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SUBAQUEOUS SEDIMENT INSTABILITIES IN THE OFFSHORE MISSISSIPPI RIVER DELTA

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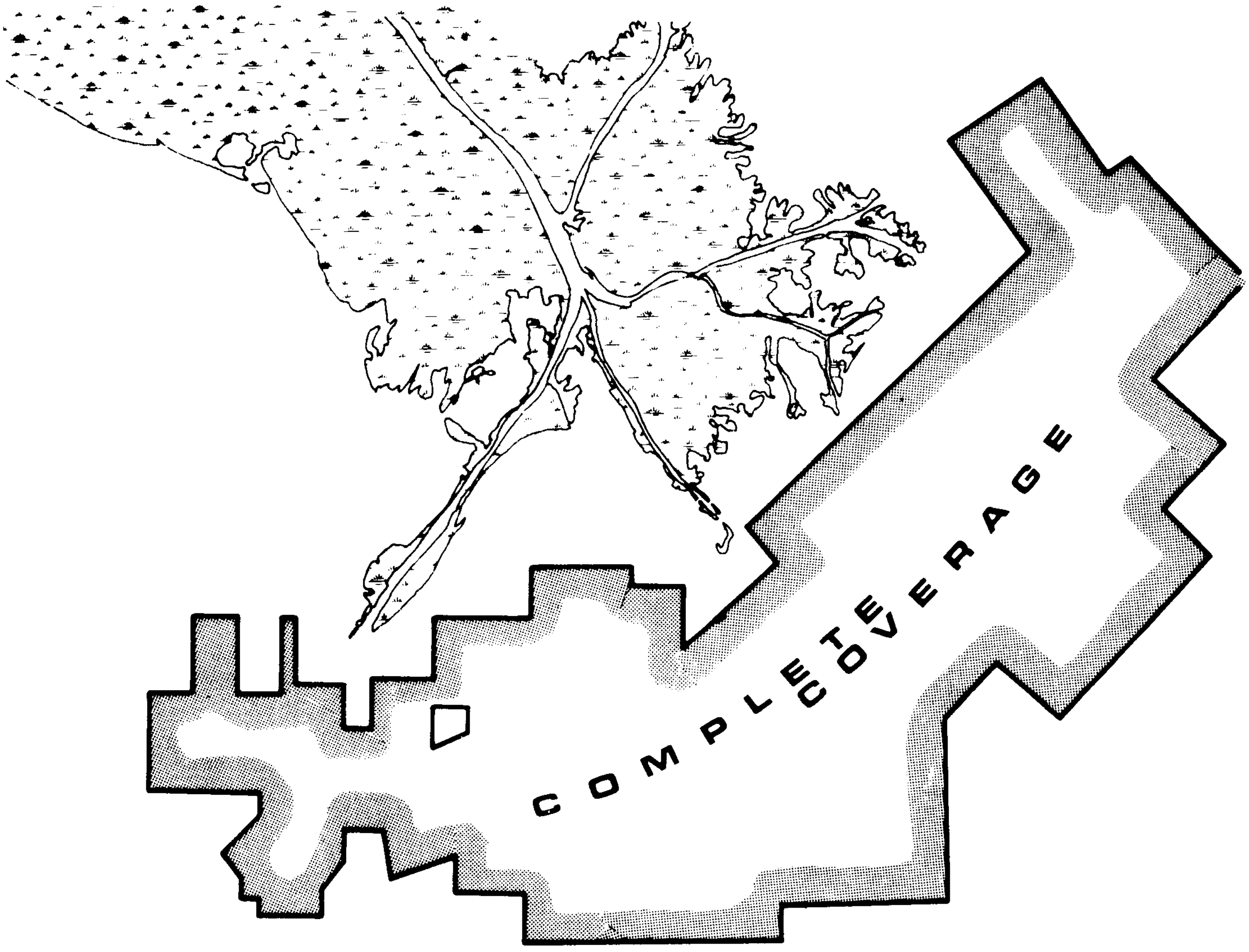

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INTRODUCTION

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. 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 1950s, 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 1960s, 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 and 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 plate and illustrates 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 an almost undistorted acoustic view of sea-floor 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 feet 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 set-back 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).

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 contribution of data and interpretations, helped to fill in some of the blank areas in our coverage.

The drafting was done by Mrs. G. Dunn and the photography by Mr. Kerry Lyle, both employees of the Coastal Studies Institute.

MISSISSIPPI RIVER DELTA SETTING

The Mississippi, the largest river system in North America, drains an area of 1.3 x 10^6 sq mi. 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 salt water 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 mi 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 Balize 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 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 to 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 to 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 sea floor; 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 subsidence ranges of 0.1 to 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 exceeding hydrostatic pressure, and some pore-fluid 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 transgressive 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, medium-grained 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 to 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 shell 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 to 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

The maps accompanying this text were prepared at an original scale of 1:12,000 and have been reduced to 1:48,000. There are 10 sets of maps and diagrams, and each set bears a plate number. Plates 1-5 and 9-10 are at a scale of 1:48,000, and plates 6-8 are at larger scales to show greater detail. Each set of maps (plates 1-5 and 9-10) consists of four sheets that cover the Mississippi Delta offshore and is numbered according to the scheme shown in figure 1. The original base maps utilized were the Bureau of Land Management offshore tract maps and were on film base to avoid any shrinkage or scale distortion. Reference grids on the maps consist of latitude and longitude, Lambert, and UTM coordinates. Lease block boundaries and block numbers are also shown. The type of map and appropriate legend are shown on each map.

PLATE 1. TRACK-LINE MAP (four maps, scale 1:48,000)

The four maps composing plate 1 show 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,

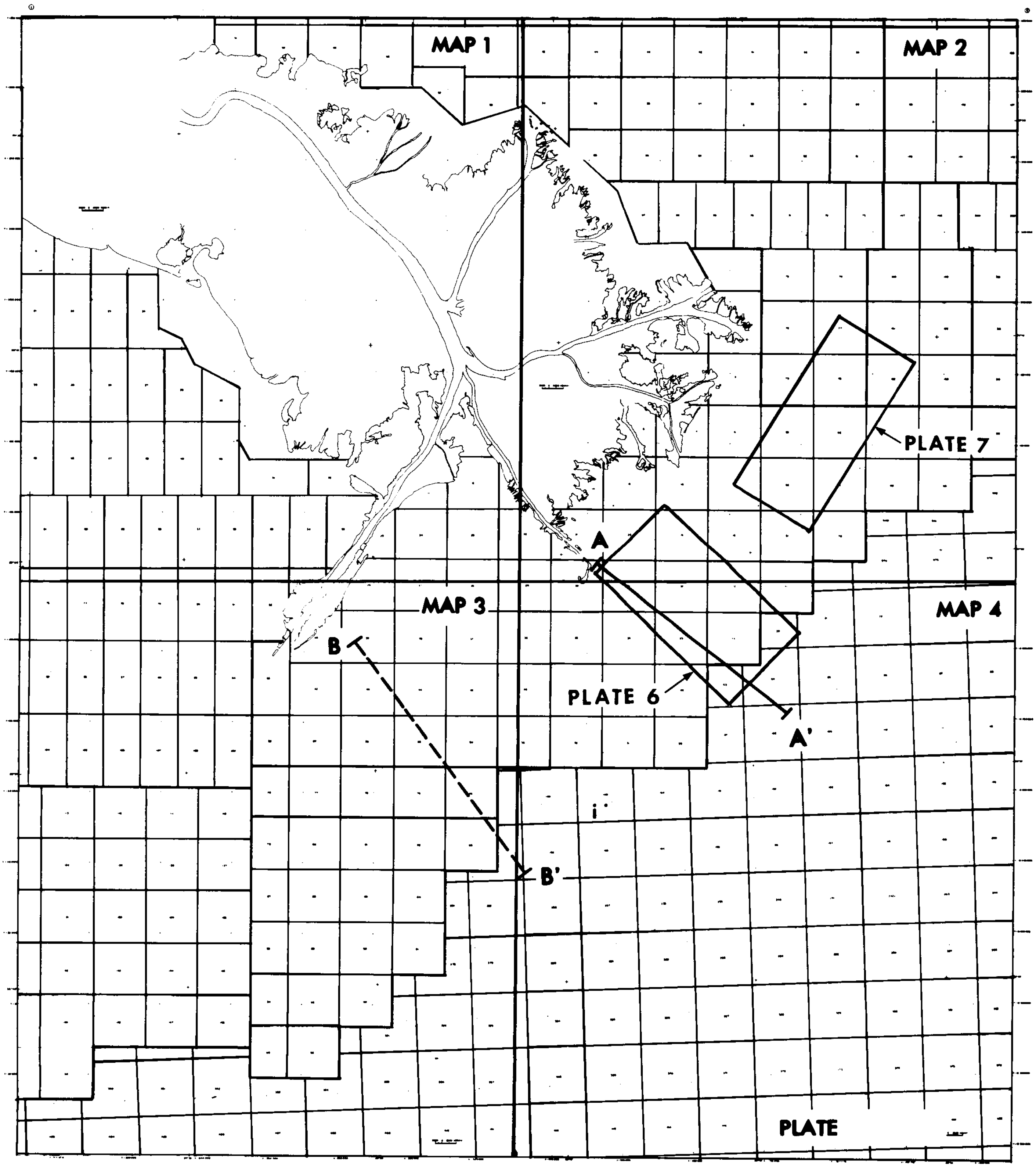

Figure 1. Map-numbering system for plates 1-5 and 9-10. Profiles A-A' and B-B' are illustrated in figure 3.

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 mi of data was collected, interpreted, and mapped over a 774-sq-mi 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 to 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. The last category, "No Data," represents those areas where no data or only widely spaced regional data 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.

PLATE 2. 1874 BATHYMETRY (four maps, scale 1:48,000)

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 Southwest 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.

Plate 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 Hydrographc Office map 94 and corrected for changes in 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 sounding points. Apparently, great care was taken in producing the sounding sheets, and the accuracy of the map is quite good. Therefore, plate 2 is useful for comparisons with more recent maps to obtain accumulation rates.

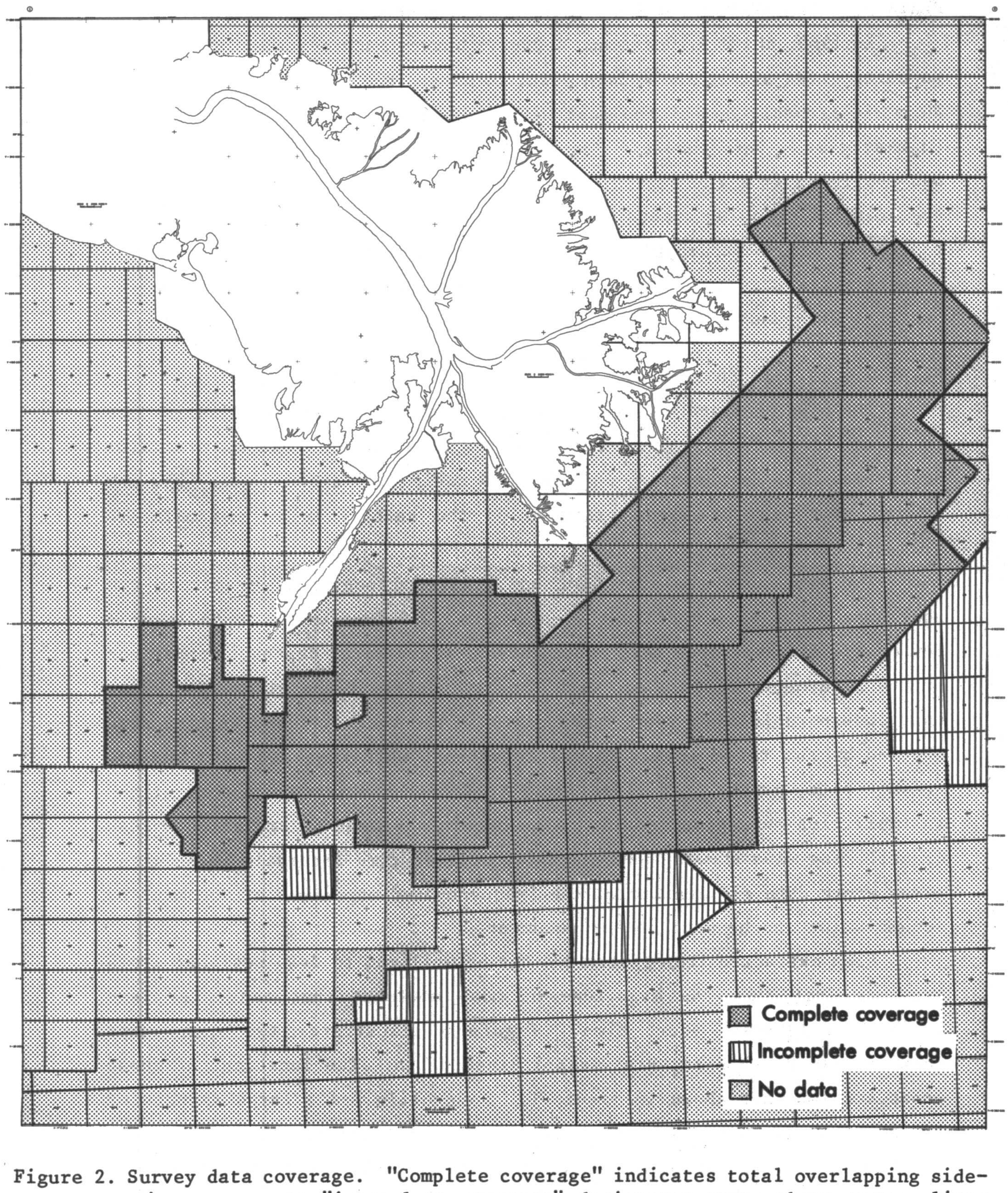

Figure 2. Survey data coverage. "Complete coverage" indicates total overlapping side-scan sonar imagery areas; "incomplete coverage" designates areas where survey lines were spaced more than 2,000 feet apart, requiring considerable interpretation; "no data" indicates those areas having no survey coverage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

PLATE 3. 1940 BATHYMETRY (four maps, scale 1:48,000)

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 bathymetric map shown in plate 3, the original sounding sheets were obtained, and individual areas were contoured and then photographically reduced to the scale of 1:48,000. The map appears quite accurate, and no major problems were encountered in merging one area with another.

PLATE 4. 1977-79 BATHYMETRY (four maps, scale 1:48,000)

The maps of plate 4 were constructed from the data whose distribution is shown in plate 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 this map with 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 plates 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

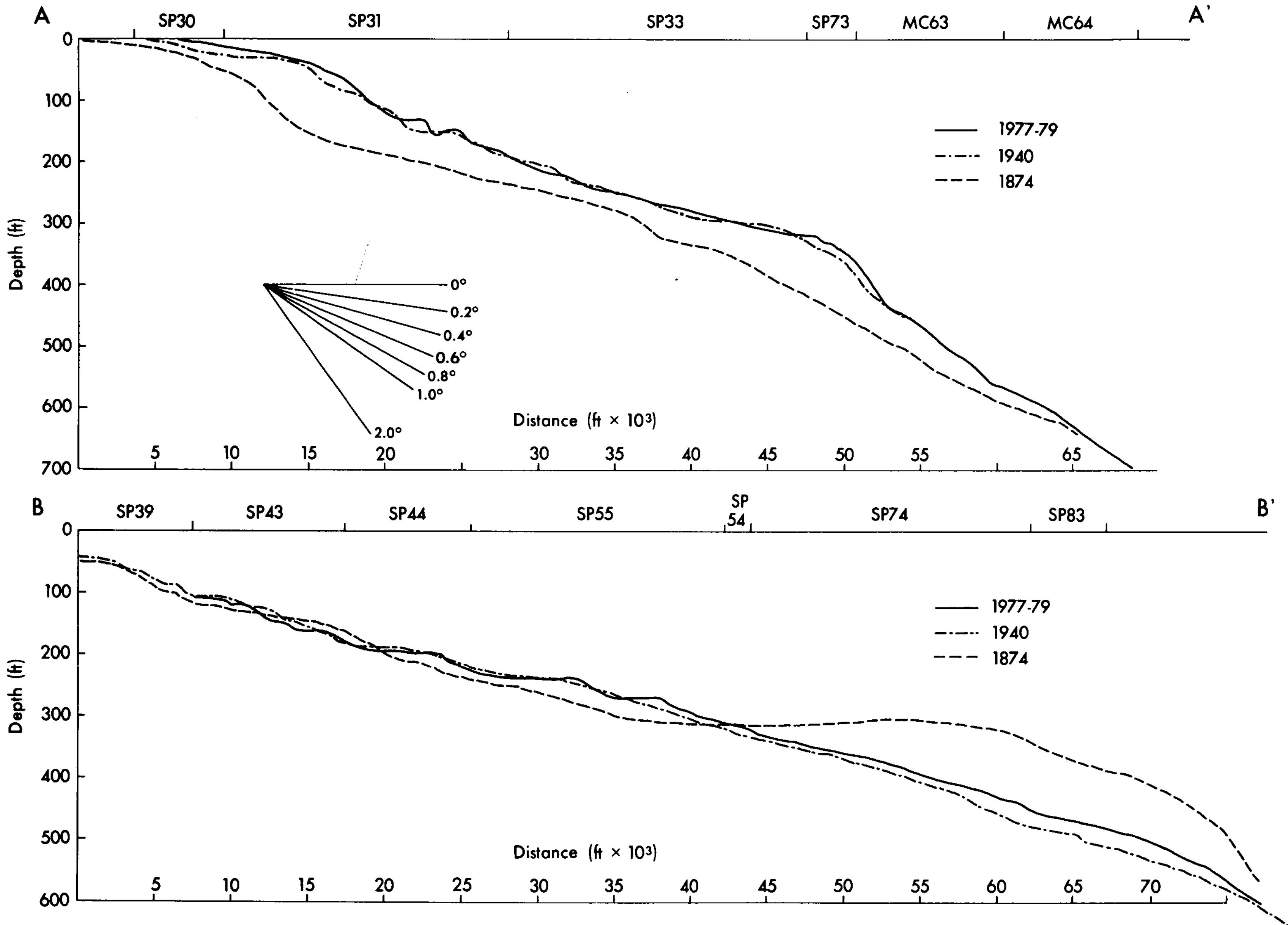

Figure 3. Cross sections showing bathymetric changes between 1874 and 1979. Locations of profiles shown in figure 1.

column and thus represents deposition by subaqueous mass movement. In profile A-A' (fig. 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' (fig. 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 to 400 feet. This accumulation undoubtedly represents large subaqueous mass movements of sediments off an old distributary called "Grand Pass" (see plate 2), which branched off South Pass and built a distributary west of South Pass into East Bay from the late 1700s through the early 1900s. This distributary pass is discernible on many maps during this interval (1838, 1872, 1898, 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 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 to 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

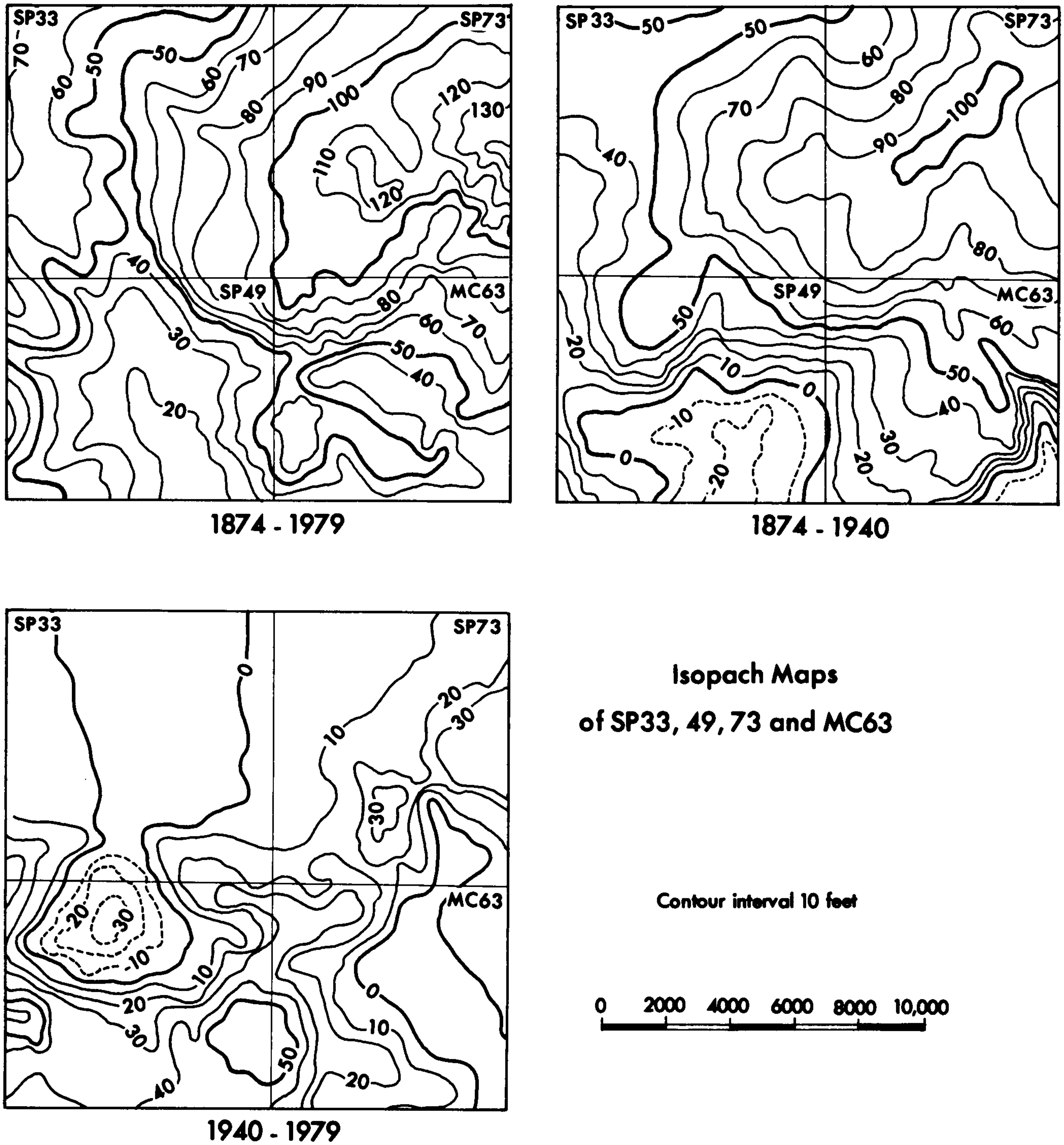

Figure 4. Sediment isopach maps of South Pass Blocks 33, 49, 73, and Mississippi Canyon Block 63 for the intervals 1874-1979, 1874-1940, and 1940-1979.

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.

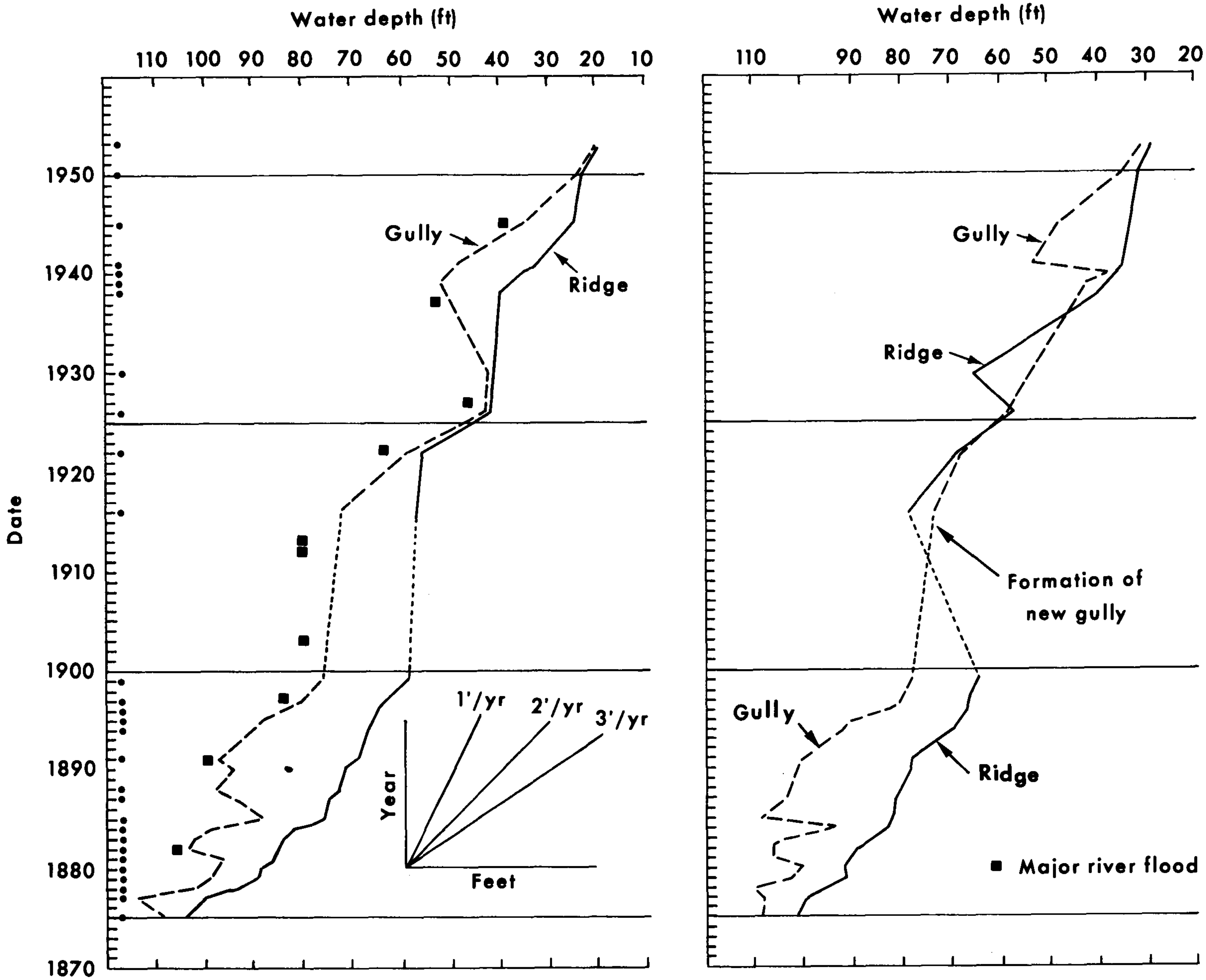

Figure 5. Sediment accumulation in mudflow gullies and adjacent ridges in South Pass Block 30 during the period 1874-1953. A dot denotes that a map is available for that time period.

PLATE 5. SEA-FLOOR MORPHOLOGY (four maps, scale 1:48,000)

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

In addition, these maps serve 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.

The following features are shown on this set of maps:

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

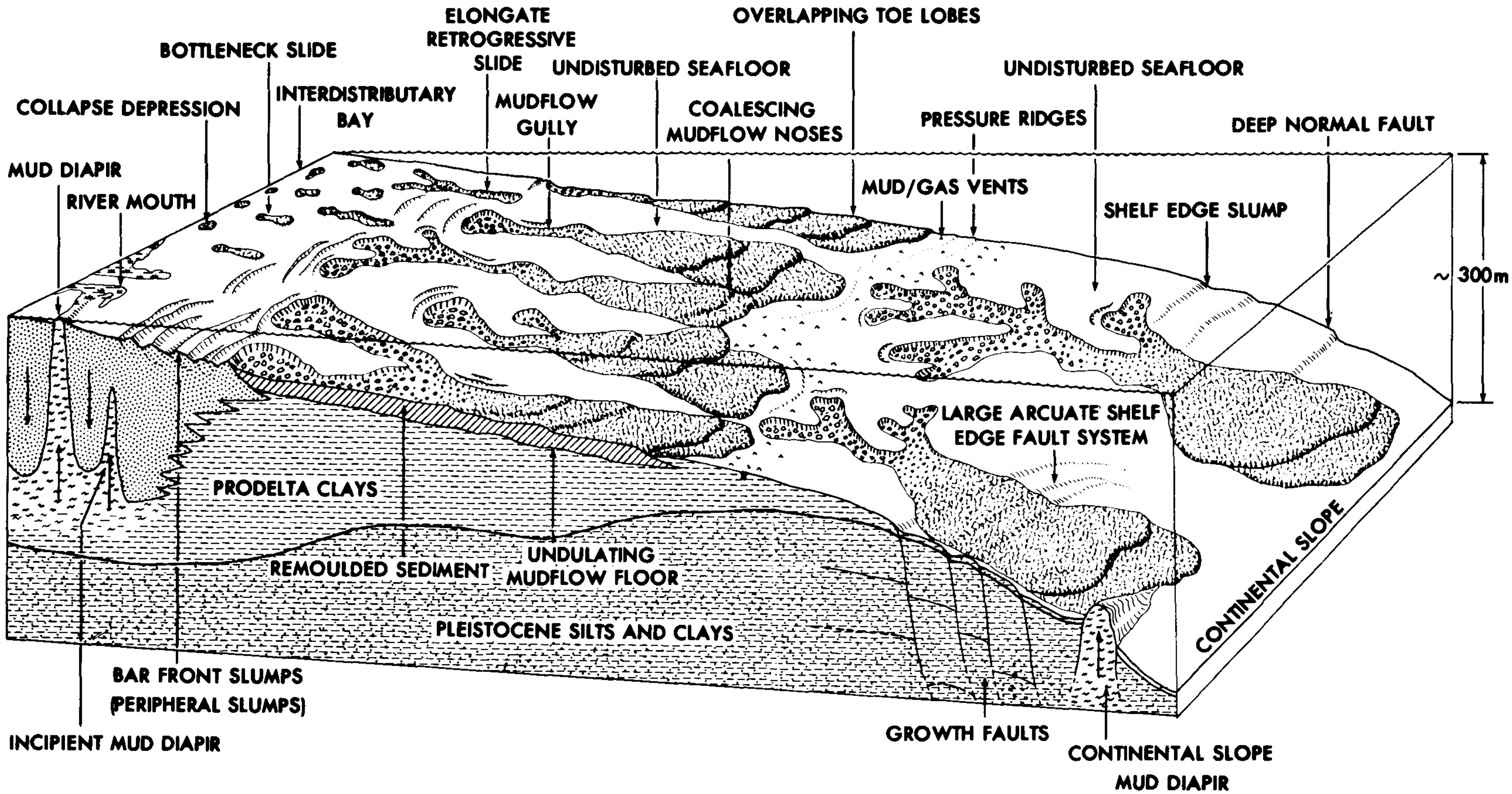

Figure 6. Schematic block diagram showing the relationship of the various types of subaqueous sediment instabilities.

scarps, have been displaced vertically and represent distinct depressions of the sea floor. 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 no slope and are horizontal. In addition, the floor of the feature is on many records the area where several sea-floor multiples exist, giving some indication that the sediments flooring the depression have slightly higher densities that 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. 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

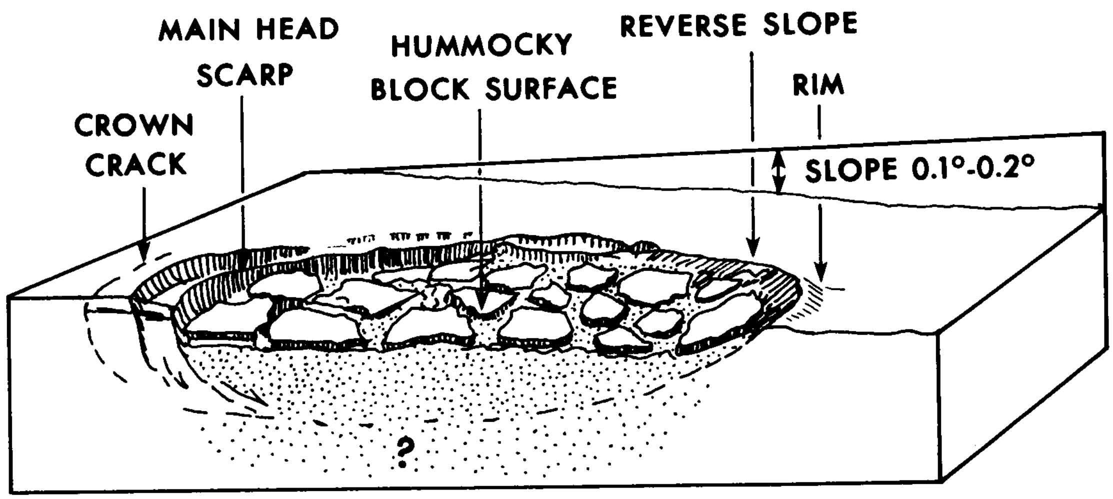

Figure 7. Schematic diagram illustrating the morphology of collapse depressions. Stippled area represents disturbed sediments whose depth is unknown.

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 and have depressed floors that range from 2 to 10 feet below the surrounding sea floor. 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 sq ft. 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 sea floor.

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 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°-4°. In many areas, they give the bar front a stairstepped

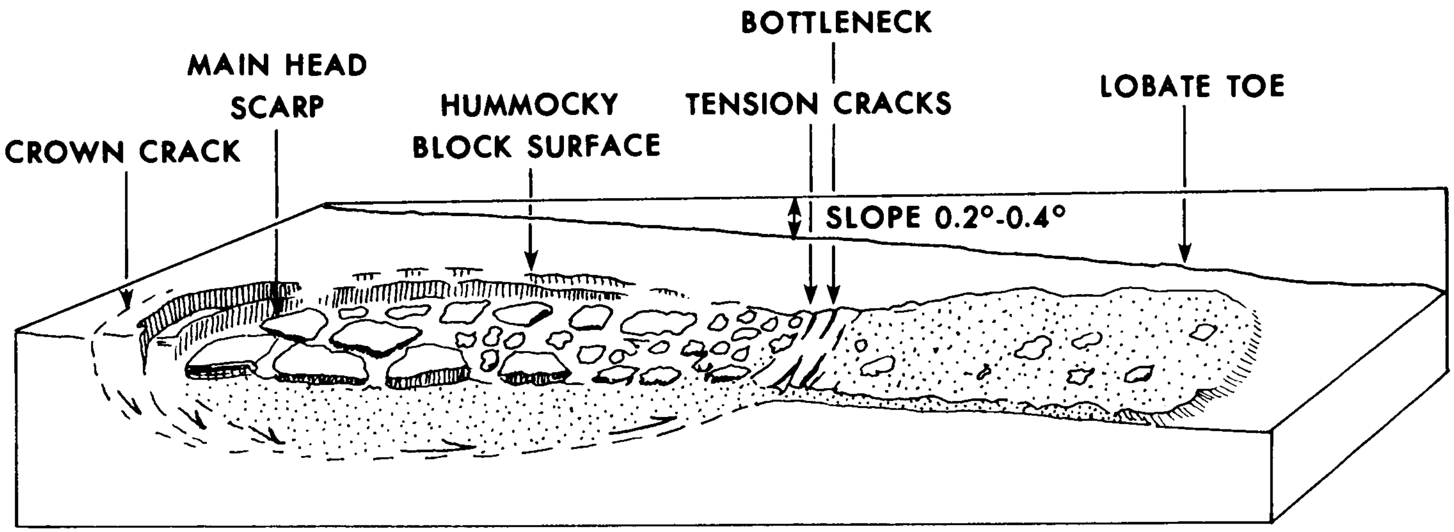

Figure 8. Schematic diagram illustrating the morphology of bottleneck slides. Stippled areas represent disturbed sediment.

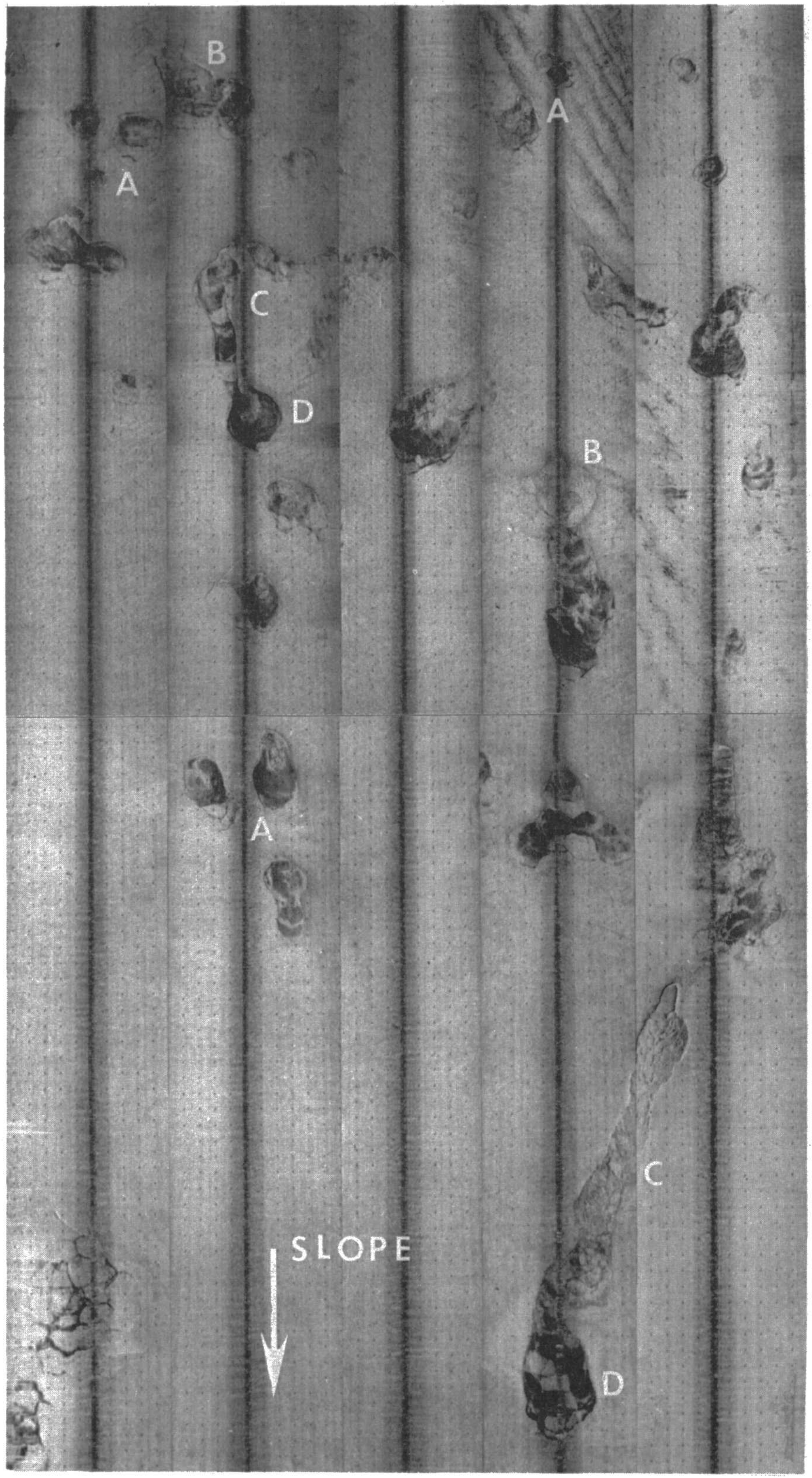

Figure 9. Side-scan sonar mosaic, illustrating several collapse depressions and a bottleneck slide. The grids are 82 feet (25 m) apart, and the mosaic covers a region 0.8 x 1.4 mi. A, collapse depressions; B, crown cracks; C, bottleneck slide; D, depositional lobe of bottleneck slide.

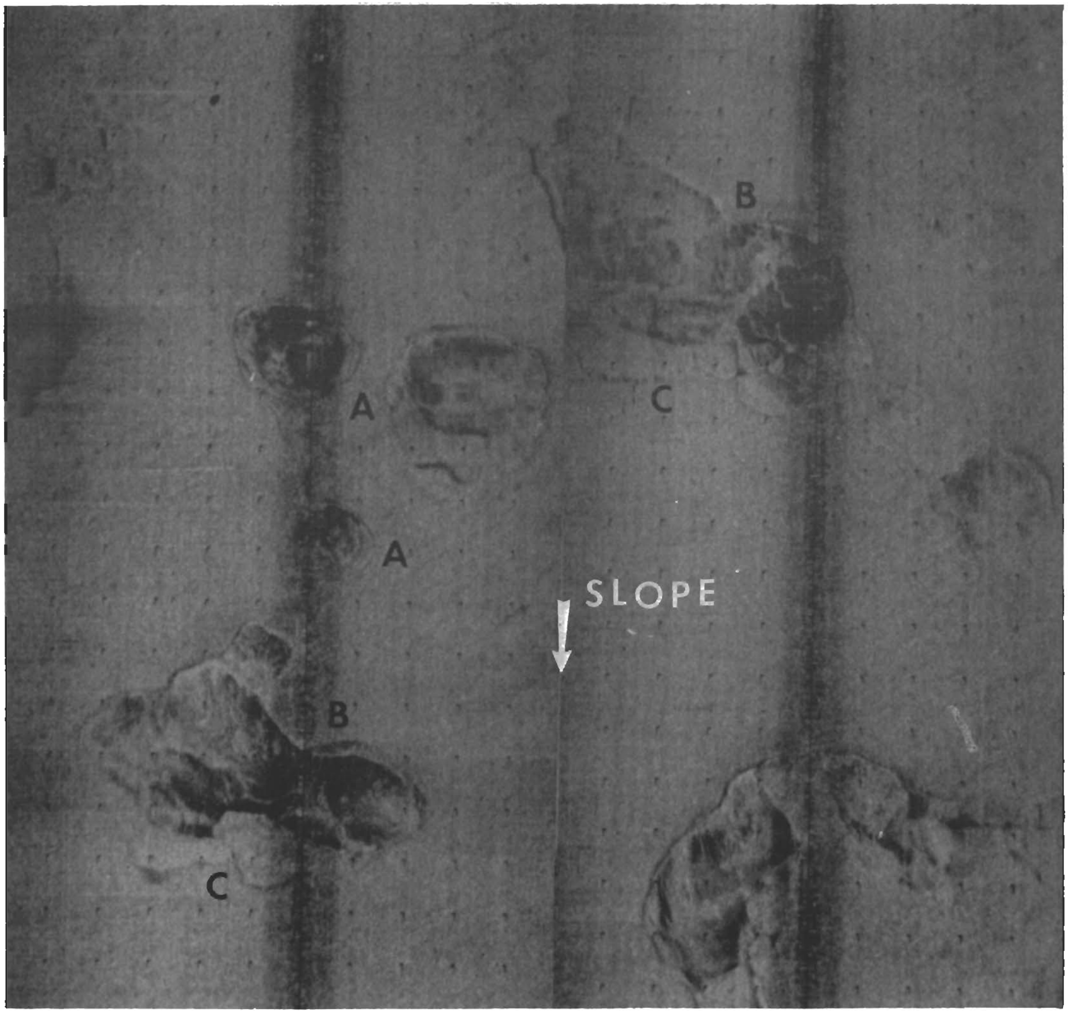

Figure 10. Enlarged part of side-scan sonar mosaic (fig. 9) showing some of the details of the collapse depression. A, circular collapse depressions; B, more elongate and irregularly shaped collapse depressions; C, crown cracks associated with the edges of the collapse depressions.

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 slid-

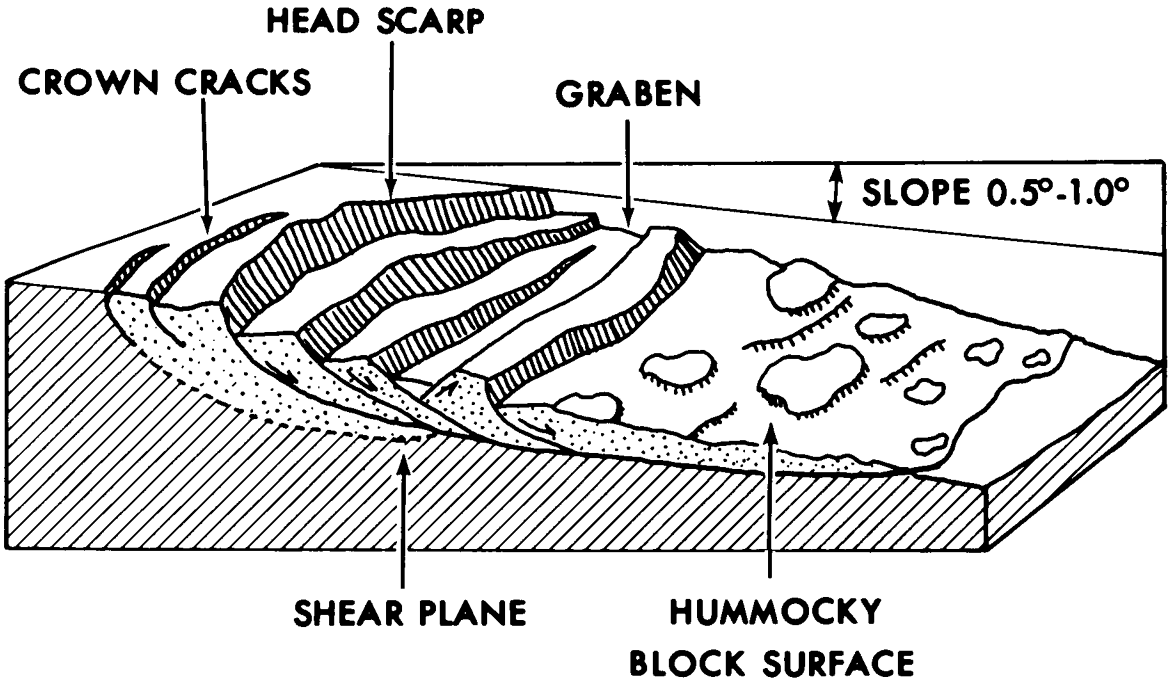

Figure 11. Schematic diagram illustrating the morphology of rotational peripheral slides. Stippled areas represent disturbed sediment.

ing 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 mi in a 1-year period.

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. <u>Mudflow gullies</u>. Extending radially seaward from each of the distributaries in water depths of 20 to 300 feet are major elongate systems of sediment instabilities referred to as delta-front gullies or mudflow

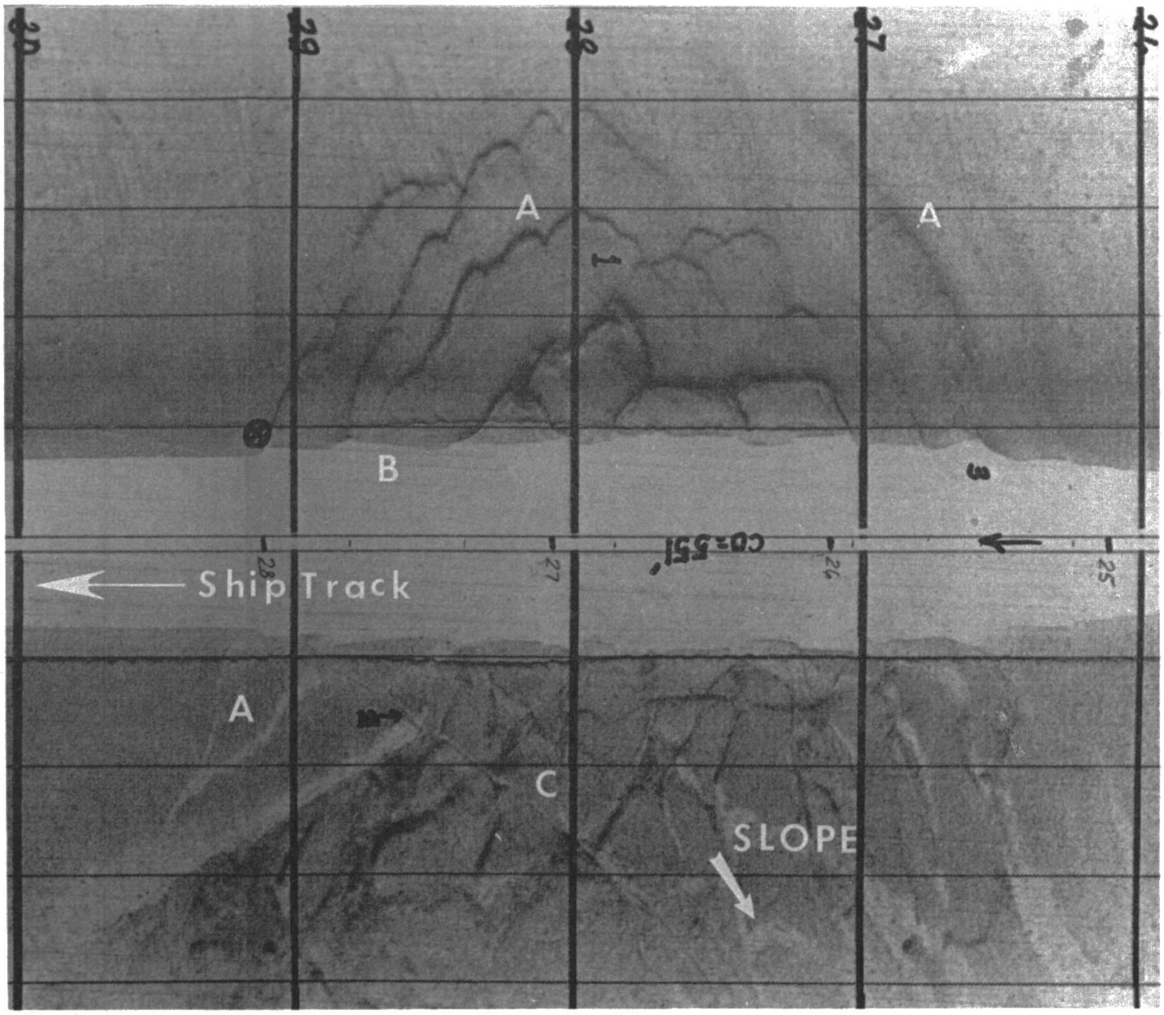

Figure 12. Conventional side-scan sonar record, showing several rotational slides. Navigation fixes are 500 feet apart, and lateral timing lines are 82 feet apart. A, shear planes showing up as scarps on the sea floor; B, rotated block; C, shrimp trawler's drag mark.

gullies. The features were first described on hydrographic maps by Shepard in 1955, and the bathymetric maps of plate 4 (1977-79 bathymetry) illustrate 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.

Each mudflow gully possesses a long, sinuous, narrow chute or channel that links a depressed, hummocky source area on the upslope margin to

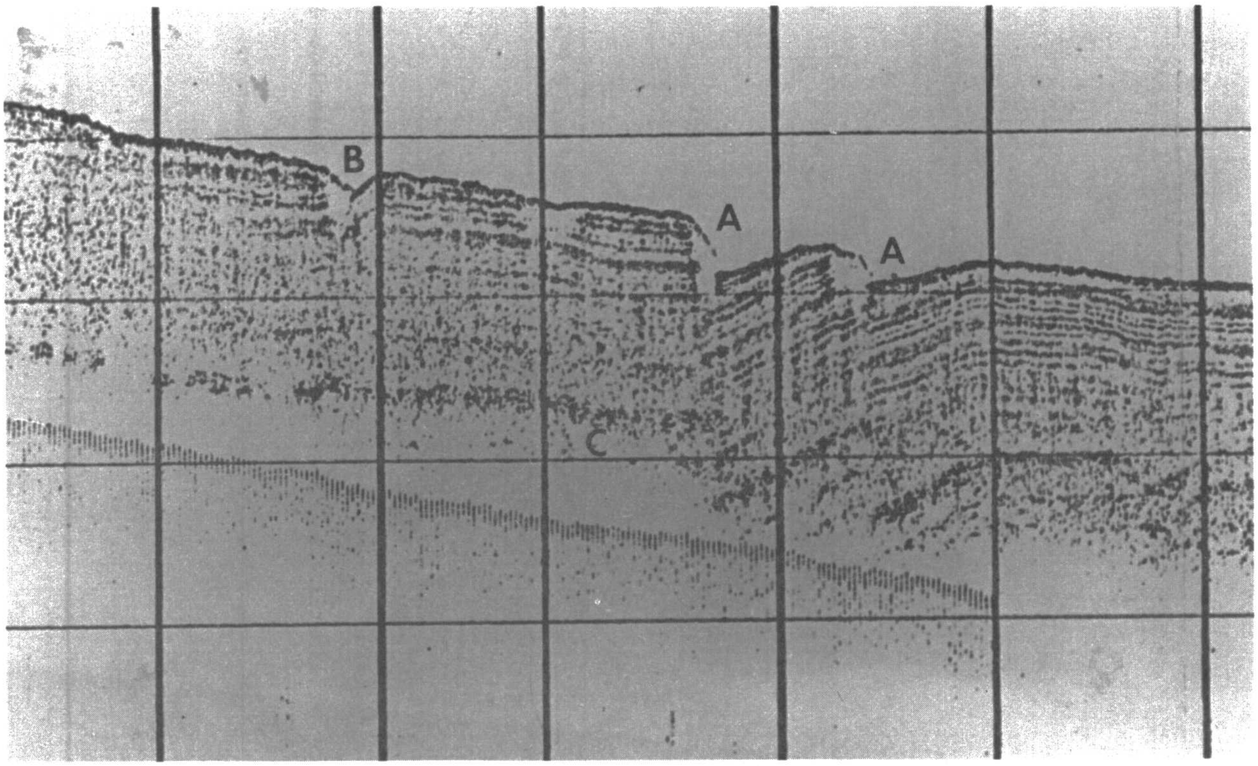

Figure 13. High-resolution seismic line run across several peripheral slides. Navigation fixes are 500 feet apart, and timing lines are 31.5 feet apart. A, rotational slides; B, newly forming rotational slide upslope; C, note the offset in this reflection horizon.

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

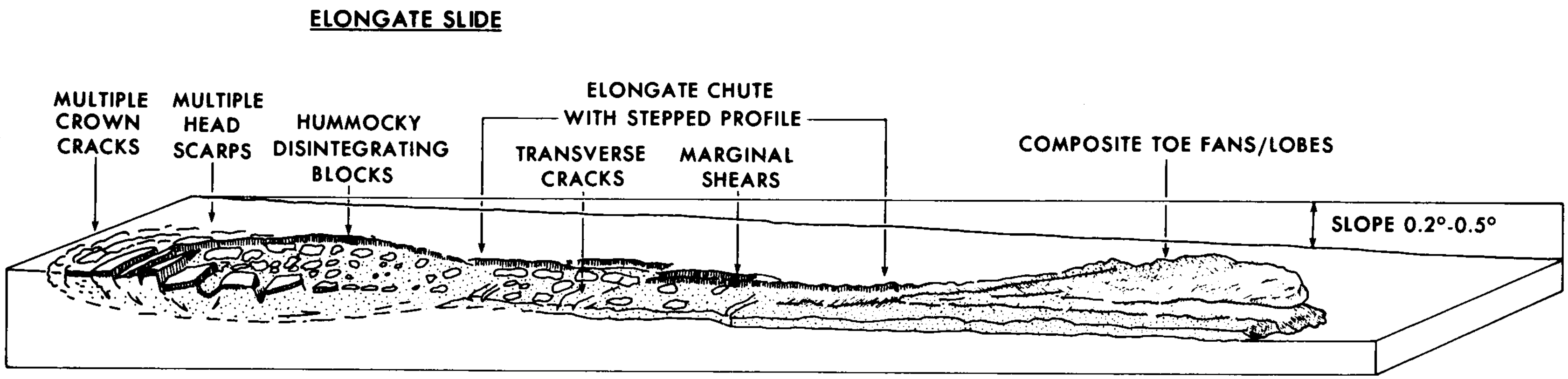

Figure 14. Schematic diagram illustrating the morphology of mudflow gullies and depositional mudflow lobes. Stippled areas represent disturbed sediment.

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 mi 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 landslide gullies. The area covered by the mosaic is 0.7 mi by 1.1 mi. 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 have 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 feet 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 mi 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 discharged 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.

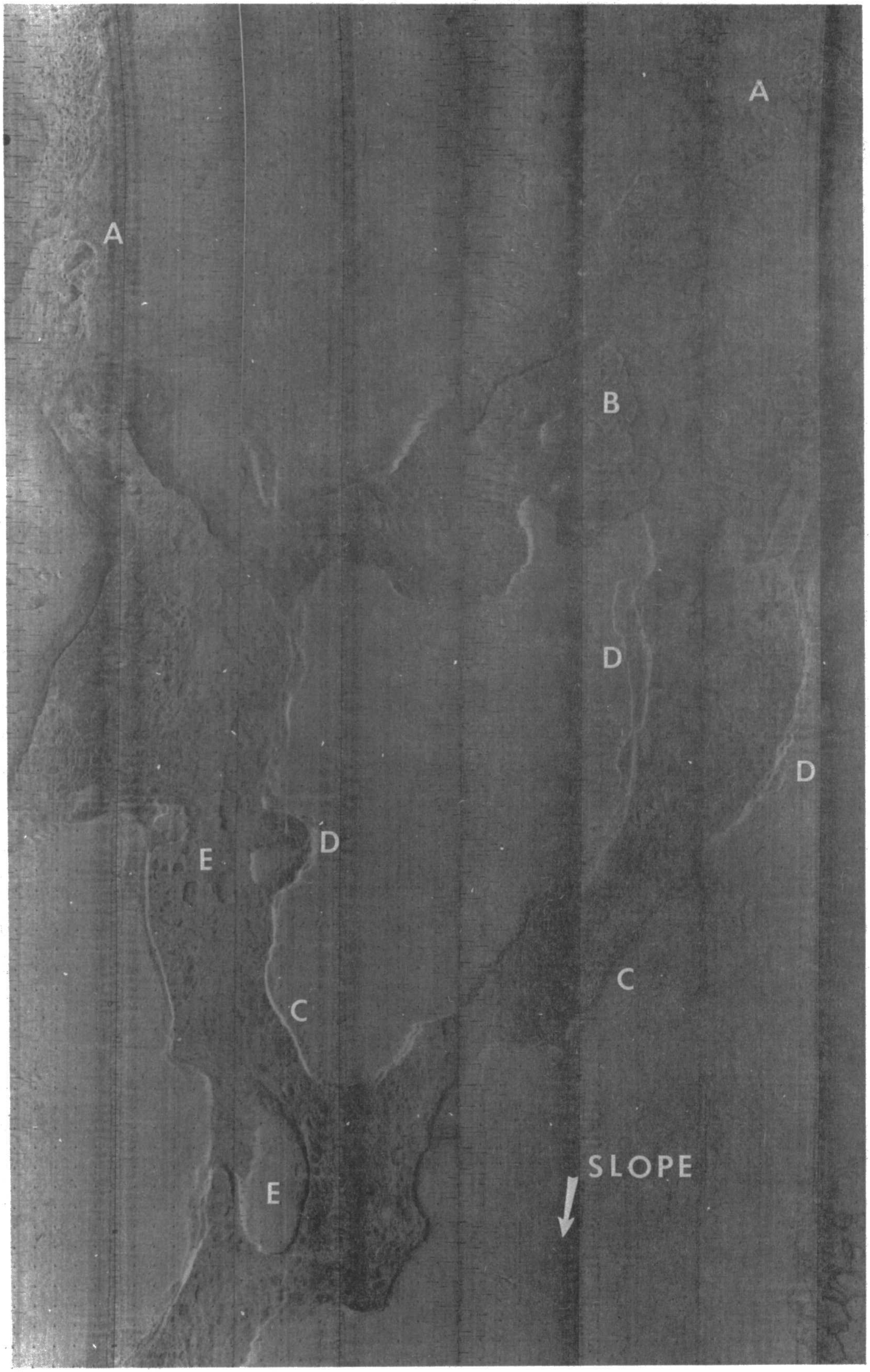

Figure 15. Side-scan sonar mosaic showing several landslide gullies. Grid is 82 x 82 feet, and the mosaic is 0.7 x 1.1 mi. Water depths are approximately 70 feet at the top of the figure and 110 feet at the lower end. A, source areas; B, retrogressive gully; C, narrow incised gully; D, sidewall-instability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

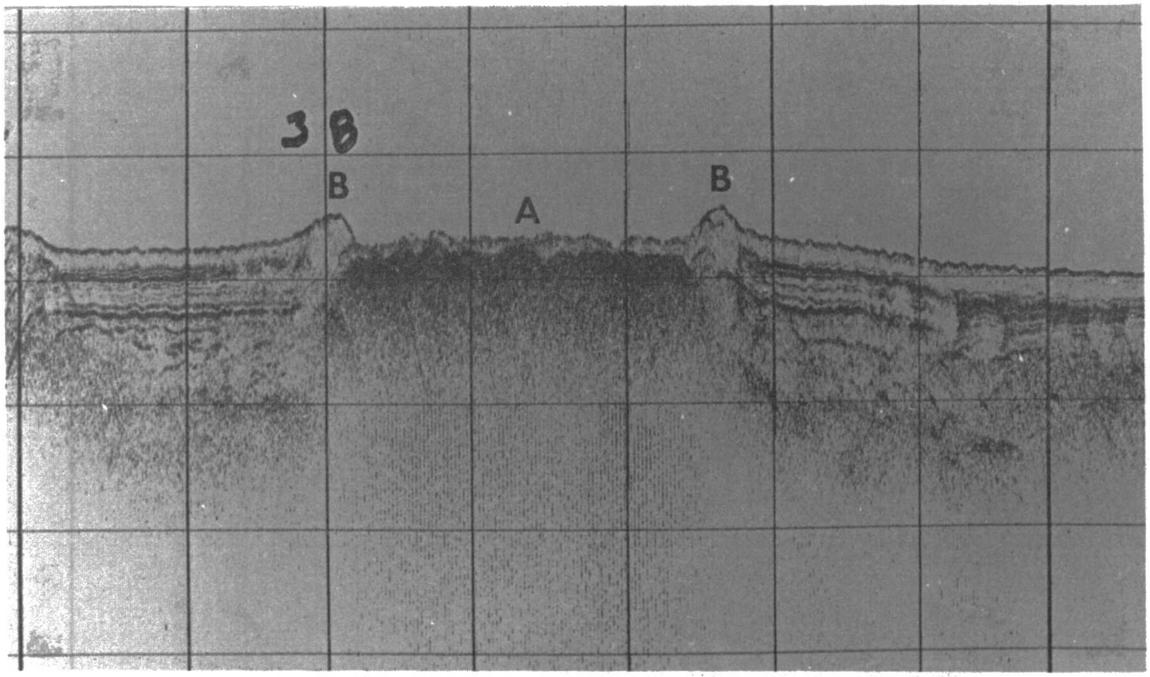

Figure 16. High-resolution seismic record run across a gully where remolded debris has been ejected out of the valley onto the adjacent slopes, forming natural levees. Navigation fixes are 500 feet apart, and timing lines are 31.5 feet apart. A, mudflow gully floor; B, topographic overbank natural levees.

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 formation of large blocks along the sides of the depressed bowl. Figure 18 is a high-resolution 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.

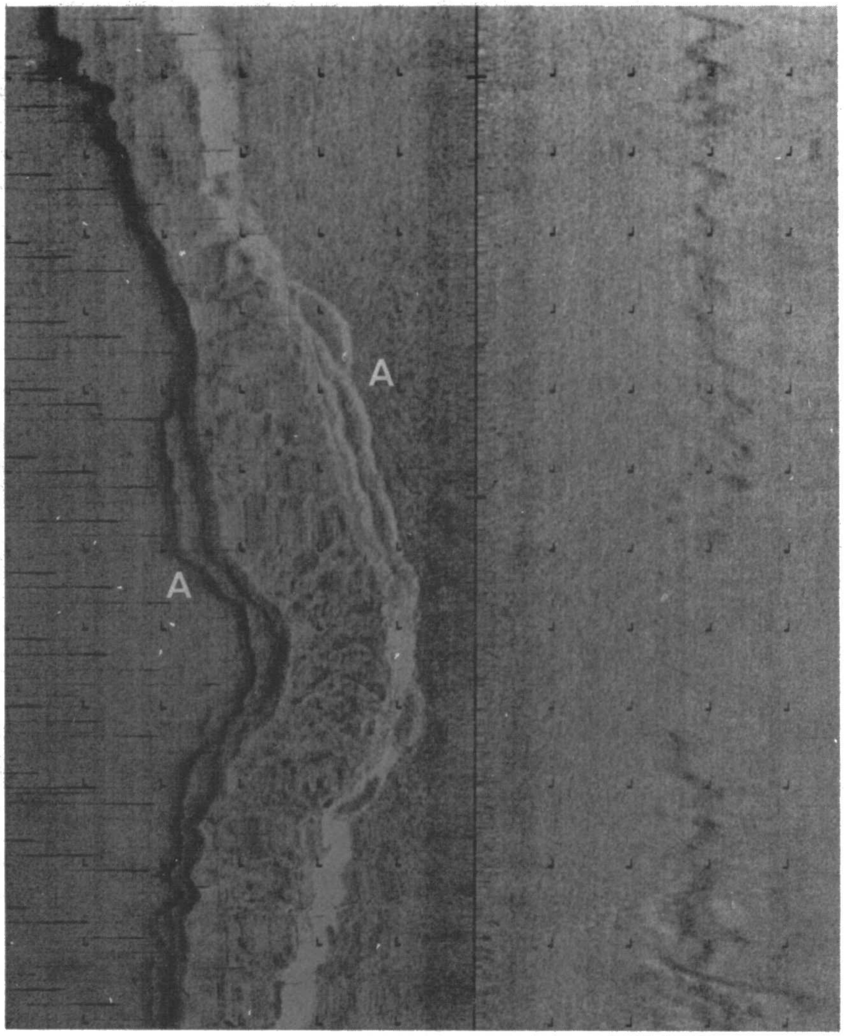

Figure 17. Side-scan sonar image showing a narrow mudflow gully having many sidewall slumps. Grid is 82 x 82 feet.

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 channels generally emanate from upslope slump 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 dis-

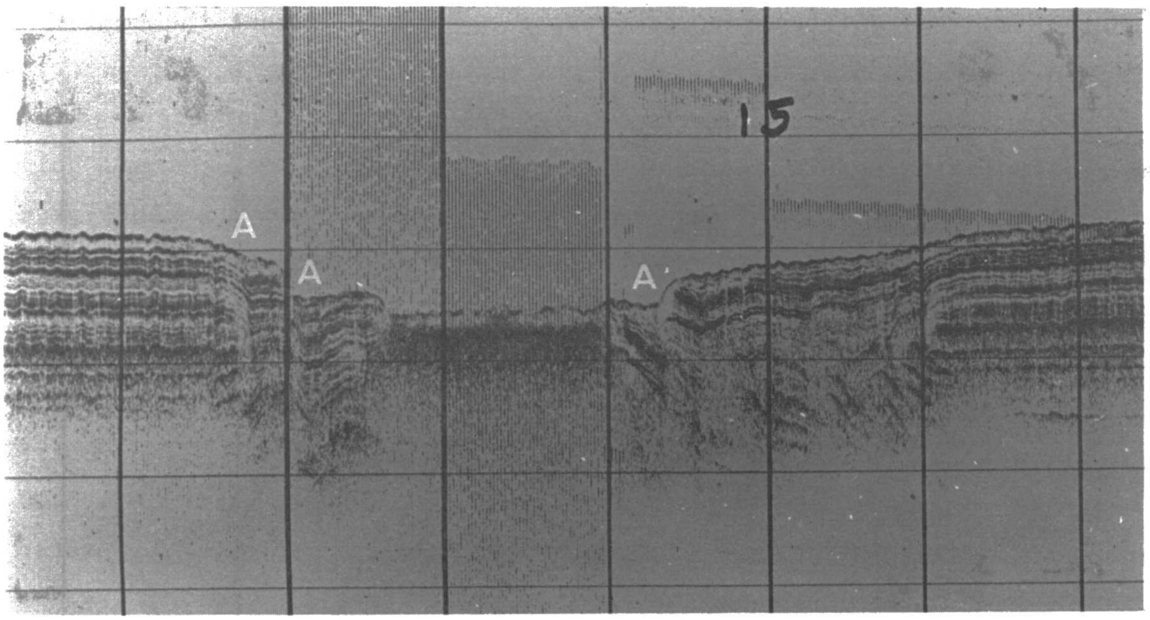

Figure 18. High-resolution seismic line run across a mudflow gully that shows numerous sidewall rotational slides (A). Gully is approximately 1,200 feet wide and has a relief of 25 feet. Navigation fixes are 500 feet apart, and timing lines are 31.5 feet apart.

integrated 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 plan 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°-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 mi. 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 by 6,800 feet) of a depositional mudflow lobe emanating from an upslope mudflow gully off 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, Fig. 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, fig. 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 to 2 1/2 mi. 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 feet to 1,500 feet in length and have smooth undisturbed topography on their surface. Figure

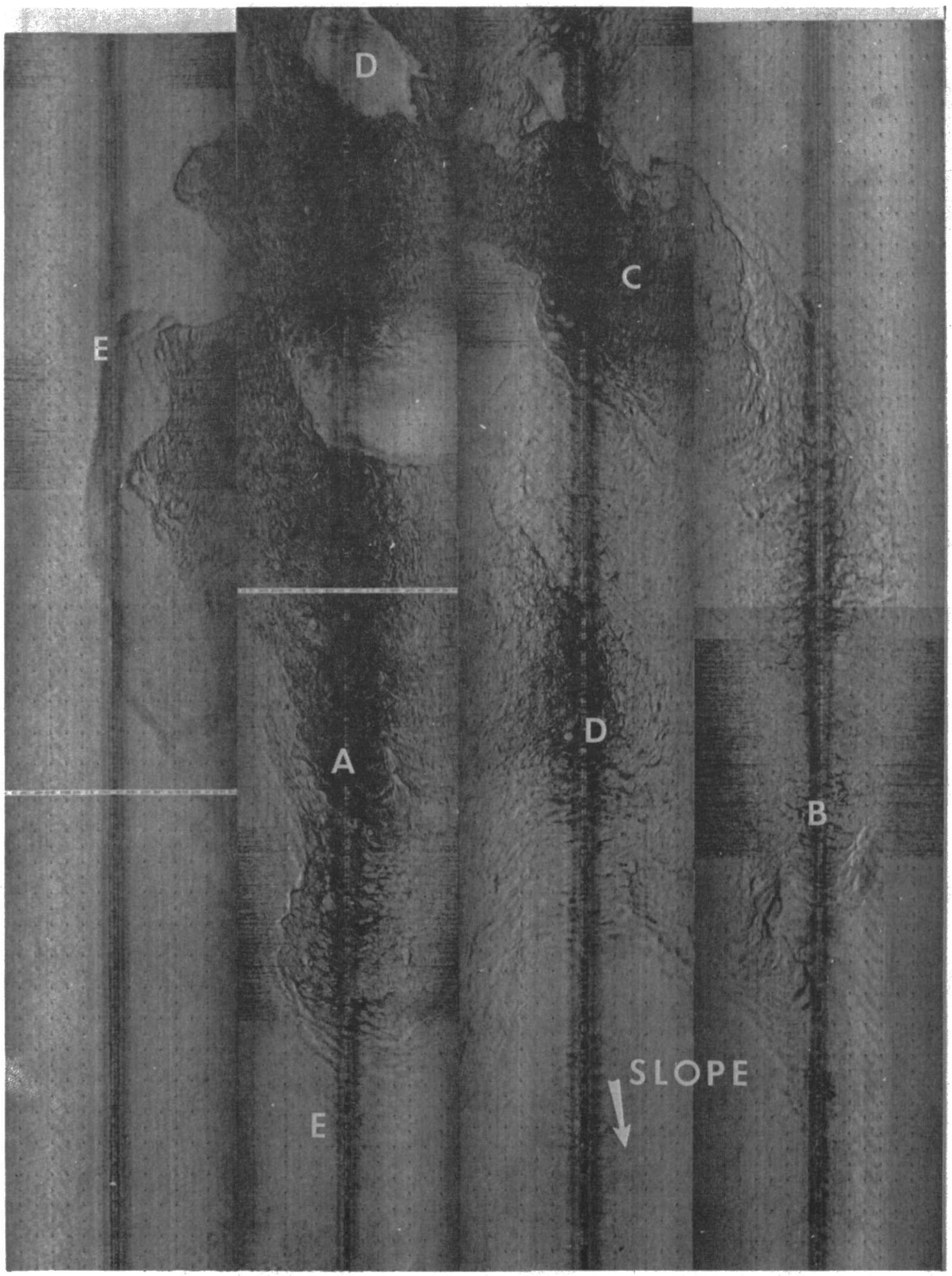

Figure 19. Side-scan sonar mosaic showing multiple overlapping mudflow depositional lobes. The grid tick marks are 82 feet apart. A, B, C, mudflow lobes; D, erratic blocks; E, pressure ridges.

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

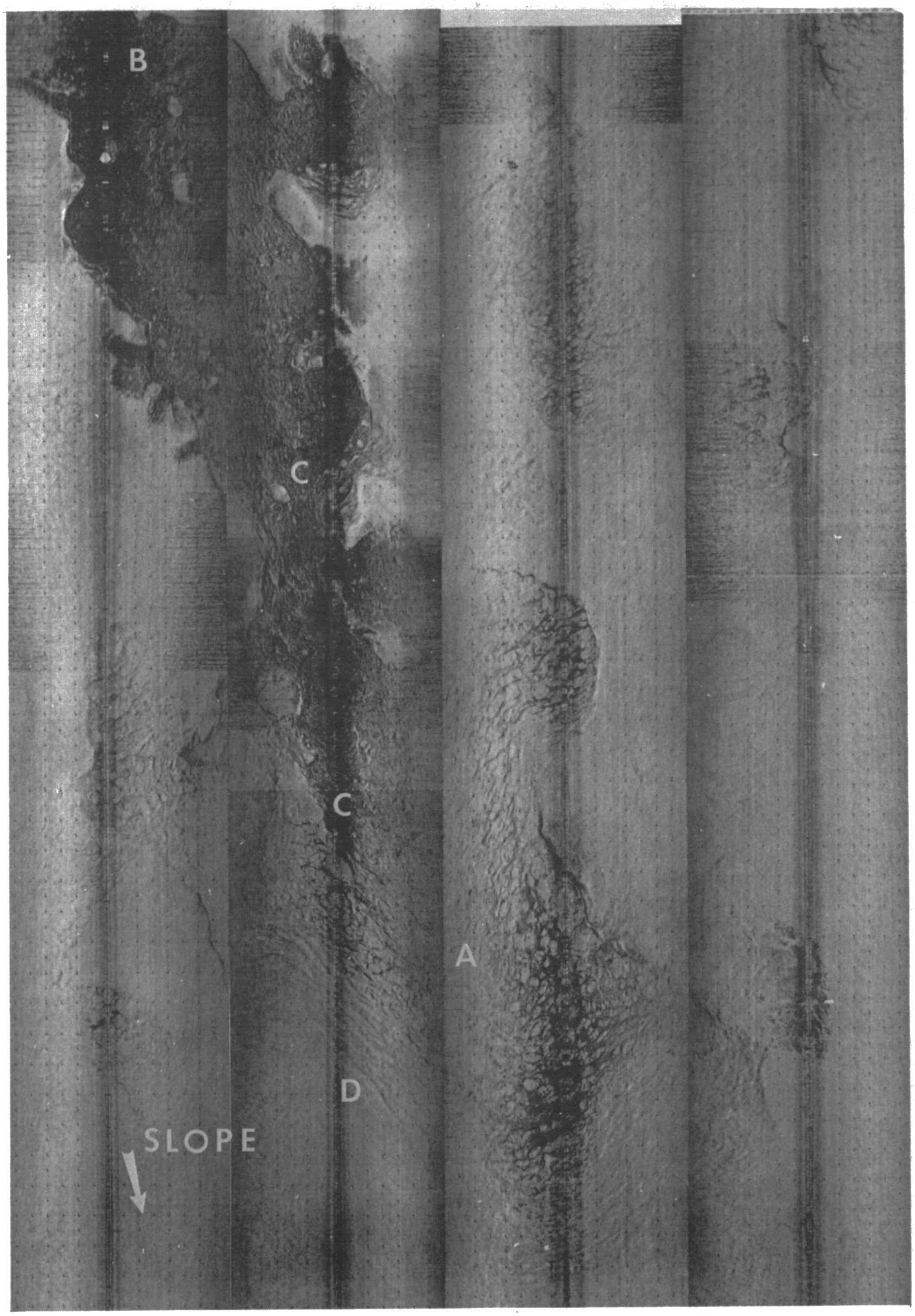

Figure 20. Side-scan sonar mosaic showing lower part of mudflow gully and a single large elongate mudflow depositional lobe. Grid tick marks are 82 feet apart, and mosaic covers an area 1.0 mi by 1.4 mi. A, mudflow depositional lobe; B, mudflow gully; C, large erratic blocks; D, pressure ridges.

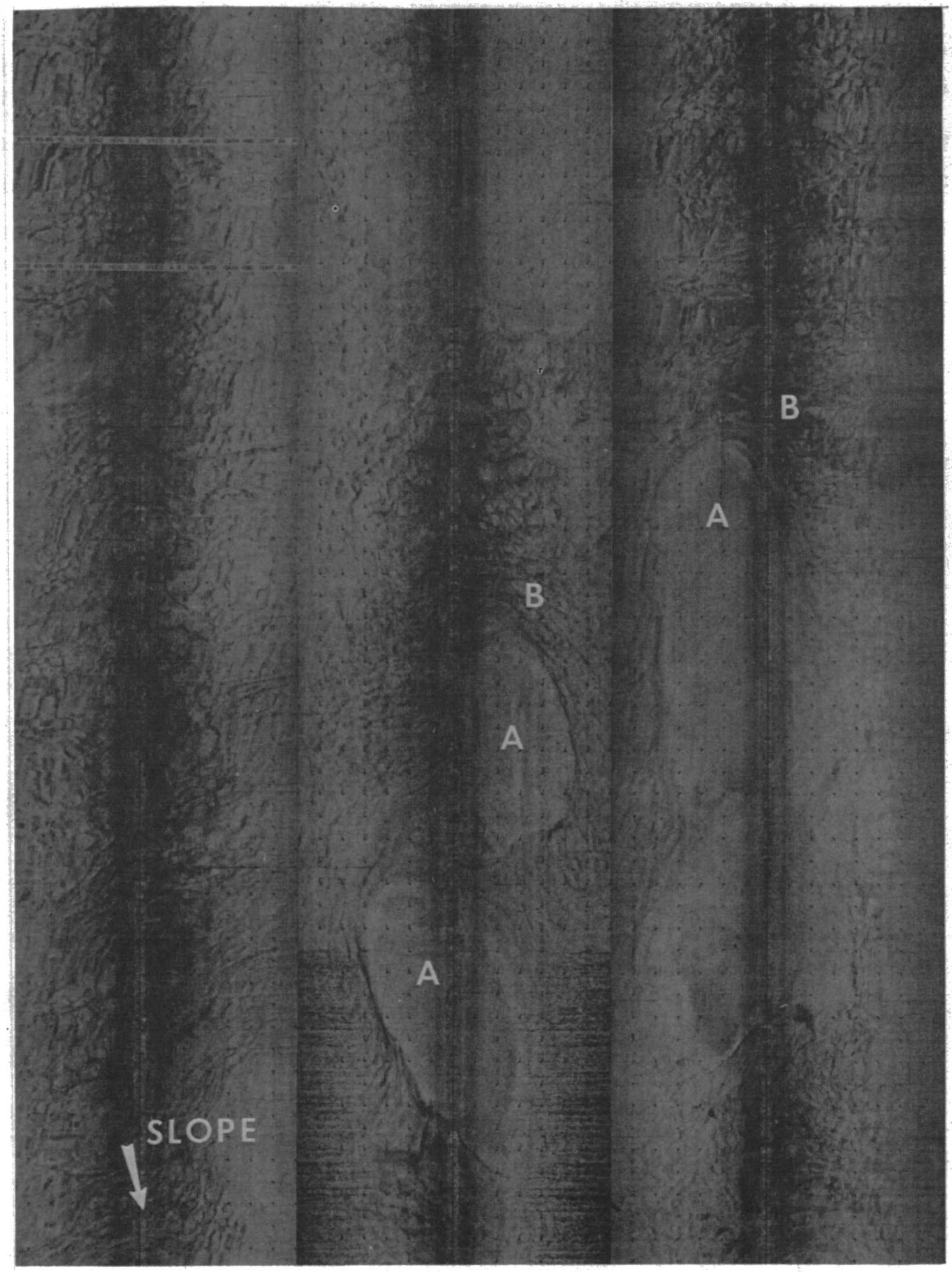

Figure 21. Side-scan sonar mosaic showing large erratic blocks in mudflow lobe. Grid tick marks are

reflections can be seen. Whether these blocks represent stable areas of the sea floor 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.

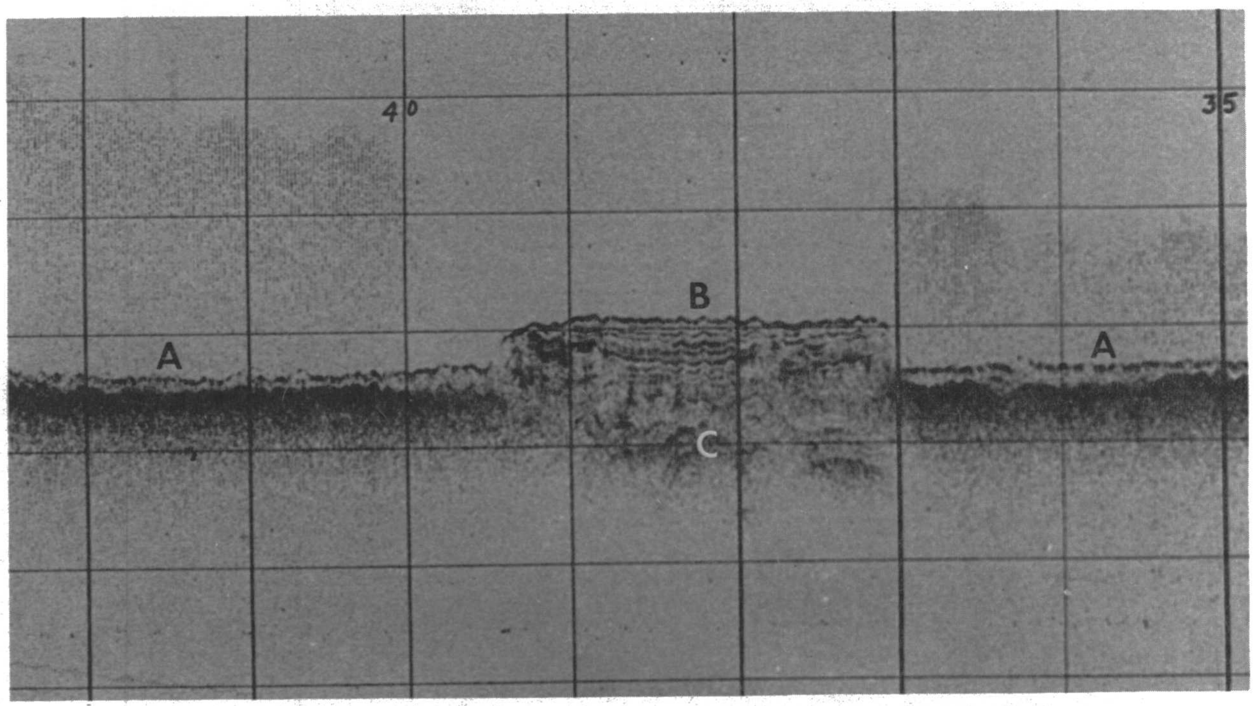

Figure 22. High-resolution seismic line run across large erratic block in mudflow lobe. Navigation fixes are 500 feet apart, and time-line intervals represent 31.5 feet.

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 figure 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, 4) interfinger with acoustic stratified sediment (a, b, c). Note that each mudflow at this site is rather thin, ranging from 20 feet 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 sea-floor 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 pre-existing 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 sea floor and mud volcanoes and vents. Around the periphery of the seaward-coalescing mudflows a band or rim of disturbed sea floor 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 sea floor 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 vol-

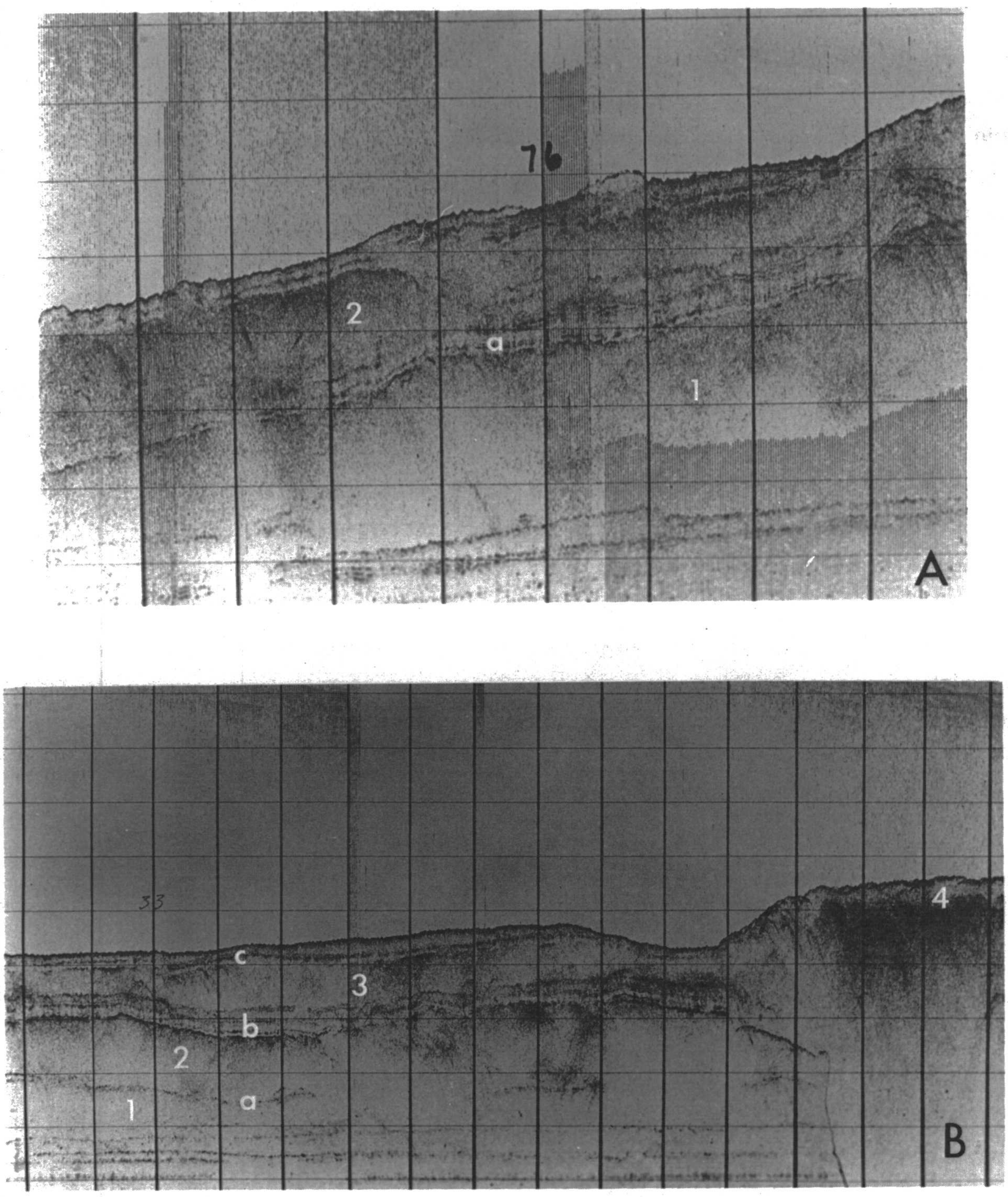

Figure 23 A and B. High-resolution seismic records run across mudflow depositional lobes. Navigation fixes 500 feet apart and timing-line interval 31.5 feet. A, seismic section run parallel to axis of mudflow movement; 1, 2, mudflow lobes; a, acoustically stratified sediments; B, seismic section run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

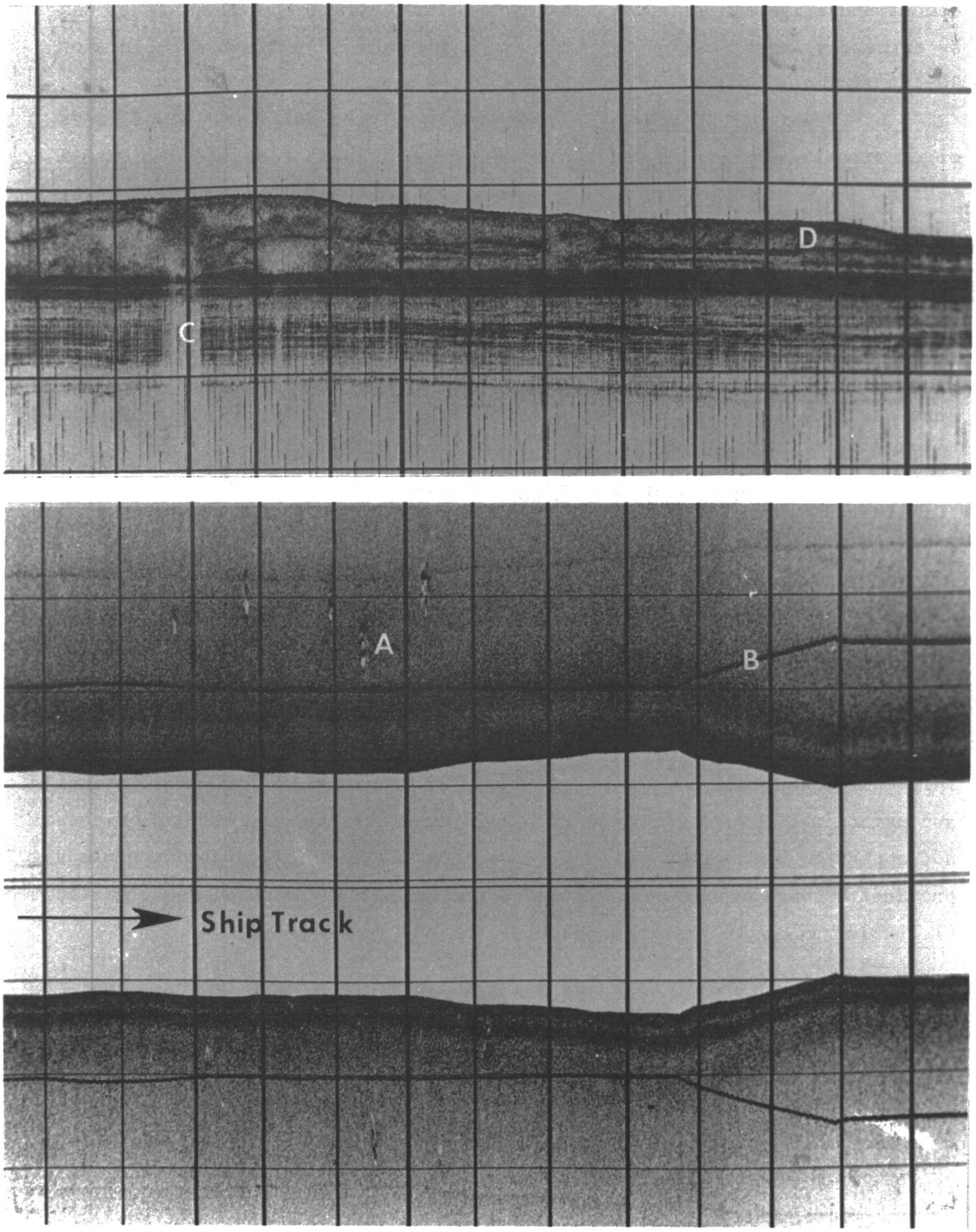

Figure 24. Side-scan sonar image and high-resolution seismic line run across seaward end of mudflow lobe. Side-scan sonar image: Navigation fixes are 500 feet apart, and timing lines are 82 feet apart. A, mud volcanoes; B, tow fish cable length change. High-resolution seismic profile: Navigation fixes 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.

canoes 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 3 mi and are generally oriented at right angles to the depth contours. Those off South Pass are in water depths of 400 to 1,300 feet and undoubtedly continue downslope, but side-scan sonar data are lacking. The furrows are 30 feet to 80 feet wide and have depths ranging from 3 feet to 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 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 mi) illustrating a part of the outcropping reef.

PLATE 6. DEFORMATIONAL FEATURES - SOUTH PASS (one map, scale 1:12,000)

Plate 6 represents a part of the smaller scale maps of plate 5 and is presented at a scale of 1:12,000, which was the original mapping scale from which the photographic reductions of plate 5 were made. The location of this plate is shown in figure 1. Considerable detail can be shown that is lost upon reduction to a scale of 1:48,000. The region just east of the active mouth of South Pass is characterized by large mudflow gullies, collapse depressions, bottleneck slides, and large mudflow depositional lobes. The mudflow gullies are rather sinuous, and sidewall instability and enlargement processes are evident. The mudflows are composed of broad

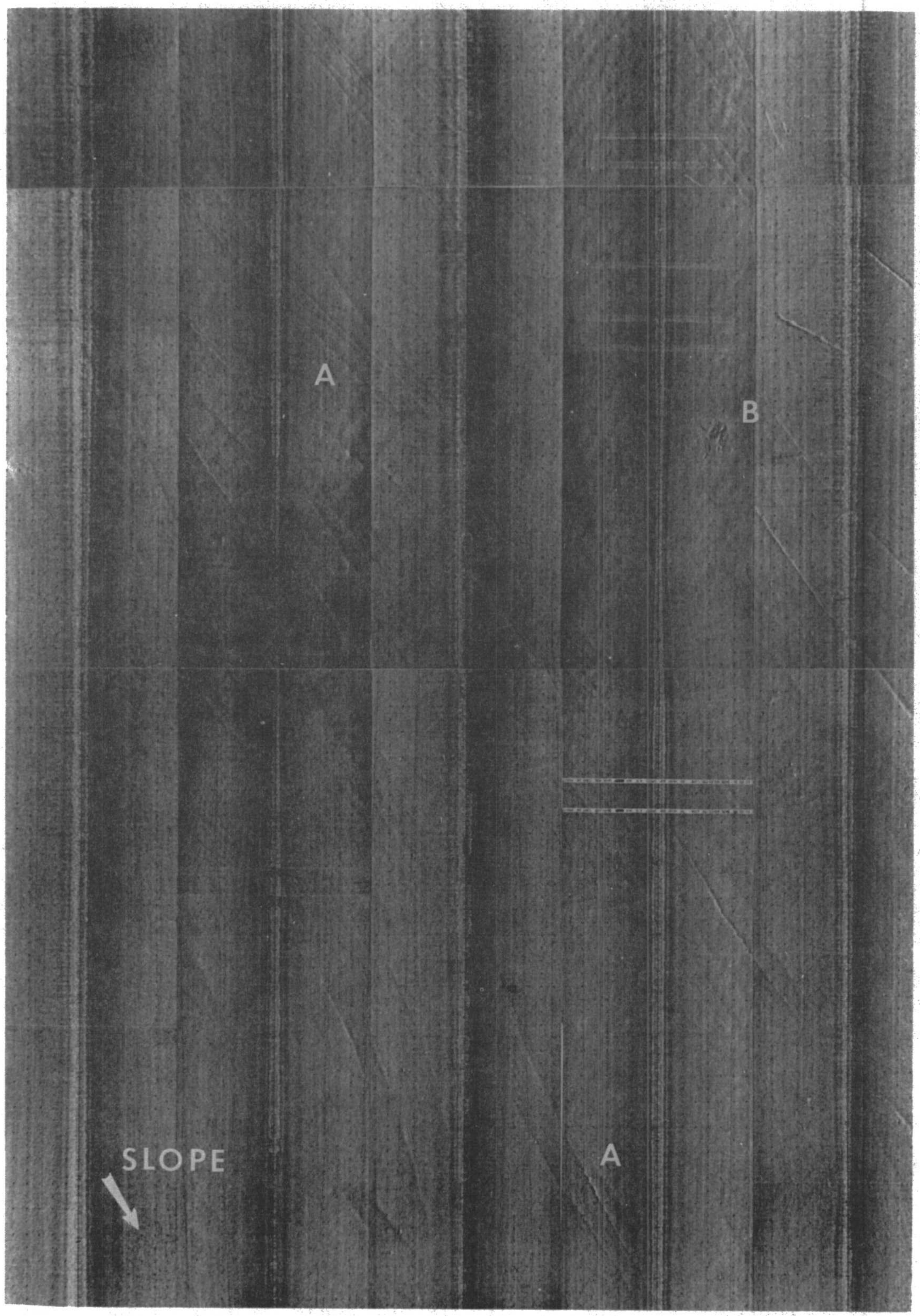

Figure 25. Side-scan sonar mosaic illustrating erosional furrows on the sea floor off South Pass. Mosaic covers an area of 6,150 by 8,900 feet, and grid tick marks are 82 feet apart. A, erosional furrows; B, drill-site location.

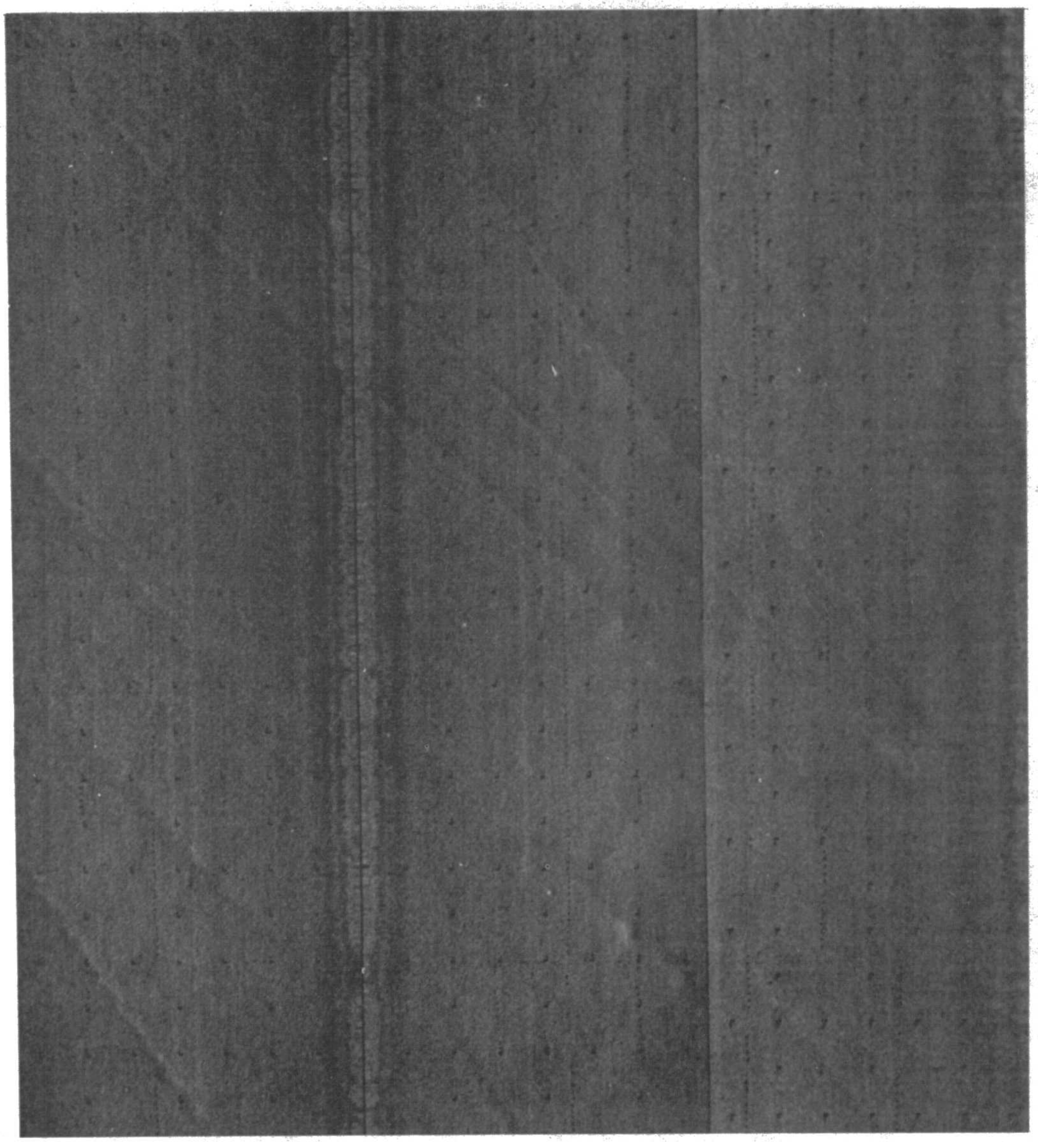

Figure 26. Enlargement of a part of the mosaic shown in figure 25 to illustrate the details of the erosional furrows. Grid tick marks are 82 feet apart.

overlapping lobes coalescing into a major zone of mudflow deposits around the seaward periphery of the delta.

PLATE 7. DEFORMATIONAL FEATURES OF SOUTHEAST PASS (one map, scale 1:12,000)

Plate 7 represents a part of the larger scale maps of plate 5 and shows the southeast part of the delta near Southeast Pass (fig. 1). In this region of the delta, the mudflow gullies are extremely narrow and have a complex bifurcating pattern at their seaward ends, where the long linear

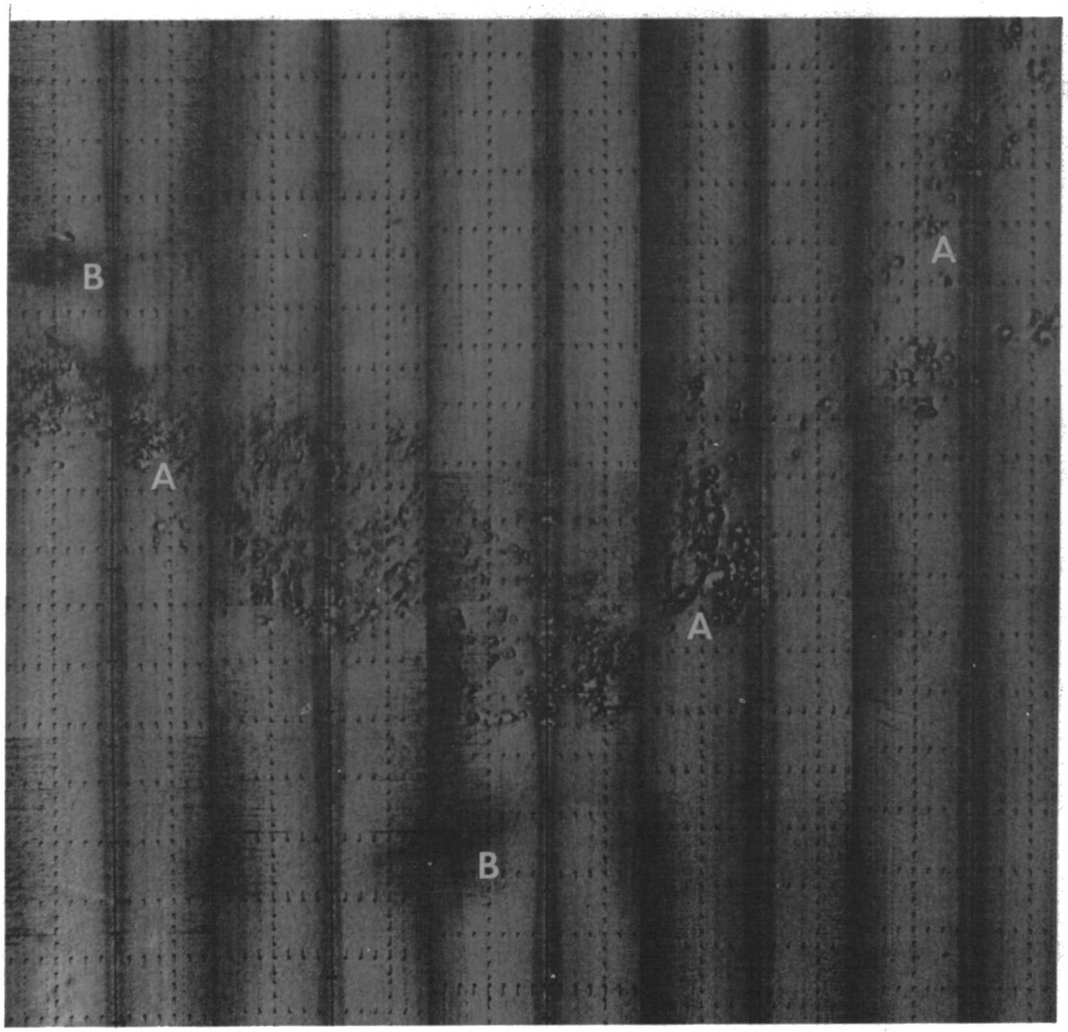

Figure 27. Side-scan sonar record showing distribution of reef around the southern rim of a salt dome (Blocks SP 60-67). A, outcropping reef; B, petroleum-production platform. Grid marks are 82 feet apart. Mosaic covers an area 1.1 x 1.1 mi.

mudflow lobes begin. On the bottom right-hand side of the map, the broad, flat, undisturbed sea floor represents the shallow-seated underlying salt dome. The reef trend along the periphery of this dome is also mapped.

Characteristic of this region are extremely large blocks within the zone of mudflow deposits. These blocks are shown on the map as undisturbed sea-floor pattern.

PLATE 8. SIDE-SCAN SONAR MOSAIC (one map, scale 1:12,000)

The use of the digitally acquired, scale-corrected side-scan sonar imagery greatly enhanced the interpretation of sediment instability features in the Mississippi River delta. Plate 8 illustrates one possible use of the side-scan sonar data, that is, the construction of acoustic mosaics of the sea floor that are nearly true to scale. The mosaic covers some 52.0 sq mi of the sea floor and was constructed from 27 lines, each 8.6 mi long, of side-scan sonar records. The track lines were 1,200 feet apart, and the total swath width of each line was 1,320 feet, giving an overlap of 120 feet for each line. The original mosaic was 15 feet by 37 feet before it was photographically reduced to its present size. Because of the reduction, a considerable amount of detail was lost in the final copy.

The area of the mosaic includes all or parts of the following South Pass Blocks: 6, 17, 59, 60, 61, 66, 67, and 70. This mosaic shows the various types of features that have been illustrated in the regional maps on plates 1-7. Small collapse depressions and bottleneck slides are labeled A on the mosaic. Many mudflow gullies crease the delta front, and some of these are labeled B. Note the complexity of the erratic blocks in the gully floors and the complex pattern of the overall morphology of the gully. The mudflow lobes are on the lower half of the diagram and are labeled C. The large erratic blocks within the mudflow are labeled D.

The large smooth bottom area (E) on the mosaic is over the salt dome. On the southern edge of the dome, a carbonate reef (F) crops out and forms rough and irregular topography. Several active platforms (G) are shown on the mosaic, and even with the large amount of reduction, a few pipelines (H) leading away from the platforms are apparent. The sites of the three platforms that were destroyed or damaged during Hurricane Camille in 1969 are labeled I.

PLATE 9. ISOPACH MAP OF DISTURBED SEDIMENT (four maps, scale 1:48,000)

Plate 9 shows the distribution of the thickness of the disturbed sediment based upon measurements from high-resolution seismic data, primarily boomer records. The upslope 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 10 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.

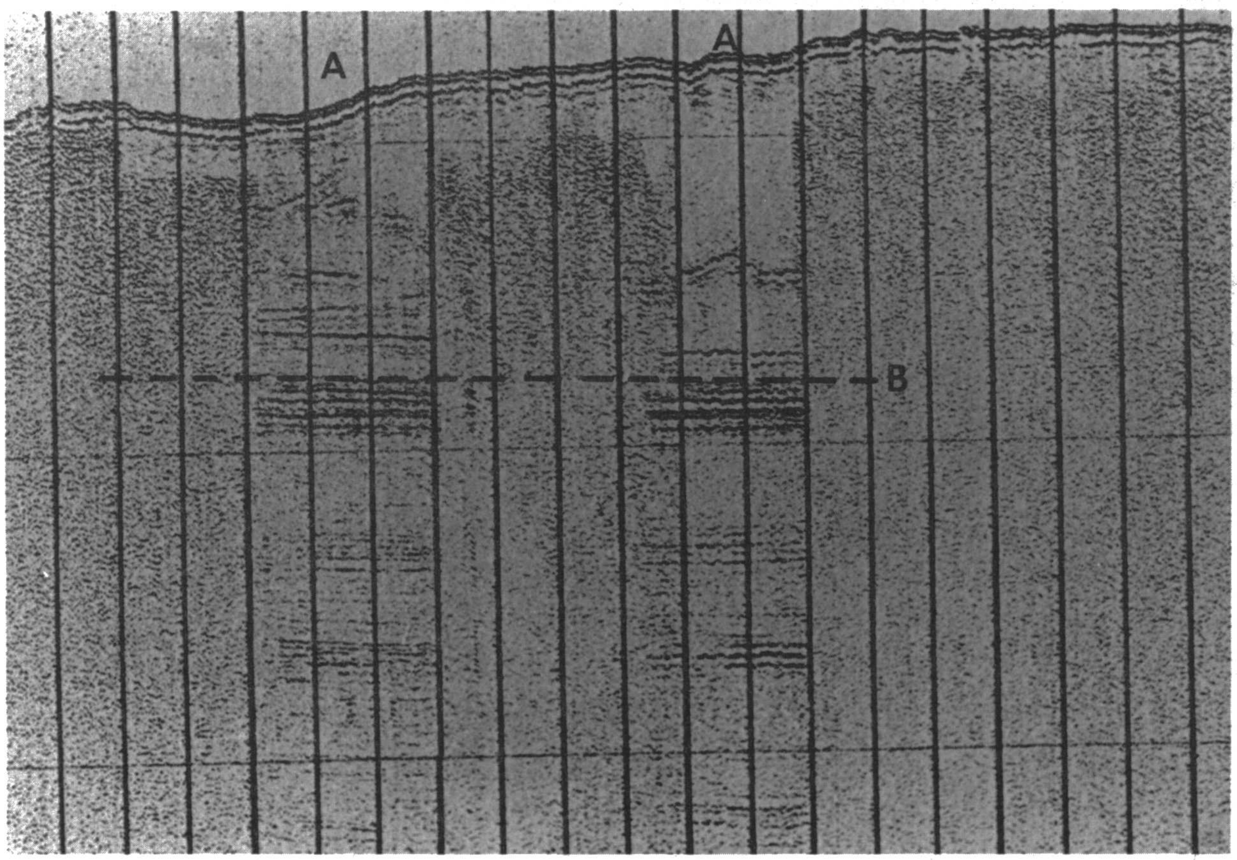

Figure 28. High-resolution seismic record illustrating seismic windows (A). The horizon labeled B represents the base of disturbed sediments. Navigation fixes are 500 feet apart, and timing lines are 125 feet apart.

PLATE 10. GEOLOGIC STRUCTURE - SHALLOW SUBSURFACE (four maps, scale 1:48,000)

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. The maps presented in plate 10 show the distribution of these features as interpreted from each seismic line.

Examples

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 plate 10. 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 plates, 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 plate

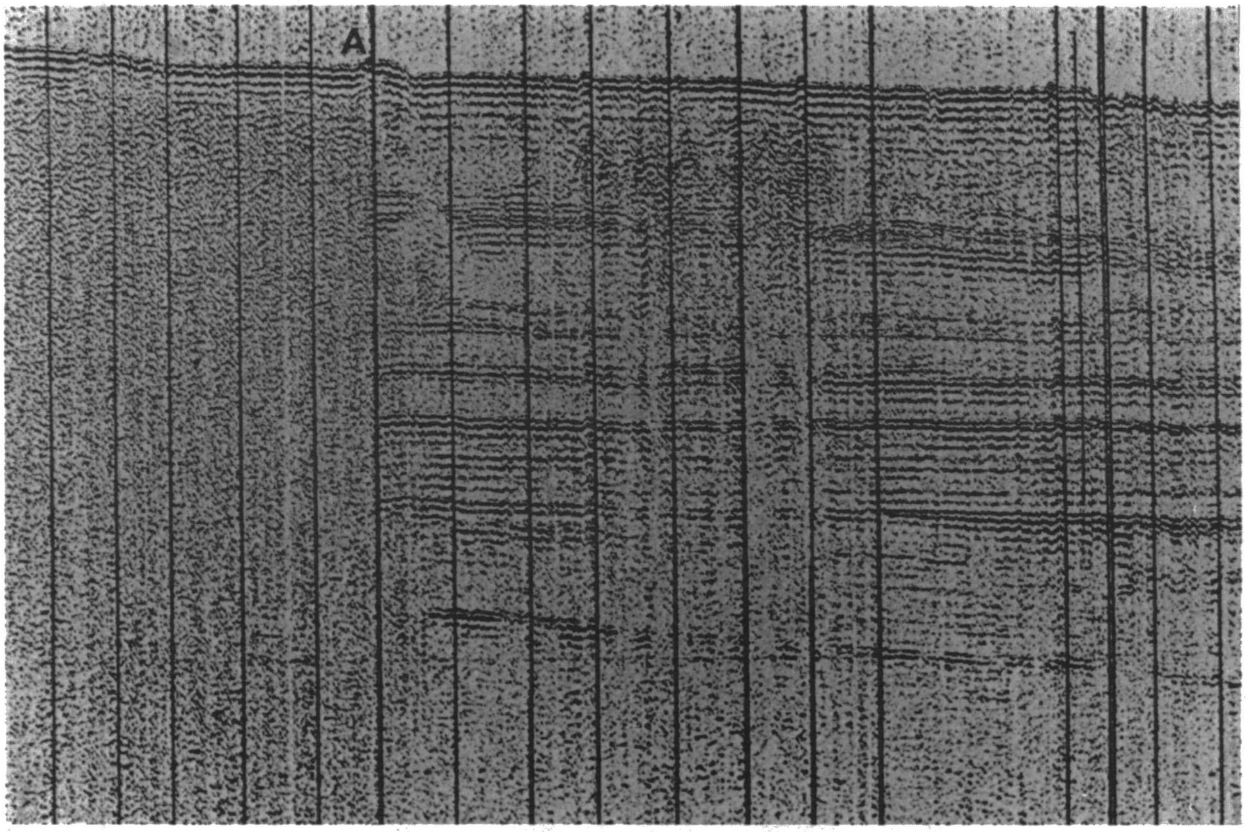

Figure 29. High-resolution seismic record illustrating the effect of gas in sediments on seismic signals. Navigation fixes are 500 feet apart, and timing lines are 125 feet apart. Mosaic covers an area 1.1 x 1.1 mi.

10. 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 sea floor, 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 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 sea floor 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

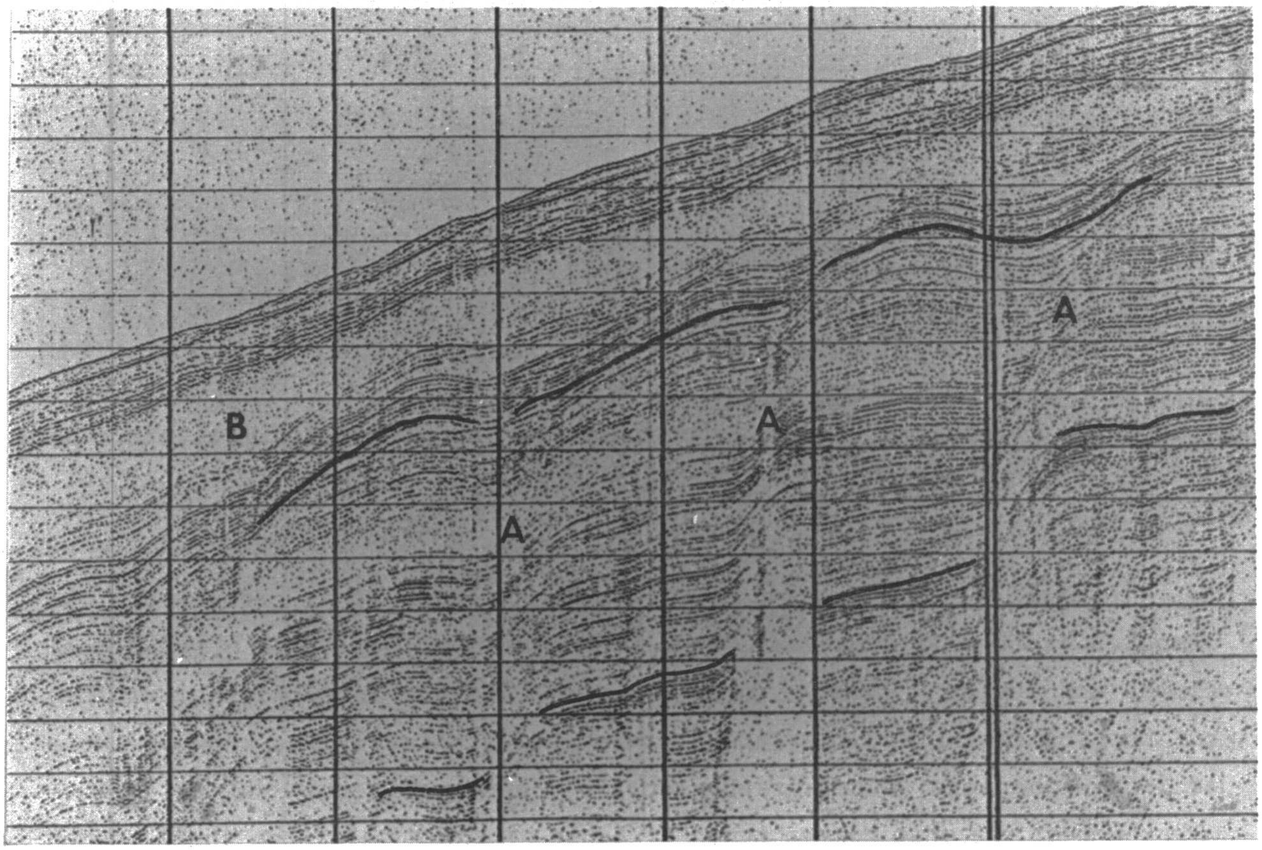

Figure 30. High-resolution seismic record run across several contemporaneous faults (A) near the shelf edge off South Pass. Note that offset of marker beds increases as depth increases along a given fault. The mudflow unit (B) also appears to increase in thickness as it crosses this zone of faults. Navigation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

increase in offset with depth and the higher accumulation on the downthrown side of the fault are well illustrated in this example.

Figure 31 shows another seismic section run across a contemporaneous fault and illustrates the presence of a thickened section of mudflow mater-

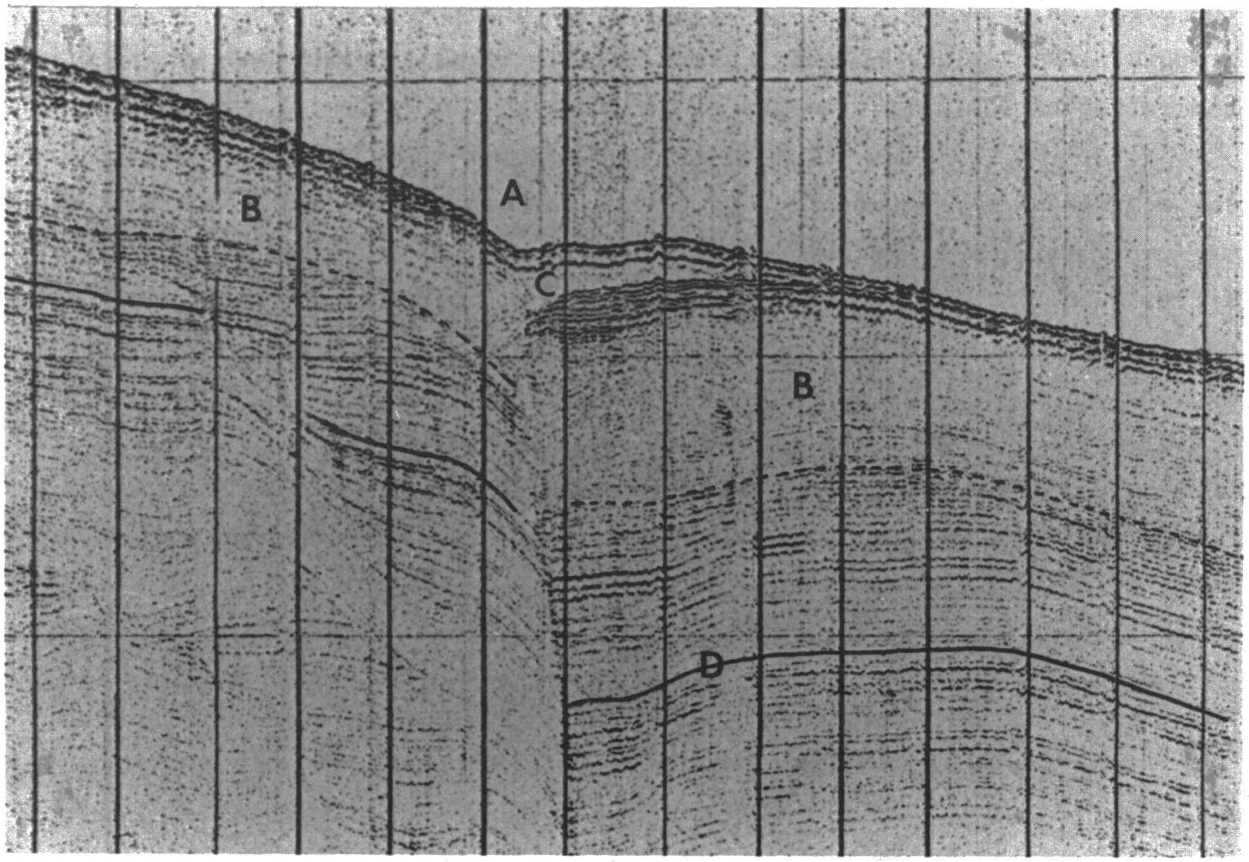

Figure 31. High-resolution seismic record run across a contemporary fault (A) showing the increased thickness of a mudflow (B) as it crosses the fault. Note the small zone of mudflow material (C) accumulating on the fault scarp on the sea floor. Marker horizons (D) also show greater displacement at greater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

ial 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 (plate 4, maps 3 and 4) has a width of approximately 5-7 mi 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 the seismic data, and even has sea-floor 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 in the maps of plate 10. The folding is generally asymmetrical; the folds are broad anticlines and exceptionally tight synclinal troughs. Relief between the crest of the fold and the 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

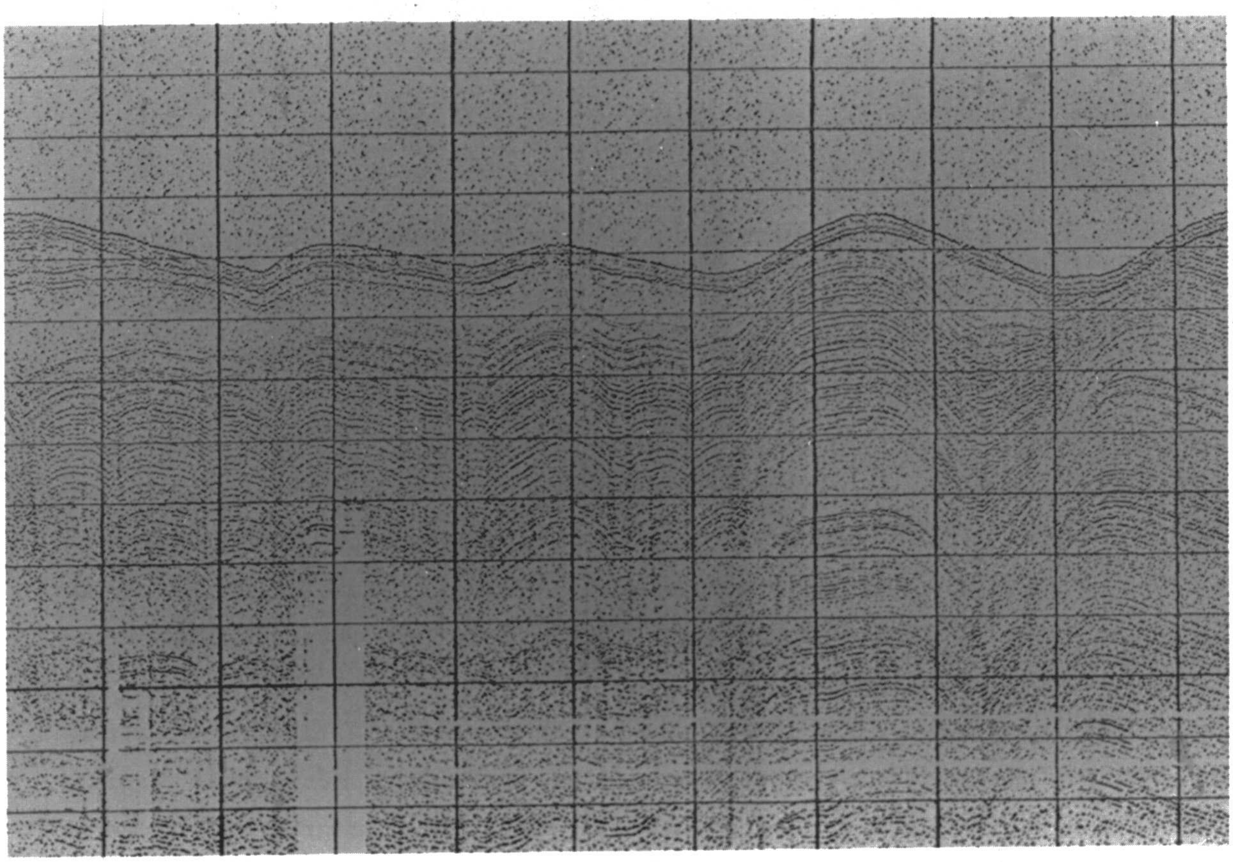

Figure 32. High-resolution seismic record run across a series of folds off South Pass. Note the tight synclines and the broad anticlines. Navigation fixes are 1,000 feet apart, and timing-line intervals represent 25 feet.

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.

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

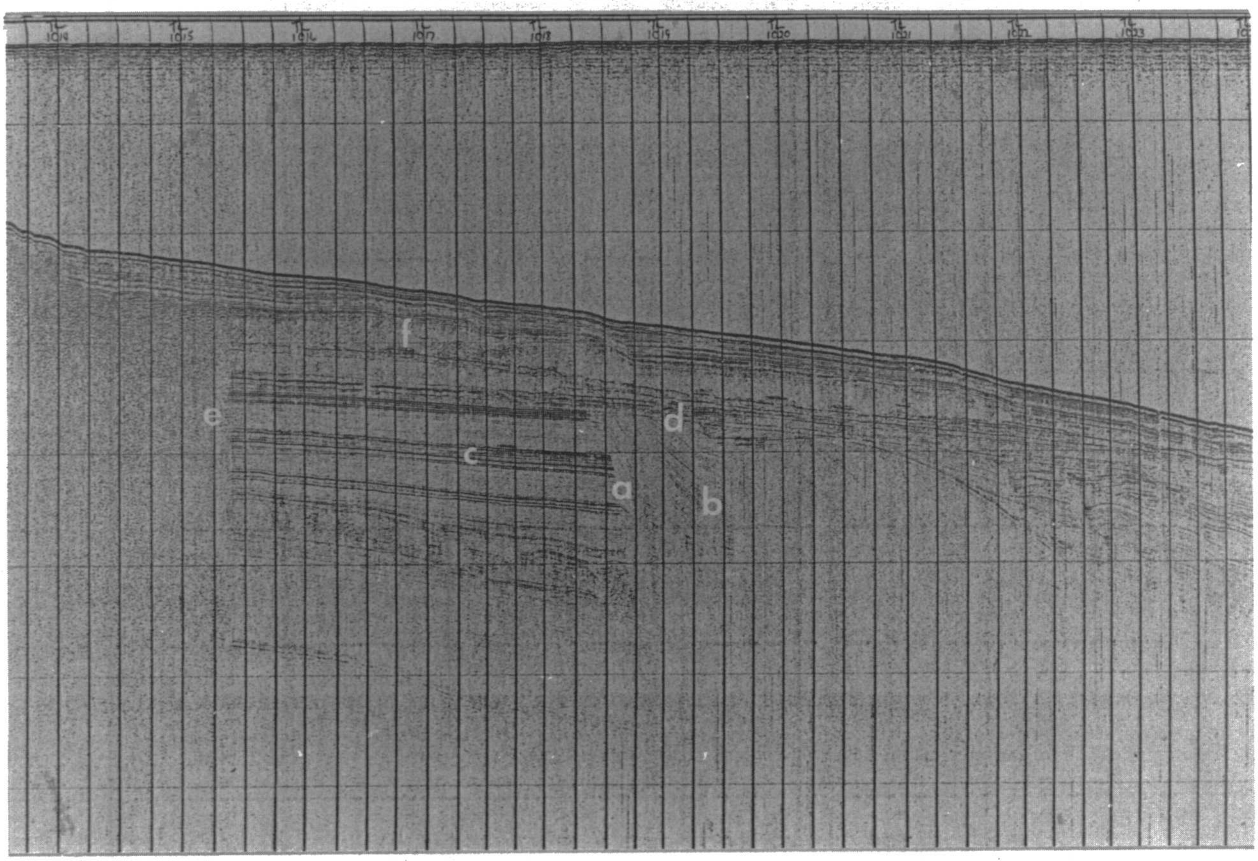

Figure 33. High-resolution boomer record run across the shelf-edge separation scar. Navigation fixes are 500 feet apart, and timing-line interval is 125 feet. a, failure scar; b, steeply inclined infilling bedding; c, marker horizon correlated seismically to borings and dated at 35,000 years B.P.; d, 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.

illustrate the major characteristics of this feature along high-resolution seismic lines. As can be seen, reflections are abruptly truncated (a, fig. 33; A, fig. 34) and then, an infilling of strata shows relatively high dip angles. These infilled sediments have been termed an "accretion unit."

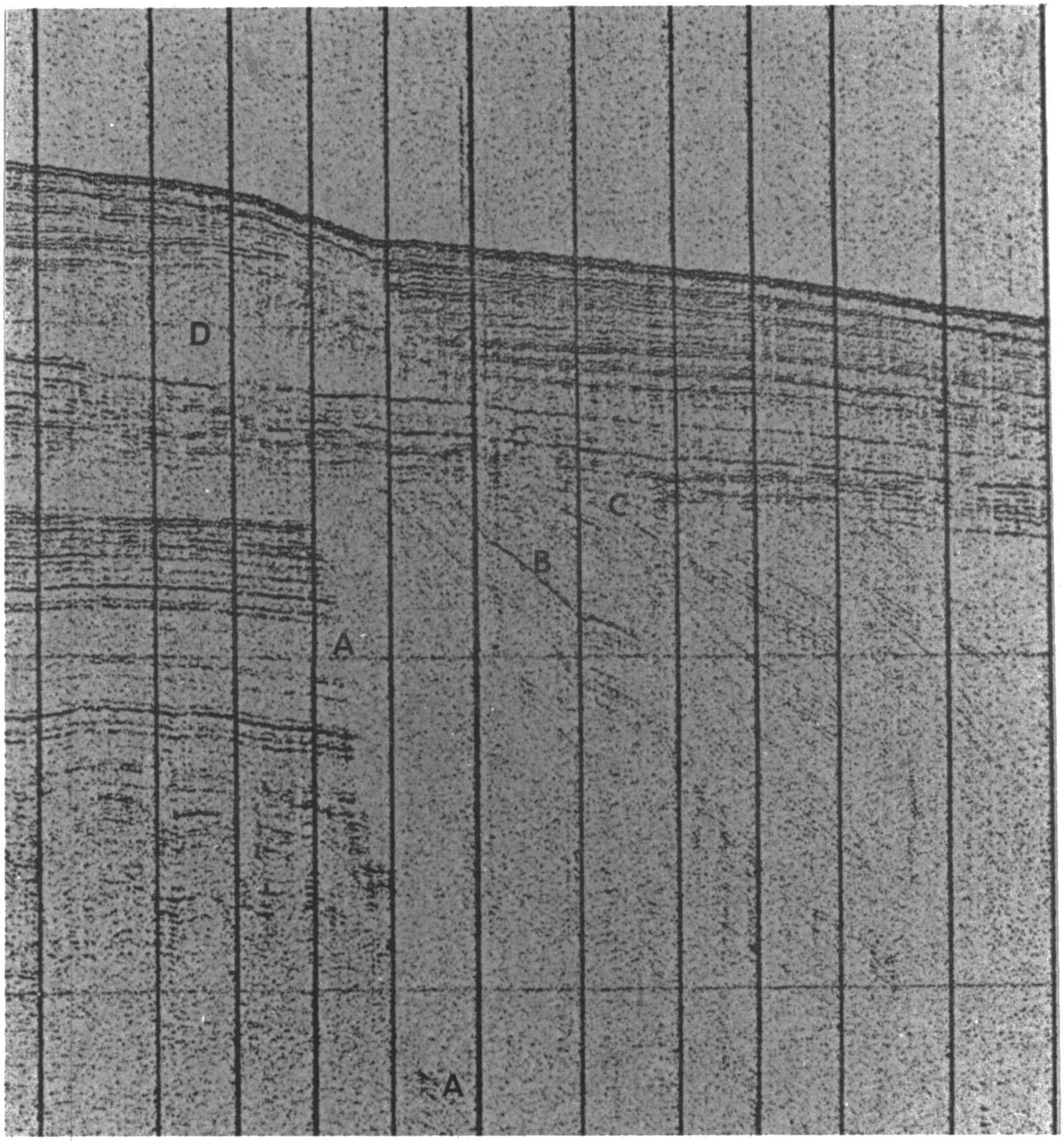

Figure 34. Detailed high-resolution seismic line run across shelf-edge separation scar. Navigation fixes are 500 feet apart, and timing-line intervals represent 125 feet. A, shear plane of failure; B, steeply dipping infilled sediments; C, erosional unconformity (approximately 15,000 years B.P); D, modern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

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 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 30,000-35,000 years B.P.) and that the infilling had been completed by the last low 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 Block 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.

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

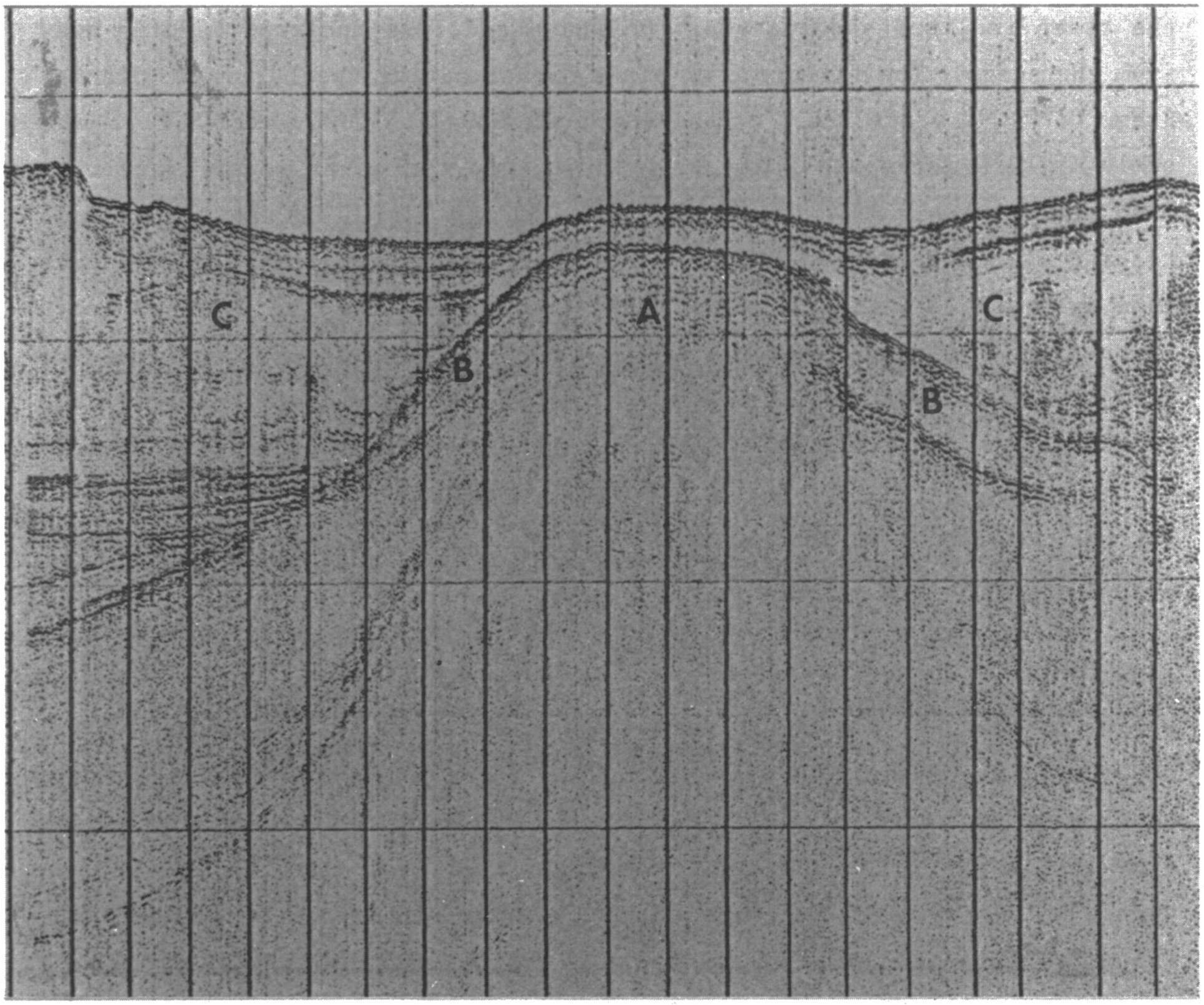

Figure 35. High-resolution boomer record run across shallow-seated salt dome (A) in SP 60-67. Note the steep dips along the sides of the dome (B) and the mudflow lobes (C) that have formed around the sides of the dome. Navigation fixes are 500 feet apart, and timing lines are 125 feet apart.

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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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.