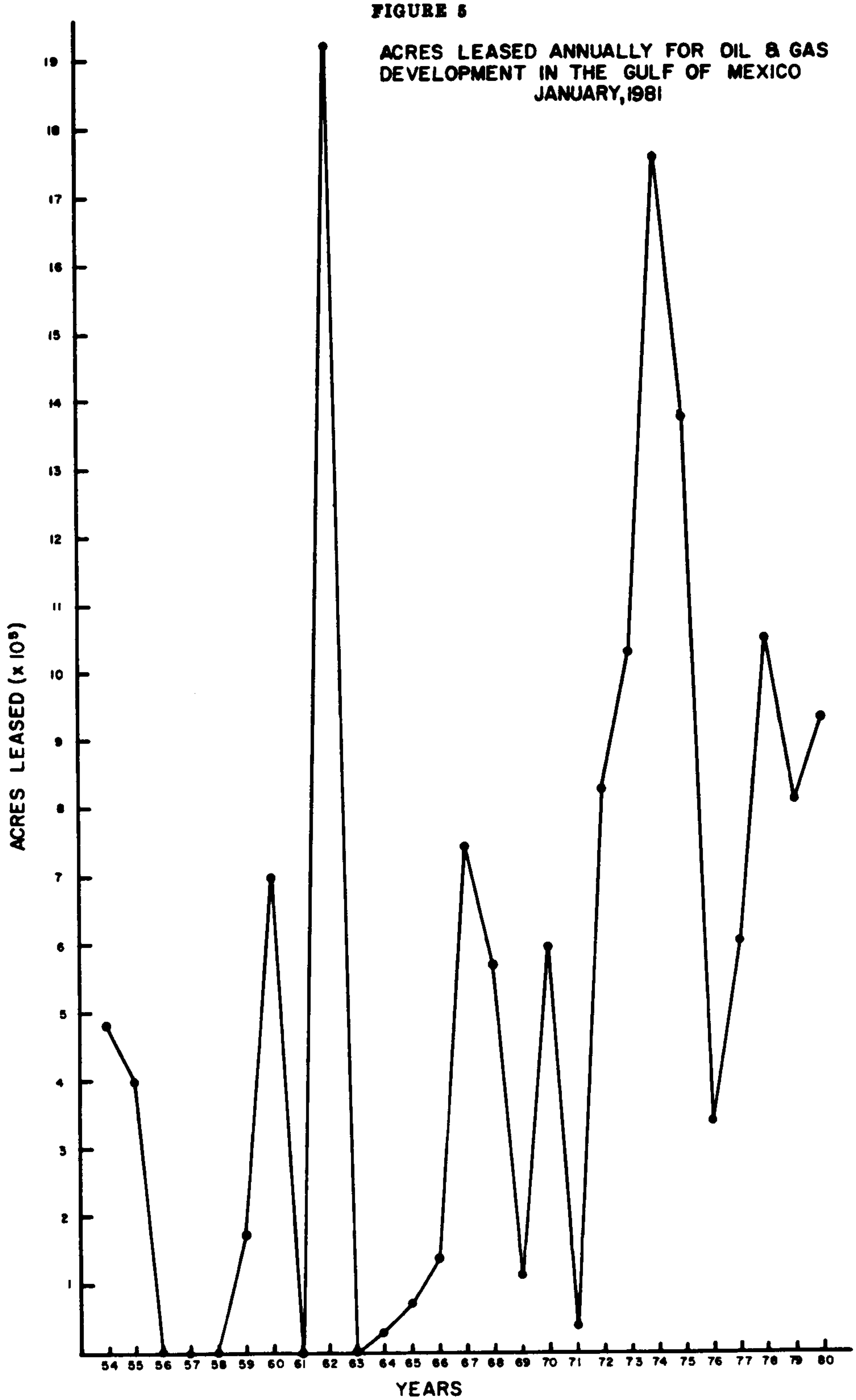

ACRES LEASED ANNUALLY FOR OIL & GAS
DEVELOPMENT IN THE GULF OF MEXICO
JANUARY, 1981
ACRES LEASED (x 10^5)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80
YEARS

FIGURE 6

GULF OF MEXICO TRACTS OVER 200 METERS WATER DEPTH
OFFERED FOR LEASE BY BLM

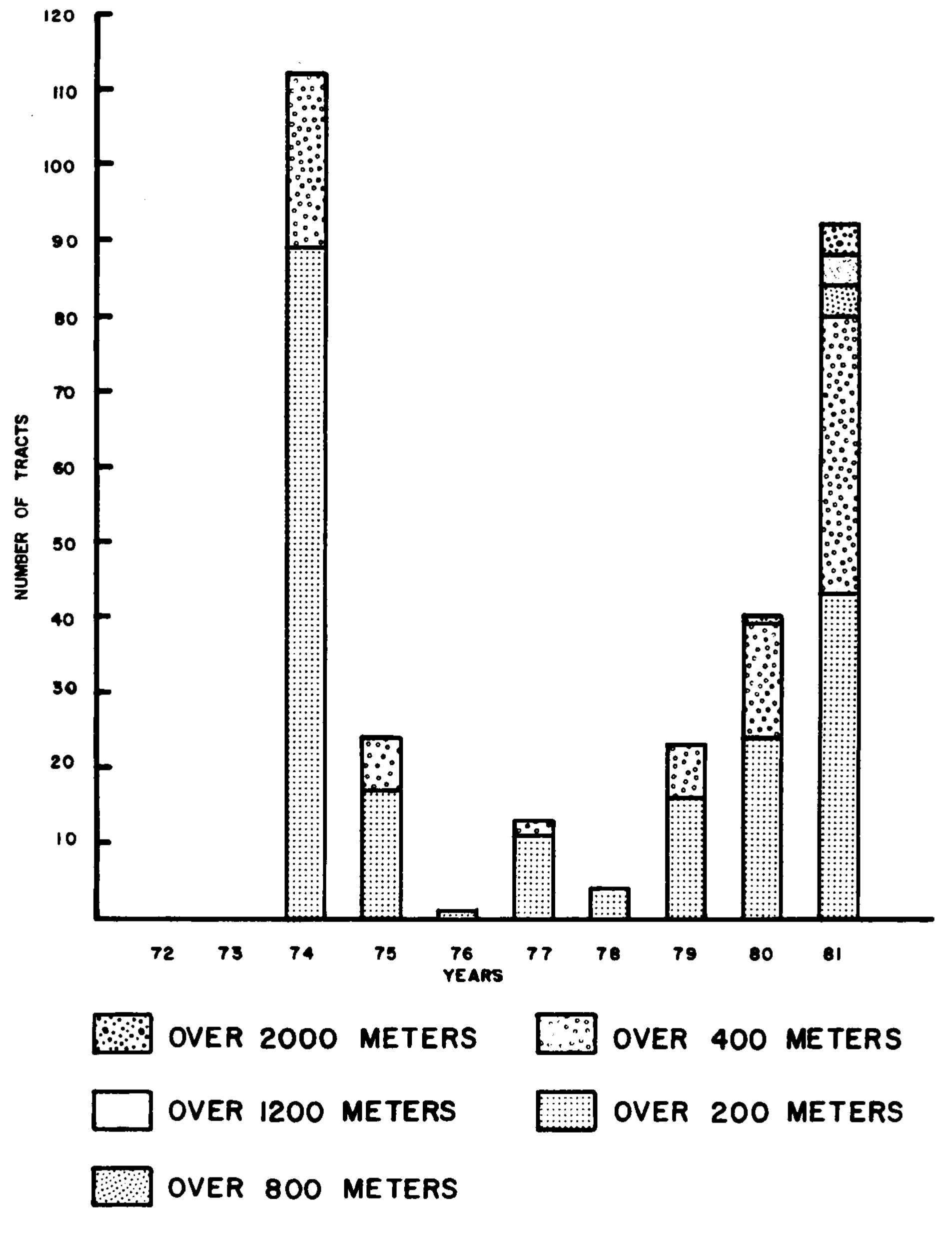


FIGURE 7

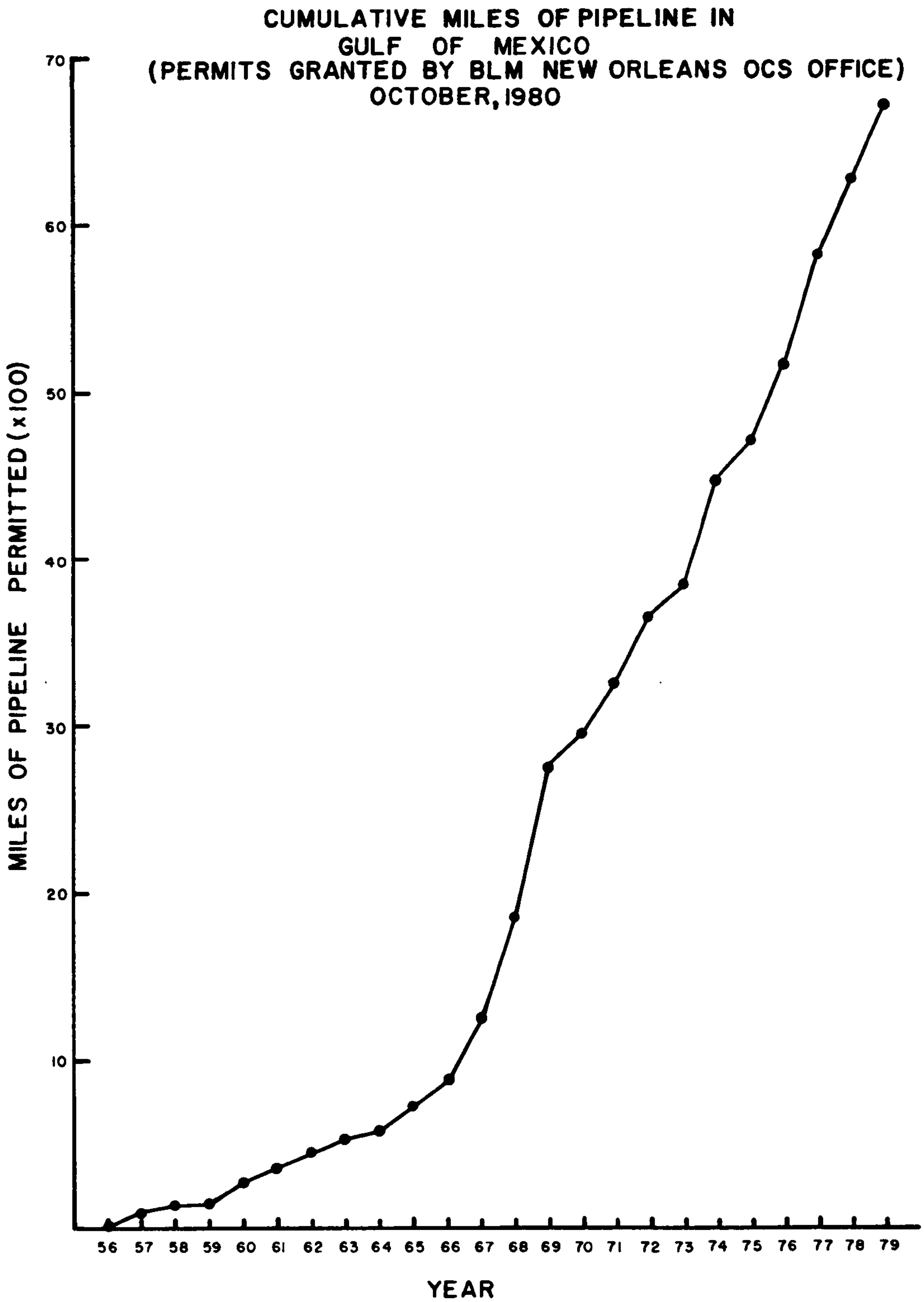
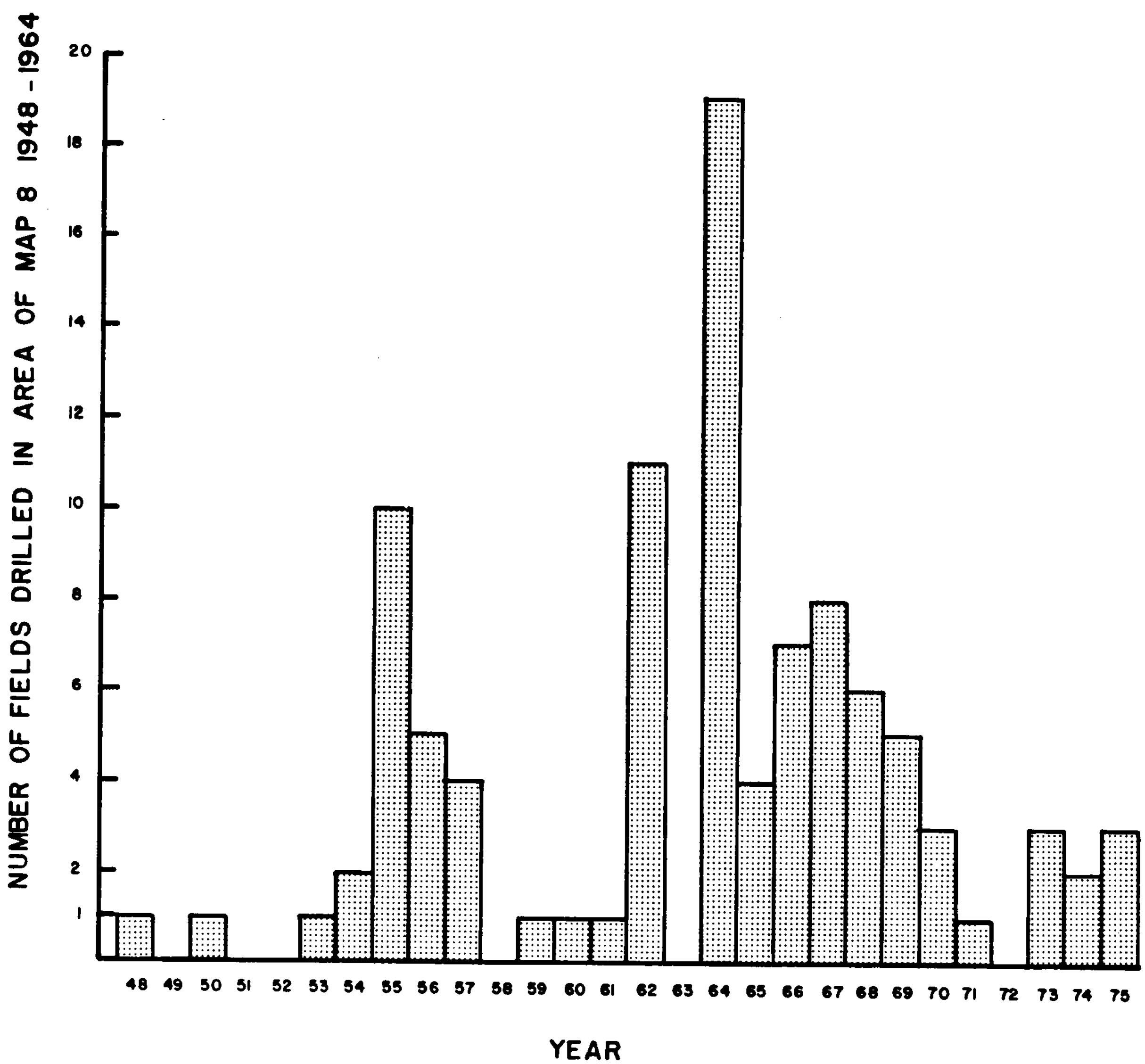

CUMULATIVE MILES OF PIPELINE IN
GULF OF MEXICO
(PERMITS GRANTED BY BLM NEW ORLEANS OCS OFFICE)
OCTOBER, 1980
MILES OF PIPELINE PERMITTED (x100)
70
60
50
40
30
20
10
56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79
YEAR

FIGURE 8

SOURCE: HEINS, WILLIAM, ED.
INTERNATIONAL OIL & GAS DEVELOPMENT YEARBOOK, 1964
INTERNATIONAL OIL SCOUTS ASSOCIATION, AUSTIN, TEXAS
VOL. XXXV, 1965 pp. 171-178
VOL. XLVII, PART II, 1978, pp 214-226



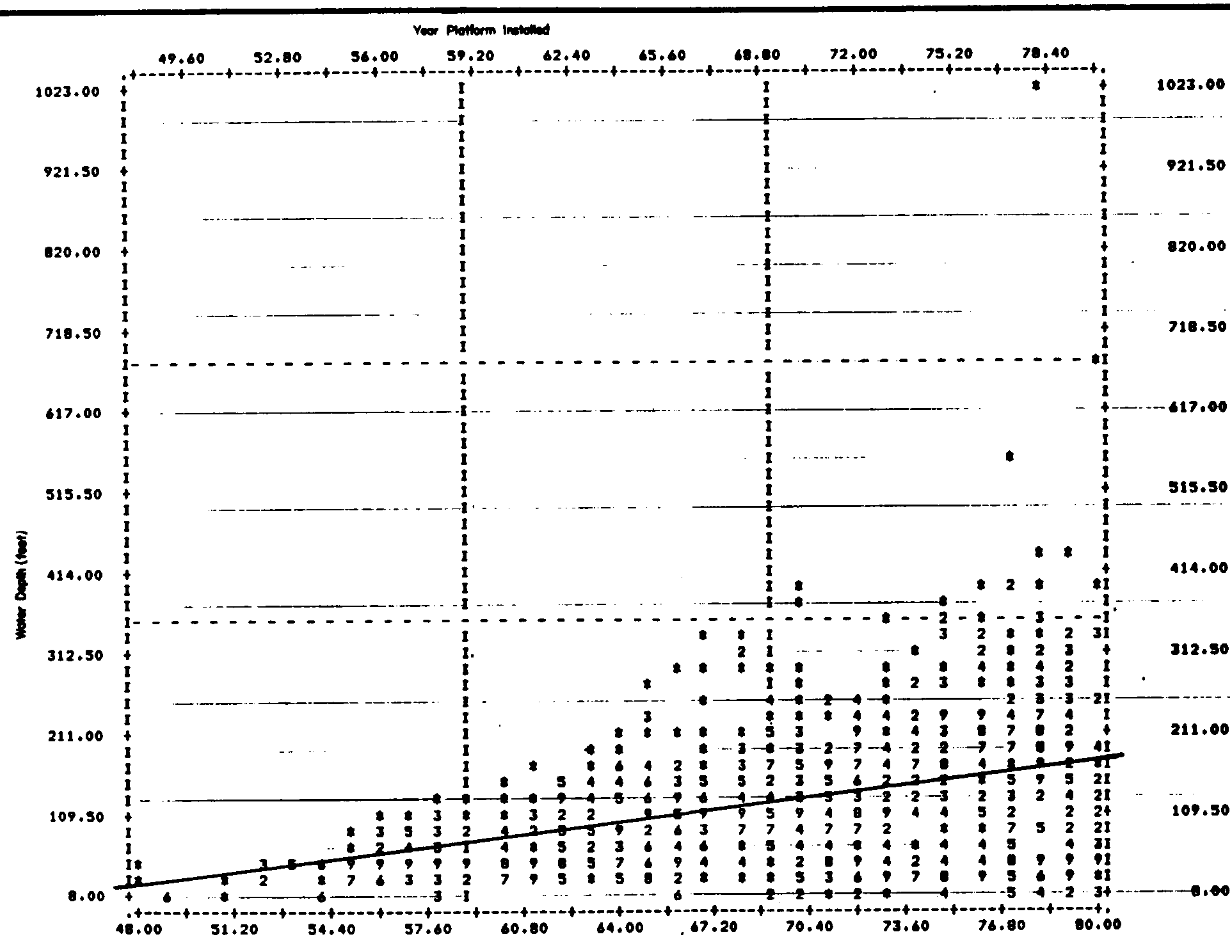


FIGURE 8

MAJOR PLATFORMS INSTALLED IN THE GULF OF MEXICO*

*MAJOR PLATFORMS ARE DEFINED AS THOSE BEING OVER 50 FEET ON ONE SIDE

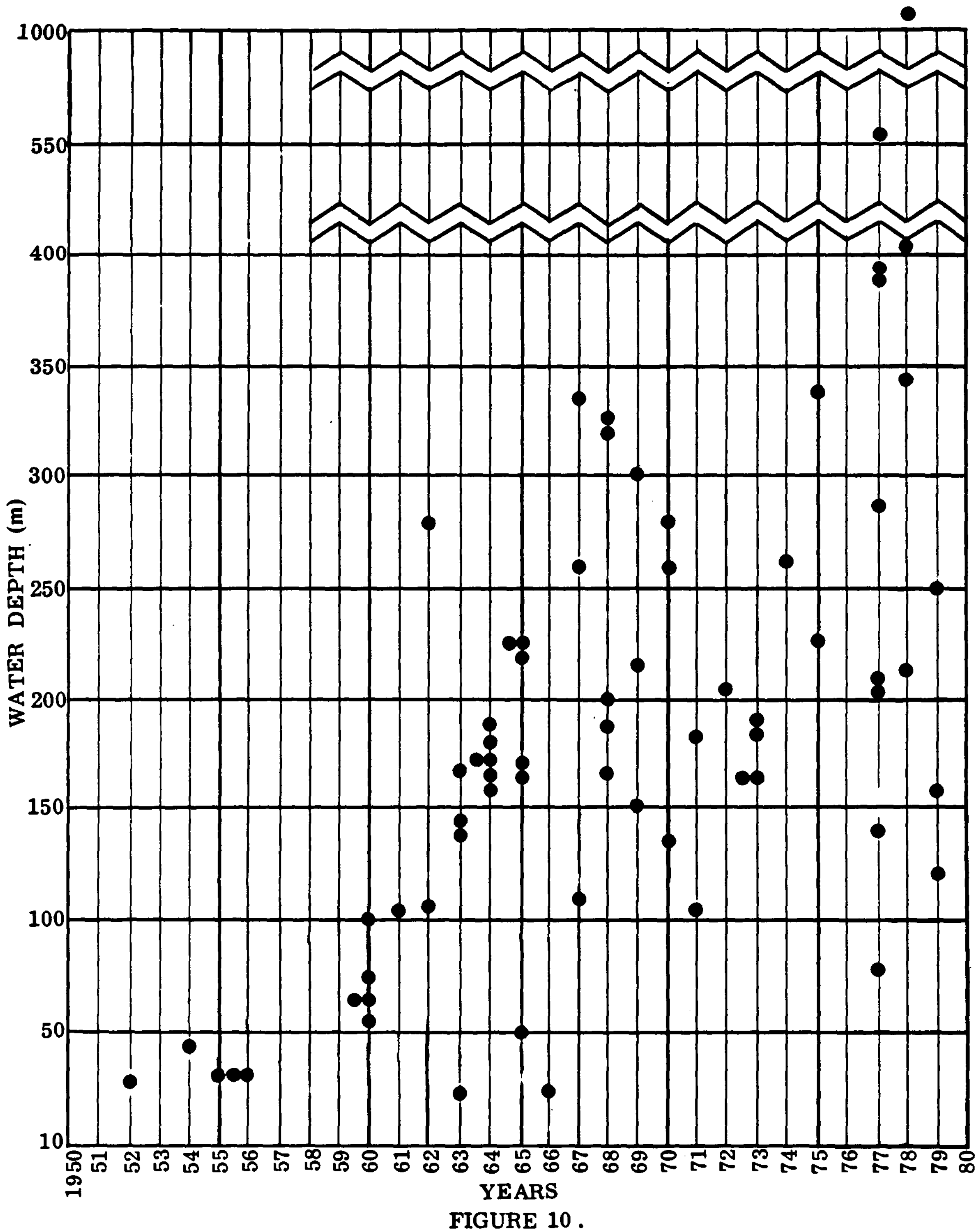


FIGURE 10.
MAJOR PLATFORMS - SOUTH PASS, MAIN PASS, WEST DELTA, VIOSCA KNOLL, AND MISSISSIPPI CANYON AREAS.

SOURCE: USDI, GEOLOGICAL SURVEY, 1980 COMPLEX STRUCTURES LIST

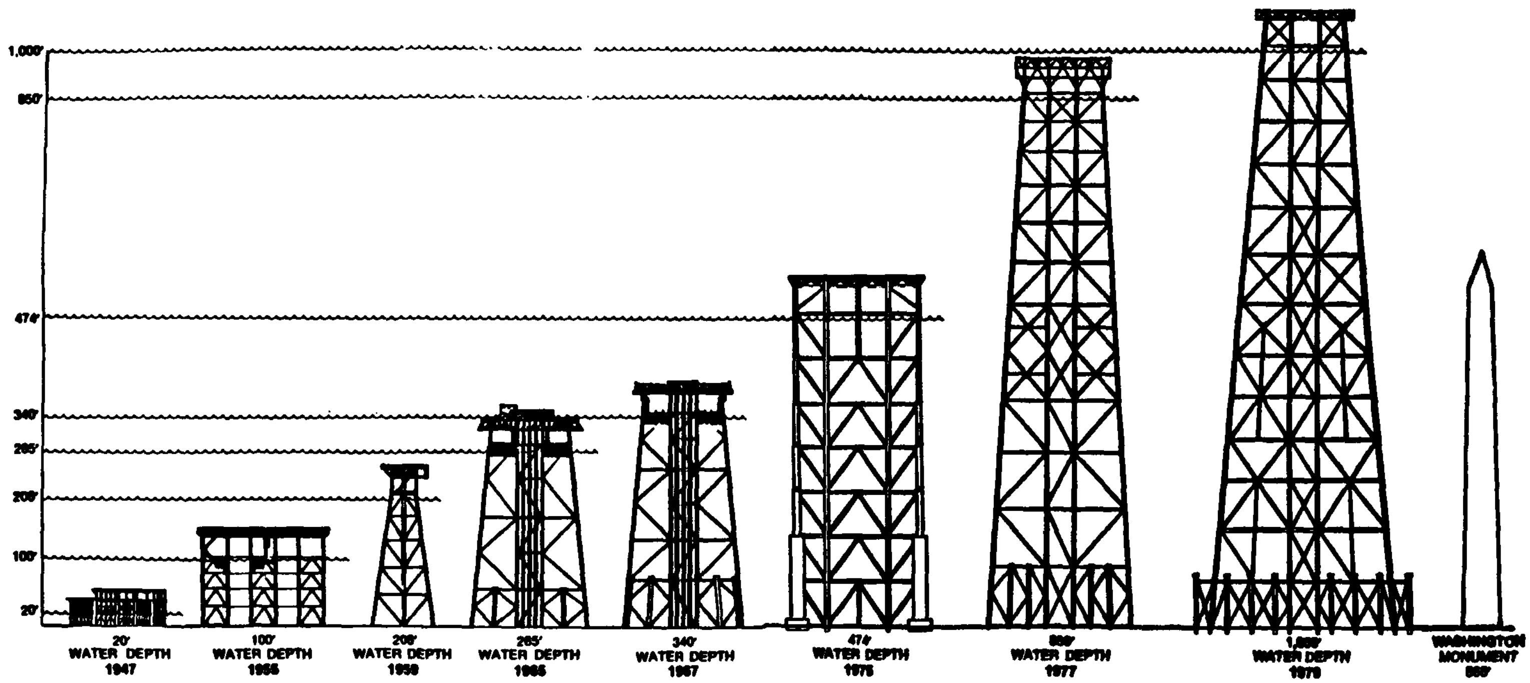


FIGURE 11

GULF OF MEXICO PLATFORMS INCREASE IN HEIGHT CHRONOLOGICALLY onshore facilities over greater distances and to lay pipelines in greater water depths. Beginning in 1954, the Shell Oil Company built several short pipelines to connect the oil field in South Pass Blocks 24 and 37 with onshore facilities. Pipeline construction in federal waters offshore of the delta did not attain any major proportions until the mid-1960's (Figure 12).

Subsurface Geology

The primary interest in oil and gas production on the OCS is related to sediments of Tertiary Age. Principally, Pliocene, Miocene, Oligocene, and Eocene formations deposited in an east-west trending geosyncline by ancient rivers flowing southward across the continental landmass. These sediments dip southward (Figure 13) and are predominantly composed of unconsolidated sands and shales with some interbedded lime sediments and an occasional reef deposit.

Generally, the Miocene and Pliocene sediments under the Gulf are of major petroleum interest. The Miocene-Pliocene section thickens southward, and several wells drilled offshore to depths over 4,500 m (15,000 feet) have failed to reach the upper Oligocene sediments.

The predominant reservoirs in the Gulf are associated with piercement and deep-seated salt domes (Figure 14) that in diapiric fashion have created structural traps for oil and gas (Figure 15). These salt domes vary from exposure at the surface to buried depths over 3,000 m (9,800 feet). Several producing petroleum reservoirs are associated with regional faults (Figure 13). These faults are normal and the oil and gas traps are found in anticlinal structures on the downthrown-south blocks. However, since the faults are buried in Miocene sands, are confused by other near-surface faulting, and are distorted in many places by salt dome intrusions, these faults have not been delineated in the abundance they exist. The salt dome traps have been the primary producers of oil and gas; as a result, other traps generally have been regarded of secondary importance.

Other potential reservoirs in the offshore delta region are large sand accumulations on the outermost shelf and slope. In particular, submarine channel sands concentrated in the upper portion of the Mississippi Fan (Figure 16) appear to be the ". . . most prospective for gas and oil accumulations" (Caughey and Stuart, 1976).

Surface and Near-surface Morphology

Upon the massive organic-bearing Tertiary sediments, Pleistocene and Holocene deposits were laid as alluvial and deltaic sequences related to changing coastal interface between a sequence of deltas and the sea (Figure 17). In fact, during the 3 million years of Pleistocene deposition, the coastal margin was extended southward over 96 km (60 miles). In the late Pleistocene, 17,000 years B.P., a drop in sea level induced scour by the ancestral Mississippi River and the development of the Mississippi Canyon. The subsequent Holocene rise in sea level to nearly its present state, about 7,000 years B.P., resulted in a marine deposition again on the continental shelf, a back-filling of the entrenched Mississippi valley, and the beginning of the present deltaic progradation.

In the past 7,000 years the Mississippi River has constructed a broad deltaic plain composed of several large, small, and often overlapping depositional lobes. Within the last 5,000 years there have been at least seven of these deltas built by the Mississippi River, as the river has alternated its depositional focus while prograding southward farther into the Gulf (Figure 17).

The modern bird-foot, or Belize, delta is the youngest lobe of the Mississippi River deltaic formations. The 1,900 km^2 (733 mi^2) of this delta have formed within the last 600 years, and although it is small in areal extent by comparison with some of the older deltaic lobes that average 6,200 km^2 (2394 mi^2), this delta has accumulated five times the thickness of sediment of the older deltaic deposits.

The sediment transported by the Mississippi River into the Gulf waters is comprised of fine sands, silts, and clays. The rapid deposition of fine-grained material in an aqueous environment yields a sediment with a high water content and the entrapment of large amounts of organic material that decomposes to form accumulations of methane, carbon dioxide, and hydrogen sulfide.

The delta front configuration indicates the presence of several topographic zones based upon slope and roughness (Figure 18). The uppermost zone is the narrow shallow platform of very low slope (less than 1% slope). From 15-

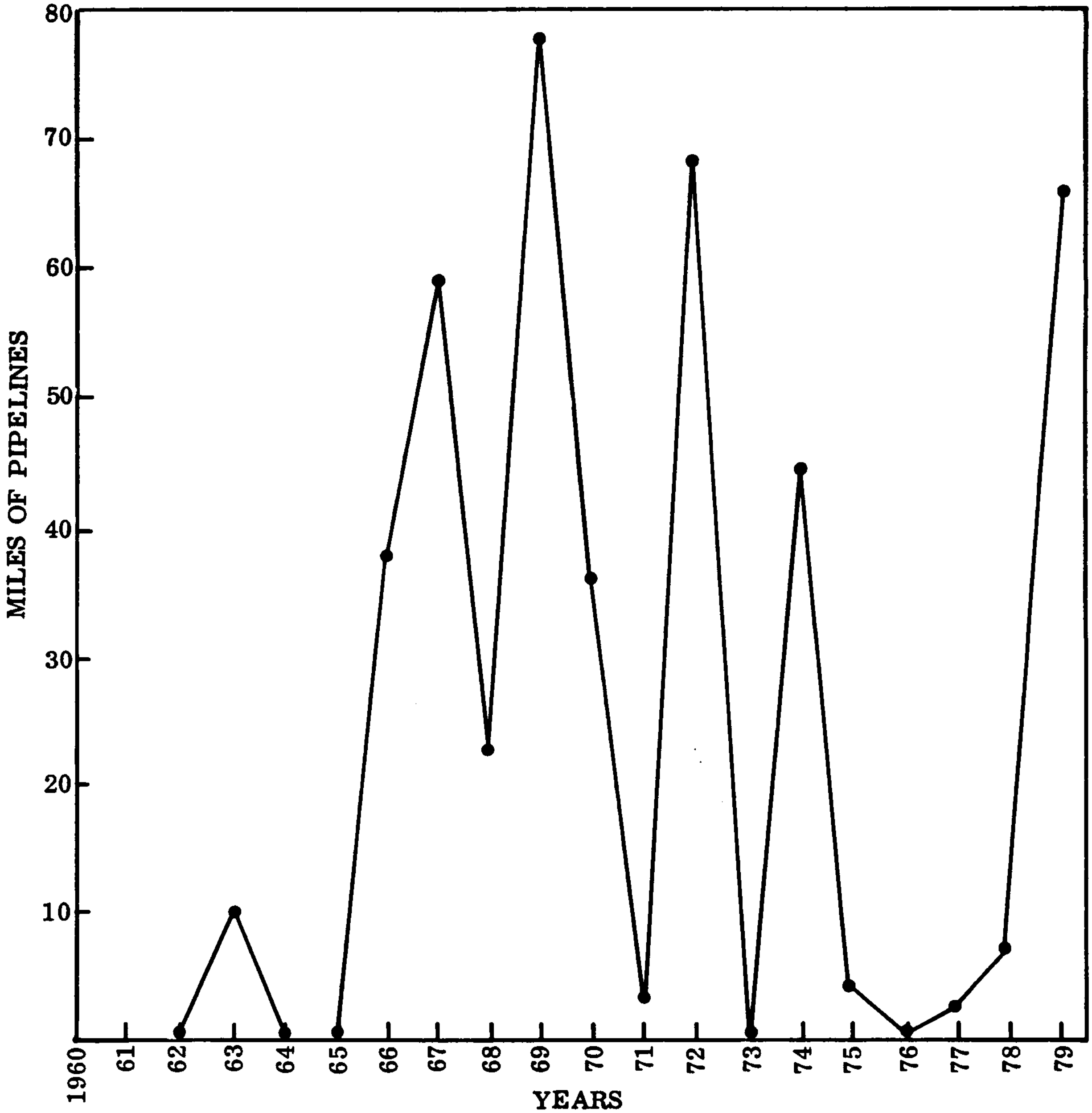


FIGURE 12.

MILES OF PIPELINE CONSTRUCTED PER YEAR IN SOUTH PASS, MAIN PASS, AND WEST DELTA AREAS

SOURCE: BUREAU OF LAND MANAGEMENT STATISTICS, 1980

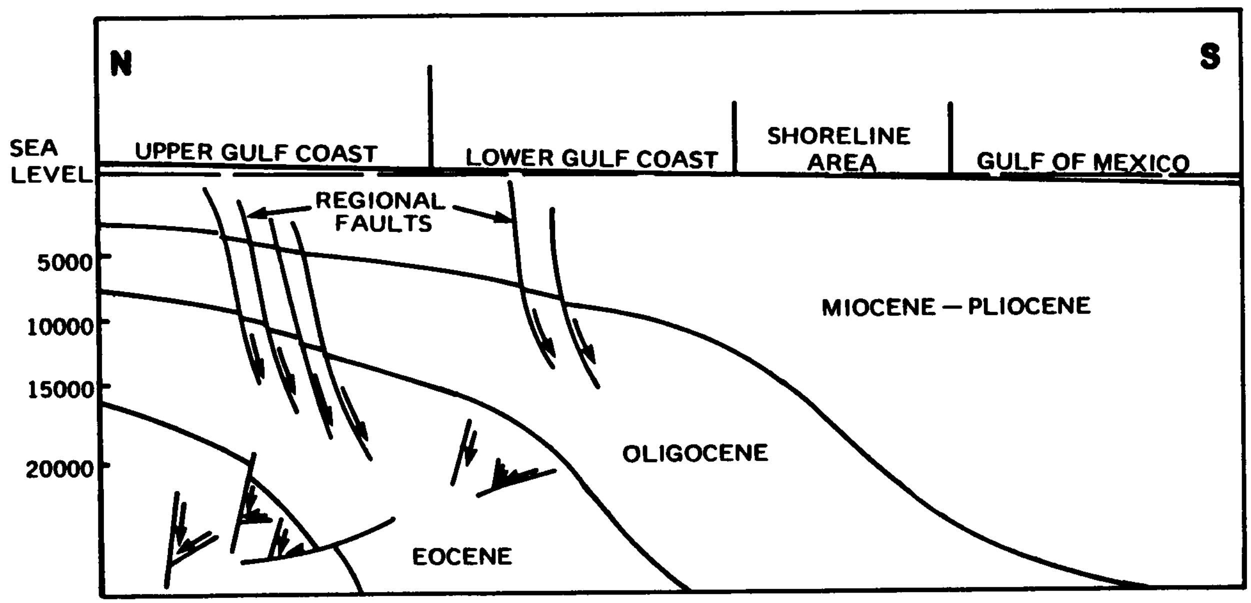


FIGURE 13.

GULF COAST - CONTINENTAL SHELF CROSS-SECTION

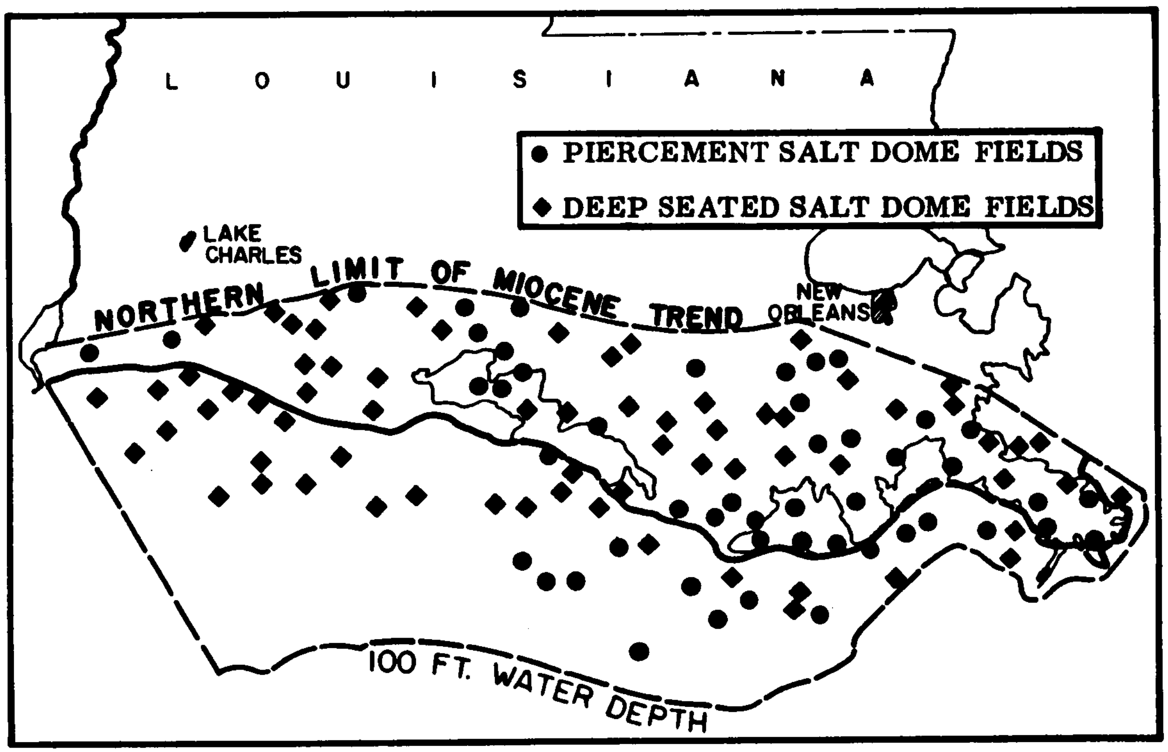


FIGURE 14.

SALT DOMES OF THE LOUISIANA GULF COAST

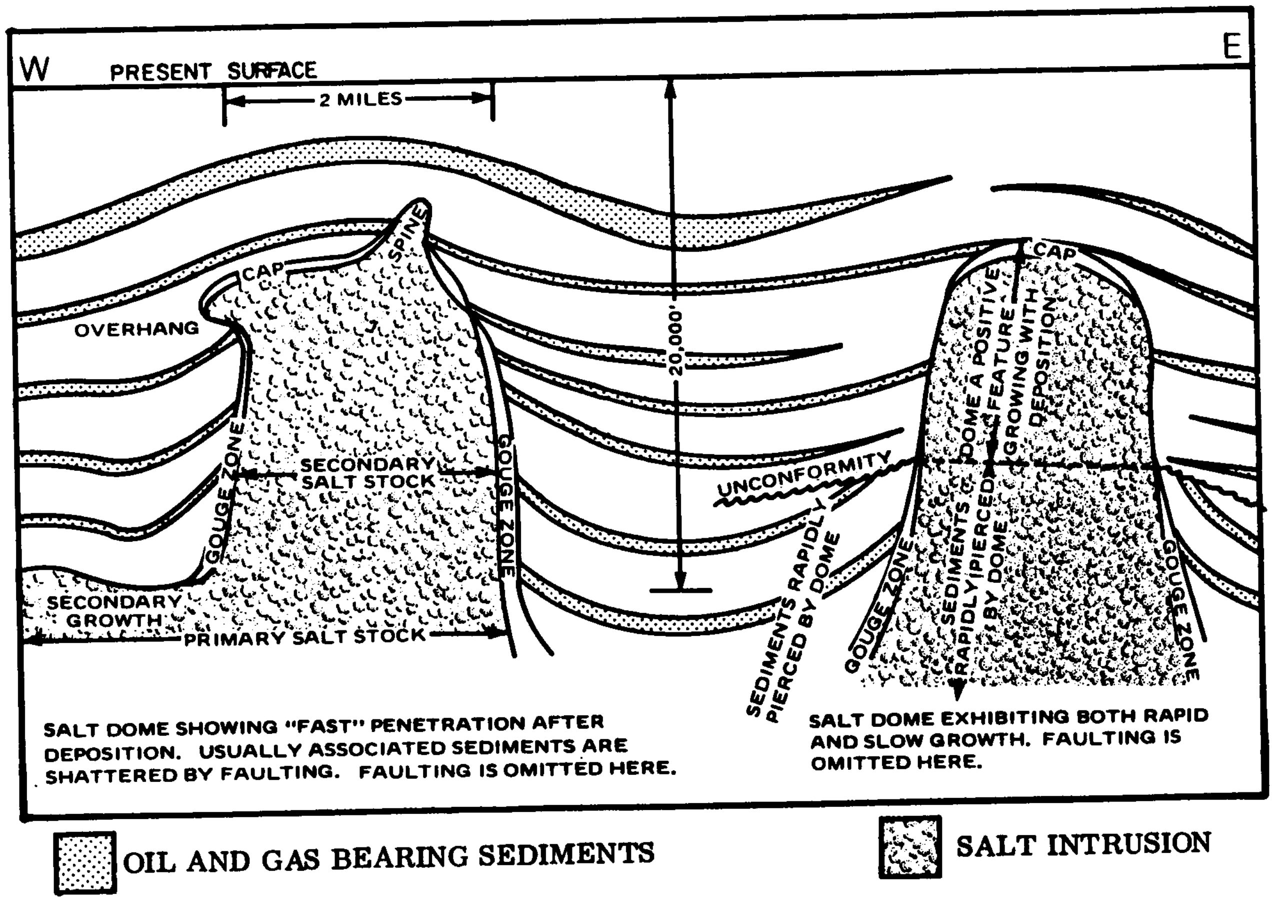


FIGURE 15.

GENERALIZED SALT DOME DEVELOPMENT WITH ASSOCIATED OIL AND GAS STRUCTURAL TRAPS

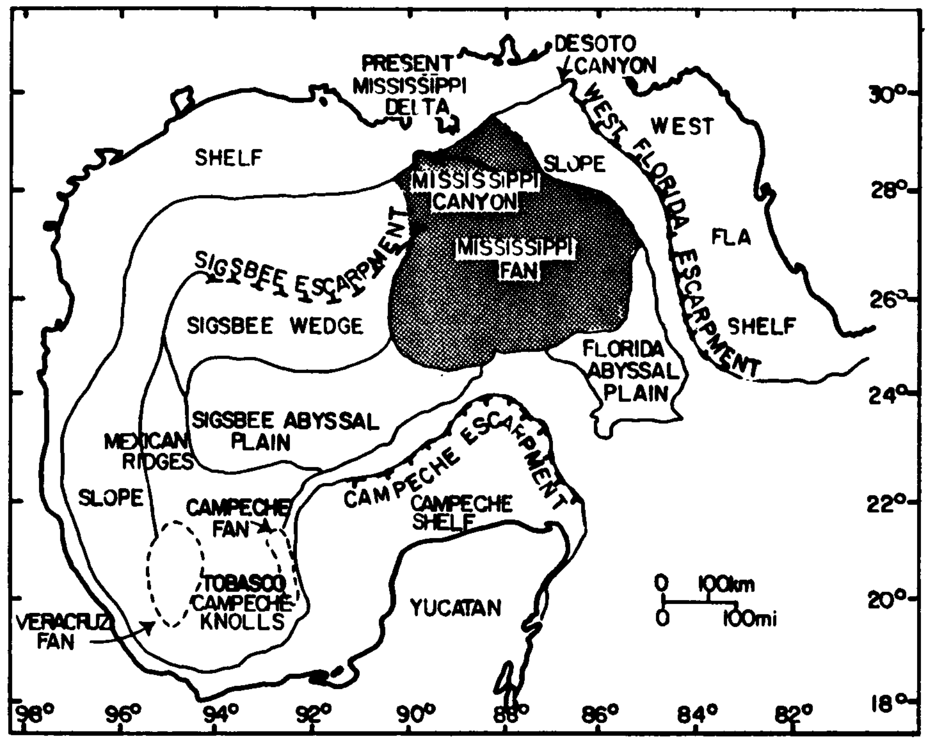
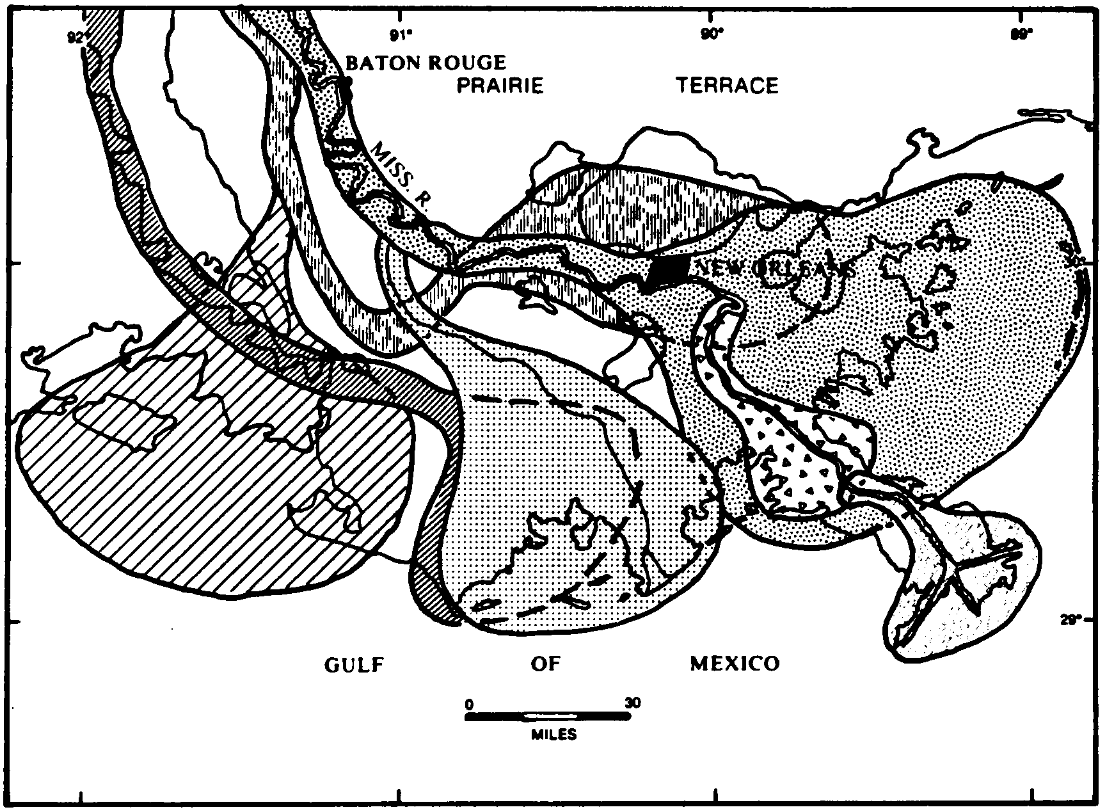


FIGURE 16.

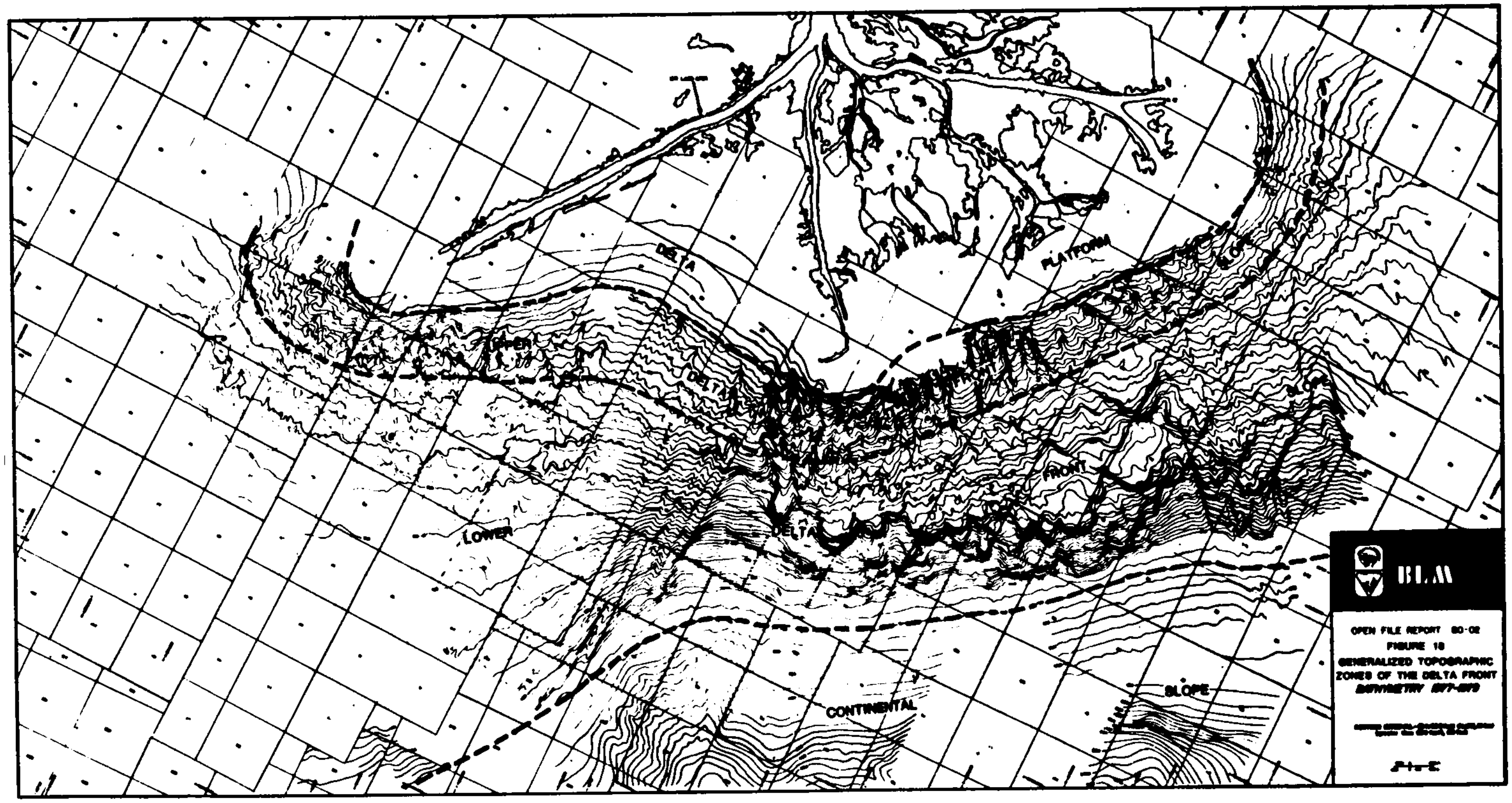
GULF OF MEXICO - PHYSIOGRAPHIC UNITS



SALE CYPREMORT		>4600 YRS. B.P.	
COCODRIE	CA	4600 - 3500 YRS. B.P	
TECHE	CA	3500 - 2800 YRS. B.P.	
ST. BERNARD	CA	2800 - 1000 YRS. B.P.	
LAFOURCHE	CA	1000 - 300 YRS. B.P.	
PLAQUEMINE	CA	750 - 500 YRS. B.P.	
BALIZE		<550 YRS. B.P.	

FIGURE 17 CHRONOLOGICAL DELTAS OF THE MISSISSIPPI RIVER

SOURCE. JAMES P. MORGAN. LOUISIANA DELTAIC GEOLOGY GUIDEBOOK, NEW ORLEANS GEOLOGICAL SOCIETY. MAY. 1976. P.S.


DELTA
PLATFORM
UPPER
DELTA
FRONT
LOWER
DELTA
CONTINENTAL
SLOPE
BLM
OPEN FILE REPORT 80-02
FIGURE 18
GENERALIZED TOPOGRAPHIC
ZONES OF THE DELTA FRONT
BATHYMETRY

62 m (50-200 feet) water depth is a zone of rough irregular topography made up of closely spaced ridges and gullies. The overall slope within this zone is a 1%-3% slope, but locally it can be greater. The lower zone of the delta front is smoother topography of broad valleys and higher terraces and is marked by an area of surface scarps caused by numerous deep-seated faults. This lower zone delimits the delta, or continental shelf, from the continental slope at approximately 200 m (656 feet) depth (Map 4).

Thus, the Mississippi River delta front possesses several characteristics that have influenced offshore oil and gas development: (1) The river's high sediment capacity adds 60-121 cm/year (23-47 inches/year) of sediment accumulation onto the delta's offshore platform near the distributaries' mouths. As much as 3-4.5 m (10-15 feet) of sediment may be accumulated from a river flood, and the sediment accumulation drops off rapidly away from the river's mouths. For instance, only a few cm/year of sediment may accumulate in water depths of 45 m (147 feet) to a couple of mm/year at 200 m (656 feet). Thus, the initial sediment deposition is confined to the upper edge of the delta platform; (2) The sediment is composed of fine-grained sands and clays that retain high amounts of water and organic material, producing sediments of low consolidation, low strength, and large quantities of interstitial gas; (3) A steepening delta front slope has evolved with time as progradation has averaged anywhere from 45-90 m/year (147-295 feet/year) outward from the mouths of the distributaries. As the delta platform encroaches on the continental slope, more sediment is deposited on the delta front to compensate for the greater slope and water depth, causing an over steepening of the upper delta front slope; and (4) The passage of storms, particularly hurricanes, sets up high amplitude waves that cause sediment loading and movement at depths farther offshore. (For greater detail of hurricanes in the Gulf of Mexico and their offshore impact, see Section III).

These four characteristics of the delta front produce sediment instability, conditions and processes for sediment flowage, and resultant mass movement in the forms of slumping, surface faulting, shale diapirs, and mudflows. (For a more detailed analysis of the subaqueous sediment instabilities, see Section I and Map 5).

Application of Morphology to Development

The morphology of the ocean bottom is crucial in determining the siting of offshore platforms and pipelines. In all areas of the continental shelf, the factors involved in siting are the degree of slope, bottom topography, water depth, and composition of bottom sediments. However, the factors imposing the greatest influence on siting vary from one locale to another. In some cases, the factor which may have the greatest influence is the degree of slope; in other cases, water depth will be of major importance. For example, on the continental slope off the Atlantic coast of the southeastern U.S., the ruggedness of the topography is a prime consideration. In the offshore Mississippi Delta the stability of seafloor sediments is a critical factor in siting oil and gas facilities.

The process involved in delta instability is mass movement of seafloor sediments. This mass movement frequently takes the forms of slides, slumps, flows, and subsidence. They may occur in any water depth, in any kind of sediment on slopes less than 1.5%, and at velocities of a few mm/year to m/sec. The cause for the movement is gravity once the mass has been set in motion by a local overloading. The overloading may be related to high amplitude wave action, such as those established by hurricanes, faulting, excessive local accumulations of sediment, or overextension of slopes in sediment deposits.

These overloading mechanisms will vary in intensity, duration, and scale. In some instances, an overloading of seafloor sediments over larger, more regional areas may result, while in other cases mass movements within a smaller locality, such as near the mouth of a particularly active river distributary, may be induced.

From previous discussions in this section, Section I, and Coleman, et al., 1980, the Mississippi River delta environment provides all the necessary ingredients to make sediment instability a critical geohazard to be dealt with in a productive oil and gas region. Major oil and gas development in the offshore delta is recent and escalating. Some of the early development has encountered problems with the unstable sediments, as pipelines have been ruptured and platform foundations have been damaged. Today, all of the production companies that have interest within the delta intensively plan

Table 1

PIPELINE LEAKS

Date	Line Size/Service		Location of Leak	Location of Line	Description of Cause
9/10/74	8"	Oil	1½ miles north of SP 60 C	SP 60 A to subsea tie-in with 12" Cobia P/L in MP 73	Major riser at SP 60 "A" dropped 5 feet and pulled from vertical approximately 10°. Welded braces, brackets, bolting, and piping severely damaged. Divers report bottom of riser displaced laterally 40 feet. The line has been ripped off at the subsea tie-in with Cobia and has not been located as yet.
9/11/74	12"	Oil	Block 27	SP 37 to onshore facility	Severed in Block 27. Mudslide suspected induced by Hurricane Carmen.
9/11/74	12"	Oil	MP 73 - subsea tie-in with 8" Atlantic Richfield Line	MP 290 field to shore facility	Line ripped off the Cobia line at the subsea tie-in. Mudslide induced by hurricane.
9/13/74		Oil/Gas	Counted nine leaks on lease	Flowlines in SP 27 & 28	Unknown. Mudslide suspected.
1/5/75	12 3/4"	Oil	150' from "VV" plat, SP 28, OCS 0693	SP 28, FWKI No. 3 to SP "VV"	Mudslide.
3/20/75	12 3/4"	Oil	1,500' from well No. 3 SP 28, OCS 0353	SP 28 FWKI No. 3 to SP 28, "VV" Plat	Mudslide.
9/23/75	8 5/8"	Oil	SP Blk. 60 "A" plat	SP "A" plat. to Cobia 12" tie-in	Mudslide caused by Hurricane Eloise.
3/28/77	12 3/4"	Oil	2 miles from "C" platform, SP 37	South Pass Blk. 27	Mudslide.
7/12/79	12 3/4"	Oil	3,800' north of Platform "A"	Platform "A" WD 79 to shore	Mud movement associated with "Hurricane Bob."
9/21/79	8 5/8"	Oil	Approx. 3,000' from SP Blk. 55 "A" plat.	From SP 55 "A" to shore	Mudslide.
10/8/79	12"	Gas	SP Blk. 26 approx. 2¼ miles from shore in state waters	South Pass Blk. 54 "A"	Mudslide.

their pipeline routes and platform sites utilizing studies and surveys of the delta front mudslide areas.

Accidents

Although F. P. Shepard speculated in 1955 that mudslides existed in the delta front area, it was not until the mid-1960's that surveys and studies confirmed the presence of instabilities during early oil and gas development. The absence of information and the priority of developing economically feasible oil and gas structures outweighed the consequences of damages incurred from the active seafloor. As a result, platforms have slid several inches after installation, have moved enough to list, and have been completely destroyed. Also, the hazards of the mudslides have taken a greater toll on the pipelines laid throughout the area. Table 1 indicates the numerous pipeline accidents caused by subsidence or mudslides that have occurred, yet they have not been reported because oil spills did not occur or because they were gas or water pipelines.

In several cases, breaks in the pipelines were numerous enough, often enough, or large enough to warrant abandonment of the line. Figures 19 and 20 show a couple of the abandoned pipelines in the mudslide area. As a result of numerous mass movements, both pipeline B (Figure 19) and pipeline C (Figure 20) have been severely contorted, as opposed to the more recently laid parallel pipelines A and D, traversing the same mudflow areas. Figure 21 indicates, in greater detail, that between 1972 and a 1980 survey, the lateral displacement of pipeline B has been 128-219 m (420-720 feet). Also note the displacement of pipeline A between 1976 and the recent 1980 survey. In four years downslope movement has been between 60-120 m (200-400 feet), and the tie-in point for connecting pipelines has been offset 91 m (300 feet). This movement with the mudflows has necessitated a change in the proposed routing of a connecting pipeline, an extension of 88 m (200 feet) of pipe, a change in right-of-way, and an increase in the pipeline permit fee. In addition, the recognition of pipeline movement with the mudflows will require special engineering adaptation, such as flexible joints that allow some movement in the pipeline angles, and a reduction in tension placed on the pipe between tie-ins and joints.

In South Pass lease Blocks 37 and 29 one oil company has had to reroute a portion of their pipeline due to four breaks caused by subsidence in seafloor sediments within the past two years (Figure 22). The company has determined that the cost of rerouting will be more economical in the long run than the frequent repairs and interruptions to flow that may have cost upwards of one-quarter million dollars over the last two years.

While some mudflows causing pipeline breaks may be prompted by a normal sediment build-up-subsidence, and an associated motivator confined to a small locality, most of the major and widespread structural damages to offshore oil and gas facilities are caused by tropical storms and hurricanes.

In particular, 6 of the 11 reported pipeline accidents were directly related to hurricane damage (Table 1); in September 1974, Hurricane Carmen accounted for four breaks; in September 1975, Hurricane Eloise accounted for one break; and in 1979, Hurricane Bob accounted for one pipeline break. In 1957 Hurricane Audrey did considerable damage to western Louisiana and in 1964 Hurricane Hilda destroyed six offshore platforms south of Morgan City, but neither did much damage to the delta front area because offshore development was just beginning at that time. However, in 1969, Hurricane Camille had a major impact on the offshore delta development as the center of the hurricane passed just to the east of the delta. Seafloor mudslide activity was widespread and of sufficient magnitude to damage or destroy three platforms in South Pass lease Blocks 61 and 70 (Map 8). One platform was completely toppled and lost, one was sufficiently damaged to warrant removal from the offshore, and the third was damaged and listing but was able to be reused and replaced in another location in lease block 61. None of the platforms were in production at the time; in fact, one platform had been in place only a month, but the loss of the three platforms and an 1,828 m (6,000 feet) pipeline (not yet in use) was over $40 million.

There was little doubt that the failure of the platforms was caused by storm-induced mudslides. In a report, "The Failure of the South Pass 70 "B" Platform in Hurricane Camille," the conclusions were (Sterling, 1973, p. 723):

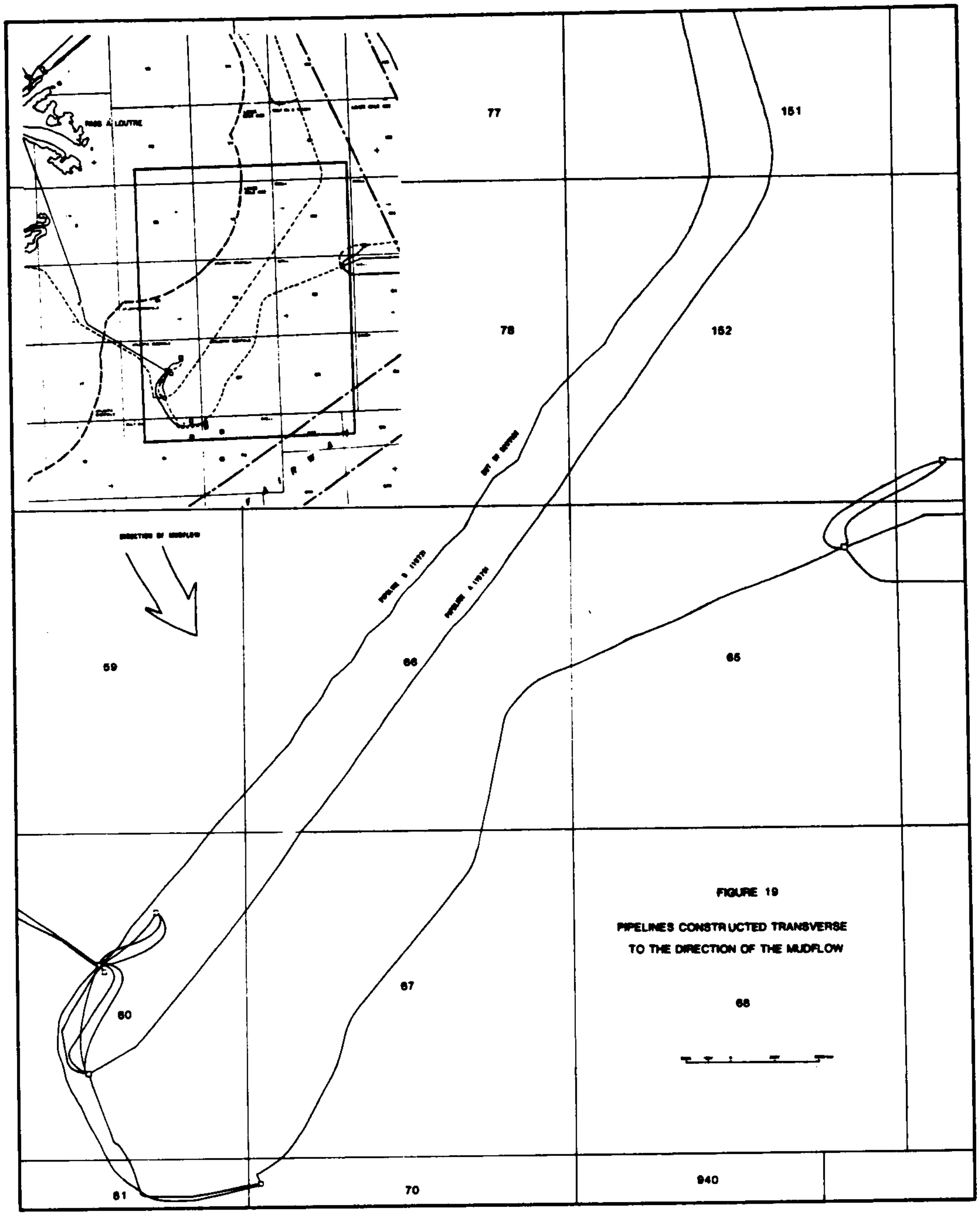


FIGURE 19

PIPELINES CONSTRUCTED TRANSVERSE TO THE DIRECTION OF THE MUDFLOW

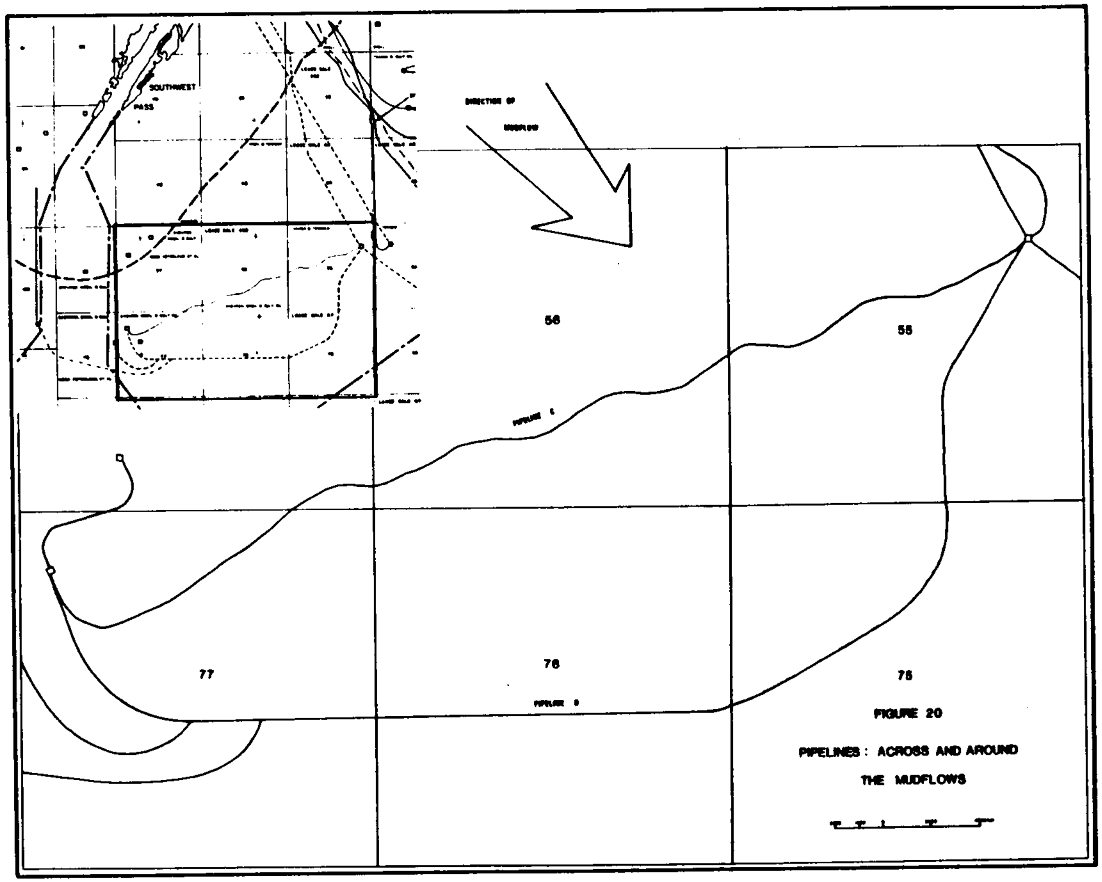


FIGURE 20

PIPELINES: ACROSS AND AROUND THE MUDFLOWS

PIPELINE MOVEMENT IN THE MUDFLOW AREA

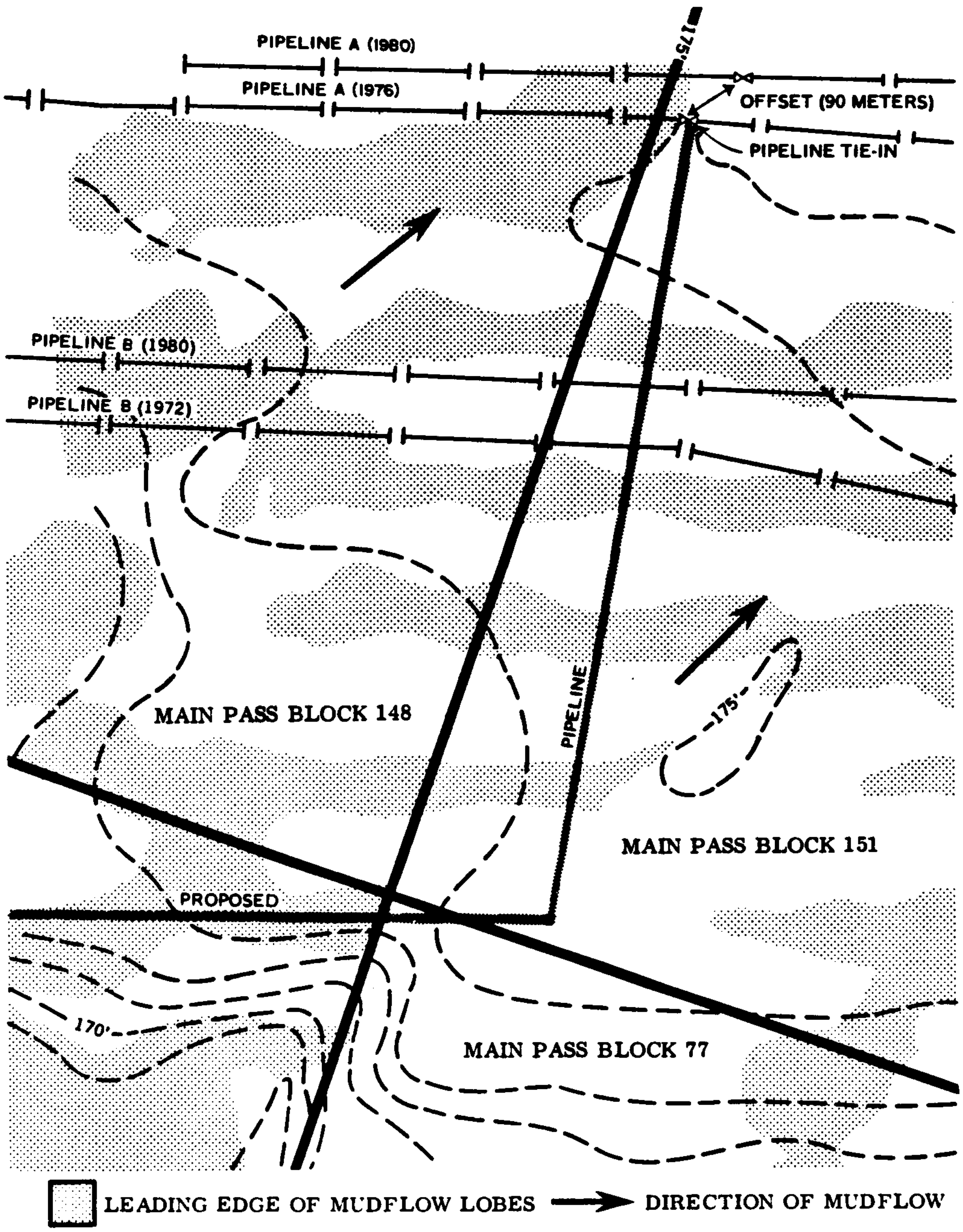


FIGURE 21.

SOURCE: UNITED GAS PIPELINE COMPANY. PRELAY SURVEY UC23138, 1980 (OCSG4358)

PIPELINE RE-ROUTE AFTER MULTIPLE FAILURES ON THE EXISTING ROUTE

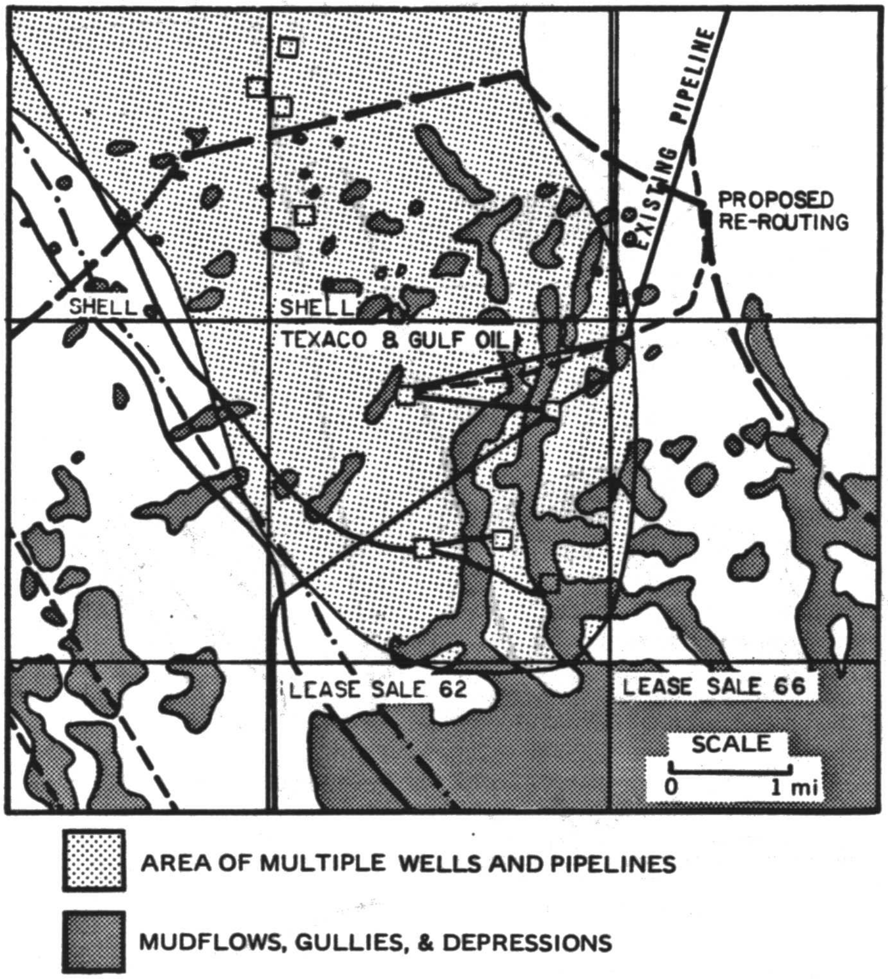


FIGURE 22.

There was large scale soil movement in South Pass Block 70 caused by Hurricane Camille.

The comparison of pre- and post-Camille borings indicate disturbance caused by Camille to a depth of about 70 feet near the "A" and "B" platforms.

The South Pass 70 "B" platform failed primarily because of wave-induced soil movements which caused the foundation elements (pilings) to fail in bending.

Recognition of the Problem

After the impact of Hurricane Camille in 1969 on offshore oil and gas structures, subsequent research revealed that mudslides induced by the hurricane were the major destructive factor and that this mudslide area extensively covered the delta front. BLM and USGS became concerned about future development in the area. In 1974 a map published by USGS showed zones of relative bottom sediment stability (Figure 23). However, at the time information from pioneer studies was not sufficient enough to know the depth of the disturbed sediments, the rates of gravity movement downslope, the activity of faulting, and the gaseous accumulations in the sediments. It was felt that without the vital information to fully understand the mudslide problem, it would be irresponsible to allow further development in the offshore delta front at that time. As a result, in 1974, BLM requested the withdrawal of ten lease tracts (Figure 24) from Sale 33 '. . . pending further evaluation of the foundation conditions." (Federal Register Document 74-4525, February 25, 1974, pp. 7209-7212).

USGS began studies of the mudslide area in 1974. Since that date a steady progression of surveys, data acquisition, and research have been done with a total of $3,000,000 being spent. In 1978, BLM and USGS combined to conduct research on the delta front mudslide area. In two years BLM has contributed $1,931,585 to this research. Maps 1-8, Open File Report 80-01, and Section I of this report are all outgrowths of these surveys and research to be used by government and industry. Future research is scheduled by BLM and USGS to provide detailed surveys of other areas of unstable sediments on the continental shelf and the entire Gulf of Mexico continental slope.

At present, just as in 1974 when several tracts were withdrawn from Sale 33, debate is focused on the withdrawal of three deepwater tracts in the Mississippi Canyon Area from proposed OCS Sale 66. Preliminary surveys indicate unstable sediments in deepwater, and consternation has developed over leasing prior to a full understanding of the geohazards structure, process, rate, and scale. BLM, USGS, and LSU are cooperating in the collection and interpretation of new data for the Mississippi Canyon Area that will provide a better comprehension of what geohazards exist and whether they present a significant problem to oil and gas development.

The oil and gas industry has responded to the geohazards of the mudslide environment by improving the engineering technology of their platforms and pipelines and by intensive surveys and soil borings of sites and routes.

In the construction of platforms, the increased engineering developments have meant an overall strengthening of the well jacket, legs that are stronger and heavier (e.g., some legs are over 230 cm (90 inches) in diameter), piles that are thicker walled, cross-member strength that is increased, and the pilings that are longer than those normally used for platforms of similar size in other areas of the Gulf. All pilings are driven through the projected depth of unstable sediments. In some cases this is 90-150 m (300-500 feet), as opposed to the depth of pile driving for platforms outside the mudslide area which usually will vary between 18-60 m (60-200 feet). Other engineering developments have included the addition of mud-skirt piling to the platform. These external pilings are designed to provide greater stability in the direction of the mudflow and to dissipate the mudflow's force against the actual legs of the platform. Figure 25 illustrates one of the newest of the mudslide area platforms in the South Pass Block 49 structure. As a result of these and other engineering developments, the platforms placed in the mudslide area are overstrengthened for the normal continental shelf environments and are overdesigned for the high waves and winds of hurricanes. However, their design is contemplated to withstand the great forces placed against the platform's base by the 15-30 m (50-100 feet) thick mudslide–a

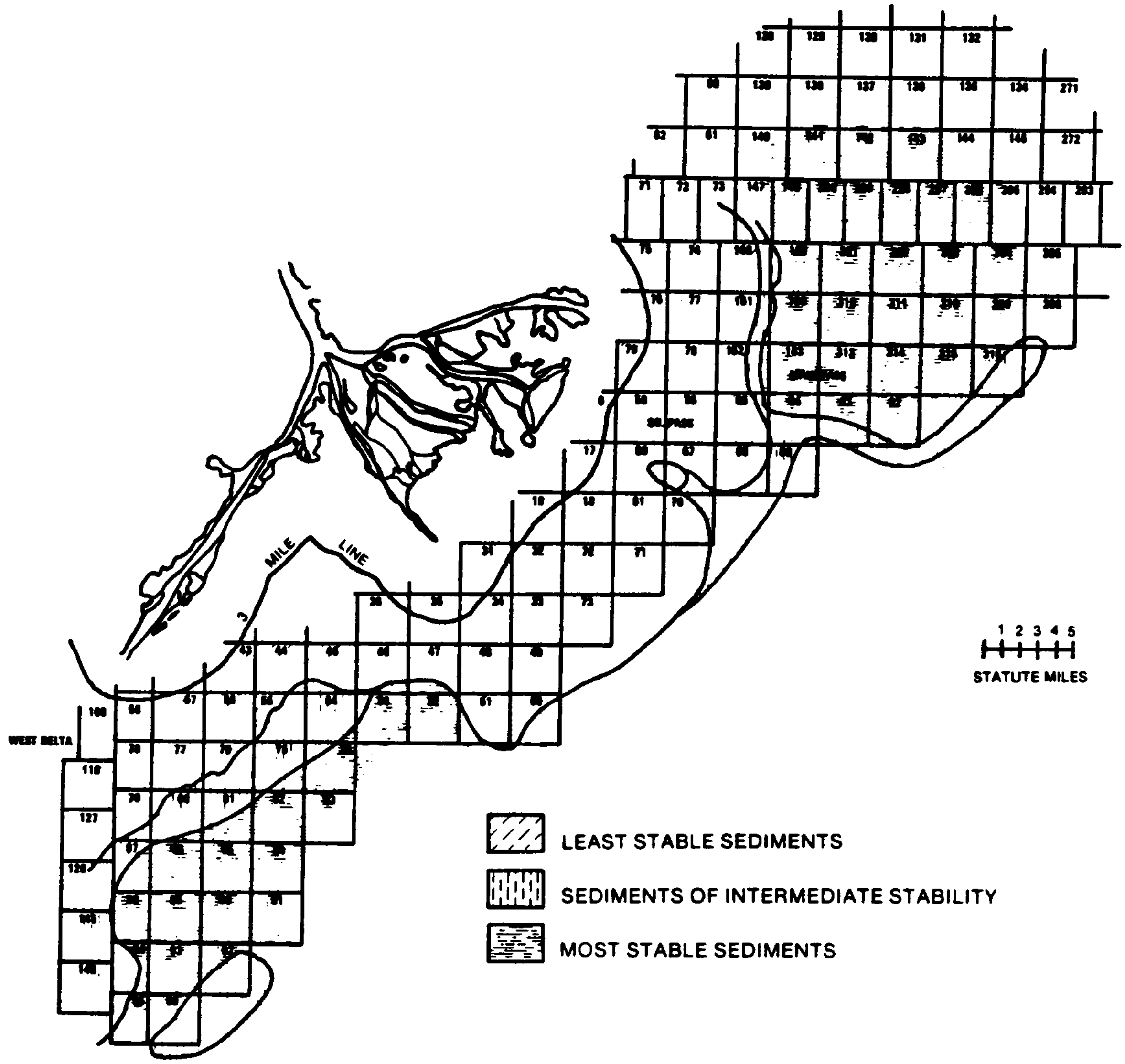


FIGURE 23 ZONES OF RELATIVE BOTTOM SEDIMENT STABILITY

SOURCE: USDI, GEOLOGICAL SURVEY, 1974

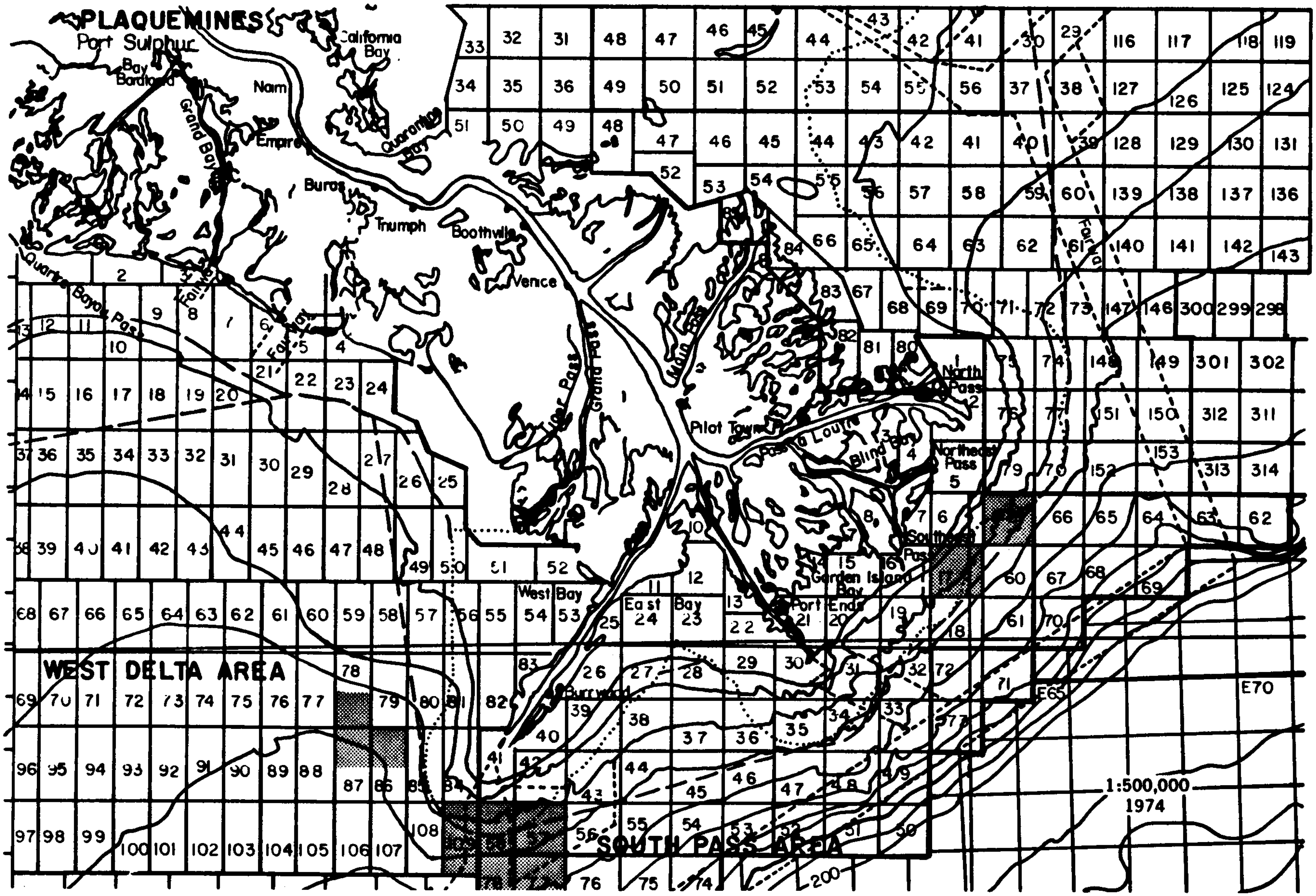


FIGURE 24.

TRACTS WITHDRAWN SALE 33

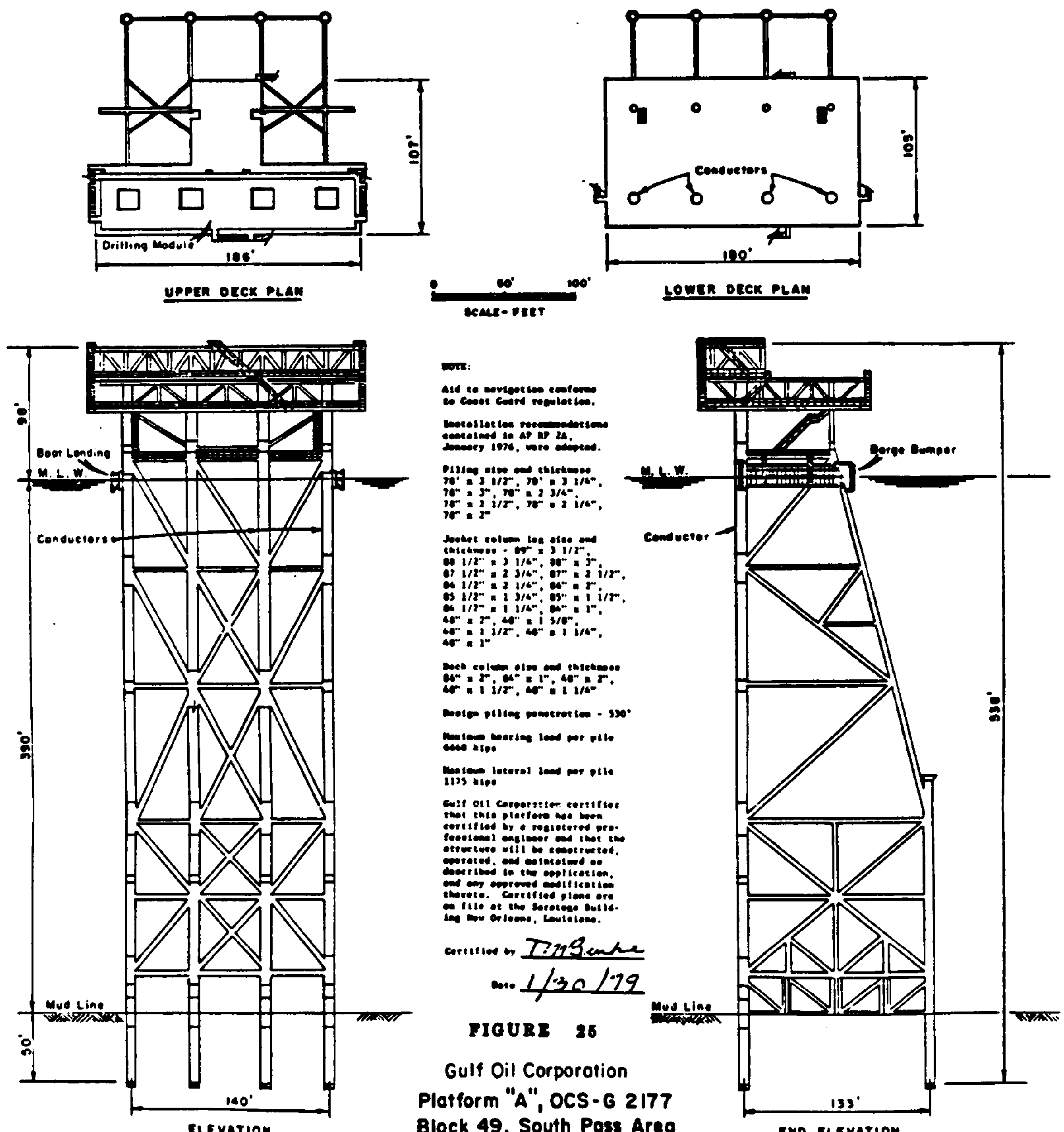


FIGURE 25

Gulf Oil Corporation
Platform "A", OCS-G 2177
Block 49, South Pass Area
186' x 107' PLATFORM
8 PILE JACKET 390' WATER DEPTH

SOURCE: DRAWING COURTESY OF GULF OIL EXPLORATION AND PRODUCTION COMPANY, NEW ORLEANS, LA.

force which earlier platforms designed for normal continental shelf seafloor conditions could not withstand in 1969.

Texaco's platform installed in West Delta Block 109 (Map 8) is typical of the platforms being constructed for Mobil, Shell, Gulf, Union, Atlantic Richfield, and Chevron in mudslide areas.This platform is located four miles from the mouth of Southwest Pass in 56 m (184 feet) water depth. The 4,000 ton jacket will require 12,000 tons of steel piles driven to depths of 192 m (630 feet) and 159 m (525 feet) below the mudline (Offshore, 1980). The four corner legs are 274 cm (108 inches) in diameter with 101.6 mm (4 inch) walls and have 243 cm (96 inches) and 149 cm (84 inches) insert piles driven in telescoping fashion below the main legs. The four skirt legs are 172 cm (93 inches) in diameter with insert piles 149 cm (84 inches) driven into the seabed. The total length of the platform and pilings is approximately 335 m (1,100 feet).

Additional engineering and design adaptations have tripled the cost of a platform for a mudslide area over a platform designed for stable bottom conditions in the same depth of water. A platform in 61 m (200 feet) of water with a known stable foundation will cost $10-15 million, whereas a platform designed and installed for 61 m (200 feet) of water with 30 m (100 feet) of unstable sediment in the mudslide area of the delta front will cost $35-40 million.

The siting of each platform has become very important considering the cost of the structure. After intensive surveys and soil borings are made in the vicinity of the oil or gas pays, an evaluation of the site is made. Since directional drilling is used, the platform may be sited in an alternate location to reduce hazards and/or costs. Union Oil Company of California has a lease on South Pass Block 48 but cannot place a platform conveniently within the lease block because the shipping fairway prevents them from doing so. They have studied the southwest corner of adjoining Block 33 for the possible siting of their platform. From a platform in this location, they could easily directionally drill into the oil or gas pay under Block 48. However, this 12-slot platform would be located in about 70 m (230 feet) of water in the middle of the active mudflow area with about 45 m (150 feet) of unstable sediment under it and cost $35 million to construct and install (Figure 26). In searching for alternative locations, the southwest corner of Block 49 also proved to be a favorable location utilizing directional drilling (Figure 26). This site was chosen for their smaller 6-slot platform even though it is in deeper water, over 120 m (400 feet). However, the soil borings showed the unstable sediments were only 15 m (50 feet) thick, making the cost of the platform in this location $17 million, which is half the cost of the platform in shallower water with thicker unstable sediments.

Pipelines present a greater problem for design and construction than platforms in the mudslide area because they lay on the surface of the mudlobes and are susceptible to the creep, slides, flowage, and subsidence components of each lobe. Several engineering adaptations have been made for pipelines in the mudslide area with more innovations to be made in the future. Some pipeline companies are beginning to insert flexible joints and safety couples in their pipelines. The flexible joints will allow some movement in the angle of a pipeline, whereas the normal, rigid angle connection would cause a break with movement. The safety couplers allow the pipeline, if it is moved, to severe at predesigned locations along the line, activating an immediate shut-off of the line flow. Basic pipeline engineering techniques utilized within the mudslide area for a number of years have been: lay the line with low tension between connecting points; reduce the specific gravity of the pipeline to allow the line to lay ("float") on top of the mudflows rather than sinking into the sediments; and install additional shut-off valves spaced throughout the route. Since these are all additional engineering requirements, a pipeline laid within or through a mudslide area is more costly than a pipeline laid in areas without geohazards.

An example of pipeline and riser installation departing from conventional rigid pipelines and risers in the mudslide area can be noted in the following description of the unique flexible system used to connect the South Pass Block 49 platform of Gulf Oil to a 48 km (29.6 mile) pipeline to shore (Edwards and Relfel, 1980). Figure 27 graphically illustrates the flexibile system components, and layout.

The flexible system lies on the seabed and can be stretched out several hundred feet by the anticipated movement of the mudflow that

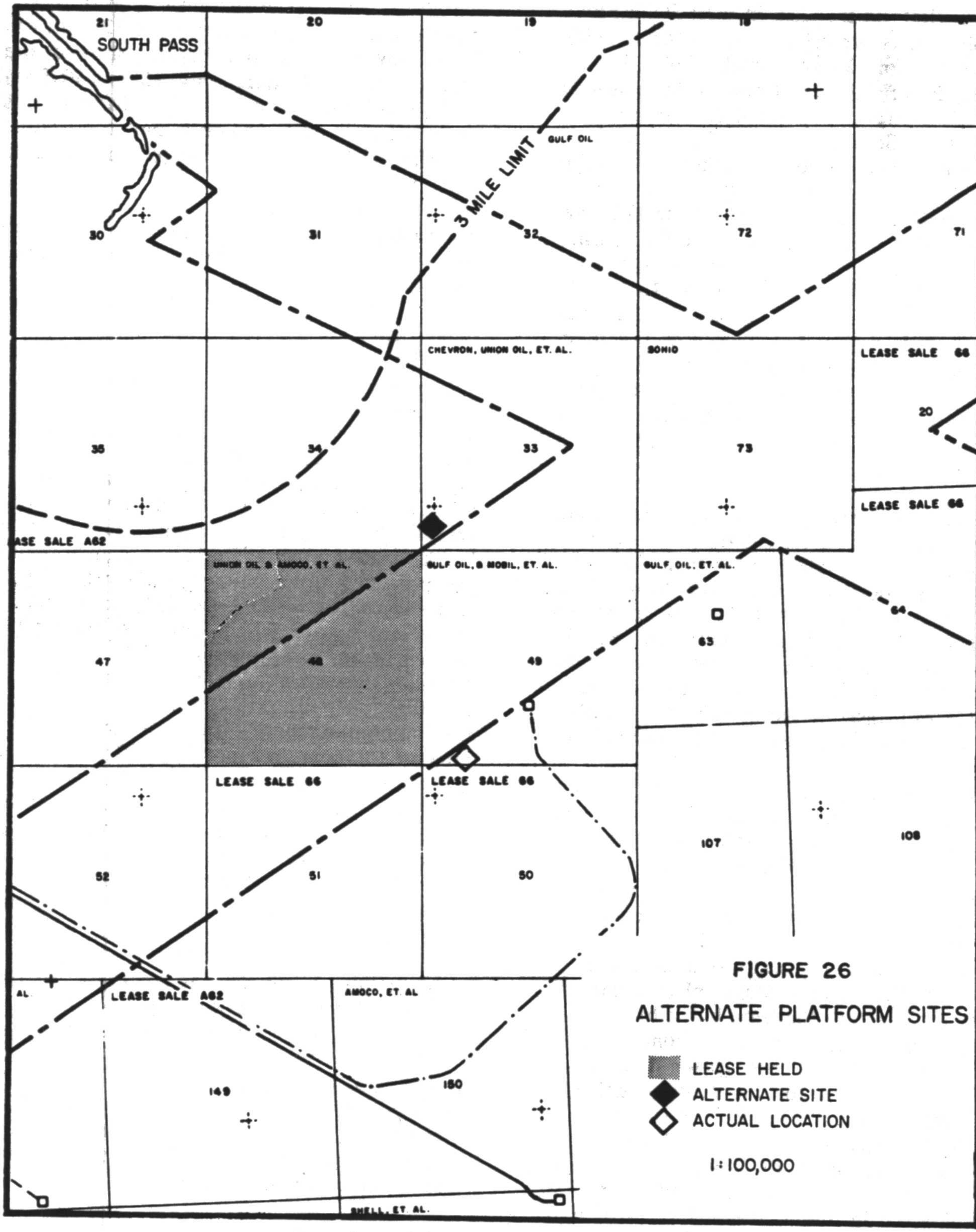


FIGURE 26

ALTERNATE PLATFORM SITES

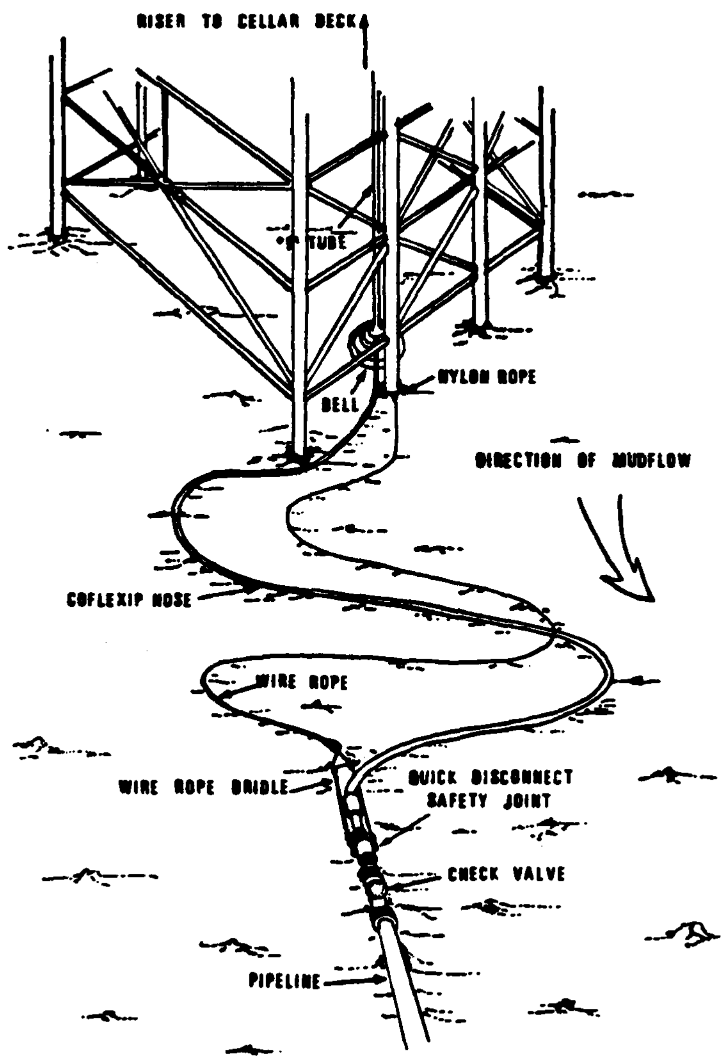


FIGURE 27

GULF OIL PLATFORM "A" ,

SOUTH PASS BLOCK 49

FLEXIBLE PIPELINE AND RISER

SOURCE : EDWARDS ANL RELFEL, OFFSHORE, NOVEMBER, 1980, P. 156

surrounds the platform. Components of the system include: (1) 304 m (1,000 feet) of Coflexip flexible pipe laid in an S configuration to span the 60 m (200 feet) from the base of the platform to the steel pipeline, (2) a nylon rope and wire rope bridle used to secure the flexible pipe to platform leg and a quick disconnect safety valve and check valve to sever the flexible pipeline from the rigid pipeline and shut off flow in case the mudflow pulls the flexible line beyond its designed length; (3) the flexible line is continued up through an I-tube riser to permit riser flexibility and rotation, and (4) the final 16 km (10 miles) approach to the flexible pipeline is made of heavy-walled steel pipe that sinks into the mud minimizing the effects of surface mudflow, yet providing sufficient tensile strength to resist small mudflows by catenary action.

In the event of a mudflow, the S configuration allows the pipeline to move while protecting the integrity of the line and riser. If a massive mudslide ensues, the pipeline is sacrificed by the quick disconnect safety joint and the riser is saved. The disconnect takes place as the wire rope becomes taut, activating the check valve attached to the safety joint which immediately seals the pipeline, thereby preventing an oil spill. After the mudslide, the flexible pipe is repositioned in an S configuration and reconnected to the lengthened and repaired steel pipe.

> "If a conventional steel riser and I-tube had been installed on Gulf's A platform in South Pass Block 49, it might have failed during the first day following installation. The pipeline below the platform dropped four feet in the mud in the first 24 hours after installation. This could have buckled a rigid steel pipe riser." (Edwards and Relfel, November 1980).

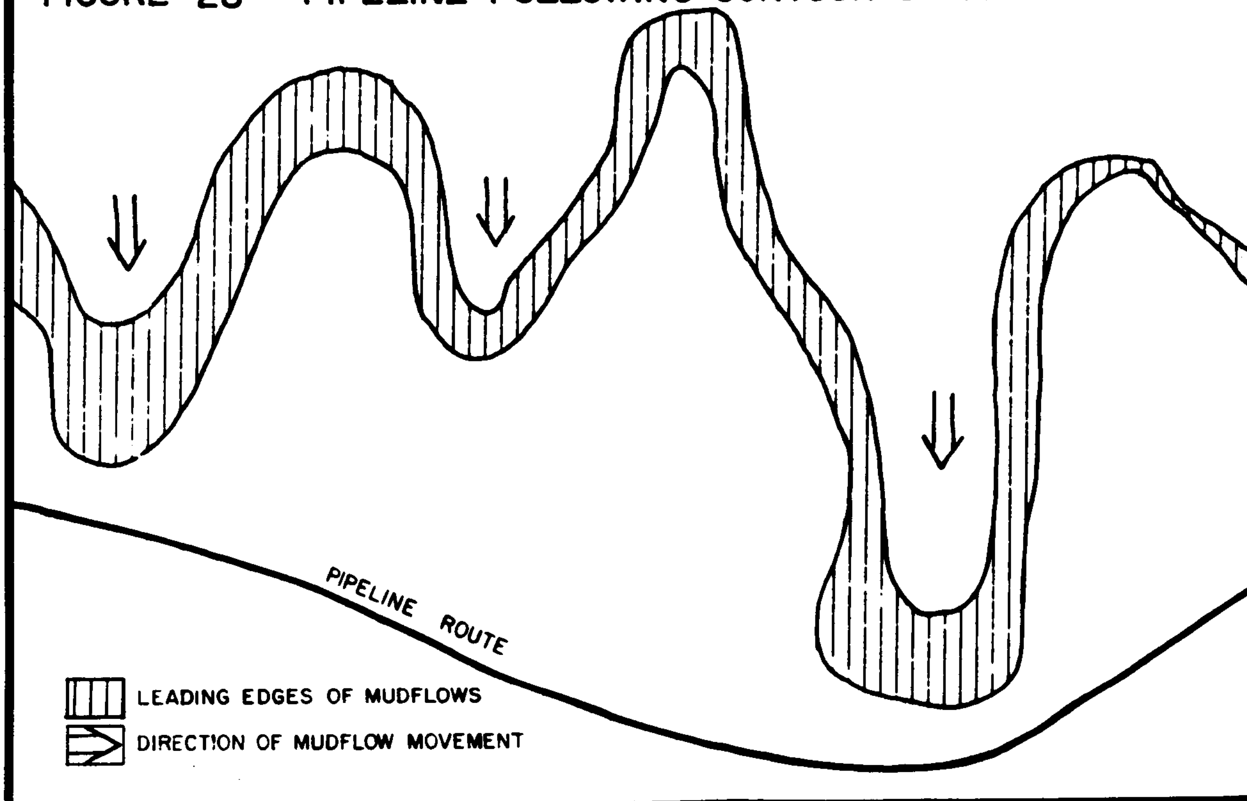
Engineering applications for pipelines within the mudslide area do not prevent breaks; they only minimize the chances of a break occurring and provide safety features to prevent large oil spills.

One method of minimizing the potential damage to pipelines by the mudslides is to route the pipeline in such a fashion that it does not traverse a straight line across a mudflow lobe but follows the contour of the lobe from one side to the other (Figure 28). Another method allows the pipeline to cross the mudflows in the direction of the flow of mud rather than at right angles to the flow, thus minimizing the surface drag of the mudflow on the pipelines (Figure 29). A third method of laying pipelines is through the areas of the mudslides showing lesser disturbance. In particular, several pipelines have been successfully routed from the undistrubed sediments in front of the mudflow lobes through the mudflows to shore by finding zones of slight to no disturbance. It is conspicuous on Map 8 that four pipelines traverse the mudslide area in the vicinity of South Pass Blocks 53, 54, 44, and 45 using a "pass" of undistrubed and slightly distrubed sediments (Map 5). Even so, one of the pipelines had a recent break in Block 44 as a result of a mudslide (Table 1). The routes of these four pipelines indicate the application of surveys and research to pipeline route design in order to reduce the risk of failure.

Described here are two other examples of pipeline routings that cross as little of the mudslide area as possible, even if the route is somewhat circuitous. The Tennessee Gas pipeline constructed from South Pass Block 77 to Block 55 is a good example of a pipeline being routed to avoid as much of the unstable sediments as possible (Figure 30). This circuitous route was chosen because farther out the mudflow lobes tend to be more stable, "the sedimentation rate is slower than in other areas and burial of the pipeline by sediments deposited from suspension is doubtful within the projected life of the pipeline" (Hazard Survey Report . . ., 1979, p. 9). Within this same pipeline route an alternative was proposed even though this route would require an additional 975 m (3,200 feet) of pipe and be in greater water depths (Figure 31). The alternate route was recommended because it was ". . . relatively more stable and any future lobal movement is anticipated to move roughly parallel to the alternate route . . ." (Hazard Survey Report . . ., 1979, p. 10).

In the second example, the circuitous route of an oil and gas pipeline from South Pass Block 49 to shore (Figure 32) ". . . has been routed to the south from the platform location to avoid crossing unstable ground transverse to the direction of bottom movement and thence in a westerly direction to the proximity of the Shell Cognac pipeline." (Geophysical Survey and

FIGURE 28 PIPELINE FOLLOWING CONTOUR OF MUDFLOWS



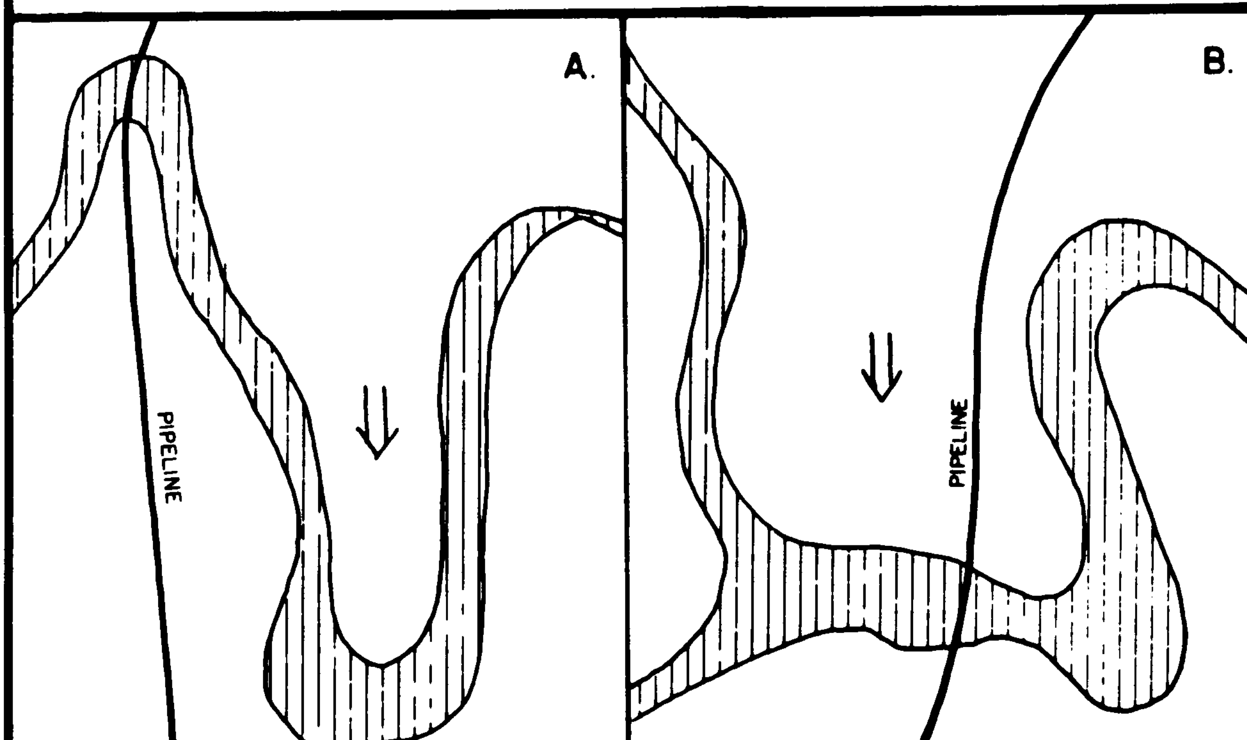


FIGURE 29 PIPELINE LAID PARALLEL TO MUDFLOW MOVEMENT

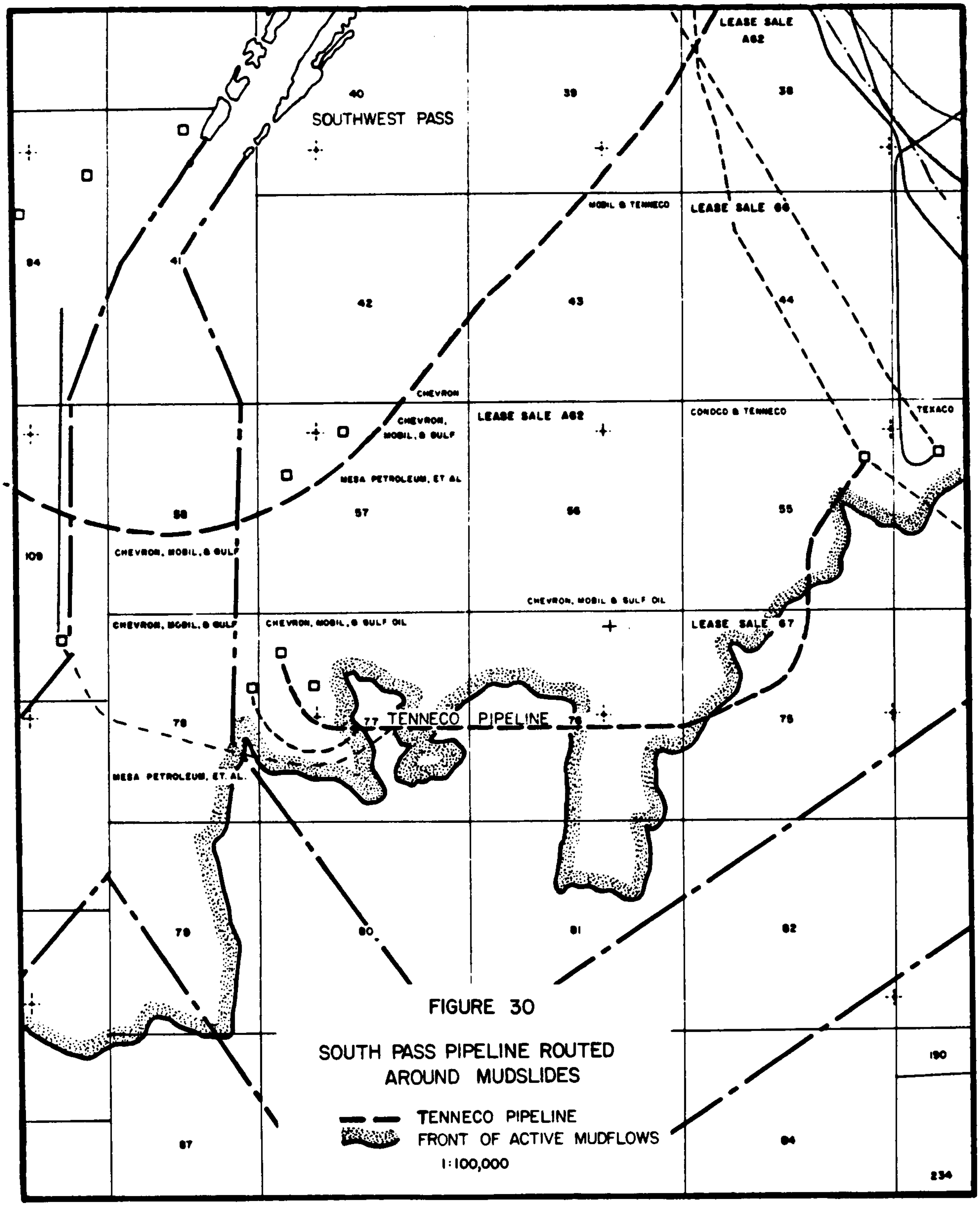


FIGURE 30

SOUTH PASS PIPELINE ROUTED AROUND MUDSLIDES

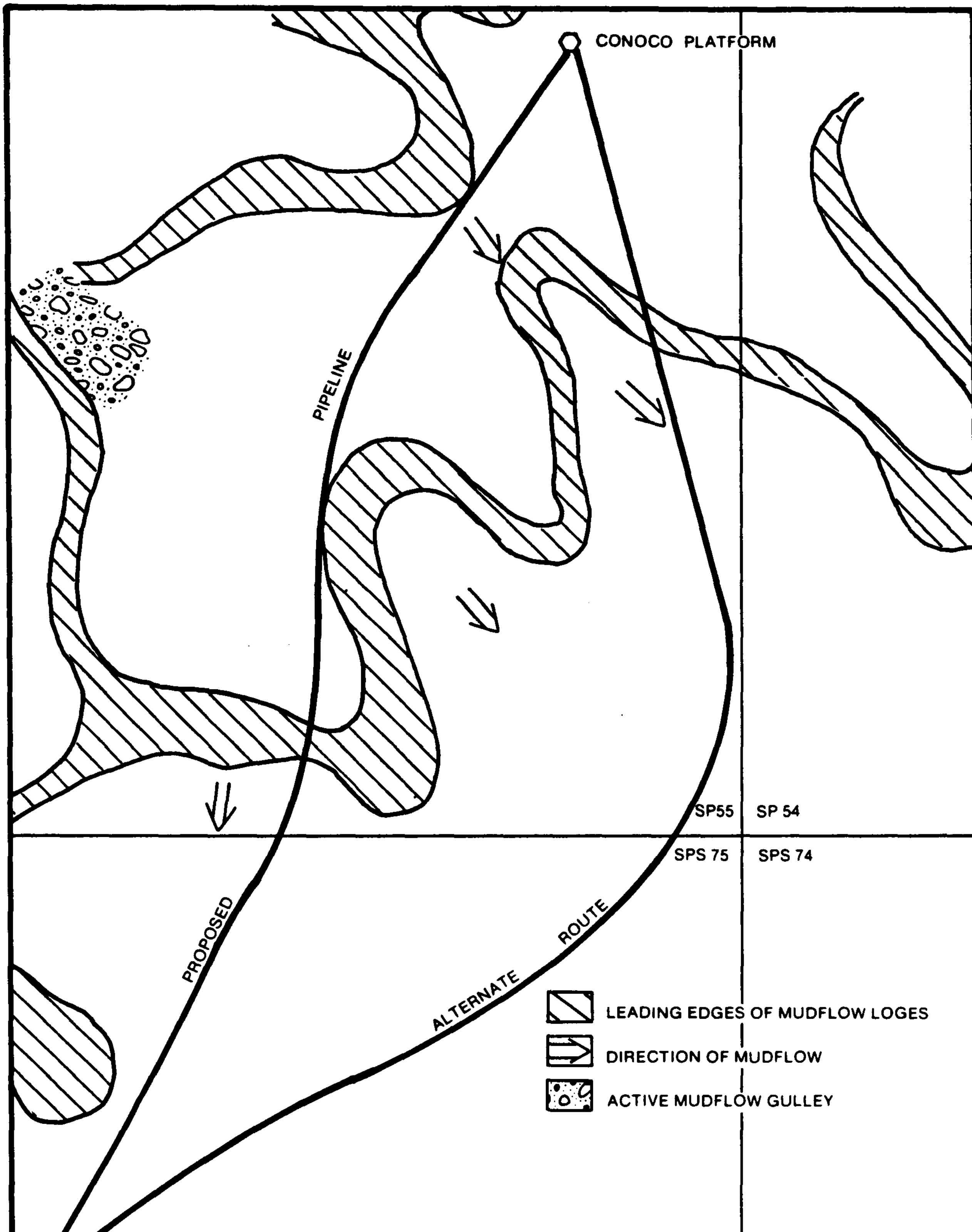


FIGURE 31 SURVEYED PIPELINE ROUTES THROUGH MUDSLIDES

SOURCE: TENNESSEE GAS PIPELINE COMPANY,PIPELINE PRELAY SURVEY. 1979

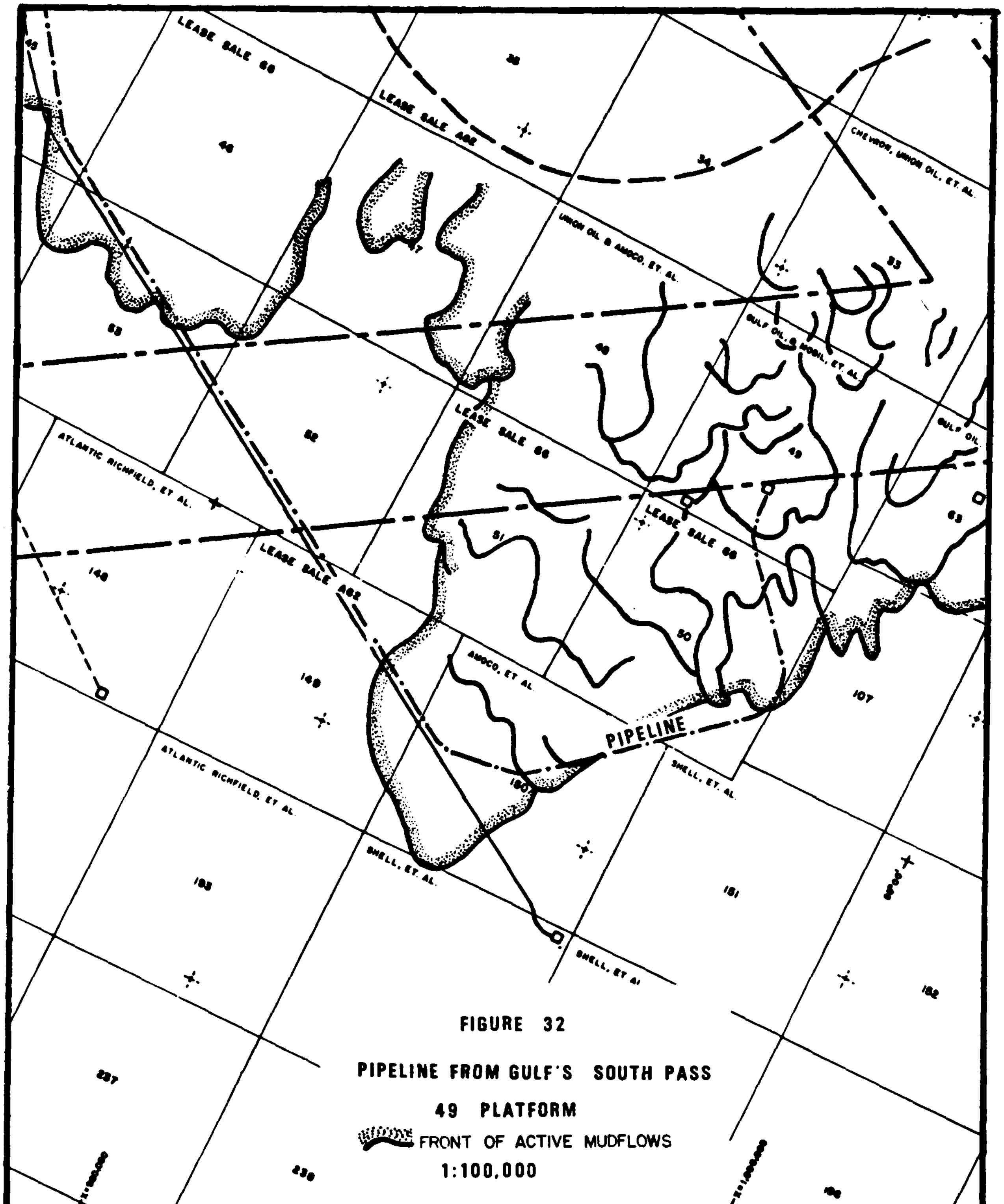


FIGURE 32

PIPELINE FROM GULF'S SOUTH PASS 49 PLATFORM

FRONT OF ACTIVE MUDFLOWS

1:100,000

Soils Investigation . . ., 1979, p. 1). The total length of the pipeline was 45 km (28 miles) which is 11-16 km (7-10 miles) longer than a more northerly and direct route would have been. As seen in the bathymetric cross section (Figure 33), the pipeline flow is downhill and then uphill with water depths varying between 237 m (780 feet) and 6 m (20 feet), but a large part of the pipeline in South Pass Block 50, where the pipeline is deepest, is on a firm, sand bottom.

Basically, even the proposed route of the pipeline is in a precarious position with regard to the mudflows (Compare Maps 5 and 8). At the platform in Block 49, bathymetric maps for 1874-1979 (Map 2, 3, and 4) indicate as much as 22 m (75 feet) of sediment accumulation—18 m (60 feet) since 1940. Most of that sediment accumulation is the result of the advancement of mudflow lobes. In this area the pipeline crosses several mudflow lobes and their front scarps, traverses close to several large mud volcanoes up to 60 m (200 feet) in diameter and 6 m (20 feet) in height, crosses a contemporary growth fault, and avoids or is threaded between large blocks of sediment, mudflows gullies, and collapsed depressions (Geophysical Survey and Soils Investigation . . ., 1979). In review of the survey for this pipeline and Shell's surveys ("Pipeline Route Study for Cognac, Mississippi Canyon Addition, Phase II, Vol. I, Evaluation and Selection of Pipeline Route," November 1977 and "Pipeline Route Study for Cognac, Mississippi Canyon Addition, Phase II, Vol. II, Assessment of 1977 High-Resolution Geophysical Survey, Cognac Area," December 1977), it is notable that the pipeline route is parallel to the general direction of the mudflows in this area and would be favorably oriented to withstand mudflow sediment loading. A comparison of Maps 5 and 8 show ". . . there is no other more favorable route available for the pipeline. It is anticipated that within the life of the pipeline movements will occur within the lobes or newer lobes will move down . . ." across the pipeline route (Geophysical Survey and Soil's Investigation . . ., 1979, p. 12). In the end, it is inevitable that movement of the pipeline will take place with possible failure.

An obvious way of preventing pipeline movement and failure is to lay the pipeline outside the mudslide area as much as possible. While this provides safety from the mudslides, it would be, in many cases, very costly and uneconomical for companies to attempt. However, Figure 34 shows that the delta front can be divided into three major sections for the purpose of pipeline routing from offshore production areas to onshore facilities. As referred to on Map 8 and previous figures, the primary corridors of transmission pipelines for Sections C, B, and A have been as follows: Section C—north and then west around or skirting the outer edges of the mudflow and Section B—the identification and use of the natural "pass" between the mudflow lobes.

For most of Section A a corridor or route pattern has not been identified. Chevron's pipeline routes in South Pass Blocks 77 and 78 have primarily flowed east to use the corridor of Section B, while a pipeline from the Exxon platform in South Pass Block 93 has been built to the northwest. The Texaco platform in West Delta Block 109 has an oil pipeline laid due north from it through the mudslide area as alternative routes south and southeast were unacceptable due to crossing the shipping fairway once or even twice (Map 8), and, as will be explained later, the route to the north was considered to have a lower incidence of pipeline failure in the ensuing 20 years.

Considering the route of the future pipeline to be laid from the Marathon platform in South Pass Block 89 to shore, what problems should be considered for the proposed routing? It is 14 miles east to the pipeline corridor in Section B, then 15 miles to shore for a total of 29 miles. It is 17 miles due north to shore through a very active mudflow area, and 24 miles northwest to the Marathon-Amerada Hess platforms and pipelines in West Delta Blocks 79 and 80.

It is also necessary to understand that at present Southwest Pass is the only Mississippi River pass maintained by the Corps of Engineers for deep draft ships, and it has an estimated 40% of the river's discharge. As a result of the high flow and associated high sediment load, the sediment accumulations at the mouth of Southwest Pass are great, particularly in sand and silts, and the mudflows are very active. The mudflow front in the vicinity of Southwest Pass will advance rapidly as the greater discharge and higher velocity of water carries the suspended and bedload sediments out to greater distances from the mouth of the pass. In the same light, South Pass is shoaling at water depths of 17-19 feet and Pass A'Loutre shoals in at 12-14 feet. Both passes are not maintained by the Army

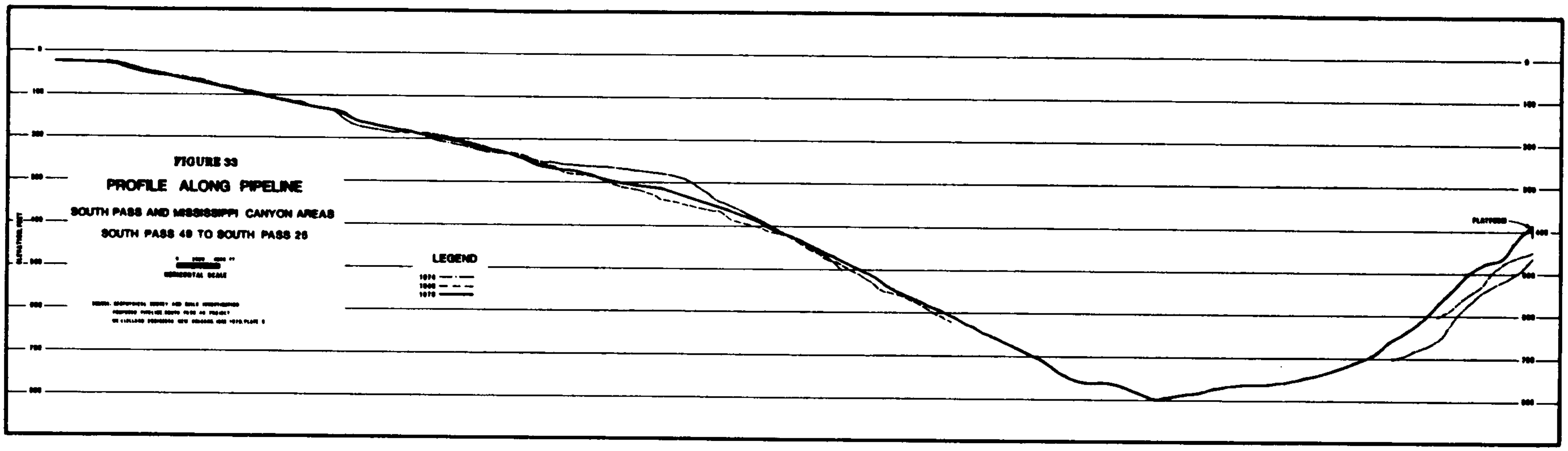
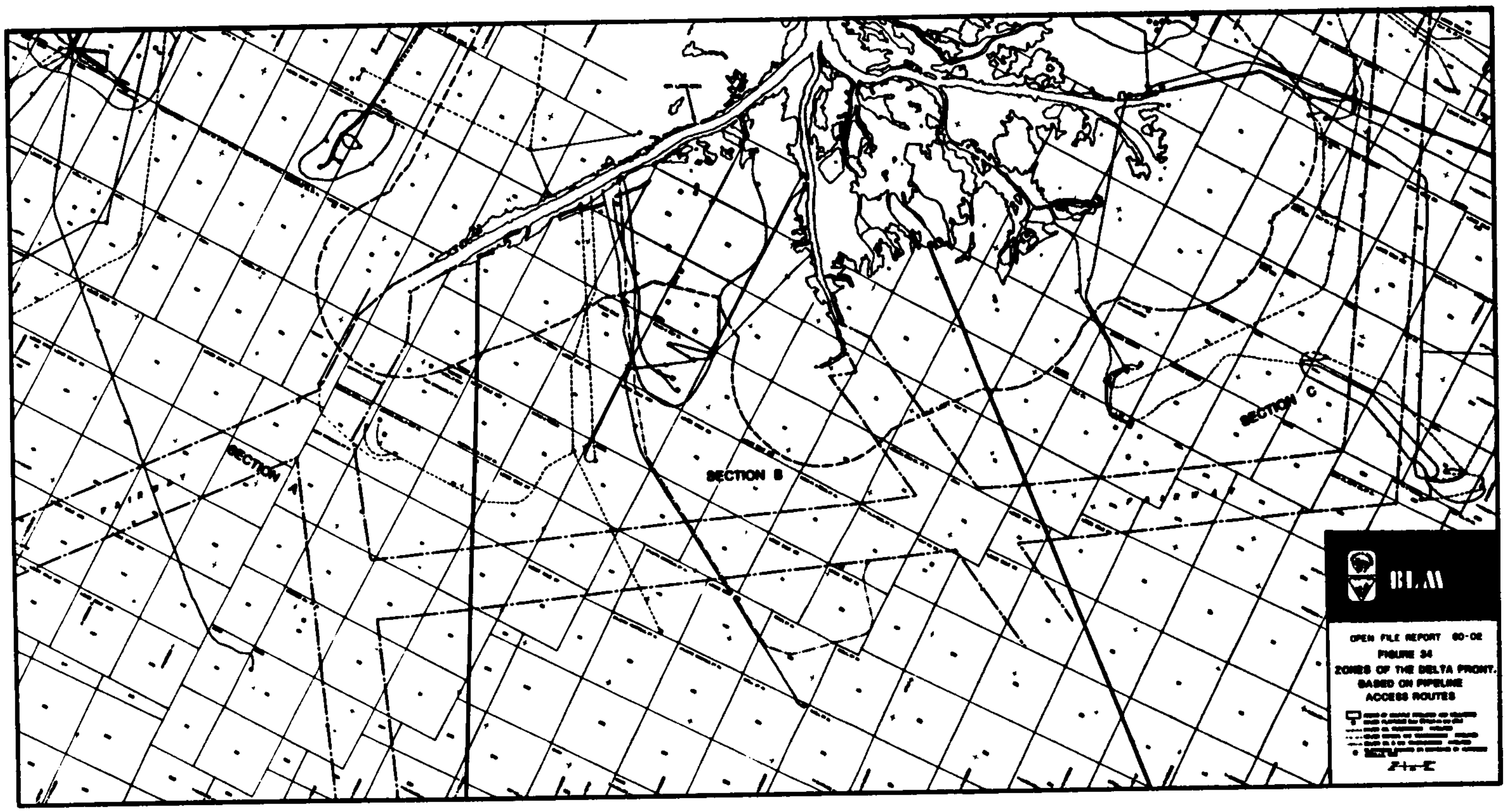


FIGURE 33

PROFILE ALONG PIPELINE

SOUTH PASS AND MISSISSIPPI CANYON AREAS

SOUTH PASS 49 TO SOUTH PASS 26


SECTION A
SECTION B
SECTION C
BLM
OPEN FILE REPORT 80-02
FIGURE 34
ZONES OF THE DELTA FRONT,
BASED ON PIPELINE
ACCESS ROUTES

Corps of Engineers any longer, while Southwest Pass is maintained at a 47 foot draft. As a result, the discharge and sediment load carried by Southwest Pass is likely to increase, and the possibility exists for lower sediment accumulations, a lessening of mudflow activity and slower advancement of the mudflow front in the vicinity of South Pass and Pass A'Loutre.

Geomorphologically, the following scenario will explain the changes that could take place on the seafloor off Southwest Pass over the 20-year period of 1980-2000 utilizing the data presented in Maps 1-8. The methodology is to use bathymetric surveys made of the delta front and plot those surveys on a slope profile as R.G. Bea has done for Woodward-Clyde Consultants of Houston (Figure 35). This illustrates the sedi mentation that has taken place both horizontally and vertically. Using these profiles and data derived from them, a projected profile may be constructed for 25-30 years hence (Bea, 1980).

Similarly, the author has taken the previous bathymetric surveys of 1874, 1940, and 1978 of Maps 2, 3, and 4 to construct the composite bathymetry seen in Figure 35. The depth of sediment accumulation is not considered, only its horizontal extent. The horizontal extent of the mudslide area in the vicinity of Southwest Pass has been noted on Map 5 and can be easily overlain by the isobaths (Figure 36). In Figure 37, the isobaths for the year 2000 have been projected using measurements derived from the linear differences between the 1940 and 1978 isobaths. In 20 years the isobaths are projected to be 243-364 m (800-1,200 feet) seaward of their respective 1978-1979 isobaths. In similar measure, because the sediment accumulation will cause changes in the bathymetry, a progradation of the mud accumulations, downslope movement of the mudlobes, and a general seaward extension of the disturbed seafloor will occur. As a result, Figure 37 shows the mudslide area shifted farther seaward to remain juxtaposed to the projected year 2000 bathymetry. The projected progradation of the area of seafloor instabilities (mudflows) varies between 300-1,000 m (1,000-3,200 feet) over the next 20 years.

Given the potential advance of the mudflow front over the ensuing 20 years in the vicinity of Southwest Pass, a pipeline route to avoid any mudflows should follow a route from South Pass Block 89, similar to that proposed in Figure 38. Note the circuitous route is in advance of the projected progradation of the mudflow front. The pipeline routed in this manner is in no imminent danger of failure from present mudslide acitvity nor will it be for probably the next 20 years (the expected production life of the oil and gas field).

As mentioned earlier, the pipeline was laid from the Texaco platform in West Delta Block 109 (Figure 38) upon the recommendation of Woodward-Clyde Consultants that the area the pipelines passes through may be active now, but given the discharge of the Mississippi River from Southwest Pass, the major sediment accumulations and associated mudslide activity will have progressed seaward of the pipeline route and platform within 5-10 years. If the gas field is calculated to produce for 20 years, the pipeline will need to last an initial 10-15 years with a low probability of failure to give the oil company the least down time for repairs and the greatest return on both the pipeline and platform.

These scenarios demonstrate the need and utilization for the maps (Maps 1-8) and the geohazard surveys and research being conducted by BLM, USGS, LSU, and industry.

Conclusion

Until 1960 very little was known of the delta front geohazards even though oil and gas production had been present for a decade. Within the last 20 years studies and research of the area have provided a great source of detail and background for subsequent leasing and development. However, uncertainties will always be present in an area that is geomorphically complex.

There have been a number of platform and pipeline failures as a direct result of massive mud movements. Most of the evidence indicates that widespread instability can be associated with overloading caused by high amplitude, hurricane-generated waves although researchers are investigating other causes of overloading that may be more critical at times.

The uncertainities in dealing with the hazards of mass-wasting on the continental shelf or slope will never be reduced to zero. From experience and surveys, the government agencies and industry involved on the continental shelf are

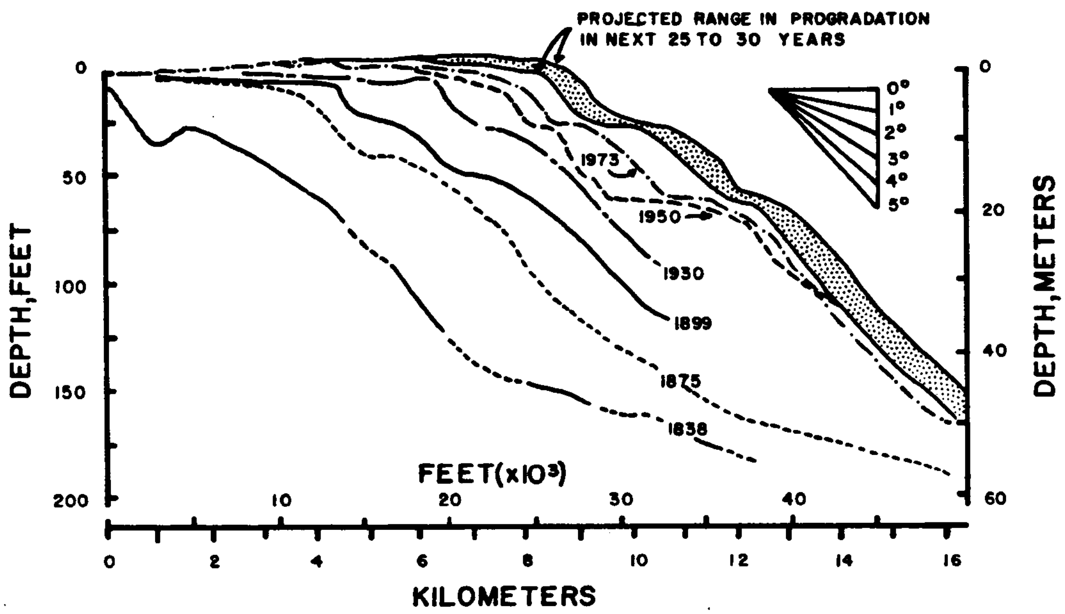
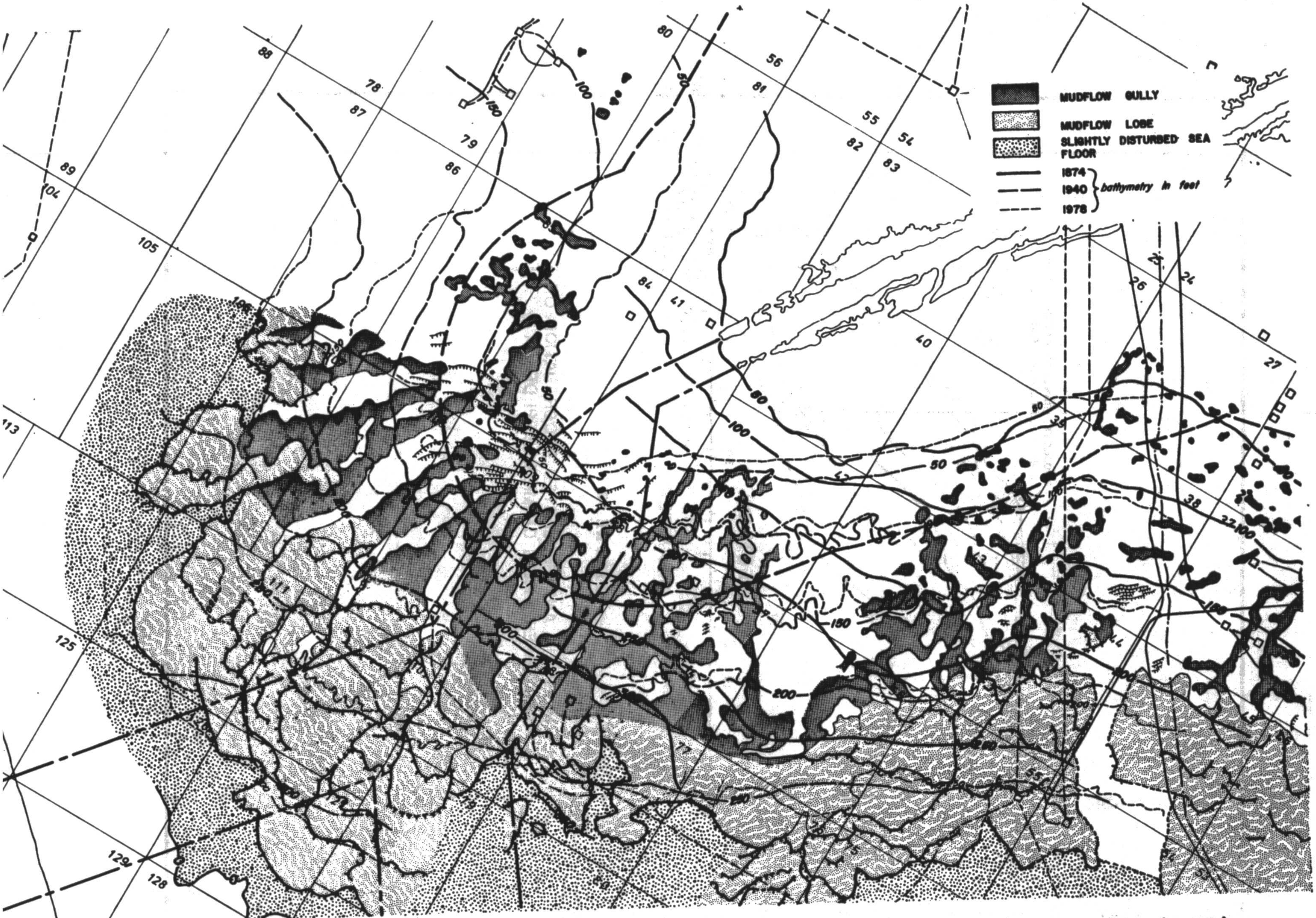


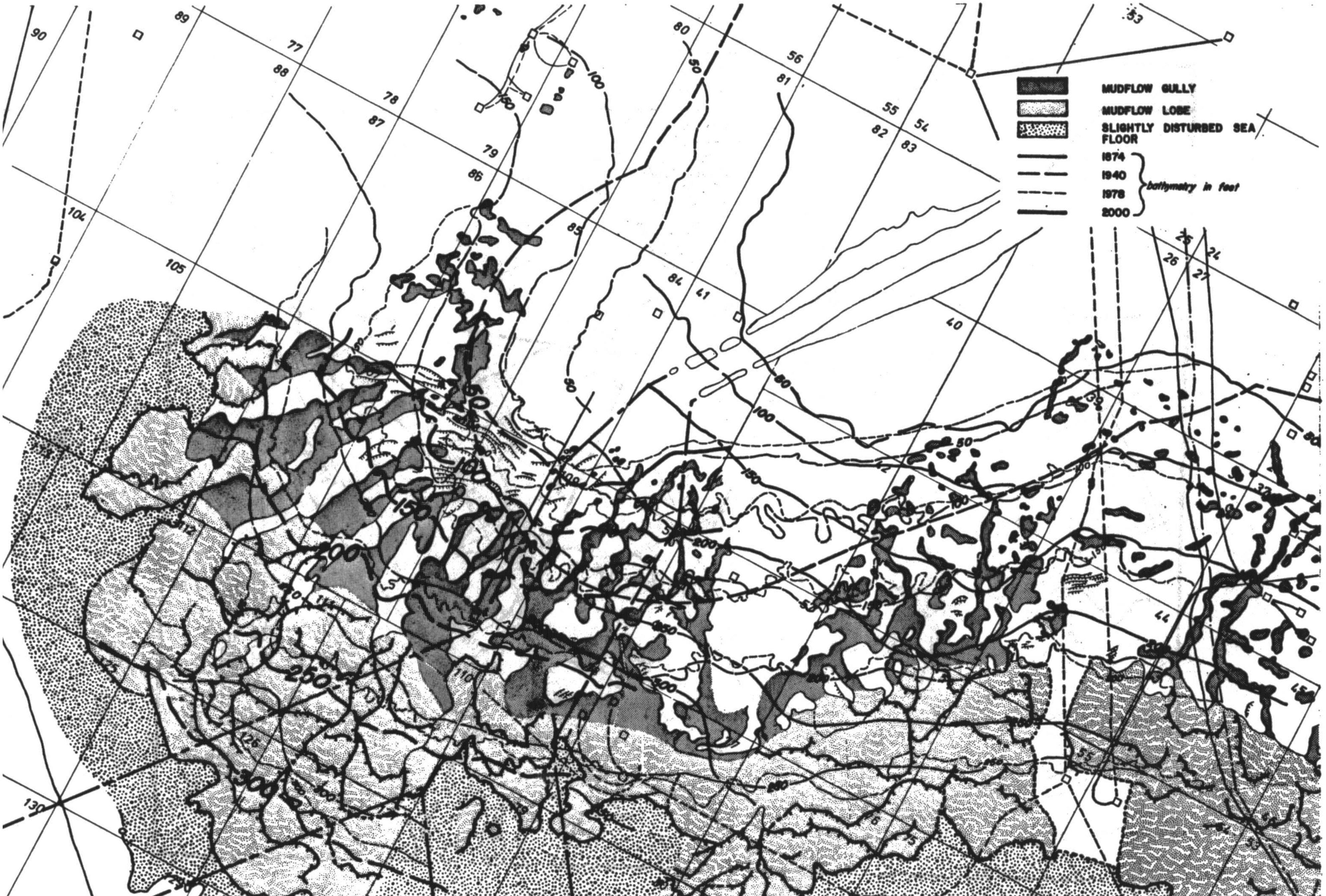
FIGURE 35

HISTORIC AND PROJECTED PROGRADATION OF SOUTHWEST PASS OF MISSISSIPPI DELTA

SOURCE: R.G. BEA, 1980, P. 10



jure 36 SOUTHWEST PASS-COMPOSITE BATHYMETRY (1874,1940,1978) AND SEAFLOOR INSTABILITIES (1978).



ıure 37 SOUTHWEST PASS-PROJECTED BATHYMETRY (2000) AND PROJECTED PROGRADATION OF SEAFLOOR INSTABILITIES (2000)

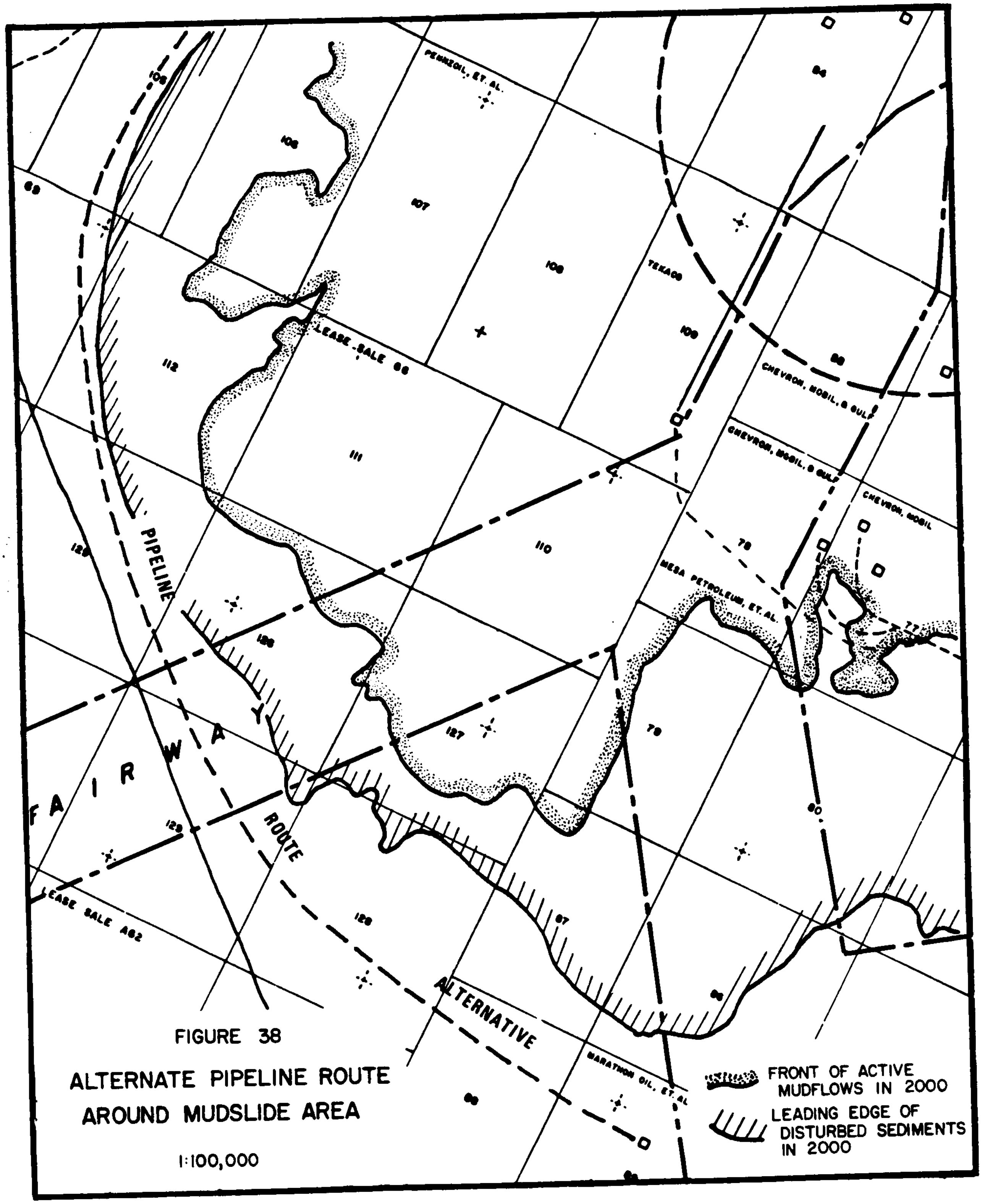


FIGURE 38

ALTERNATE PIPELINE ROUTE AROUND MUDSLIDE AREA

1:100,000

well atuned to the nature of the instability, mechanism of movement, rate of movement, and structural failure that can result. To minimize the loss or damage of property and natural resources, BLM and USGS have been given responsibility to monitor the oil and gas activity, provide a leasing program that is in line with current deepwater technology and engineering capabilities, and permit platforms and pipelines after assurance of their correspondence to surveyed instabilities through possible engineering adaptations and proper route and site selection.

As more and more development has taken place in the offshore delta, recognition of the large area of very active geohazards by the oil and gas industry has produced tremendous amounts of data, various engineering adaptations to platform structures and pipeline laying, and the proposal of several alternatives for platform sites and pipeline routes. The cost to industry has increased (i.e., they have increased site and route surveys, structural strength and/or flexibility, exploration techniques, etc.) by minimizing the geohazards problem to prevent damage to their investments and the loss of operating time, life, and natural resources.

Certainly, the Mississippi River offshore delta is neither a unique marine environment nor does it have the greatest geohazards problems of all continental shelf areas. However, it is an area where the continental shelf and the geohazards are combined with the presence of substantial deposits of oil and gas. This combination of water depth, oil and gas, and bottom instabilities presents a situation where government, academia, and industry are working together to provide a safe yet productive seascape, and a model for the development of other continental shelf areas and future continental slope development.

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SECTION III

SEVERE STORM AND HURRICANE IMPACTS ALONG THE GULF AND LOWER ATLANTIC COASTS

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1980

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Introduction

Coastal and continental shelf zones of the eastern and southeastern United States are vulnerable to severe storms generated over the Atlantic Ocean and the Gulf of Mexico. These severe storms containing some of the more violent aspects of weather are cyclonic rotating whirlpools of air called vortices (Miller and Thompson, 1970). Three principal types of vortices are: the wave cyclone-the largest but usually the least violent; the tropical cyclone-smaller in size but much more destructive; and the tornado-the smallest and most powerful. Of these, the tropical cyclone has the greatest potential for damaging impact on offshore oil and gas activities.

Cyclonic Disturbances

A cyclone may be defined as masses of air rotating in a counter-clockwise direction in the Northern Hemisphere (clockwise in the Southern Hemisphere) around a low pressure center; one that develops over warm tropical water is a tropical cyclone. Depending on the measured speed of sustained surface winds near the center of the system, the tropical cyclone is further classified as a tropical depression (33 knots and less), tropical storm (34 to 63 knots, inclusive), or hurricane (64 knots or greater). Deriving its energy from the latent heat of condensation of water vapor, the tropical cyclone is a large scale, nonfrontal, low pressure weather system that is often hundreds of miles in diameter. It travels widely bringing driving rains and often great destruction.

Modification of tropical cyclone characteristics occurs when the system moves into a nontropical environment where waters are more temperate. When this occurs, normally a reclassification to an extratropical cyclone may result during the latter stages of the life cycle of a tropical cyclone over water.

Recently, through the use of satellite imagery and other observational evidence, storms exhibiting both tropical and extratropical characteristics were investigated. These "hydrid" storms are now identified as subtropical cyclones. These types of severe storms occur frequently in the Atlantic tropical cyclone basin between the months of May and November. The Atlantic hurricane season is a six-month period from June 1 to November 30 with the greater incidence of tropical storms normally occurring during August, September, and October.

Area Influenced

Geographical areas influenced by tropical cyclones have been called tropical cyclone basins (Neumann, et al., 1978). There are six such areas in the world of which the Atlantic tropical cyclone basin is one. It includes much of the north Atlantic Ocean, the Caribbean Sea, the Gulf of Mexico, and a substantial portion of the adjacent coastal areas of the eastern and southeastern U.S. The outer continental shelf onto which the petroleum industry has expanded through increased oil and gas exploration along the southeastern U.S. and the Gulf of Mexico is a part of the Atlantic tropical cyclone basin (Figure 1).

Probability Of Occurrence

The assessment of risk involved on the hurricane-prone coastline of the U.S. is increasing in importance as the population migrates to the coastal areas, particularly for the metropolitan areas and for the locating of industrial sites. Realizing a summarization of hurricane events was needed for planning purposes along the Atlantic and Gulf coastlines of the U.S., Simpson and Lawrence (1971) reviewed pertinent tropical cyclone events between 1886-1970. Since the unpredictability of hurricane events precludes a stable climatological summary of the risks for storm recurrence at any one locality, their effort was directed toward preparing the best possible information available.

From Brownsville, Texas, northward along the Gulf and Atlantic coastlines of the U.S. to Eastport, Maine, the probability of occurrence and severity of tropical cyclones was summarized for coastal strips approximately 50 nautical miles in length. Simpson and Lawrence felt the 50-mile strip was the smallest segment of coastline for which meaningful summaries could be made using only 85 years of hurricane events. The coastal strips, along with the earliest and latest recorded dates of landfall for tropical cyclones within the respective strips, are shown in Figure 2.

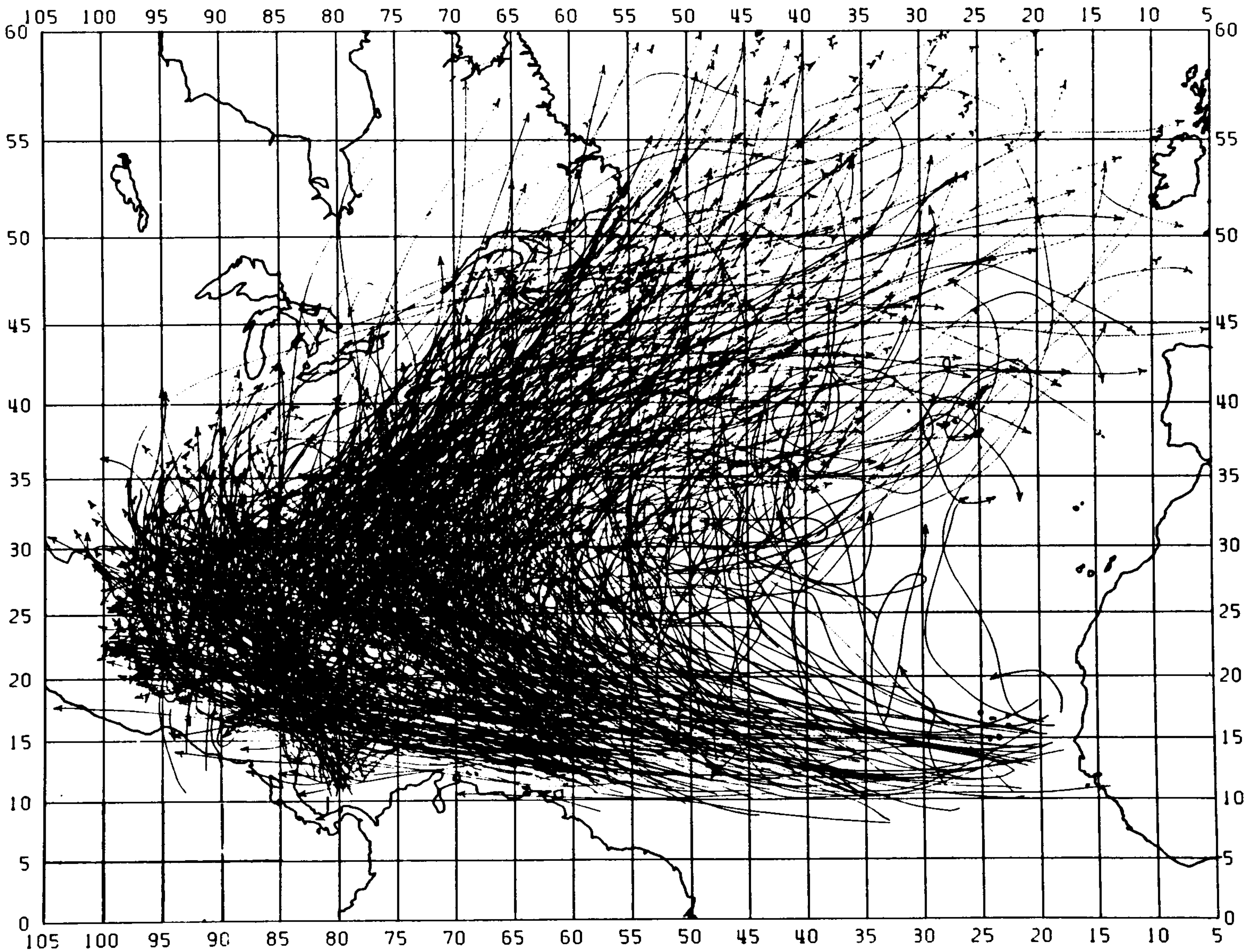


FIGURE 1 TROPICAL STORM TRACKS, 1886-1976

A computer plot showing tracks of 755 tropical storms originating in the Atlantic tropical cyclone basin between 1886-1976.

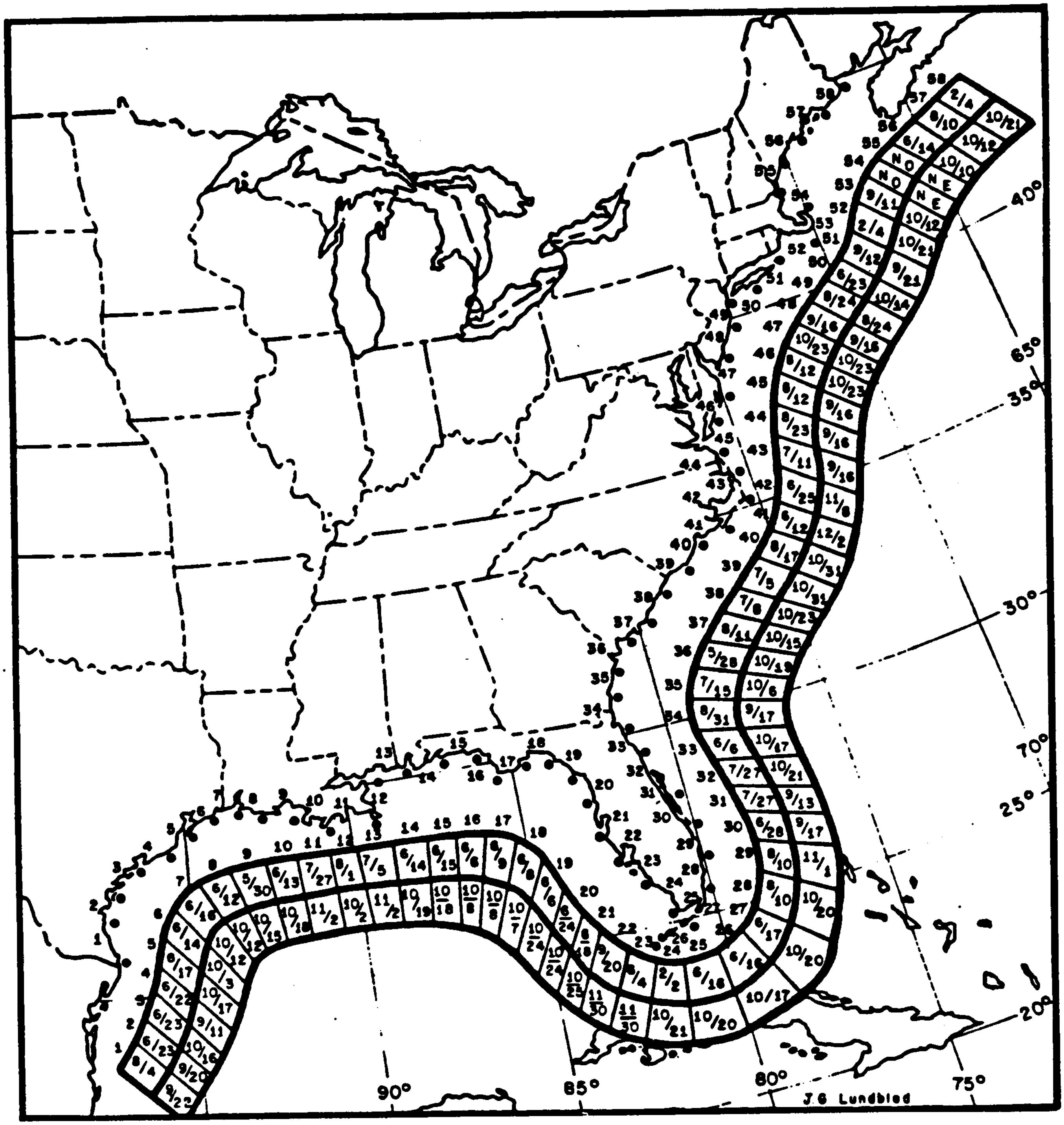


FIGURE 2 TROPICAL STORM INCIDENCE ALONG THE GULF AND ATLANTIC COASTS

Coastal segments indicated are approximately 50 nautical miles in length. Month and day in box indicates the earliest and latest date of landfall for tropical cyclone occurrences for each segment from 1886-1970.

Hurricanes vary considerably in behavior, intensity, and track pattern (Visual 7, Hurricanes and Earthquakes). Using only storms that entered the coastal area and assuming that a hurricane crossing the coastline of a 50-mile sector also affected the adjacent sector that lay in the right semicircle of the storm, they determined the probability of severe storm occurrence for each segment. Expressed in percent, the probability of some kind of tropical cyclone crossing the coastline of a sector is shown by the histogram and accompanying figures (Figure 3). The current probabilities do not consider the probability that a storm could cross the coastline of a particular sector more than once. That hurricanes do not "understand" averages is evident. However, the probability of future occurrences based on climatological averages is a standard procedure and is considered a reliable guide.

Storm Surge

At least three killers are contained in a hurricane: wind, flood, and storm surge. Of the three, the storm surge is considered the most deadly to the coastal areas. Likened to a huge dome of water, Dunn and Miller (1960) stated that the storm surge is a rapid rise in water produced by onshore hurricane winds accompanied by falling barometric pressure. Reaching a height of 15 feet or more above normal sea level, the surge is a piling up of water along the coast by the driving winds. Augmented by storm waves that are 20 feet or more, the abnormally high rise in the level of water sweeps across the coast near the area where the eye of the hurricane makes landfall inundating at times, large inland areas (Figures 4a and 4b). The greatest surge heights occur in the right front quadrant of a hurricane where the onshore winds are strongest. Maximum surge height at any one place is influenced by not only the size and intensity of the hurricane, but many other factors, including: the angle at which a storm crosses the coastline (a right angle approach produces a higher storm surge than one which hits obliquely); the state of the normal tide; the slope of the seafloor; the surface of the seafloor (whether it is smooth or irregular); the configuration of the coastline; and the density of vegetation and/or man-made structures in the impact area. All have their effect in diminishing the severity of the storm surge as it inundates a landward area. The storm surge is often confused with the hurricane tide, which is a gradual rise in water level along the seashore that may begin when a hurricane is as much as 500 miles from shore and will continue until the storm moves inland or beyond the area. Because of the many complex factors involved, the height of a storm surge is not always accurately forecast in a given area. The extent and distribution of maximum tide heights above mean sea level (MSL) during a representative hurricane is illustrated by Figure 5.

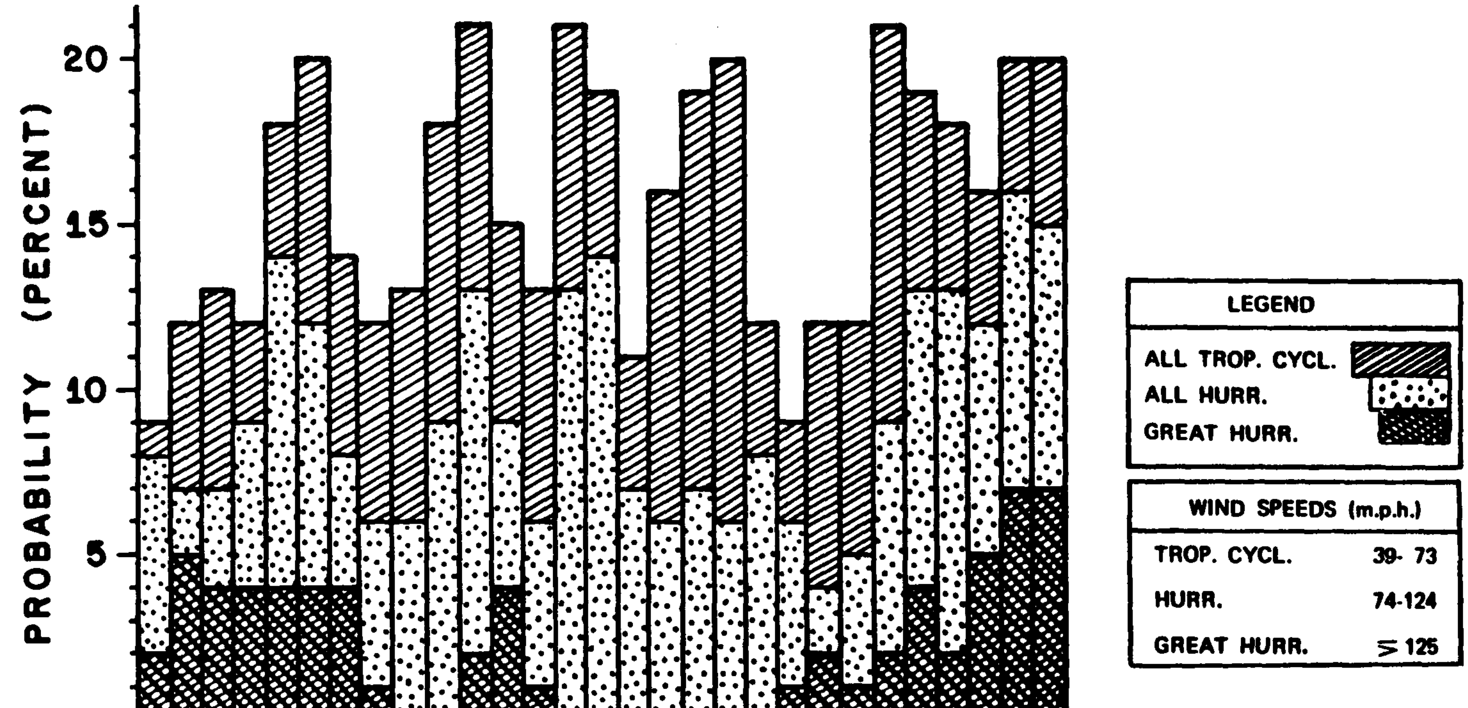
Selected Hurricanes of Historical Impact

The impact of hurricanes on coastal populations and their property has been documented for many years. The town of Indianola, Texas, was hit by a hurricane in 1875 which resulted in three-fourths of the town being carried away and the deaths of 176 people by the storm surge. In 1886 the town was struck again by a hurricane-related storm surge that either carried away or left uninhabitable every house in the town. It was never rebuilt. Galveston, Texas, was hit by a hurricane in 1900 during which 6,000-8,000 people lost their lives and more than 3,600 homes were completely razed by storm surge tides that were 15-20 feet high, making it the worst disaster in U.S. History (Henry, et al., 1980). Hurricane Camille came ashore at Pass Christian, Mississippi, in 1969 with a recorded storm surge of 22.6 feet above the normal level of the Gulf; fragmentary evidence indicates that it may have risen higher. It caused extensive damage from flooding and triggered massive landslides along her track inland to Virginia where she dumped up to 27 inches of rain (U.S. Army Corps of Engineers, 1970). For sheer devastation, Camille probably typifies the once-in-a-lifetime hurricane of exceptional violence referred to as the 100-year storm. Two hundred-sixty two (262) people are known to have died from this storm. Frederic, a wind devastating hurricane hit the Mobile, Alabama, area in 1979 causing damages estimated at $2.3 billion. The accompanying storm surge to this hurricane varied in height from 5.9 feet at Pascagoula, Florida, with the highest of 10.8-12.1 feet recorded at Gulf Shores, Alabama (Schroeder, 1979).

RISK OF TROPICAL CYCLONES

U.S. Gulf of Mexico Coastline

This histogram and table show the probability (percentage) that a tropical storm, hurricane, or great hurricane will occur in any one year in a 50 mile segment of the coastline.



COASTAL SECTOR *	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
ALL TROPICAL CYCLONES	9	12	13	12	18	20	14	12	13	18	21	15	13	21	19	11	16	19	20	12	9	12	12	21	19	18	16	20	20
ALL HURRICANES	8	7	7	9	14	12	8	6	6	9	13	9	6	13	14	7	6	7	6	8	6	4	5	9	13	13	12	16	15
GREAT HURRICANES	2	5	4	4	4	4	4	1	–	–	2	4	1	–	–	–	–	–	–	–	1	2	1	2	4	2	5	7	7

TX | LA | MI-AL | FL

(Simpson and Lawrence 1971)

FIGURE 3

FIGURE 4a Septic tanks exposed by storm surge action of hurricane FREDERIC (1979) near Gulf Shores, Alabama (Courtesy of L. Handley).

FIGURE 4b Following hurricane FREDERIC (1979) only pilings remain of houses that once stood near Gulf Shores, Alabama (Courtesy of L. Handley).

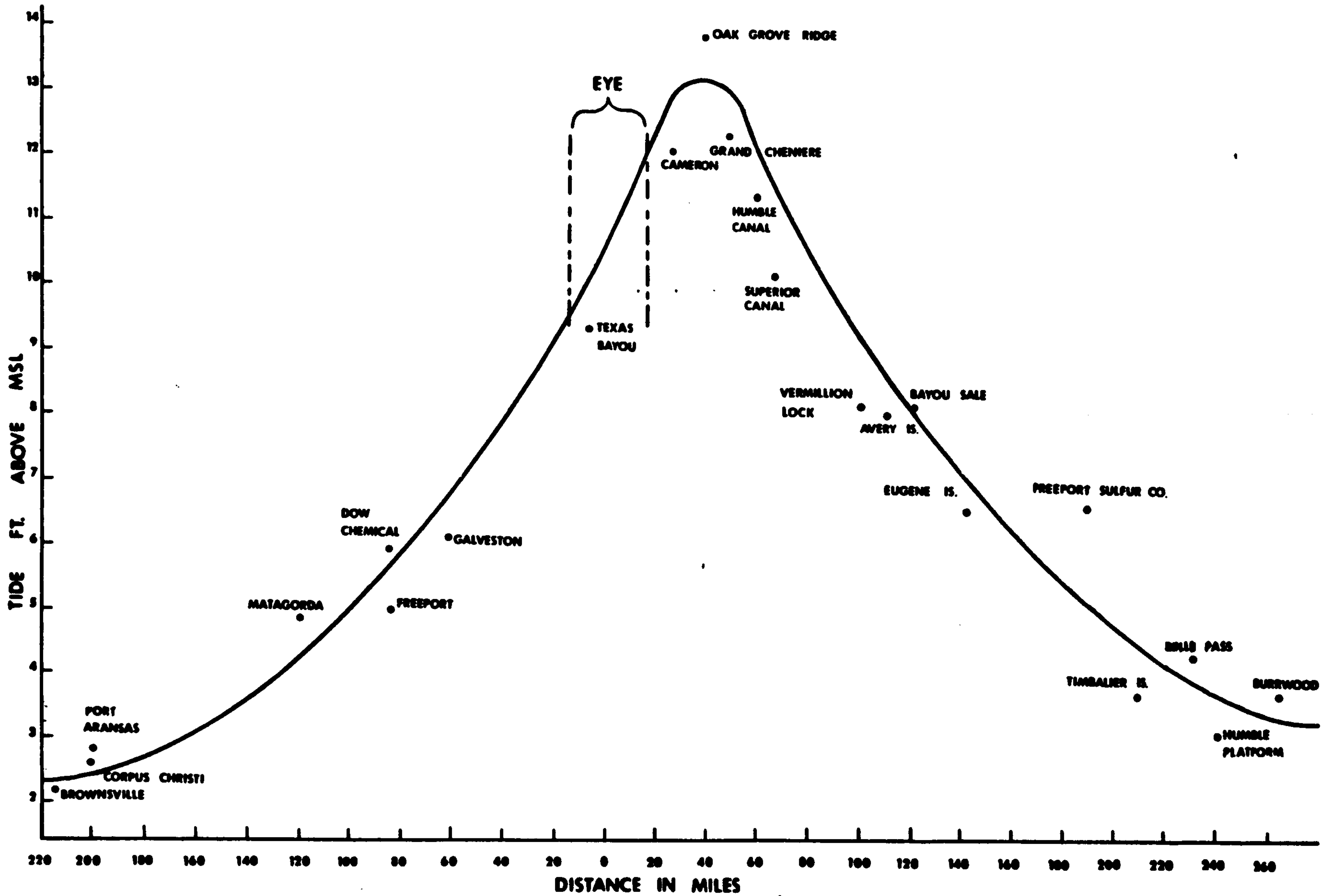


FIGURE 5 HURRICANE AUDREY TIDE HEIGHTS, 1957

This chart shows the distribution of maximum tide heights above mean sea level (MSL) recorded during Hurricane Audrey of 1957 (Harris 1963).

The eastern coast of the U.S. is not without its share of memorable hurricanes. One of them, Hazel, roared ashore near Cape Fear, North Carolina, in 1954 after meandering across the Caribbean for several days. She was probably the most severe tropical storm for over 100 years in that area and one of the most severe combined tropical and extratropical storms ever to visit the northeastern U.S. Devastation by combined wind and wave action along the coast was almost unbelievable. Every fishing pier along the coast from Myrtle Beach, South Carolina, to Cedar Island, North Carolina, was destroyed-a distance of 170 miles. Despite the severity of the storm and a total damage estimate along the Carolina beaches of $61,000,000 there were only 19 casualties. The latter attests to the excellent warning and concern of public spirited individuals who spent long hours at great personal risk to alert the populace.

Hurricane Detection and Direction

The detection of hurricanes prior to World War II was dependent largely on their chance encounter with populated areas and shipping lanes. Cirrus clouds, which cover a tropical cyclone and extend outward from it for hundreds of miles in some instances, and slowly falling barometric pressure are precursors to coastal inhabitants that a severe storm approaches. The shipboard observations of yore, while of no immediate value as a warning to those on shore of a pending storm, are used extensively in the reconstruction of the tracks of all major storms over oceans. Routine reconnaissance by aircraft for purposes of early detection of tropical cyclones and the obtaining of data from inside a hurricane was found feasible during World War II. Technological advances, including satellites and marine meteorological data buoys, aided in reducing the temporal gap from days in the case of shipboard observations to a few seconds required by a computer to receive and plot measurements transmitted at 60 second intervals from aircraft on the scene. Accurracy in plotting the storms track has also been enhanced by satellite imagery. Another useful observational tool is the storm tracking radar with its increased range and accuracy. This permits some last minute adjustments in preparedness efforts for a storm moving shoreward that suddenly changes direction within 250 miles of a radar site.

Direction

One of the most difficult parts of forecasting the motion of a hurricane is anticipating the point of recurvature. Knowledge of this change in track or direction from northwesterly to northeasterly is of vital importance to public and private interests along the Atlantic and Gulf coasts of the U.S. Should recurvature not occur a hurricane could move onshore and probably dissipate over land; whereas; the occurrence of recurvature may cause a hurricane to move harmlessly out to sea. The problem of dependence upon precision in forecasting the storm track was summarized by Simpson (1955) who stated that the city of Miami required a full 12-18 hours notice to prepare adequately for a hurricane at a cost of more than three-quarters of a million dollars. A difference of only a few degrees in storm heading over a 24-hour period could mean that these expensive precautions will be made uselessly. Or, consider the individual case of the Dow Chemical Company on the highly industralized Texas coast. This company's large plastics plant is vulnerable to high water from hurricanes. As little as a 10-mile variation in the track of a storm can spell the operational difference between this plant having to close down or remain open. To close the plant would cost the company more than $900,000. In view of the complex nature of forecasting hurricane movements and the technical aspects related thereto, the interested reader is referred to available material from libraries and organizations whose expertise is in this field.

Effect Offshore - Platform Design And Production Cost

Annual hurricane threats have been an important consideration to the petroleum industry since offshore operations began over 30 years ago. Its activities are ruled by the daily presence of the dangerous potential of a natural phenomenon that is now beginning to be understood. The designing of equipment to weather severe storms of the sort experienced in the waters over the outer continental shelf in the north Atlantic Ocean and Gulf of Mexico is not too dissimilar; however, consideration for that once-in-a-lifetime hurricane with exceptional violence must also be included. Researchers collect data about this theoretical catalysm, and by defining its extremes scientists provide engineers with design information enabling them to build platforms that are neither too light nor too heavy for the job. According to Ray Brannon, a scientist of Exxon's Production Research Company, "over-designing wastes capital resources" through unwarranted high initial costs, but underdesigning may be even more costly. A drilling rig shut down for repairs can mean $40,000 a day or more down the drain (Brown, 1974).

Whether the severe weather is a hurricane of horror or simply a rambunctious tropical depression, it can be costly to some area of the offshore petroleum industry. Though little or no damage may be incurred, evacuation and shut down costs to industry can be anticipated in the tens of millions of dollars. Within a one-week period during 1977, two hurricanes, Anita and Babe, caused the evacuation of 4,500-7,000 personnel from offshore installations, including service and supply companies and a shut down of production (except for some automated production). This occurred in the Gulf of Mexico off the coast of Louisiana in an area of heavy industry activity. Anita moved slowly westward through the Gulf about 200 miles offshore, threatening the entire Gulf coast and generating high seas and tides and some gale force winds. Babe traveled a northerly course through the heart of southeast Louisiana's oil country, both offshore and onshore, with the highest sustained winds of only 75 mph. No significant storm damage was reported. For this 6-day period, the loss in production of oil and gas was estimated by the U.S. Geological Survey to be roughly 3 million barrels of oil and 40 billion cubic feet of gas. One company estimated that Anita alone cost them $500,000/day in rental, transportation, salary, and lodging expenses related to evacuation.

In view of the foregoing and that a considerable investment is required for an offshore platform, great care is taken in its design, construction, and installation. Every platform is designed as a separate structure with consideration for water depth, wave conditions, and geotechnical properties of the soil for the specific location where the platform will be positioned. Every platform is, therefore, tailor-made for its location (Shell Record, 1979). This is significant in that the industry must operate safely in a hostile environment while finding, producing, and transporting oil and gas from offshore wells.

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SECTION IV

INDUSTRY DEEPWATER CAPABILITIES

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1980

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PREFACE

Changes in areas such as industry attitudes toward deep water activities, changing economic conditions, actual field results of techniques and equipment, and improvements in deep water methods and technology have come about since the original printing of this Open File Report. The following is a partial list of recent articles indicating some of these changes. Because of these, a complete rewrite of this report is currently in progress and should be available in the near future.

Brano, P. and Bianchi, S. 1982. Deepwater pipelaying global dynamics. Pipeline and Gas Journal 209 (4): 17-24.

de Sivry, B. 1982. Electron beam welding to make J–curve pipelaying possible. Pipeline and Gas Journal 209 (6): 58-62.

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Offshore producers apply new engineering solutions to harsher operating conditions. 1982. Journal of Petroleum Technology 34: 780-783.

Research and field testing advance technology needed to fulfill offshore development hopes. Journal of Petroleum Technology 34: 527-529.

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Introduction

As the "easily accessible" hydrocarbon resources onshore and in shallow water are exploited, the industry must explore in deeper and more hostile environments to help meet society's need for energy. Oil and gas development in these environments will require the use of new equipment suitable for working at such depths; however, the major factor determining the ability to produce oil and gas in deepwater is economics. In order to justify the drastically increased cost of operating in deeper water, substantial reserves must be found. Drilling of exploratory wells to date has been limited to water depths shallower than 1,486 m.

Exploitation of hydrocarbon reserves occurs in several stages: exploratory drilling; development drilling and establishment of production facilities; and transportation of the products.

Exploratory Drilling

The rigs most commonly used for exploratory drilling are drill barges, jack-ups, semi-submersibles, and drill ships. Drill barges are most commonly used in inland waters and shallow offshore waters. Jack-up rigs are limited in water depth by the length of the legs, 100 - 200 m maximum. Semi-submersibles and drill ships are most commonly used for deepwater drilling.

Semi-submersible drilling rigs, also known as column-stabilized drilling units, provide a much larger deck space than drill ships but offer substantially less storage capacity in terms of weight. This is due to the much smaller waterplane area of semi-submersibles as compared to drill ships. Semi-submersible vessels are quite stable; roll seldom exceeds 5° on a properly found vessel, even in the most severe seas. All but one of the semi-submersible drill units utilize conventional catenary mooring systems, which is one of the limiting factors in water depth capability. At present, there are approximately eight semi-submersibles capable of drilling in water depths of 450-610 m, only two are capable of operating in depths of 610-760 m, and one, the SEDCO 709, has a water depth capability of 2440 meters (Hammett, 1979). This vessel is the only semi-submersible rig with a dynamic positioning system and has more horsepower than any vessel (approximately 26,000 HP).

Due to the greater load capacity resulting from the greater waterplane area of the hull, drillships in general have greater capabilities for drilling in deeper water. For deep drilling from a floating vessel, the blow-out preventer stack (BOP) and well controls must be placed on the seafloor. If retrieval of the riser is necessary, the retrieval of all drilling mud in the riser may be necessary. Most drill ships have a greater mud storage capacity then semi-submersible vessels (see Table 1).

The deepest exploration well drilled to date was drilled by the drillship DISCOVERER SEVEN SEAS off Newfoundland in 1486 m of water. Drillships, such as the SEDCO 445, SEDCO 471, SEDCO 472, DISCOVERER 534, DISCOVERER SEVEN SEAS, and NEDDRILL 2 are designed to drill in waters up to 1830 m deep. Most of these types of vessels utilize dynamic positioning systems, although some use conventional catenary mooring systems as well.

One drillship, the GLOMAR CHALLENGER, has drilled in water more than 6100 m deep. This vessel, however, was involved in scientific sampling and drilled without blowout preventer and riser and, therefore, purposely avoided any potential oil and/or gas prone areas.

The GLOMAR EXPLORER is currently being converted to a drillship capable of drilling with a riser and blowout preventer in water depths to 3960 m. Current plans are for the GLOMAR EXPLORER to begin drilling for the Ocean Margin Drilling Program in 1984.

Floating drill units make up about 50% of today's mobile offshore fleet. Drilling from a floating platform is very different from drilling on a bottom-supported platform or onshore and requires some very specialized equipment. In any type of drilling, the ability to keep a constant preselected weight on the drill bit is extremely important. To counteract the up and down movement of waves, all floating units have some sort of heave compensator. These units are attached to the traveling block or crown block, and through the use of high pressure air or air/oil, the loads caused by the rise and fall of the vessel are balanced out (Figure 1).

TABLE 1

Comparison of Ship and Semi-Submersible Drilling Units

	Ship Units	Semi-submersibles
Approximate Number Operating	54	119
Initial Cost	$5-65 Million	$5-81 Million
Displacement, Long Tons		
Smallest	5,000	8,000
Largest	36,000	39,000
Normal	11,000	14,000-25,000
Travel/Towing Speed, Knots	6-12	3-10
Natural Roll Period, Sec	8-14	18-33

Typical Storage Capacities of Larger Units

(Long Tons Except As Noted)

	Ship Units	Semi-submersibles
Tubular Goods	1,270	490
Sack Mud and Cement	540 (12,000 sx)	230 (5,000 sx)
Bulk Mud and Cement	230 (5,000 sx)	280 (6,100 sx)
Liquid Mud	680 (3,000 bbl)	200 (900bbl)
Fuel	1,110 (8,150 bbl)	610 (4,460 bbl)
Drilling water	2,400 (15,000 bbl)	1,450 (9,100 bbl)
Potable Water	80 (500 bbl)	50 (330 bbl)
Approximate Water Capacity	6,300	3,300 (due to smaller water plane area)

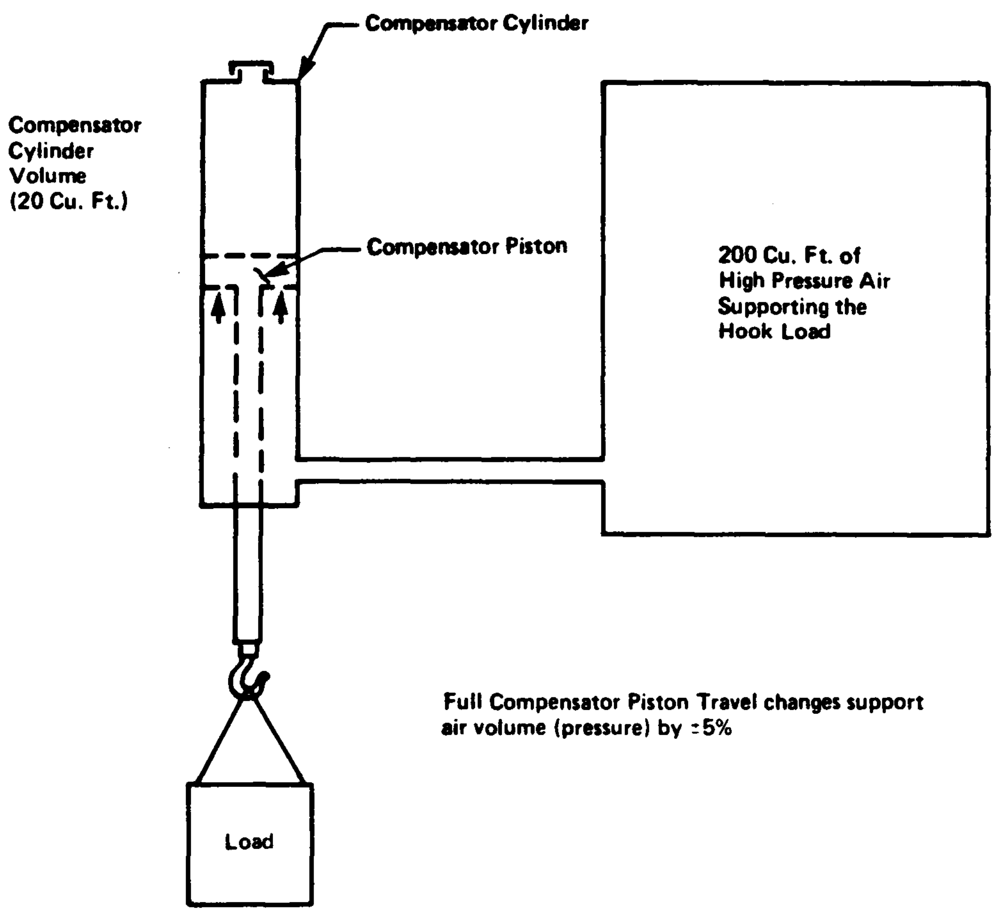


Figure 1. Simple Pneumatic Compensator System

Additional problems are posed by the riser system in a floating drilling operation since it must also allow for the up and down movement of the waves. This problem is mitigated through the use of slip-joints in the riser itself and a riser tensioning system which operates similarly to the heave compensator previously described. If guidelines leading to the subsea blowout preventer and wellhead are used, they also have similar tensioning systems.

Another piece of equipment common to floating rigs is the traveling block guide rails and dolly. This equipment keeps the traveling block, which hangs from the crown block on the derrick, centered over the rotary table and the hole. In addition, floating rigs sometimes have power-assisted pipe racking while bottom supported rigs do not.

Several major design innovations were necessary to allow shallow water drilling technology to be applied to sites in deeper water. Among these were:

- dynamic positioning
- marine riser systems
- electrohydraulic blowout preventer (BOP) controls
- re-entry procedures for guidelineless drilling

Mooring vs dynamic positioning

Mooring systems were a critical factor in the ability to drill in deeper waters. Today's drilling vessels are able to weather most any storm, but the mooring systems are not.

In moderate water depths, chain gives a better catenary action than wire rope. However, in water depths greater than 300 - 350 m, the weight and volume of the bulky chain makes its use prohibitive. In greater water depths, a combination chain and wire rope system is used.

For example, chain commonly used is 2-inch or 2¾-inch. The 2-inch chain weighs approximately 40 pounds per foot and the 2¾-inch weighs 75 - 80 pounds per foot. Wire rope commonly used is 6 x 37 in diameters ranging from 2 to 3½ inches. The 2½-inch wire rope runs approximately 11.6 pounds per foot. (Note since these figures are standards, no attempt will be made to convert this analysis to metric). For 1,500 foot water depths, the horizontal distance from the anchor to the rig in a standard mooring configuration would be approximately one mile. Along the catenary, the distance would be approximately 6,000 feet; therefore, 3,000 feet of 2-inch chain weighs around 120,000 pounds and 3,000 feet of 2½-inch wire rope weighs about 34,800 pounds for a total of 154,800 pounds for each of up to 8 moorings on the rig.

With just wire or chain, 300 m water depth is about the maximum at which a vessel may anchor and drill. Beyond this depth, the mooring system is stressed to the point it can support only its own weight. With the combination system, this maximum depth can be extended out to around 1,500 meters. To date, this system has been proven in only about 1,000 m or less. Besides the weight of the mooring system stressing itself, another factor which limits the water depth in which a mooring can be used is the horsepower rating of anchor handling vessels used to extend the anchors out around the rig.

Dynamic positioning systems use thrust to maintain the vessel on station over the subsea well. Using dynamic positioning, drilling operations can continue in 60-knot winds plus a 3-knot current.

There are currently about 17 drilling vessels equipped with dynamic positioning systems. The SEDCO 445 was the first dynamically positioned drillship and went into service in 1971 (Albers, 1980). Only one semi-submersible, the SEDCO 709, is equipped with dynamic positioning. The SEDCO 709 can carry supplies and equipment to drill in water up to 2,440 m and can continue drilling in 66-knot winds, 17-m waves, and 2.4-knot currents.

Dynamic positioning systems typically consist of four elements: sensors, controller, propulsion, and power plants.

A number of different types of sensor systems are used to detect movement off station, and usually each system has more than one sensor (see Figure 2). Seafloor beacons are placed at or near the wellhead or the seafloor. An array of hydrophones is placed on the drill vessel and feeds into the control computer. Based on time delay, the vessel's position with reference

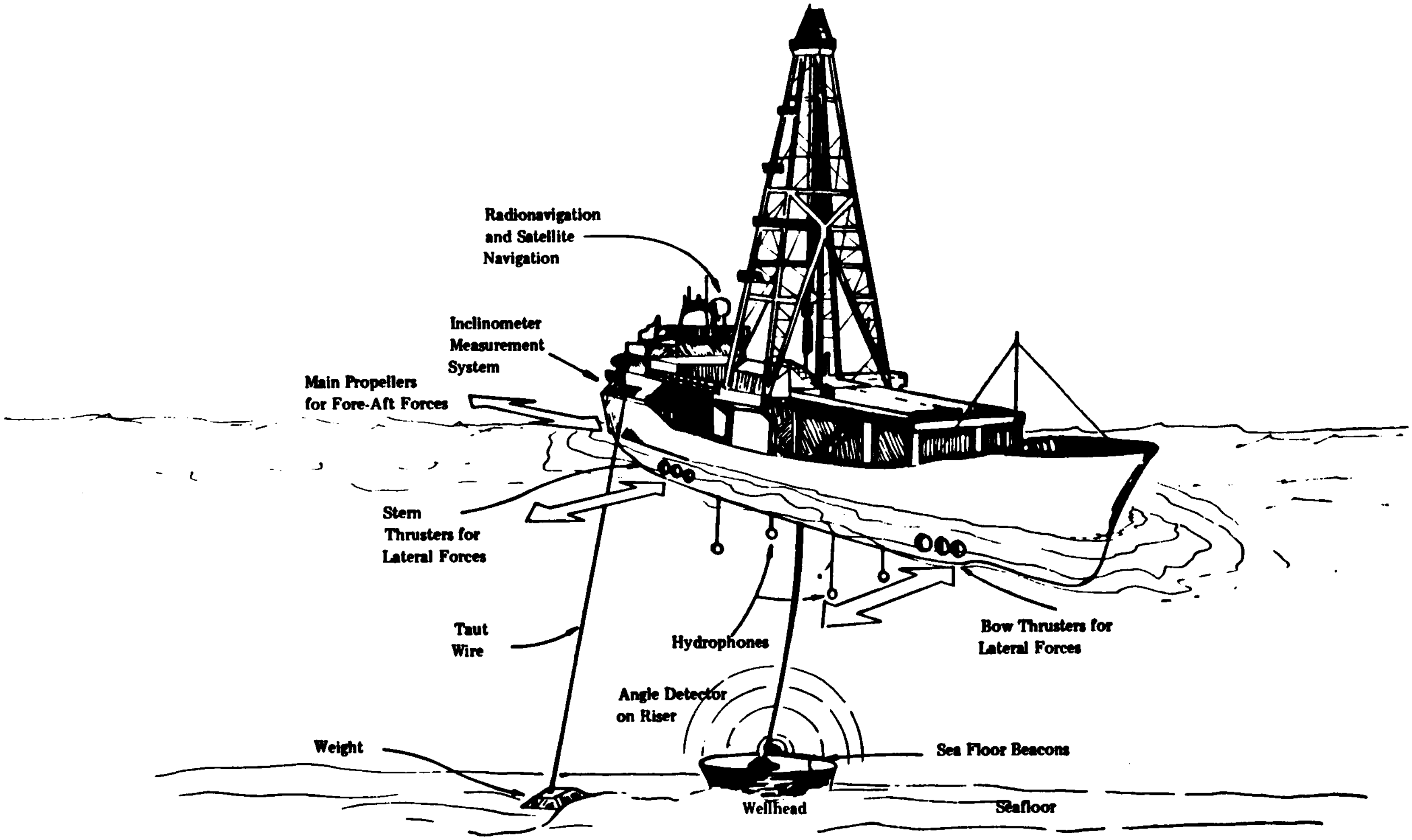


Figure 2. Systems for dynamic positioning

Source: Delco Electronics

to the beacons (and thus the wellhead) is calculated. A very similar system which operates on the same principle utilizes transponders on the seafloor and surface transmitting interrogators on the drillship. The latter system also uses four receiving hydrophones.

Another sensor which feeds into the computer which controls the thrustors is a taut wire system. A weight is lowered to the seafloor, and the wire attached to it is drawn tight (see Figure 3) and maintained at a constant tension. An angle sensor is attached to the taut wire and feeds the angle and direction to the computer if the wire gets out of a vertical attitude. A similar system is attached to the riser pipe.

A vertical reference unit is also fed into the computer. This unit consists of a vertical gyro and measures pitch and roll. Other inputs which can be fed into the positioning system include radio and satellite navigation, wind sensors, gyrocompass, inertial reference unit, and if used in conjunction with catenary mooring, tensionmeters. A "joystick, ' which can manually adjust or override the dynamic positioning, is also available in the control room.

The controller consists of the computer system which integrates all of the input from the different sensors. There are two independent controller units; should one fail the other is automaticaly switched in. The computer which is "on line" also checks incoming information for electrical failures, logic failures, or computational discrepancies. All information is processed and command signals are sent to the appropriate thrusters to apply the proper force in the proper direction to keep the vessel over the well. The computer also has built-in filtering to automatically adjust for sea-wave induced spectrum of vessel motion.

Most vessels use the main propellers for fore and aft forces; thrusters are used for port and starboard forces. Many variables are used in the design of the thrusters. Most range in size from 800 to 2500 horsepower. Two basic types of thrusters are azimuth and fixed. The azimuth thrusters can be rotated to point the resultant force in the desired direction. The fixed type has performed very satisfactorily in conjunction with the vessels main propellers.

Some thrusters are mounted in tunnels through the hull and others are mounted below the hull. Some thrusters have continuously turning controllable-pitch propellers while others are fixed propellers with controllable reversing motors. The thrusters are usually mounted with two or more near the bow and two or more near the stern. They are positioned to maximize the ability of keeping the bow of the vessel headed into the worst environmental conditions.

Power systems used to date have been diesel/generator systems. Several large generators (up to eight) are used to supply peak power to not only propulsion systems, but to drilling and support systems as well. Vessels are designed to have one generator over and above those required to meet peak loads. In the case of the SEDCO 709, these generators provide some 26,000 horsepower. Fuel usage on a vessel such as this in the dynamically positioned mode averages around 100 tonnes per day (700 barrels per day).

Marine Riser System

When drilling in deepwater, the riser itself presents some special problems and is generally the limiting factor in deepwater exploratory drilling capability. Risers are designed to be held in tension to prevent buckling. In shallow water, tension can be maintained by the drill vessel from above. In deepwater, however, the marine riser must support the column of heavy drill mud inside it; therefore, very strong and heavy pipe is required (usually grade X-52 or HY-80, up to 80,000 psi minimum yield strength) and keeping all of this weight in tension presented a problem. This problem was solved by attaching special buoyancy elements to the riser (see Figure 4). Another problem that surfaced was that under the compression of water pressure at great depth the buoyancy elements lost some of their effectiveness. A firm (Emerson and Cuming), however, has now designed and tested marine riser buoyancy modules for 3,650 m of water. Syntatic foam modules rated to 2,740 m are now operational.

Another riser-related weakness which in the past has hampered deepwater drilling was in the coupling. Couplings were only about one-half as strong as the riser pipe and were frequently the

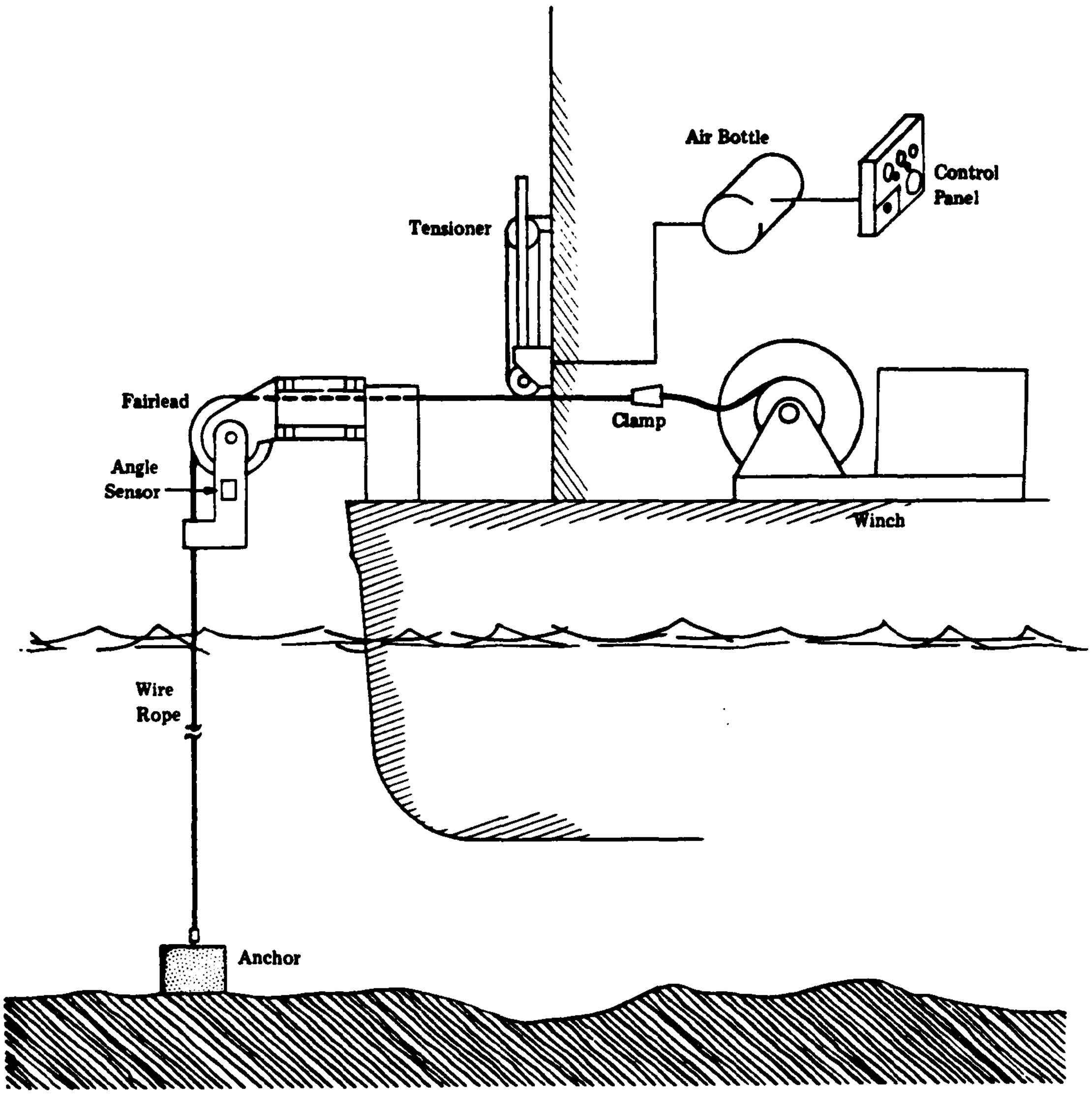


Figure 3. Taut-Wire Schematic

Source: Delco Electronics

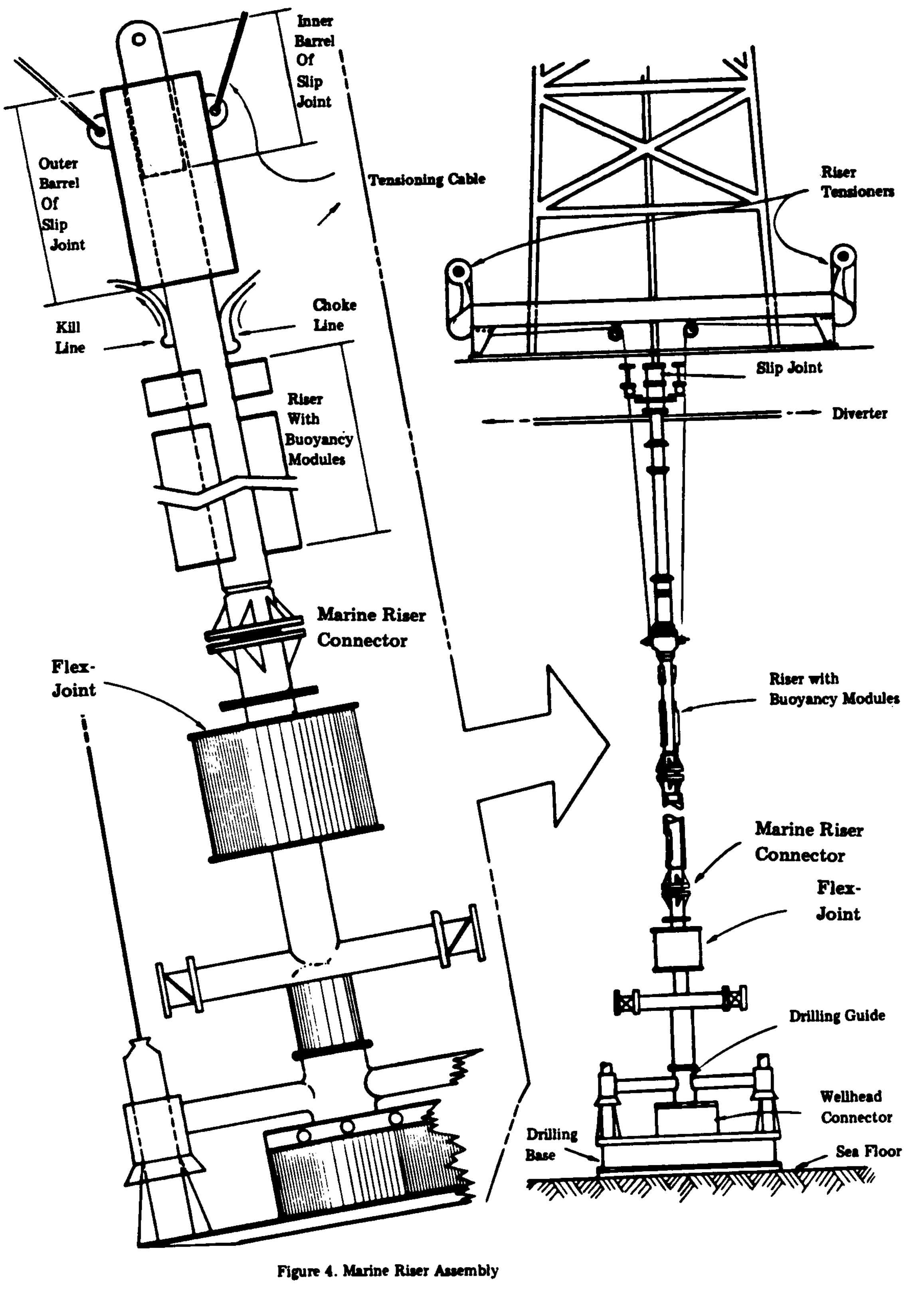


Figure 4. Marine Riser Assembly

cause of failures. Several new couplings have been developed which are of greater strength than the body of the riser.

The riser is connected to the sub-sea wellhead through a flex-joint, which allows up to 10° of angular movement of the riser with respect to the wellhead (see Figure 4). In general, operations are terminated if the flex-joint angle exceeds 3.5°.

One detail shown in Figure 4 is the diverter system which is above the slip-joint. If high-pressure gas is encountered in the shallow subsurface and the well is shut in, it might crater out around the conductor pipe. Therefore the gas would be allowed to come up the riser and diverted out to the side of the drilling vessel.

Blowout Preventer Controls

The blow-out preventer (BOP) is a device through which wells are drilled to prevent high pressure gas or oil from getting out of control and blowing back out of the hole. The BOP consists of three or more hydraulic pipe rams near the bottom which can seal around the drill pipe (see Figure 5). The upper set of rams are the sheer rams. These rams shear off the drill pipe and seal the hole. Usually above the shear rams is a device called an annular preventer, which is a "doughnut" shaped packer or bladder which can be hydraulically inflated to seal off around any tubular which might pass down through it. There is also a choke and kill system which utilizes two lines that go into the BOP at a level below some of the rams. One, the "kill line" is used to pump heavy fluids down the hole to force any high pressured oil or gas back into the formation, "kill" the well. The second, the "choke line," is used to circulate with control drilling fluids in the well when the BOP is shut-in (when the rams are closed). The BOP used in deepwater drilling is placed on the seafloor and is attached to the wellhead via a hydraulically actuated connector. Most BOP systems are rated to about 10,000 pounds per square inch (psi).

Rapid response of the rams is often vital in controlling a kick. In shallow water or onshore, simple hydraulic systems offer adequate response times. However, in deepwater, this response time is too long. For example, to close the BOP rams in 1,800 m of water with a conventional control system might require around 65 seconds. To alleviate this problem, an electro/hydraulic BOP control system has been developed which utilizes electricity to operate pilot valves to direct the hydraulic power fluid. The response time in this system is reduced to about 23 seconds. A further refinement of the electro/hydraulic system is used in ultra deep waters and involves the use of multiplexed electrical signals. Multiple electrical signals can be coded and sent along the cable simultaneously. This system reduces the size of the electrical cable needed from about 2-inch OD to about 1-inch OD and can handle some 100 seperate functions as opposed to about 40 functions for the multiconductor system (Hammett, 1979).

To attain instant response when the pilot valves are actuated, reserve accumulators are often used on the BOP (see Figure 5). These are high pressure metal bottles which contain a rubber bladder. To charge one, the rubber bladder is prepressured with nitrogen (N^2). The tank is then filled with the hydraulic fluid, and the rubber bladder is compressed to a pressure of around 3,000 psi.

Guidelines Re-entry

In shallow water drilling, guidelines are used to guide the BOP, lower marine riser package, etc. down to the wellhead. In deepwater the weight of the guidelines themselves make them prohibitive. Therefore, a re-entry technique was developed using acoustic (sonar) instruments and underwater TV systems without guidelines to find and re-enter the wellhead.

Drilling in Currents

Strong currents that further complicate the intricate task of reentering a subsea wellhead in deepwater are often encountered at drilling sites all over the world. In 1978 Sedco's drillship SEDCO 472, completed an exploratory drilling program for Esso Exploration in a deep water area off the northern coast of South America where the South Equatorial Current flows from east to west approximately parallel to the coastline. The deepest water depth drilled was 1,200 m and surface currents of 3 knots were encountered. In order to successfully complete the drilling program, an intensive research and engineering effort was undertaken to solve some new problems that this environment presented. The results were presented by Shanks, et al., 1979.

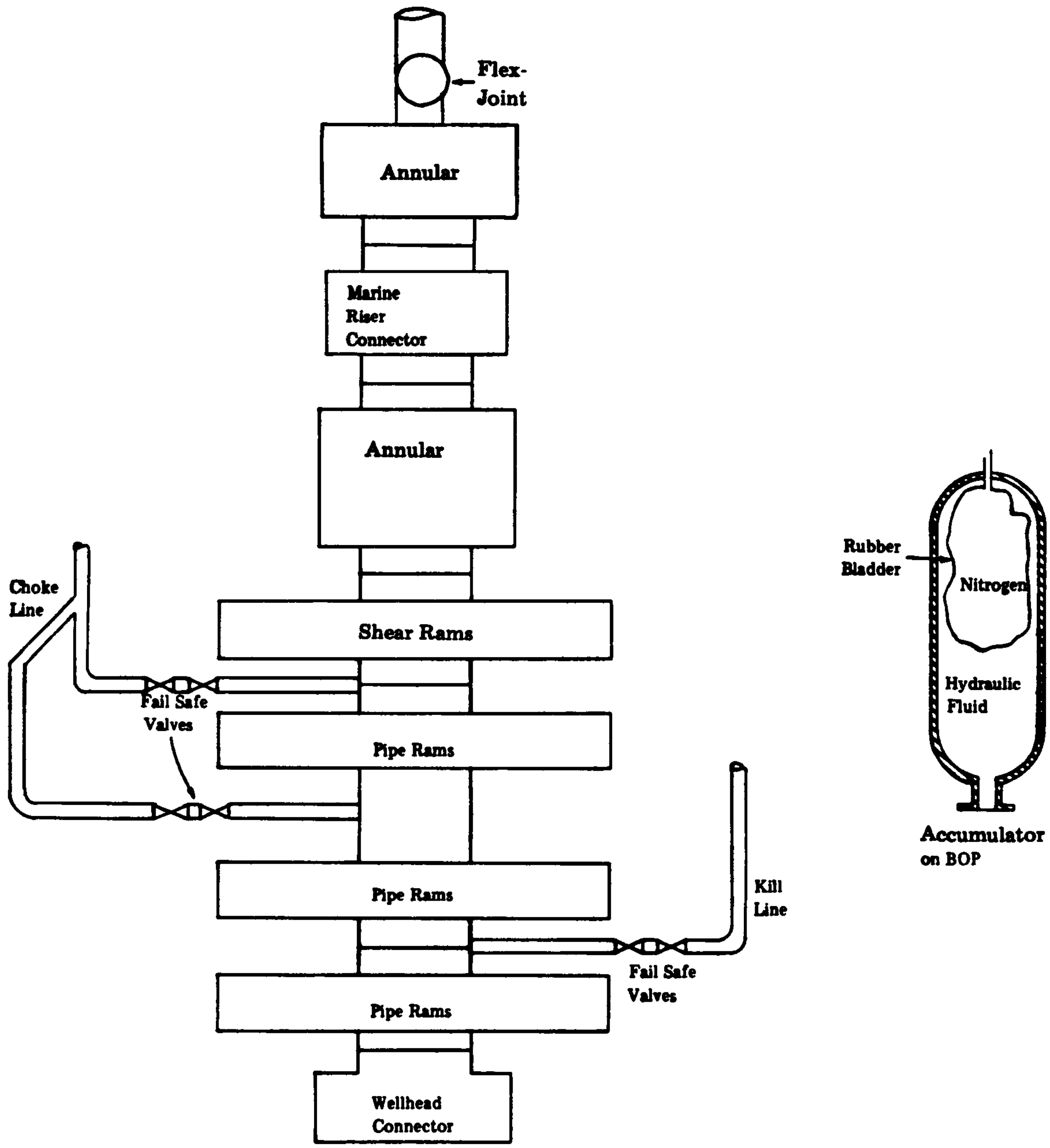


Figure 5. Subsea Blowout Preventer (BOP)

The first problem was the possibility of riser recoil. Floating drilling vessels, and particularly those which are dynamically positioned, incorporate an emergency disconnect sequence to allow the vessel to disconnect the riser from the BOP at the seafloor. The sequence takes approximately 30 seconds, during which time the well is closed off and the choke and kill stabs, etc., are retracted. Tension is maintained on entire riser string during drilling to prevent buckling due to compression. Furthermore, the riser is kept at approximately neutral buoyancy. If the riser were not controlled during disconnect, it would be drawn upward until the slip-joint collapsed and the energy would then be transferred by impact to the structure of the drilling vessel. To prevent this sequence from occurring, a system of valves and accumulators were added to the existing tensioner system which creates a closed system. Initial pressures are added to the system to balance the weight of the riser so that the system comes into equilibrium shortly after the riser has lifted off the BOP. Once lift-off has occurred, a "cushion" is provided to reduce stresses on the riser caused by the up and down motion of the vessel in the waves.

The next problem was to minimize stress in the riser caused by current. Computer runs showed that a high-stress area appears in the marine riser just below the water surface. This is usually where the current is greatest and produces the greatest action on the riser. Bending moments result which are strong enough to cause concern. To alleviate this threat, a flex-joint was added to the riser just below the slip joint and flexible hoses were installed to allow the choke and kill lines, and hydraulic supply lines to bypass the flex-joint. In addition to relieving this stress, the flex-joint could prevent loss of the riser should the angle of deflection in the riser become so great as to cause it to contact the sides of the moonpool.

Were the riser to contact the sides of the moonpool, the riser could not be raised or lowered without damaging the riser buoyancy material. As a remedy for this problem, a structure was installed below the rig floor at the moonpool level. This structure, called a riser restraint system, pivots, slides forwards and backwards and is capable of providing a force on the riser in the direction of the center of the moonpool. Axles with four pairs of 41-inch diameter truck tires were mounted on the structure. The top pair was mounted such that the center of the pair coincided with the centerline of the riser. Two pairs were mounted 1.1 m below the top pair, and were mounted to make a 45° angle to each side of the upper pair. The bottom pair was mounted 2.2 m below the middle pair and in line with the upper pair. The objective of this system was not to keep the riser in the center of the moonpool, but rather to keep the angle low enough to prevent damage to the buoyancy modules and keep the load applied to the riser within acceptable limits.

Reconnection of the upper part of the BOP (upper stack), to the lower stack after the disconnect sequence was another problem caused by current. A guideline less system was used in this program along with a tool called a Latch Bumper Head (LBH). A simplified version of re-entry procedure in high current conditions is described as follows:

> First, the lower marine riser package, riser, and slipjoint are run and suspended from the riser tensioners. The LBH is made up and run inside the riser, and a television/sonar tool is run and landed in the LBH. The BOP is located with the television/sonar tool, and since the riser string is deflected by the current, the LBH and lower marine riser assembly are positioned over the BOP stack funnel by maneuvering the drillship. As the riser assembly approaches the BOP, the LBH is lowered on the running string until it stabs into and engages the marine riser mandrel, and automatically locks into place. The riser assembly is then lowered on the tensioner until it is within about 3 m. Using external stack-mounted TV, and prior orientation of the riser with respect to the ship at a given heading, the riser is rotated until final alignment with the BOP stack is achieved. The riser package is then lowered into place with the tensioners and hydraulically locked into place. The television and LBH are then recovered and drilling can commence.

Finally, a subsea choke was developed which puts the well control choke manifold on the first joint of riser above the BOP and eliminates the adverse effects of trying to control a well through thousands of feet of small diameter pipe.

Exploratory Well Records

As technology advances, deepwater exploration drilling records are being broken almost yearly. In 1969 Exxon drilled several wells in waters deeper than 300 m, one of which was in almost 400 m of water off California. In 1970 Exxon drilled another well off California in 456 m. Shell broke Exxon's record with a well drilled off Gabon in some 633 m of water in 1974. Shell drilled another well in the same area at a depth of 698 m in 1975. Then in 1976, the depth record was extended to 1,055 m by Esso Exploration off Thailand. In 1977 Esso Exploration broke their own depth record with a well drilled off Surinam in 1,204 m. Getty, as operator for the Seagap Group and Hydro-Congo, extended the depth record to 1,325 m off the coast of Congo in 1978. Again in 1979, Getty established a new record with a well in the Mediterranean off Barcelona, Spain, in 1,353 m using the drillship DISCOVERER SEVEN SEAS. Getty's record did not last for long. On April 28, 1979, Texaco, along with several other companies, spudded in a well with the DISCOVERER SEVEN SEAS in 1,486 m of water off St. Johns, Newfoundland. This record still stands.

Completion and Production

The major limiting factor in the exploitation of hydrocarbon reserves in deepwater is not in drilling, but in completion and production. Two methods of production are possible in deepwater. One concept utilizes-subsea completions and the other uses compliant platforms.

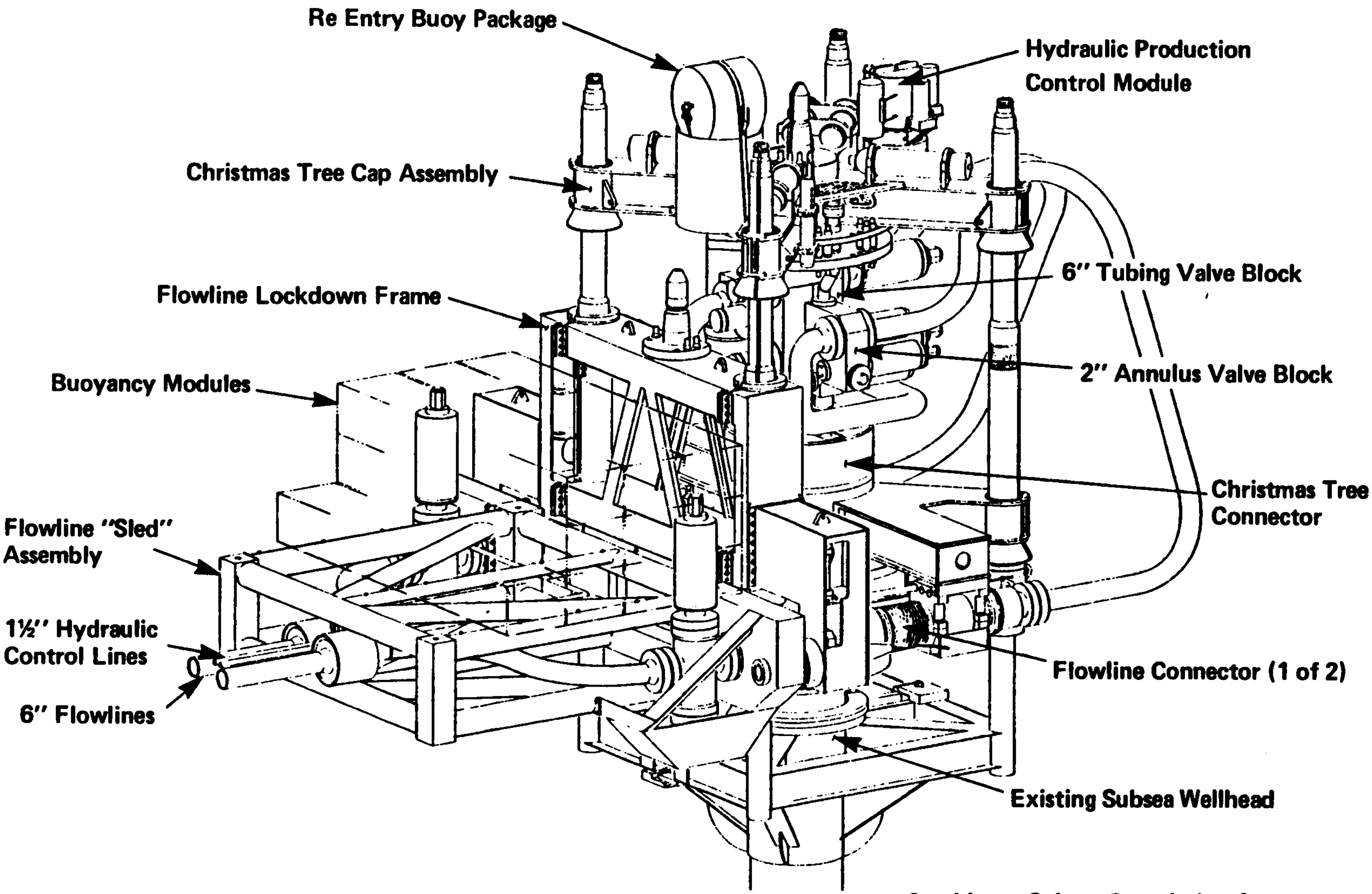
Subsea completions may be necessary in water depths too great for conventional platforms, and perhaps for some compliant structures. Subsea completions also augment conventional platforms by: 1) developing parts of smaller structures and allowing gas or water injection in the periphery of a structure; 2) allowing the development of fields not economically viable with a conventional platform; 3) providing early production allowing improved initial cash flow.

The first known underwater completion in North America was made in 1943 in Lake Erie. Since then over 300 subsea completions have been made in Lake Erie in less than 26 m of water. Subsea production technology has been under development since the early 1960's in the Gulf of Mexico. These wells are controlled by hydraulic or electrohydraulic systems, serviced with pressure activated tools through the flowline and have downhole automatic shut-in systems. Between 1960 and 1974, 106 subsea completions were made worldwide.

In completing most of the wells, the equipment used require divers. The current working depth limit for a diver is approximately 460 m, and this requires 12-14 hours to pressurize the diver to depth. The diver is allowed three hours lockout working time. About 10 days are required for decompression. Depending on the individual, 30 days can be spent pressurizing, working, and decompressing. This procedure is very expensive and time consuming.

In order to reduce the need for divers, techniques have been developed for installation of subsea completions from surface vessels. There are two types of subsea completions now in use. The first type, called a wet tree, consists of either a single wellhead or multiple wellheads on or below the ocean floor on a template (Figure 6). The second system consists of a wellhead enclosed in a chamber at one atmosphere of pressure (Figure 7). The chamber allows a man to work on the well in a shirt-sleeve environment. The advantage to the dry completions is that well control lines and the flowline can be connected from inside the chamber. The wet tree requires connections to be made on the outside by a diver, submersible, or surface guideline—a costly proposition in deepwater depths. Water depth is not a critical factor in the dry completion because the wall thickness of the chamber can be increased to withstand greater pressures. According to one industry expert the current limit to operating depths without divers is the ability to service the installation and the completion from surface vessels. Lockheed can service to 365 m with a tethered submersible. The development of umbilical cables to depths of 610 m is underway. The world record depth for commercial wellhead completions is now 189 m.

Wet tree completions have been installed and are in production in various parts of the world. One system, shown in Figure 6, is in use in the



Casablanca Subsea Completion System
Completed Well

FIGURE 6 WET SUBSEA COMPLETION

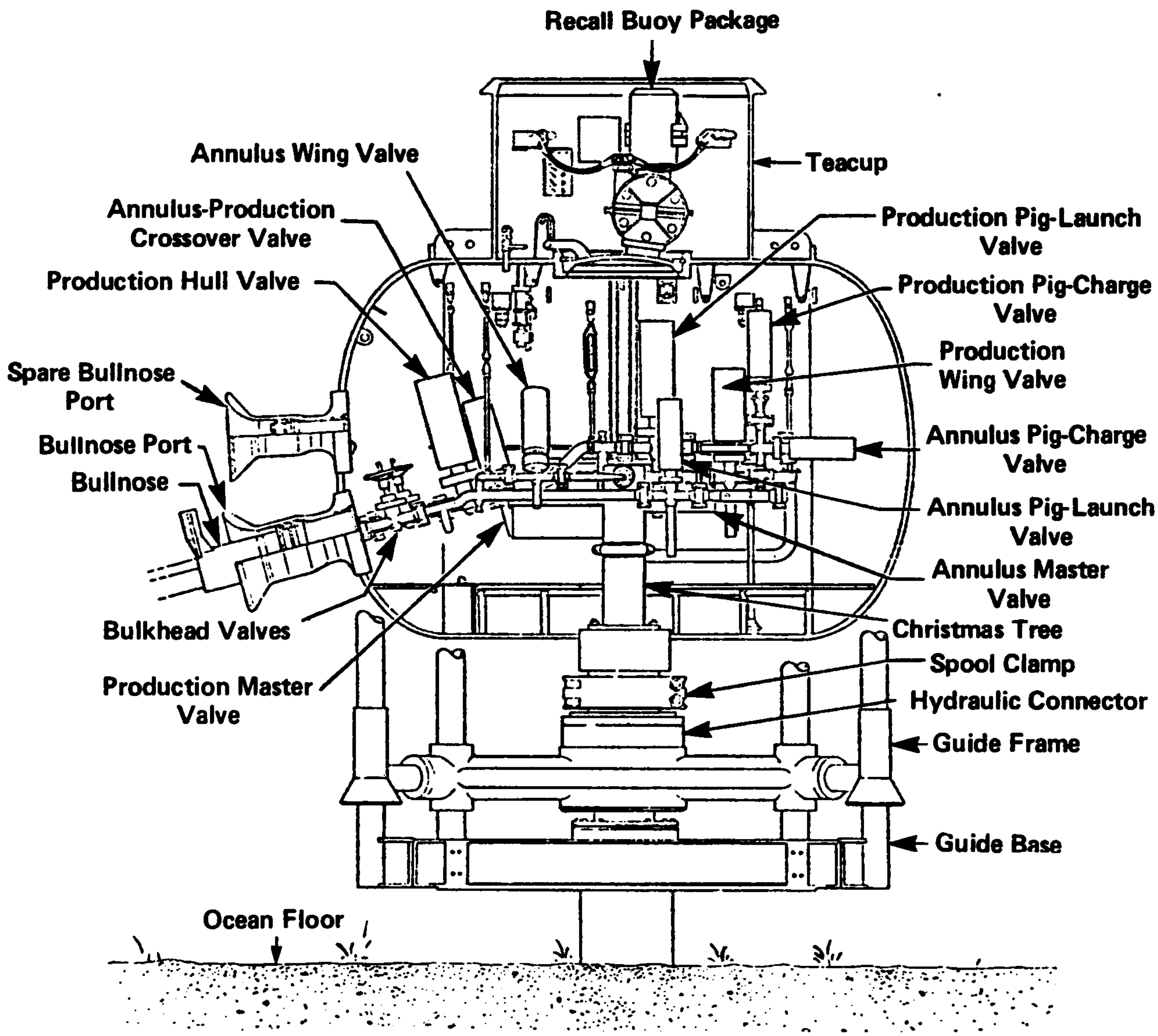


FIGURE 7 DRY SUBSEA COMPLETION

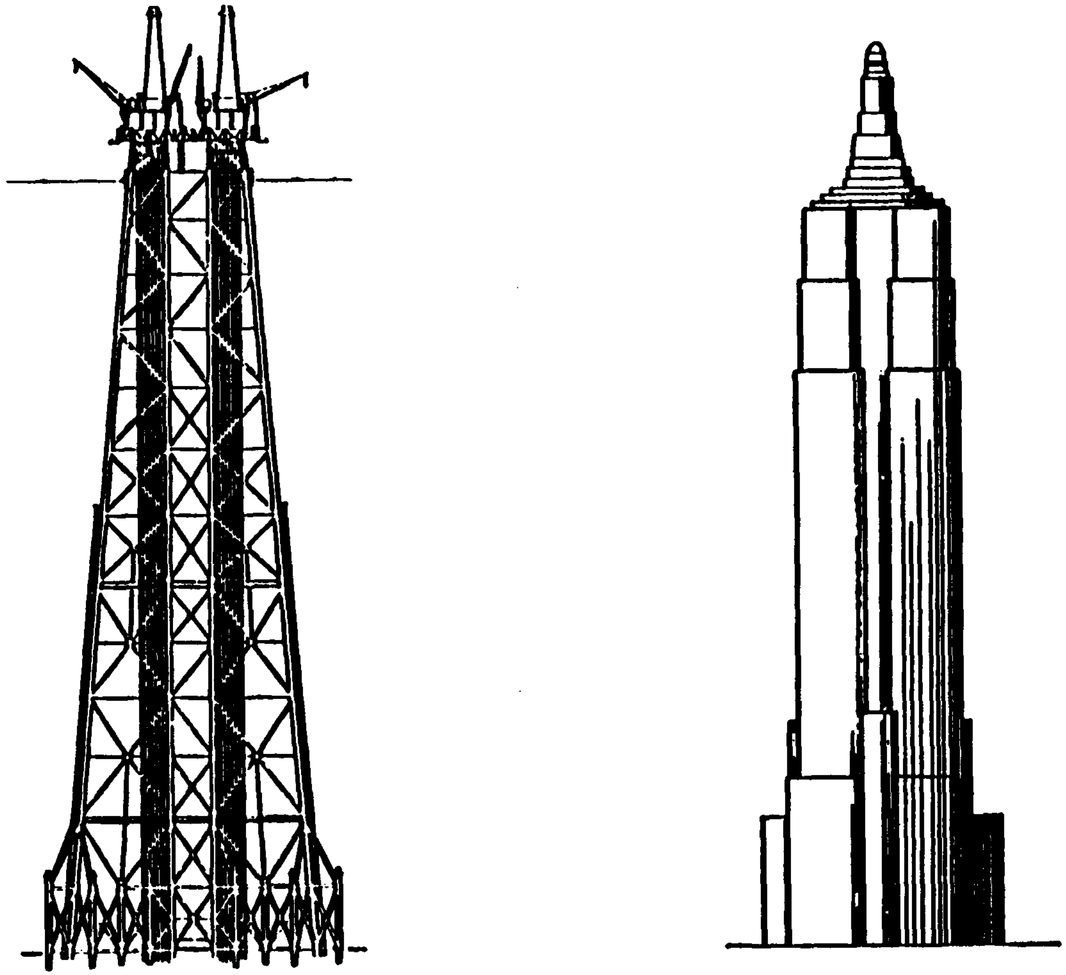
Casablanca Field in the Mediterranean Sea south of Barcelona, Spain, in 120-150 m of water. The system is designed for diverless installation with manipulator back-up. The installation of this system was accomplished without diver assistance. A tubing head adapter with four guide posts was lowered down the four guidelines attached to the existing subsea wellhead. This unit was then locked into place hydraulically and pressure tested. Then, a modified BOP stack was lowered on the guidelines and guided into position by the guide posts. It was then locked down onto the tubing head adapter with hydraulics. At this point, the tubing hanger, downhole equipment, and well tubing were installed and the well was temporarily plugged. The BOP was then removed and the Christmas Tree (wellhead) assembly was run, landed and locked into place and tested. A lower riser package containing hydraulically-operated completion and workover controls was used to attach the Christmas tree assembly and after the assembly was in place, the lower riser package was retrieved. A flowline pull-in tool and lockdown frame were then lowered and locked into place on two of the guide posts. The flowlines were connected to a "sled" which was attached to wire ropes from the pull-in tool and the sled, with the flowlines, was pulled into position in the lockdown frame. Hydraulically-actuated wedges were driven home locking the sled to the lockdown frame. The wires were cut off remotely and the pull-in tool was retrieved. The lower riser package was relowered and locked into place on top of the Christmas tree. Flowline connectors were extended, locked, and pressure tested. Both tubing plugs were pulled and the well was brought into production. When servicing is required, a pop-up buoy is remotely released. The design lifetime for the system is 20 years. With the exception of the control system, the unit may be left on the seafloor for 20 years. The control cap is designed for a service interval of five years. Several similar systems are also in production in the North Sea.

Seal-Comex, a service company, is currently conducting an economic study for Mobil Oil Corporation for installation of a subsea production system in the East Breaks Area, offshore Texas. This Maniford Center has been tested for four years and is now being considered for installation in water depths of 305-365 m.

In October 1974, Exxon installed a Subsea Production System 27 miles southeast of Grand Isle, Louisiana, in 52 m of water. The system was installed, controlled, and operated remotely utilizing equipment and diverless techniques suitable for producing oil and gas in water depths of approximately 600 m. A major component of the system is called a maintenance manipulator. When needed, this robot can be lowered to the template and moves around the unit on a track. The manipulator has a system of underwater television cameras built in so the operator on the surface can control its movements. Initial production began in February 1977.

If a subsea completion is not used for deepwater production, then some type of platform is necessary at the site. In shallow waters, conventional platforms have become the industry standard for production. From these platforms a number of wells are typically drilled, and the wellhead completions are on the platform and not on the seafloor. The maximum depth to date for the installation of a conventional platform is 312 m by Shell Oil Company's 46,000 ton Cognac platform 24 km south of the mouth of the Mississipi River (see Figure 8). The platform stands 386 m above the seafloor and 73 m above the surface of the ocean. It will have a record 62 wells. The base section was installed during the summer and fall of 1977; the other two sections were installed in the summer of 1978. Initial production began in late 1979.

In an effort to reduce the amount of steel required, and thereby the price, Exxon, as well as Mobil, Union, and Amoco, are actively involved in designing a guyed tower for use in 300 m water depths (Figure 9). This structure would be bottom-supported and held upright by 16 guys, four at each corner. Moorings are designed for the life of the structure (a minimum of 20 years). The deck of the structure would be able to move up to 40% of the wave displacement (2 - 3 m in a storm). In October



Cognac Platform
1265'

Empire State Building
1250'

Figure 8. Cognac Platform, Offshore Louisiana

Source: Shell Oil Co.

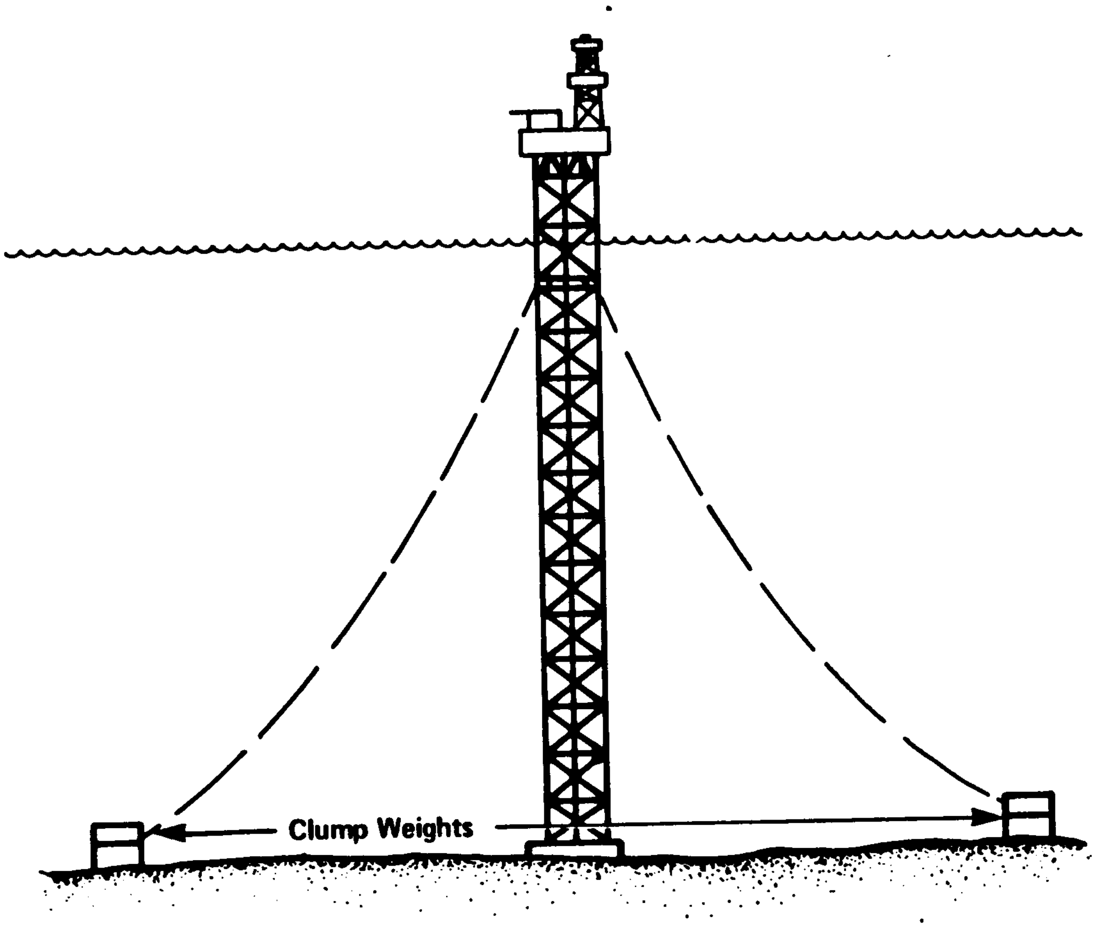


Figure 9. Guyed Tower

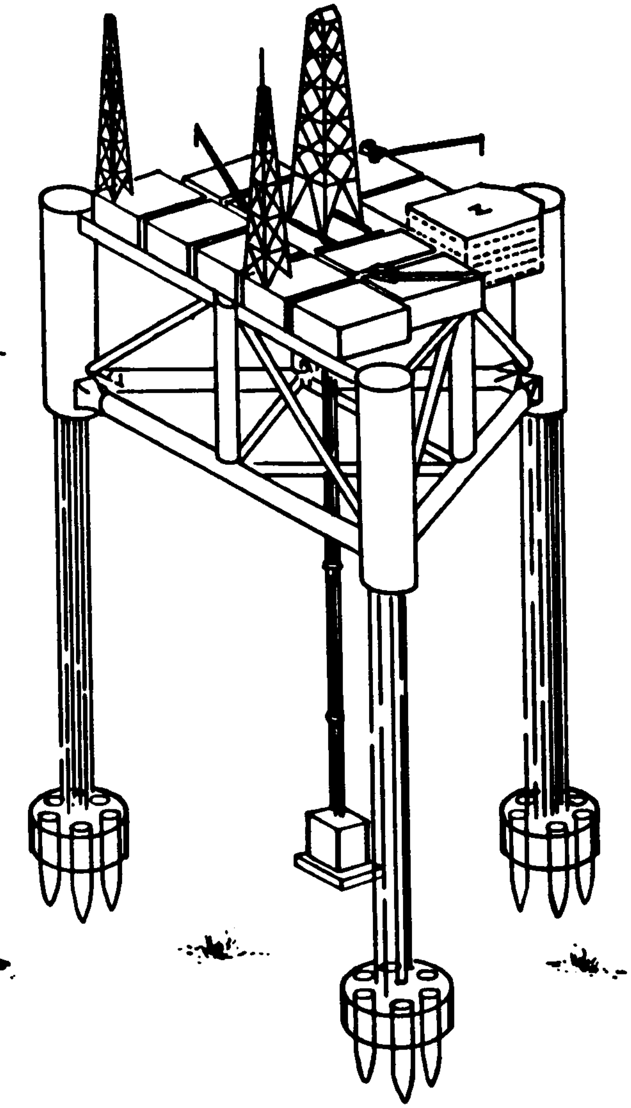


Figure 10. Tension-Leg Platform

1975, Exxon installed a one-fifth scale model of a guyed tower in 100 m of water off Grand Isle, Louisiana. The tower was highly instrumented, and over two years of data confirm that the guyed tower is a feasible and practical platform concept for water depths of 200 - 600 m.

Exxon has gone ahead with this design and is now planning to install a guyed tower to develop their Lena prospect in Mississippi Canyon blocks 280, 281, 324, and 325. Water depth at the site is about 300 m and the platform will have 50 slots. It will be supported by a foundation of pilings and buoyancy tanks will be built into the frame. The tower will be held upright by guy wires attached to clump weights which will be fastened to anchor piles by chain. Current plans are to install the tower in 1983.

Another concept in production facilities for deepwater is the tension leg platform (TLP) (Figure 10). The TLP is a floating structure which is held down by essentially vertical tension members which remain in tension regardless of cyclic loads due to current, wind, and waves. This design is a compliant structure; it is able to move with waves and currents to a tolerable extent. In 1975 Deep Oil Technology, Inc. installed a prototype instrumented TLP in some 60 m of water off California.

Conoco and Amoco will be the first to install a TLP production system when they place their design in 148 m in the North Sea. The initial design work has been completed and has been approved by the British government for installation in the Hutton Field some 95 miles northeast of the Shetland Islands. The structure is a six leg semi-submersible design which will use anchor piles to anchor the tension members. Tension members will be 9-inch diameter rods with a 3-inch hole in the middle; there will be four tension members on each corner, and each will have about 1,000 tonnes of tension on it. The system is designed so that tension members can be retracted one at a time into the legs for maintenance. The platform will have 48-well slots - 24 for initial development, 13 for production, and 11 for water injection. The 48-well seafloor template is scheduled for installation in the summer of 1981; a rig will then drill 8 producing wells and one injection well before the floating superstructure is installed in the fall of 1983 (Petroleum Engineer International, 1980).

The advantages of a TLP are as follows:

- much less material required for construction than a conventional platform
- the vessel can be fabricated and joined in the yard
- deck and hull are constructed separately and concurrently (at different yards if necessary)
- all the major lifting is done onshore avoiding the extremely high costs of derrick barges
- foundation (template) can be installed separately
- weather sensitive periods for installation are much shorter
- shorter time between installation and production
- wells can be predrilled
- lower abandonment costs.

Semi-submersible drill rigs have also been used as floating production platforms. In June 1975, the Hamilton Brothers first produced oil from their Argyll Field in the United Kingdom sector of the North Sea using the converted semisubmersible TRANSWORLD 58 connected to a seafloor manifold and anchor base by a composite riser. Six satellite subsea-completed wells currently produce to the subsea manifold in 79 m of water. After on-board processing, the gas is flared and crude is pumped back down the composite riser and to a single buoy mooring system nearby for shipment by tanker. There are currently about 18 semisubmersible units worldwide which have been converted to other uses, including three for oil production.

Although drilling riser technology, subsea completion technology, and floating platform technology have been recently extended to beyond 1,000 m, production risers along with remote flowline connectors represent the critical development component associated with deepwater production systems. The deepest floating production riser system presently in service is that of the Argyll Field in some 76 m. The composite riser in the Argyll Field is vessel-supported and consists of a central structural riser surrounded by a number of smaller independent satellite risers. The central riser, which in this case carries the low pressure crude to the seafloor and then to a single point mooring for shipment, is designed to withstand the axial and flexural stresses generated by tension, wave action, vessel offset, and current. This structural riser would also receive the buoyancy modules in very deep water. There is little doubt that a vessel-supported composite riser system could be designed to operate in 1,000 m. A major question, however, is whether the proportion of time that wells would be shut-in would be economically acceptable. The avoidance of frequent shutting-in of production during inclement weather would require specialized facilities.

Another concept for improving production efficiency and re-entry in water depths greater than 365 m is the free-standing composite riser (Figure 11). This system consists of a composite riser fitted with a buoyancy element to provide necessary support to the riser in the disconnect mode, and a remote connect/disconnect stab located at a depth of approximately 100 m in order to put it below the wave action but still within reach of divers. Guidelines from the buoyancy element at the top of the riser to the surface vessel would facilitate a diverless connection.

Another riser system which offers an extremely bright outlook for future deepwater production is the articulated riser system used for Exxon's Submerged Production System (SPS) (Figure 12). This riser, along with the system, underwent tests beginning in 1975 in the Gulf of Mexico. The system consists of a base on the seafloor to which all the flowlines run. The lower 300 m (for a system designed for 500 m) consists of a tension member which also provides a housing for the flowlines and which is supported by a buoyancy element. Unlike the free-standing composite riser, there is no provision for an emergency disconnect at the buoyancy chamber level. The SPS riser is designed to withstand maximum sea states and currents and remain connected. The upper 200 m consists of two 100+ m long sections joined in the middle and at each end by articulated joints. At the surface, the articulated joint is attached to a surface mooring buoy with a permanent yoke attached to a production vessel, probably a converted tanker. The surface mooring buoy locates and supports the upper end of the riser. Each segment has adjustable buoyancy to provide the desired support. Exxon feels that this system would be operable in depths to 1,000 m.

The fourth system, designed by Deep Oil Technology, Inc., is for use with a tension leg platform. This system consists of individual risers specifically designed to take advantage of the inherent stability of the tension leg platform. The platform and risers would be designed to withstand maximum environmental conditions without the need to disconnect the risers. The upper termination of the risers is on the cellar deck level of the platform where the production trees and wellheads are located, much like a conventional platform.

To be viable, deepwater production systems must relinquish dependence on diver assistance and convert to automated techniques. Man's diving capabilities in deepwater are quite limited. Although submersible vessels exist that provide a 1-atmosphere environment for man to any depth, his ability to perform mechanical tasks remotely is limited. For such tasks, divers are required. The French diving company, COMEX, set an open ocean, deep-diving record in October 1977 in the Mediterranean Sea off the south of France. COMEX and French Navy divers were saturated and lowered in a chamber to a depth of 430 m where they made a total of 10 hours of working dives during which a 9-inch pipeline connection was made. Two divers, one from COMEX and one from the French Navy, made two 10 - minute bounce dives to a record depth of 501 m. Decompression time from 430 m to the end of saturation was just over 7 days and 17 hours.

The hyperbaric facility at Duke University in North Carolina under the direction of Dr. Peter Bennett recently set a world depth record for chamber dives. Divers were pressured up to a similated depth of 686 m in February 1981, remained at that depth for 24 hours, and were safely returned to surface pressure.

Transportation

When production from deepwater completions is realized, a means of transporting to shore must be provided. Two choices are available: hydrocarbons may be piped to the surface and transported by tankers to land-based facilities or they may be transmitted by pipelines all the way.

ETPM has developed a method for laying pipe up to 42-in diameter in 1,000 m of water. This method is called RAT for Remorquage (towing), Aboutage (connecting), and Tension. Strings of pipe up to 1,000 m long are assembled on shore and fitted with buoyancy tanks. The strings are

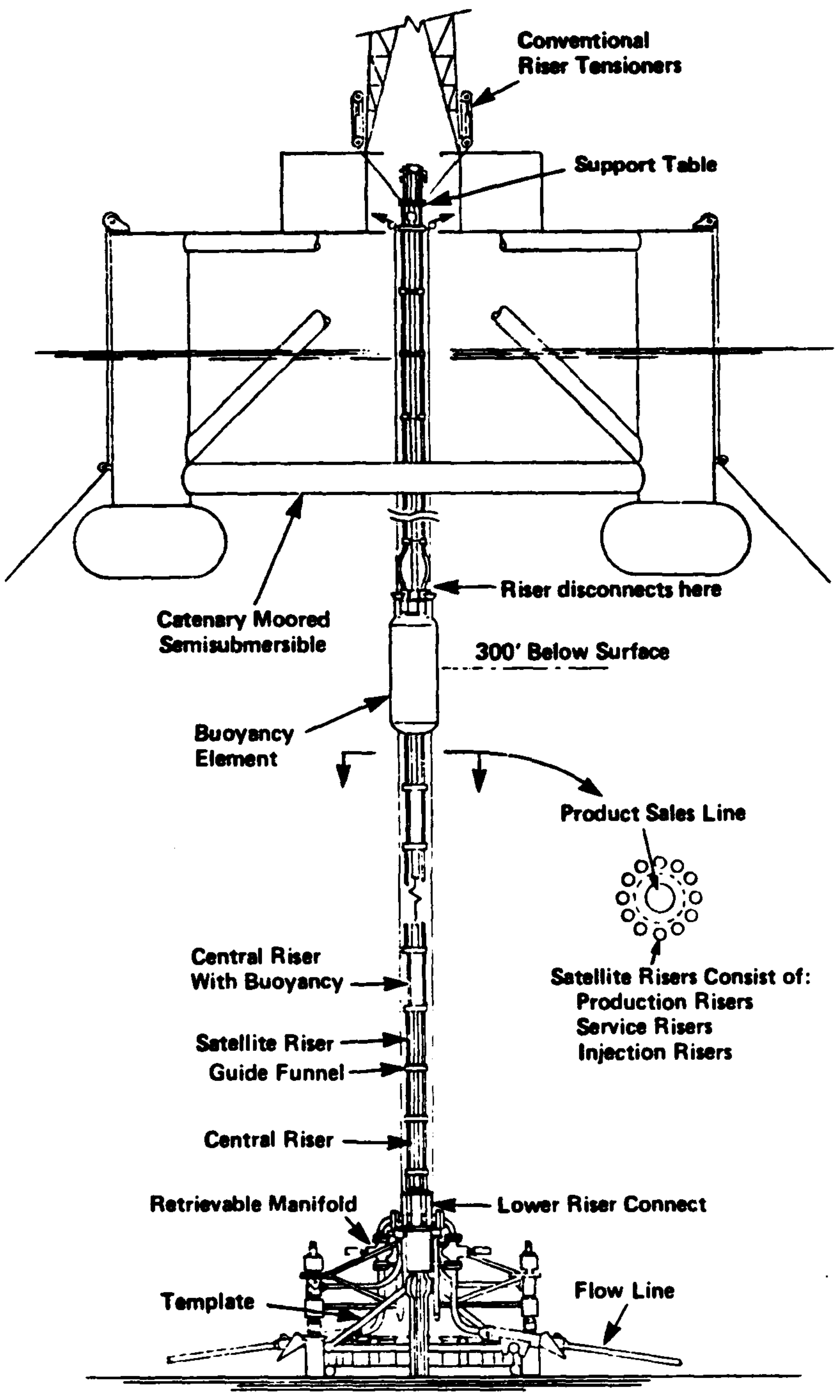


Figure 11. Free-Standing Riser

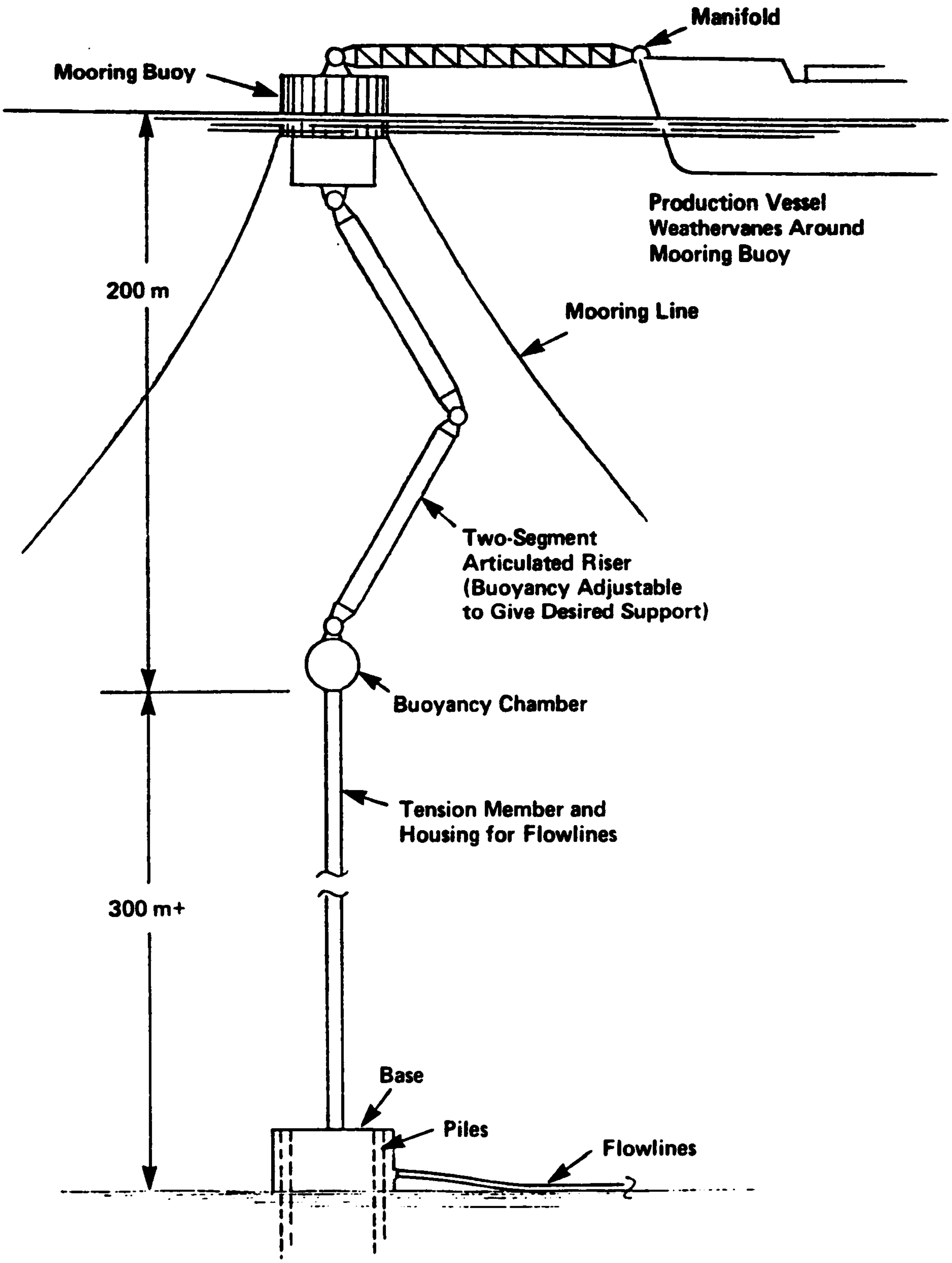


Figure 12. Exxon Articulated Riser

then towed to the laying site and connected by passing over a special dynamically positioned lay barge; they are then laid in a conventional manner. The method has been tested in the North Sea laying 42-inch pipe in 250 m of water.

Several other methods are used in deep water which are quite similar–surface tow, below surface tow, and bottom tow. In each case the pipeline is made up onshore and towed to the site, where it is connected by a conventional lay barge. Sections of pipe from 5 to 10 km long can be assembled and towed to the site using one of these methods.

All the methods discussed so far have used conventional technology. Conventional pipelaying technology utilizes tensioners to maintain tension on the pipe to keep the sag-bend radius and over-bend radius within acceptable limits (to keep the pipe from buckling) (see Figure 13). The limiting factor in conventional pipelaying techniques is the capacity of the tensioning system.

Another method of laying pipe which has proved very successful is the reel method. This method is less weather dependent than the conventional method and has been in use for many years. Santa Fe Engineering and Construction Company has constructed the first dynamically positioned reel-type pipelaying ship, "APACHE." The pipe is welded together on shore, spooled onto a large reel, and rolled off at the site. The "APACHE" is able to hold up to 50.5 miles of 4-in pipe, 5.7 miles of 16-in pipe, or various sizes in between. It is able to lay 16-in pipe in water depths around 610 m and smaller lines in water depths of 915 m. With smaller portable reels, it can lay a bundle of several pipes at one time. Using this method, a 12-inch pipeline has been successfully installed in the Gulf of Mexico in more than 300 m of water.

Saipem's 'CASTORO SEI" is a semi-submersible pipelaying barge which recently laid two 20-in pipelines from Tunisia to Sicily across the Mediterranean Sea. Water depths of up to 600 m were encountered. The production rate averaged 1.5 km per day and went as high as 2.5 km per day. The "CASTORO SEI" was able to continue work in seas up to 6 m, and the limiting factor for the vessel to continue operating was the weather limitations of the anchor handling tugs. The "CASTORO SEI" is currently laying another line along the same route. With this experience under their belt, Saipem is now testing the depth capability of the "CASTORO SEI" at 1200 m, and even this may not be the limit of the system. Officials with Saipem feel that the vessel can lay pipe in water depths up to 2,100 m (Petroleum Engineer International, 1980).

To alleviate the sag-bend and over-bend problems mentioned previously, an inclined ramp concept has been designed. This would partially eliminate the upper part of the "S-curve." Once again, tensioners are the limiting factor. To completely eliminate the over-bend, a method ("J-bend") has been devised to lay pipe vertically (see Figure 14). Conventional drilling rigs could be used to lower the pipe to the seafloor. The disadvantages of this system are that only one section of pipe could be welded at a time rather than the multistation welding used in conventional pipelaying and some sort of vertical tensioning device, such as those used in drilling, would have to be devised instead of the conventional friction pads. Research is underway on butt-welding pipe to help speed up the J-bend process.

Planning is underway for a 30-in pipeline from Algeria to Spain. Water depths approach 2,000 m and the vessel has been designed.

Summary and Conclusion

The industry presently has the capability to drill in water depths to about 2,440 m. Research is currently being conducted by several major oil companies and projections from such research are that within 5 years, technology will permit drilling in water depths to 3,000 m. The deepest exploratory well for oil or gas was drilled in 1,486 meters of water off Newfoundland. The deepest discovery to date is in 671 m of water off Spain but was of insufficient quantity to justify development. The deepest commercial wellhead completion is a dry completion in 189 m. The deepest wet tree subsea completion is in 146 m in the North Sea. A general consensus in the oil industry, however, is that they can presently produce in up to 900 m of water and that within 10 years, they will have the technology to produce in over 1,800 m of water.

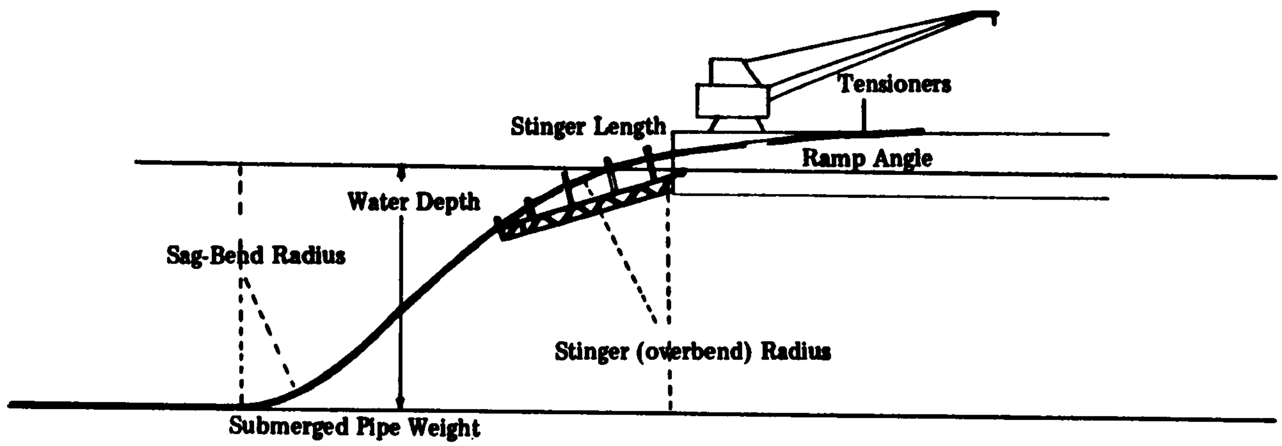


Figure 13. Conventional Pipelaying

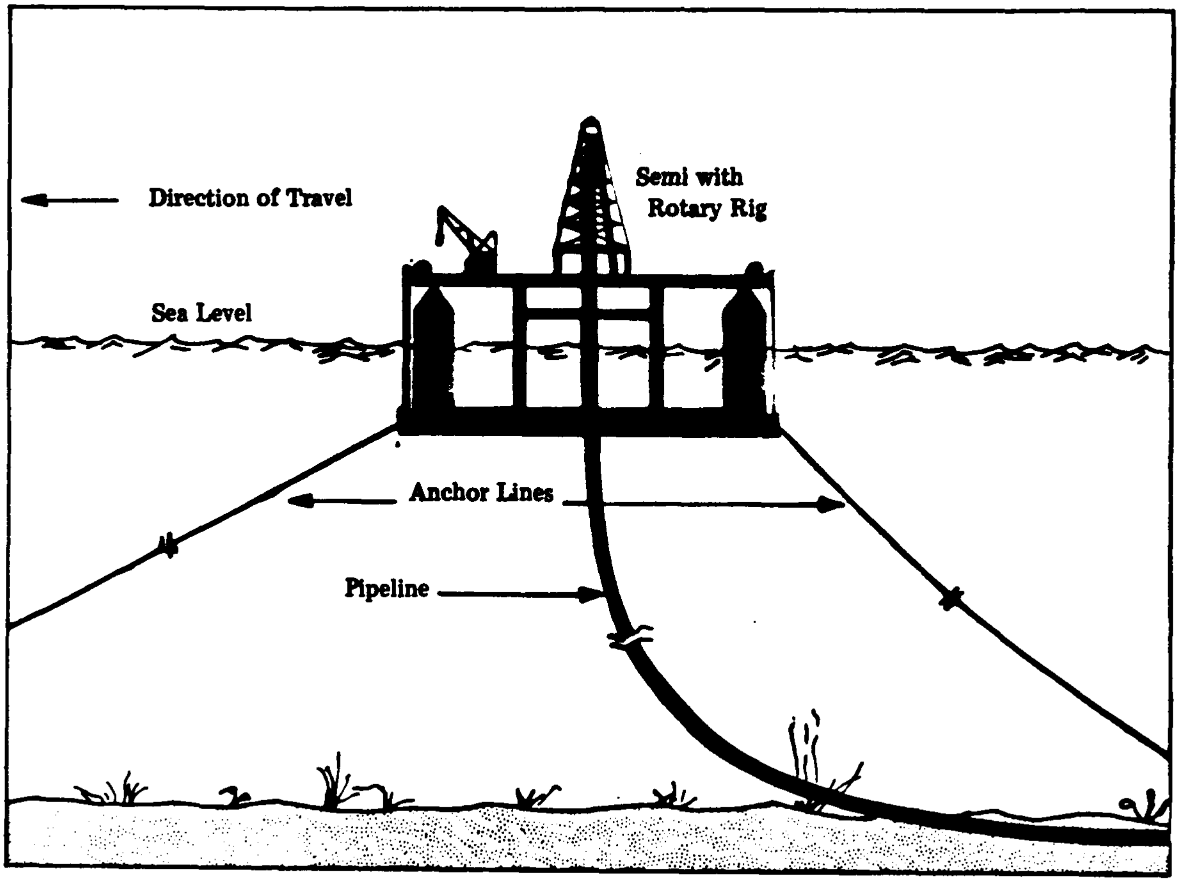


Figure 14. Vertically-laid Pipeline in Deep Water

Source: OFFSHORE Magazine

The deepest pipeline laid to date is the trans-Mediterranean 20-inch line in 600 m of water and there are plans for a line from Algeria to Spain in some 2,000 m of water.

Oil and gas operations in ever greater water depths require the use of new and more economical production systems. Subsea completion technology is being tested in shallow depths to provide procedures to be used in very deep water. All industry experts agree that if given the necessary economic incentives, the technology will be avialable. A secondary result of subsea completion technology is the ability to develop small reservoirs without the expenditures required for a surface structure. As the price of oil increases on the world market, the feasibility to utilize more sophisticated production systems will be realized.

The capability for deepwater drilling has been in existence for several years and, in fact, a surplus of that capability is expected to continue for several more years. The deep wells drilled in the next several years will probably be drilled by a dozen major oil companies in order to meet lease or concession obligations. Production riser technology is the limiting factor in the ability to exploit reserves of hydrocarbons occurring in deepwater. Before that exploitation can take place, the price of oil will have to increase significantly in order to make it economically feasible. Further incentives would be to offer larger tracts for lease (in U.S. waters) and to offer lease term extensions beyond the standard 5 years to allow additional time for development of technology for the particular site.

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The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.