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THE INSTABILITY OF SURFACE SEDIMENTS

ON PARTS OF THE

MISSISSIPPI DELTA FRONT

by

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OPEN-FILE REPORT

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1. The instability of surface sediments on parts of the Mississippi Delta front, by Louis E. Garrison. 9 p. text, 9 page-size figs., 3 pl.

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Introduction

In August, 1969, during the passage of a violent hurricane, two large Shell Oil Company platforms, standing in more than 300 feet of water off the mouth of the Mississippi River in South Pass Block 70, sustained major damage. Since all personnel had been evacuated from the platforms ahead of the storm, no lives were lost, but property damage was heavy. Platform A was displaced 3 or 4 feet from its original location, while Platform B was moved about 100 feet and toppled onto its side. A subsequent investigation by Shell proved conclusively that these failures were directly attributable to "soil movement" (Bea, 1971; Sterling and Strohbeck, 1973). The cause of this soil movement is less certain, but it is believed to have been triggered by perturbations in the bottom pressure due to hurricane waves. Although this incident and the subsequent investigation are unique as far as the published record is concerned, reports of damage to structures and delays in drilling operations due to sediment failure persist.

In order to ascertain the extent of this problem and to examine some of its possible causes, a study was initiated by the U.S. Geological Survey in December, 1973. This report will summarize the preliminary results of that study.

The principal source of data was a set of high resolution seismic reflection records made by Decca Survey Systems, Inc. during the Fall of 1971. Included were both 3.5 kHz subbottom profiles and 6 kilojoule sparker records made along NW-SE lines spaced 1/2 to 1 mile apart with NE-SW tie lines 5 to 6 miles apart. The limits of the study area are shown in Fig. 1.

Results

The results of the study are presented in three accompanying maps which summarize 1) the bathymetry of the delta front, 2) the surface geology of the delta front, and 3) the estimated relative instability of delta front sediments.

Bathymetry

Because no detailed bathymetric map of the entire delta front at a suitable scale was readily available, one was constructed from data at hand. Within the Decca survey limits, depths were taken from 3.5 kHz profiles plotted at fix locations approximately 1000 feet apart, and converted from time to depth by assuming a sound velocity of 4800 ft/sec in water. Bathymetry of the upper delta front was taken from Shepard (1955). No effort was made to join the two sets of contours because bottom changes in the 20 year interval between surveys would make such connections virtually meaningless. A heavy dashed line separates the two sets of contours on Map 1 which, if somewhat imprecise in detail, provides a useful representation of the gross morphology of the delta front.

As pointed out by Shepard (1955) the delta-front valleys are concentrated for the most part in the sector from Southwest Pass to Pass a Loutre, but are scarce in the interfluve region off East Bay. In a few cases, Shepard's valleys appear to connect seaward with valleys shown by our data, but more often no such relationship exists. Valley development apparently does extend into deeper water than covered by Shepard's work, although perhaps not with such abundance. Our data on the subject are equivocal because the preponderance of seismic lines were oriented parallel to valley axes. Furthermore, in the time available for study, it was not possible to reconcile all depth missties at line crossings, therefore many of the straight-line valleys shown in the southwestern part of Map 1 must be questioned.

Keeping these limitations in mind, however, the bathymetric map shows several features of considerable interest. At depths of roughly 150, 200, and 250 feet in the area south of Southwest Pass, convergences of the contours indicate local steepening of the slope. The slight scarps thus defined seem no higher than 20 or 25 feet, and appear to strike northeasterly. In the central part of the delta front, a similarly defined, arcuate shaped, scarp-like feature extends from Block 48 in the South Pass area, northeastward to Block 70. Its height reaches more than 100 feet in places. Landward from this feature the delta surface appears hummocky and strongly gullied in places. Another steeply sloping arcuate area appears in the eastern part of the map. It curves around a small closed elevation and swings northwestward through Blocks 63 and 64, South Pass Area, East Addition as the eastern wall of a large valley. The significance of these features is better understood by a review of the surface geology as shown in Map 2.

Surface Geology

The surface geology as shown by Map 2 is based on the interpretation of 3.5 kHz subbottom profiles and 6 kilojoule sparker records from the Decca survey. The small, circled numbers from 2 to 9 refer to text figures similarly numbered.

The series of low scarps revealed by the bathymetry south of Southwest Pass belong to the terrace-like features shown in Figure 2. From their distribution, their scalloped appearance, and their relationship to an area of heavy sedimentation, these terraces are thought to be mud flows. That they are depositional features rather than wave-eroded relicts of former sea levels seems inescapable, because high rates of deposition in the area would by now have buried any traces of early Holocene shorelines. Although no description of these features (mud terraces) was found in the literature, references to the lateral mobility of sediments in such areas are not lacking (for example: Bea and Arnold, 1973), and it is assumed that these features are manifestations of that mobility. The mechanism that governs their movement and the rates at which it occurs are not known, but perhaps some estimate of the latter could be gained from the studies of Fisk and others (1954) who reported that Southwest Pass has lengthened Gulfward since 1838 an average rate of 250 feet per year.

Other mud terraces quite similar in form but not so well developed were mapped east of Pass a Loutre. There, the eastern edge of delta deposits can be seen to overlap older, and more stable continental shelf deposits along a north-south line through the western part of Main Pass Area. Furthermore, the steepened slope noted near the eastern limits of the bathymetric map is shown here as the shelf edge curving northward toward a junction with the modern delta. The large valley which heads into Block 64 further defines the separation between these two units. Figure 3 illustrates the character of the shelf edge and, in an area of relatively slow deposition, shows an apparent shelf-edge notch cut during lower sea level.

The larger scarp shown by the bathymetric map south of South Pass is undoubtedly related to the terrace noses. It is concentric to an area of high depositional rates, is slightly scalloped in plan view, and is the seaward boundary of a large, relatively flat surface. It is not difficult to attribute the form of this feature to lateral movement as some of its steeper sections show the effects of mass wasting by block faulting (Figure 4). This suggests that the slope is being oversteepened by clay deposits migrating seaward from areas of rapid deposition near the river mouths.

The stable horizon over which this mass movement is taking place lies 100-150 feet below the delta surface (Figure 5). Although the subbottom profile showing this is marred by mechanical irregularities, faint but steeply dipping reflectors suggest deformation in the upper sediment section.

The southwestern flank of the mass of mobile sediment off South Pass has developed a lobate outline along its eastern edge.

The features shown in a northwest-southeast line which crosses these lobes (Fig. 6) clearly demonstrate the mobility of the surface sediments in this area. Although the approximately 60-foot thickness of disturbed sediment is not so great as that in Figure 5, the mobilization of previously stratified, and presumed relatively stable, sediments is shown by the continuity of reflectors into the zone of distortion. The extreme mobility of the mass of sediment southeast of South Pass is further suggested by the hummocky surface, and an abundance of mud piles and gas seeps.

Also characteristic of the shallower part of this central delta-front region is, as already noted, a preponderance of valleys. Figure 7 was taken from a northeast-southwest tie line crossing these features at almost right angles. The valleys are shallow and flat bottomed with relatively sharp sides. In many cases, a small channel appears at the intersection of wall and floor, and in a few cases, the thin, stratified material capping the area between valleys overhangs the valley itself. Shepard (1955) attributes the origin of these depressions to "mass movements probably of the earthflow type," while J. M. Coleman (written comm., 1973) believes that they are graben structures. In either case, they indicate relatively low stability.

Many parts of the delta front show evidence of local sediment slumping. These slumps are generally confined to sediment in the upper 100 feet or less, and have a low dip at the surface which flattens to a bedding plane fault at depth (Figure 8). They are marked by a depression of the up slope portion with a pile of down-slope moved sediment at its lower edge. Deeper beds remain unaffected.

From the outset of this study, it was clear that the delta-front could be divided between areas where sediments could be acoustically penetrated to yield good subbottom reflections, and others where sediments were completely impenetrable to acoustic energy and from which no coherent subbottom reflections were returned. When these differences in acoustic quality were mapped, it became apparent that acoustic impenetrability characterizes most of the areas landward of the outermost terrace noses, that is, the sediments interpreted as having greatest mobility.

However, the separation between types was not clean, for in the region typified by good subbottom reflectors, an occasional zone of impenetrability would be found. Conversely, and more frequently, the regions of impenetrability were found to be broken by "windows" in which strong reflectors could be seen. Figure 9 illustrates such a case. The spacing between survey lines was too great to afford correlation of these aberrations from line to line, but their dimensions along seismic lines ranged from tens of feet to more than 1000 feet.

Acoustic impenetrability to high frequency signals has been noted previously, both in the delta region (J. M. Coleman, written comm., 1973) and elsewhere (Grim, and others, 1970; Sieck, 1973). This phenomenon is thought to be caused by high concentrations of gas, or in some cases large quantities of shell fragments in the sediments, but as pointed out by Schubel and Shiemer (1973), little supporting evidence has been offered. The latter authors have, however, provided evidence of greater amounts of gas in impenetrable sediments in Chesapeake Bay relative to contiguous zones of good penetrability, and the thesis seems generally acceptable inasmuch as such impenetrable pockets elsewhere have been directly associated with gas seeps (Sweet, 1973). The general theory put forth by various investigators is that in highly gaseous sediment the myriad gas bubbles, each acting as an acoustic reflector, so scatter the sound waves that coherent penetration to and reflection from any underlying interfaces is prevented. If this is the case, then acoustic reflection methods might be used to provide clues to the gas content of the sediment and, indirectly, to its degree of instability. Certain questions, however, need to be answered: With what kinds of gas, in what proportions, and in what quantities are we dealing? How was it generated and at what rate? What concentrations of gas render a sediment unstable? What can cause local degassing, can it be artificially triggered, and does a degassed sediment mass become stabilized? If so, for how long? In a more applied sense, does an acoustic tool exist, or can one be developed, possibly based on sound velocity determinations in the upper 200 feet of sediment, which could be used to rapidly and continuously quantify the gas content over broad areas for mapping purposes? Schubel and Shiemer (1973) indicate a start on this problem, but much more needs to be done in order to pin-point potentially hazardous areas less expensively than by the more laborious methods of boring and core analysis.

Relative Instability

A fair sampling of the literature on the engineering characteristics of deltaic sediments indicates that the principal underlying cause of most sediment failures around modern deltas is the behavior of underconsolidated clays. Although other factors, such as intrusive salt, steep slopes, concentrations of gas, and storm waves, complicate the picture, their effects seem generally to be superimposed on the instability of these clay deposits.

Under conditions of slow deposition, normal clays give up their pore waters and undergo consolidation at a rate consistent with the increasing pressure of a growing overburden. When deposition is rapid, however, as off the mouths of major rivers, the rate of burial is greater than the rate of consolidation and clay deposits attain pore water pressures which are greater than the normal overburden pressures. Such deposits are termed "underconsolidated," and their instability is manifested by a lack of shear strength, the development of fractures, and distortion and displacement by lateral flow.

Underconsolidated clays can be identified in soils engineering tests performed on samples obtained from borings. Such tests are normally a part of the planning which precedes the location of major offshore structures, but this does not seem always to insure a stable site, as demonstrated by the history of foundation problems. Apparently certain conditions and processes of deltaic sedimentation exist which are poorly understood, but which may, under the proper circumstances, result in mass sediment failure.

Based on sediment characteristics inferred from the acoustic records, and from a thorough, albeit not exhaustive, review of the literature, an estimate was made of the relative instability of surface sediments over the delta front. The word "relative" should here be emphasized, because no quantitative data were available for this purpose and engineering measurements were assessed only in a generalized manner as they appeared in published works. Consequently, Map 3 simply suggests that sediment failure is more likely to occur in some places than in others, and it is not intended to predict failure per se. In view of the fact that bottom-supported structures have been standing within the area labeled "least stable" for years, it is apparent that stability conditions are not uniform. More detailed studies would no doubt reveal variations on a finer scale, but the problem at this point is to distinguish these variations. The data for this preliminary study and our present knowledge of the subject are not sufficient for that. These estimates can no doubt be further refined by additional study, and it is hoped that such will be the case, but meanwhile they may serve for preliminary evaluations.

The area of "least stable sediments" is essentially that defined by acoustic impenetrability following the assumption that such a condition is caused by highly gaseous surface sediments and that an excess of gas creates a potential for instability. Furthermore, the "least stable" classification is restricted to those sediments highest up on the delta-front and most recently deposited. The reasoning for this delineation is as follows:

Henkel (1970) and Mitchell and others (1972) have worked on the role of wave forces in causing submarine landslides. In addition, the very thorough but only partially published investigations by Shell Oil Company into the Block 70 failure indicate the extreme importance of the wave factor (Doyle, 1973; Bea and Arnold, 1973; Sterling and Strohbeck, 1973; Arnold, 1973). It therefore seems reasonable to suspect that whatever the combination of forces required to trigger a failure, they are most likely to occur in underconsolidated sediments whose interstices might be saturated with in situ generated methane and CO_2 gases and lying in parts of the delta subject to the greatest amplitude storm waves.

Areas defined as "most stable" are principally shelf deposits outside the immediate delta influence, and the shallow tops of salt intrusives which would seem to offer some (geologically) short term stability as foundation anchors. Areas of "intermediate stability" are those not clearly one or the other of the above, generally the outer edge of the seaward thinning, deltaic sediments, or areas where shelf-edge slump faulting seems prevalent.

With only indirect evidence such as acoustic information, inferences as to the degree of instability in a sediment body obviously must carry certain limitations. Although it may be possible from seismic configurations to say that a sediment mass has moved, it is not possible to extrapolate backward to the original conditions and predict, from similar data alone, that another sediment mass will move. It should be emphasized that the degrees of instability outlined in Map #3 are relative, and that neither our data nor our present knowledge allows us to predict a failure. At this point no more can be said than that the possibility of sediment failure appears more likely in certain areas than in others.

Acknowledgments

I wish to thank Ray Martin who assisted in the interpretation of records and preparation of maps, Dr. J. M. Coleman of Coastal Studies Institute, Louisiana State University, who discussed the problems and shared his understanding of the subject with me, and Dick Scrivner and others of the USGS in Metairie, Louisiana, who helped immeasurably. I am also grateful to Decca Survey Systems, Inc. for their generous release of the data for this report.

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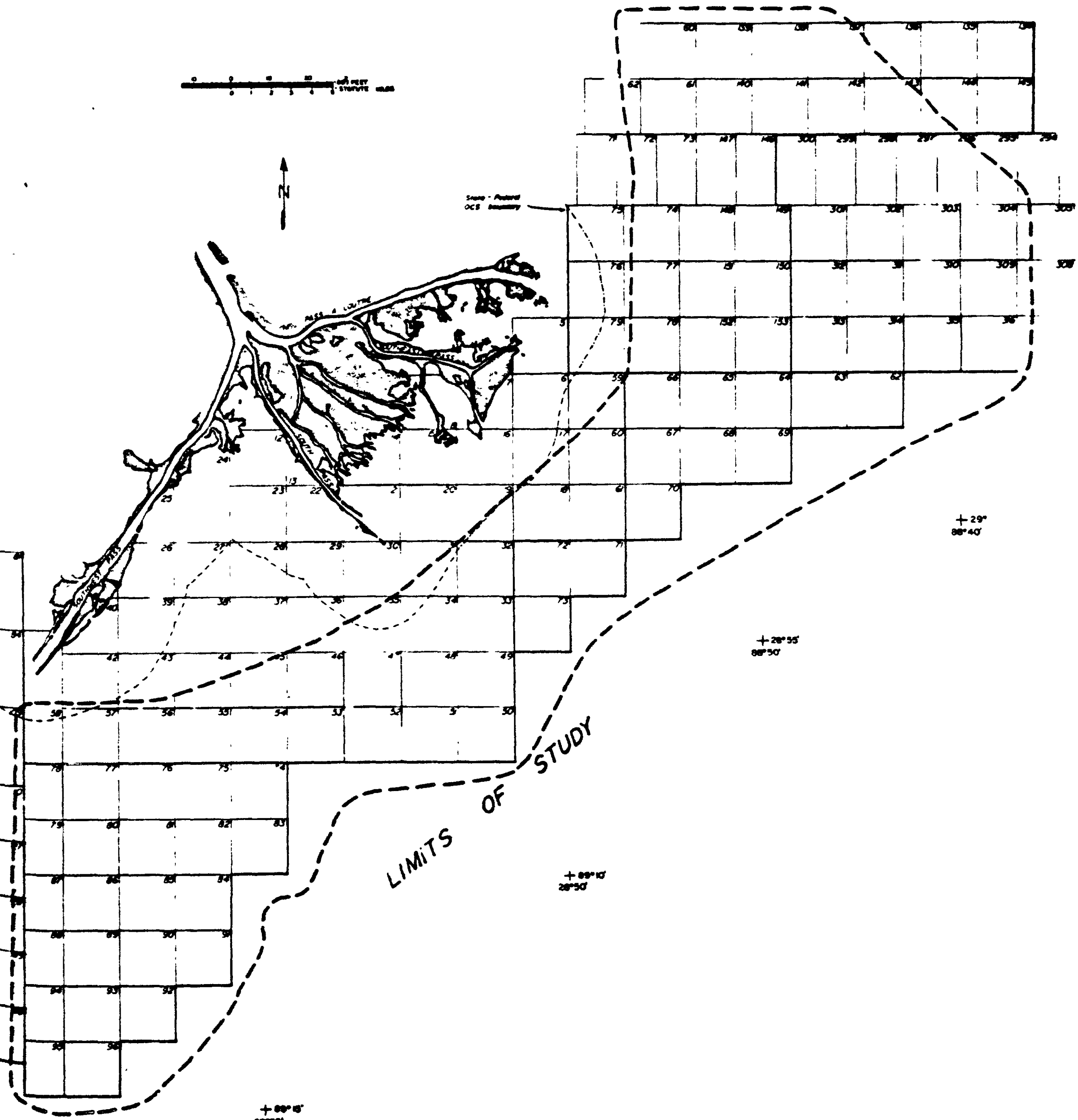
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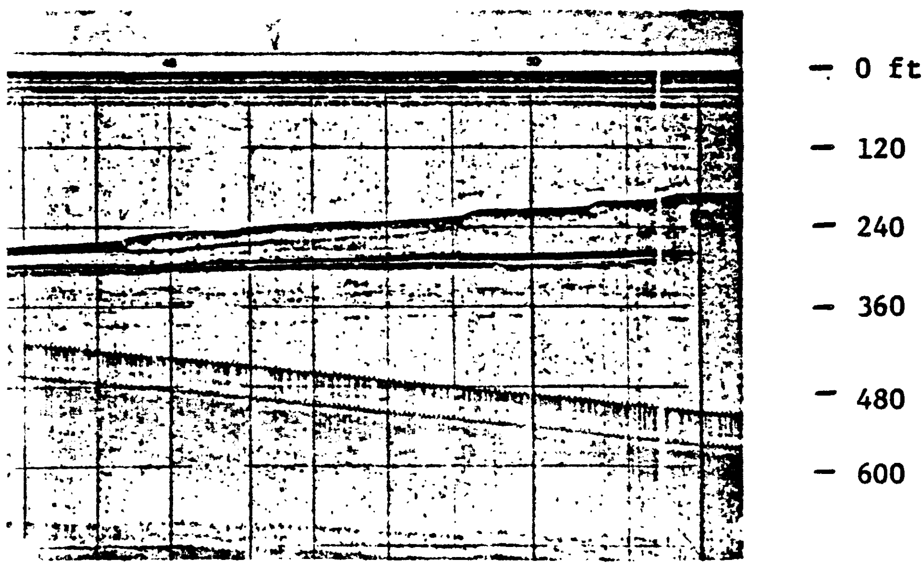
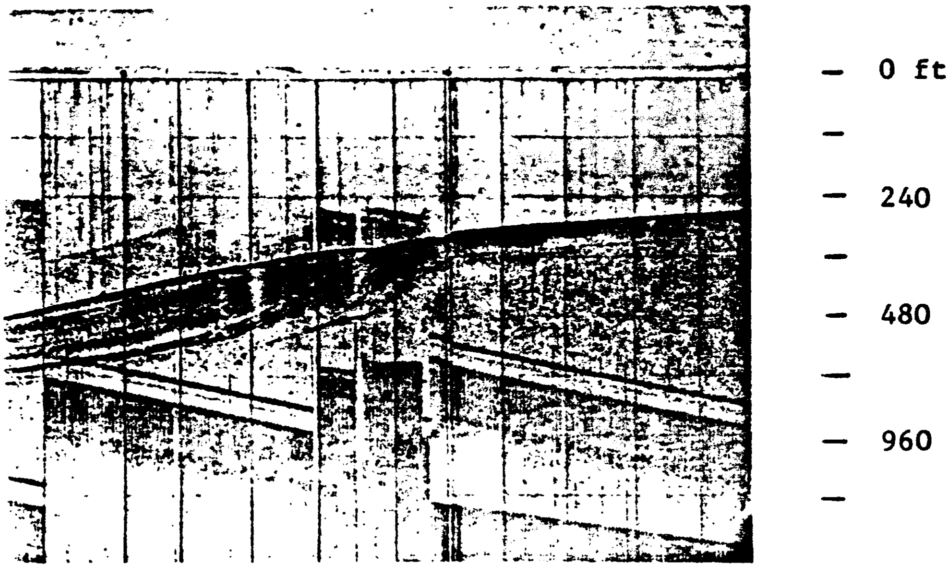
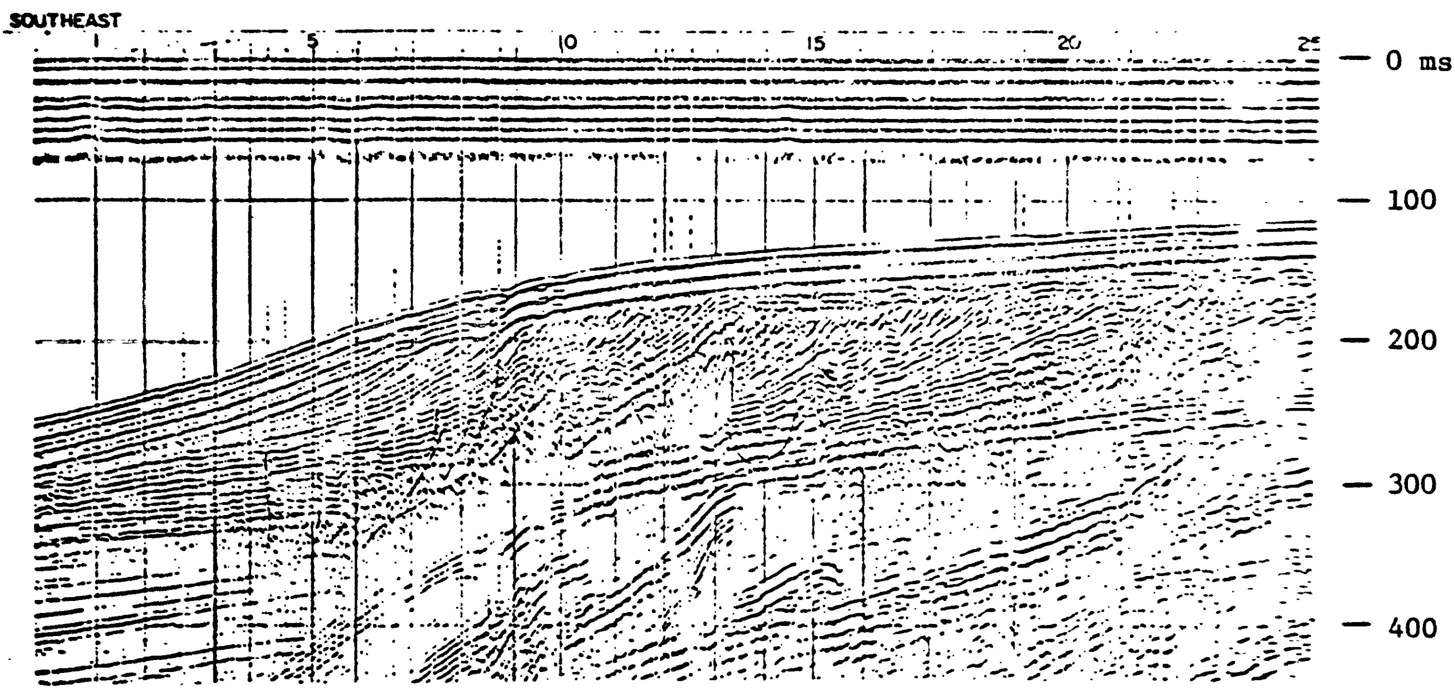


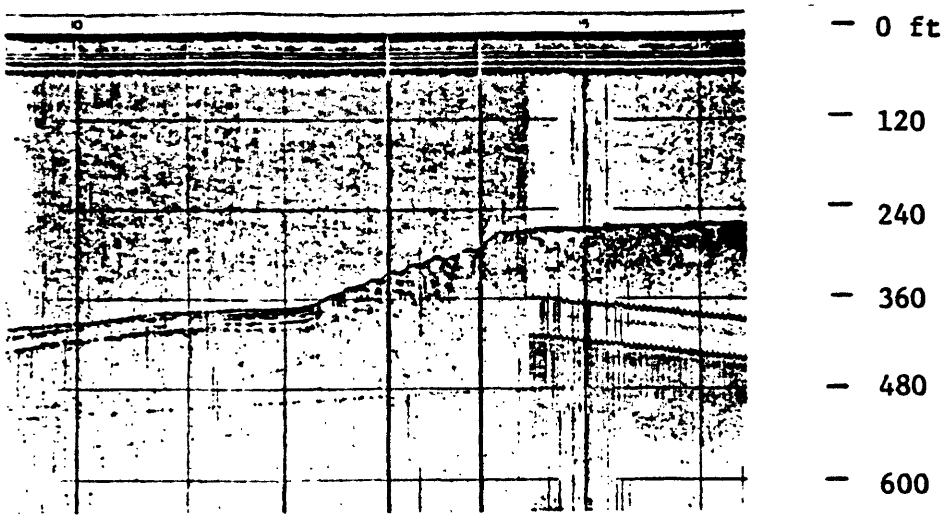
Terraced sediments in the Southwest Pass area may be episodic mud flows which are instrumental in the mass movement of fine grained sediments seaward into deeper water. The outer edge of each flow forms a nose which can be mapped as a scalloped zone. The seaward boundary of acoustically impenetrable sediment lies at right of picture. Strong reflector at about 260 feet below sea level is probably a Holocene shell bed, age 15,000 years b.p.



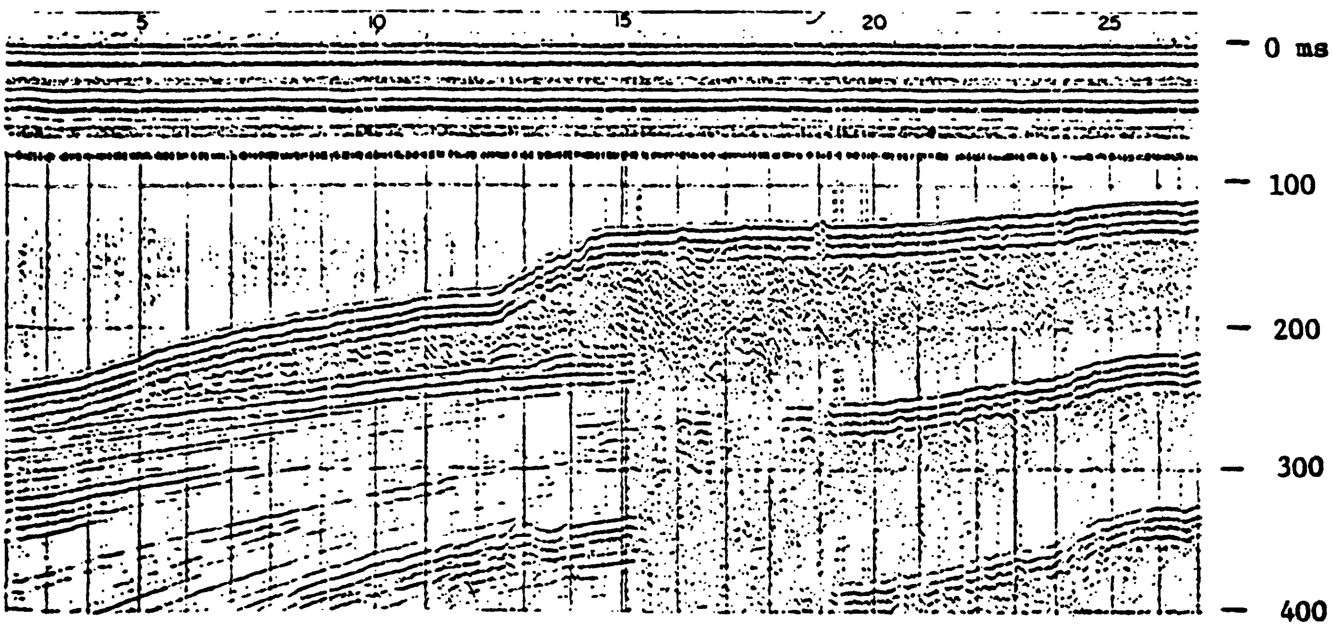
Steeply dipping beds from an episode of shelf outbuilding; subsequently truncated during Pleistocene lowered sea level.



Sparker record shows that the section has also been affected by faulting and slumping of the former shelf edge between SP 5 and 10, as well as by distortion of the clay layer into incipient mud lumps near SP's 10, 13, 15 and 22.

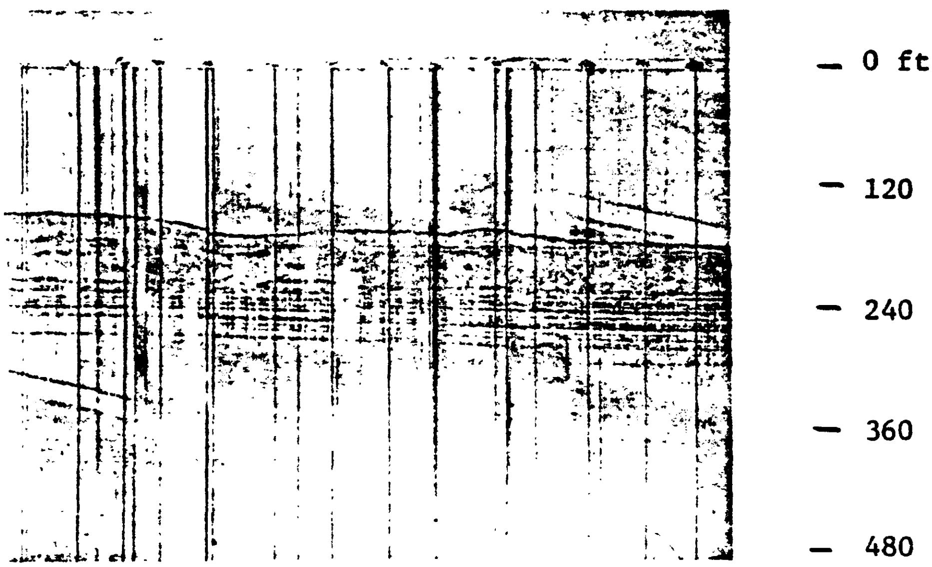


Outer edge of the mud-flow area south of South Pass. The slope of almost 3°, altered by rotated slump blocks, indicates down-slope migration of entire mass. Layered sediments to the left of the nose are part of a long ramp extending to the edge of the shelf. Note that sediments below these layers, as well as those to the right of the nose, are acoustically impenetrable.

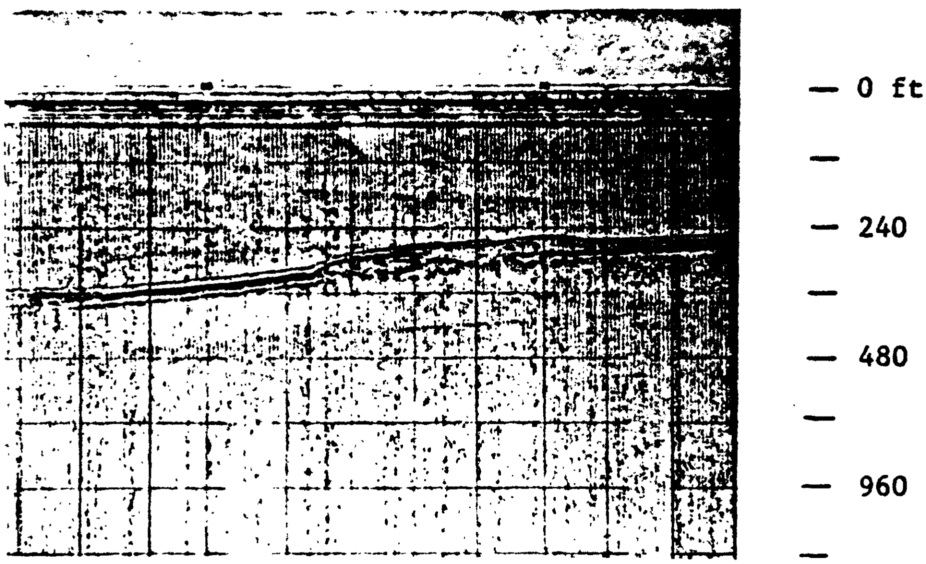


Sparker record shows the characteristic loss of all acoustic reflectors beneath absorbent materials to right of SP 15, although good reflection was obtained from deeper zones to the left.

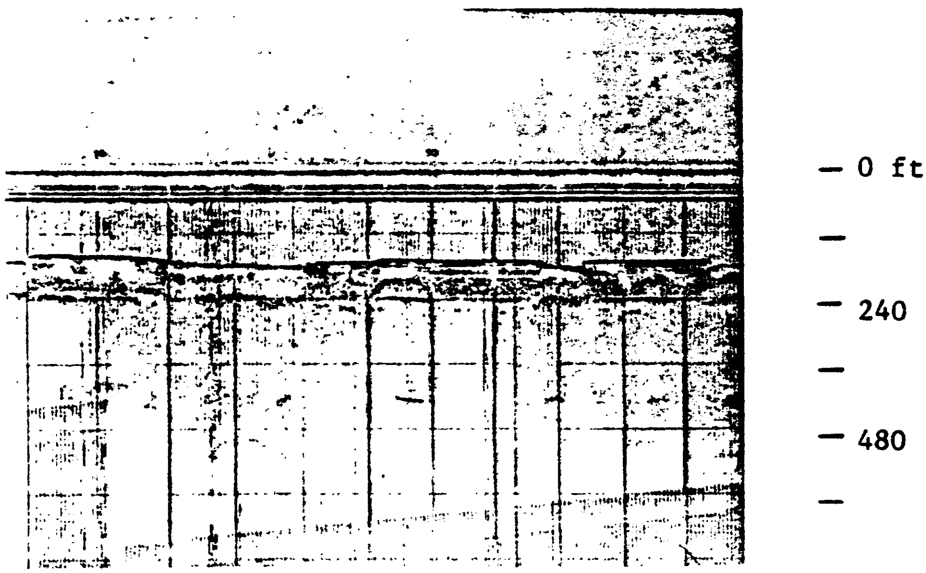
FIG. 4



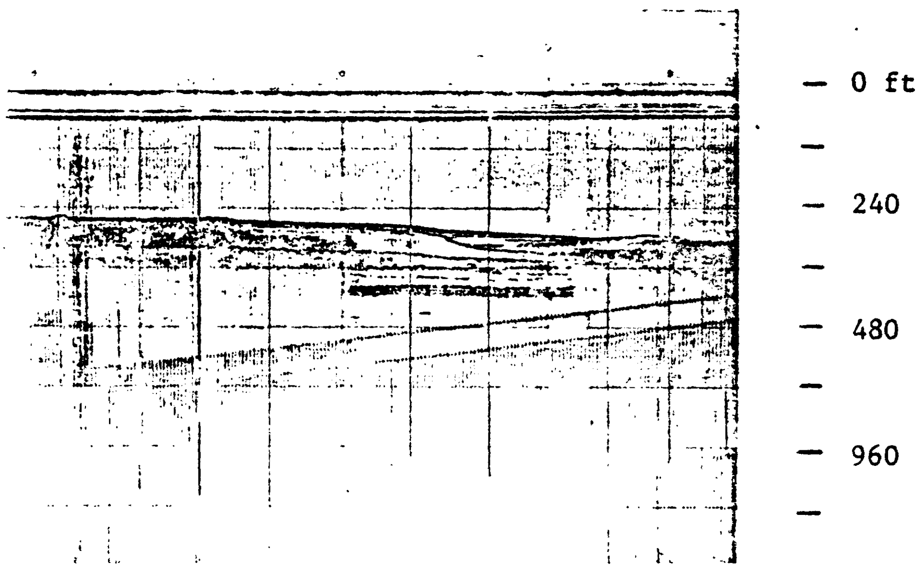
Northeast-southwest crossing of mud flow area; last SP on right is approximately same location as SP 10 in Figure 4. This picture shows parallel, undisturbed beds about 100-150 feet below bottom which are not involved in the flow.



Mud flow lobes which have moved at near right angles to the line of section and toward the viewer. Note that the flow involves sediment which is well bedded in unaffected areas, indicating that such apparently stable surfaces may become mobile. Edge of another lobe appears at extreme left, and a third lies out of the picture to the right.

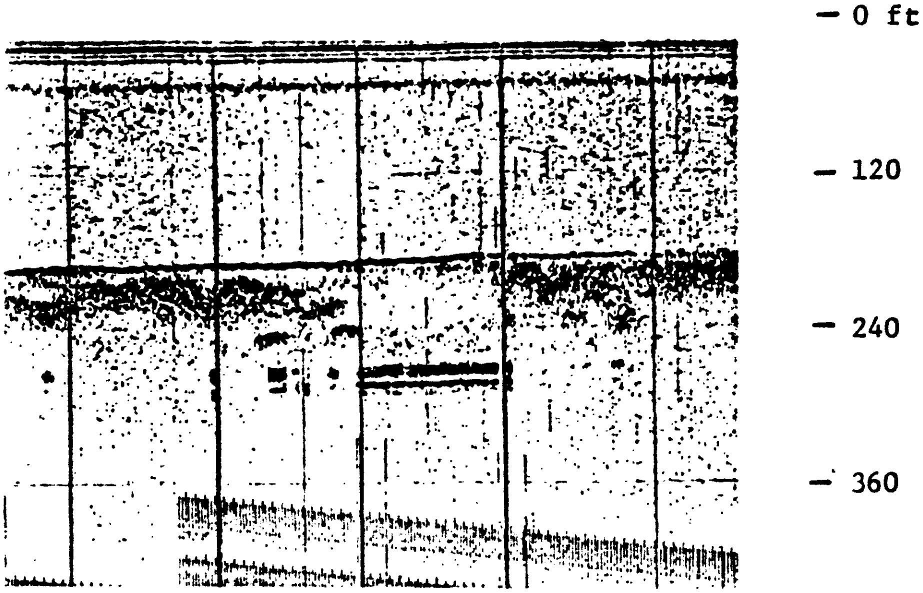


ullies on upper delta front south of South Pass. Notice that the epressions interrupt a thin, stratified surface layer, below which ies acoustically impenetrable sediment. In places, the surface ayer appears to slightly overhang the gully edge.

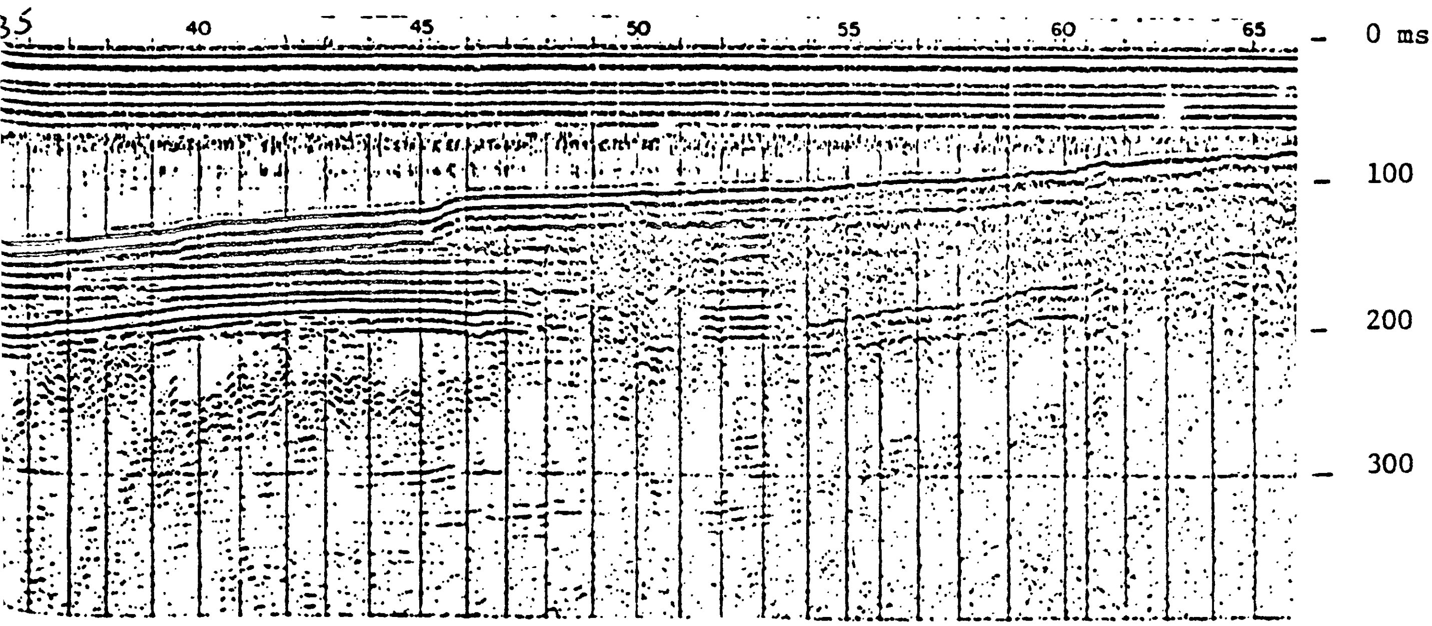


A slump in the surface sediments. Note the elliptical shape of the fault plane, the rotation of slumped beds to almost horizontal position, the depressed upper surface of the slumped mass near SP 8, and the elevated toe of the slump at SP 5. Note also that the slumped block is a "window" in an otherwise acoustically impenetrable area. A possible explanation might be that disturbance caused by slumping degassed the area.

Although the Shell 70 platforms which failed during Hurricane Camille are less than 2 miles away, this particular fault was not a factor in that accident.



The absorption of acoustic energy by upper sediment layers is indicated by a cloudy or amorphous subbottom character over most of this 3.5 kHz profile. In sharp contrast, however, is the approximately 1000-foot wide "window" in the center of the picture, which shows normal, in-place reflectors; smaller windows dot the record to right and left.



The sparker record also shows this energy loss, having only faint reflectors present in the cloudy section; window at SP 52-53 is same as the one in the photo above.

FIG. 9