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FACIES CHARACTERISTICS AND PATTERNS IN MODERN SIZE-GRADED SHELF DEPOSITS, NORTHWESTERN GULF OF MEXICO

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ABSTRACT

The continental shelf off south-central Texas is low energy and micro-tidal. The size-graded portion of this shelf is characterized by zonation of grain size of surficial sediments, macrobenthic infaunal assemblages, sedimentary structures, bedding types and bedding sequences.

General decrease in grain size of modern sediments with increasing water depth indicates the surficial bottom sediments are in equilibrium with the hydraulic regime. Gravel, a minor component, is biogenic shell detritus. The terrigenous sand fraction is the predominant constituent on the lower shore-face. The majority of the shelf is covered with clayey-silt sediment with the clay content increasing offshore.

Infaunal diversity and abundance decreases with increasing water depth. Three major taxonomic groups (Crustacea, Polychaeta, Mollusca) represent the majority of individuals collected. Species distribution patterns show crustacean and polychaete diversity about the same across the shelf but with large numbers of crustaceans on the lower shoreface. Mollusc diversity and density increases on the outer shelf.

Diversity and abundance of sedimentary structures systematically changes across the shelf. Bioturbation generally decreases with increasing depth; greater trace diversity is in relatively shallow

water. Most preservable traces have a significant vertical to subvertical orientation or represent deep burrowing relative to the sediment-water interface. A variety of bedding types characterize the shelf environment, most restricted to the inner shelf. Primary physical structures include finely laminated clean sand beds, relatively thick sandless mud beds, thinly interlaminated mud and sand beds, graded beds, and shell layers.

Unique bed sequences are characteristic to each particular shelf environment. The most complex sequences are common on the lower shoreface with sequences becoming progressively simpler in deeper water. All the bed sequences are cyclic.

During non-storm conditions, surficial sediments are in equilibrium with the hydraulic regime. The stratigraphic record, however, indicates storm-dominated shelf sedimentation resulting in zonation of sedimentary structures, bedding types, and bed sequences.

INTRODUCTION

A continental shelf whose sedimentary cover (1) is in equilibrium with its hydrodynamic regime, and (2) becomes finer in a seaward direction is termed a graded shelf (Swift, 1969). Because some 70% of modern continental shelves are covered by "relict" sediments which are in some degree of disequilibrium with the present hydrodynamic environment (Emery, 1968), most modern shelves are unsuitable for study as the uniformitarian key to their ancient graded counterparts. This paper describes facies characteristics of a modern size-graded shelf off south-central Texas (Fig. 1) and discusses the nature of, and balance between, biofacies, textural parameters, sedimentary structures (physical and biogenic), and bedding relationships. Three major size-graded shelf facies are defined: (1) lower shoreface (water depth 10-30 m), (2) mid-shelf (30-120 m), and (3) outer shelf (120-200 m).

Prior to the mid 1960's most shelf studies focused on describing texture and mineralogy of surficial sediments (e.g., Shepard, 1932; Emery, 1952) and demonstrated that most shelves were composed of a complex mosaic of relic and modern sediments. This was in contrast to early opinon (e.g., Johnson, 1919) that the continental shelf was an equilibrium surface whose sediments decreased in grain size offshore. The mid 1960's and 1970's saw a significant shift to the process-response phase of shelf studies resulting in the increased application of modern processes and product to the interpretation of ancient shelf deposits. As a result of these studies, distinctive sedimentary models have been recognized for continental shelf deposits (e.g., Swift and others, 1972) but most of them are in sharp contrast with the concept of a graded shelf (Johnson, 1978).

Due primarily to the expansion of energy related exploration into the sea during the last twenty years, continental shelves around the world are being extensively investigated (e.g., Curray, 1965; Swift and others, 1972; Swift, 1976). Studies of modern graded shelves such as the Bering Sea (Sharma, 1972), however, are not common. The first major paper on the sediments of the Texas continental shelf is included in a report by Curray (1960) on the Holocene transgression in the northwest Gulf of Mexico. Beginning in the mid 1970's, large scale environmental studies associated with offshore petroleum lease sales were initiated on the continental shelf off south Texas resulting in detailed reports on the geology (e.g., Berryhill and others, 1976), chemistry and biology (e.g., Parker, 1976), and physical oceanography (e.g., Angelovic, 1976).

ENVIRONMENTAL SETTING

Geographic Extent

The study area (Fig. 1) is part of the continental shelf in the western Gulf of Mexico designated by the Bureau of Land Management (BLM) for lease sale purposes as the South Texas Outer Continental Shelf (OCS). This area extends from Corpus Christi Bay in the north, to Baffin Bay in the south, and seaward to about the 200 m isobath. The 10 m isobath was the general inshore boundary. The study area encompasses approximately 4,650 km^2. This is the only part of the Texas continental shelf which is size-graded. The ancestral deltas of the Brazos-Colorado River and Rio Grande River lie to the north and south respectively. The deltas, of Pleistocene age, extend to near the shelf-slope break and are covered with relict sediments.

Geomorphology

The topography of the South Texas OCS can be generally characterized as a relatively smooth and gently sloping surface (Fig. 1). The average width of the shelf is 94.5 km with an average gradient of 1.8 m/km. Irregular topographic features include relict carbonate banks occurring locally within the 45-90 m interval.

Climate

The study area is in a semiarid warm-temperate climate. The mean annual rainfall at Corpus Christi is 72.5 cm; the mean monthly temperature varies from 14.0 °C in January to 29.0 °C in August, and the mean annual temperature is 22.1 °C (NOAA, 1974). The winds vary seasonally as indicated by wind data collected by the U.S. Weather Bureau at Corpus Christi (1951-1960). The winds are predominantly southeasterly during the summer. During the fall and spring, the winds begin to shift in an easterly direction. In the winter, the northerly component of the wind vector is greatest. The mean annual wind speed at Corpus Christi is 5.3 m/sec, and the resultant wind direction is 121°.

Tides, Water Properties, and Wave Climate

The tide range along the South Texas Shelf is microtidal, having a mean diurnal range of 51.8 cm at Port Aransas (NOAA, 1975). Curray (1960) predicted that the maximum velocities in the study area might be anticipated approximately 40 km offshore (45-55 m isobaths) rather than at the edge of the continental shelf.

The mean monthly water temperature at Port Aransas varies from 13.6 °C in January to 30.0 °C in August, and the mean annual water temperature is 22.7 °C (NOAA, 1973). The mean monthly salinity, calculated from the water density at Port Aransas, varies from 29.5^{o}/oo in May to 36.6^{o}/oo (NOAA, 1973).

Well defined temperature and salinity stratification exists intermittently off the southern Texas coast (Jones and others, 1965; Berryhill and others, 1976). Winter water temperatures in the northern Gulf of Mexico approach those found off North Carolina north to Long Island; in the summer, temperatures rise higher than those in the Carribbean. Parker (1960) compared summer and winter average bottom-water temperatures in the northern Gulf of Mexico and noted convergence of temperature values at about 80 m and again at 120 m.

Few data exist regarding wave climate. The heights of breakers along the nearshore are normally 0.3 to 1.0 m (personal observation). Breakers higher than 2 m occur several days per year, largely during storms in the fall, winter, and spring. Waves approach the coast from the southeast during the summer and dominantly from the northeast during the winter.

Currents

Circulation patterns of littoral and semipermanent shelf currents are complex on the South Texas OCS. A number of investigations have been conducted in the study area to determine drift rates and patterns

(Curray, 1960; Kimsey and Temple, 1963-64; Watson and Behrens, 1970; Hunter and others, 1974; Hill and others, 1975; Shideler, 1979). A comparision of these studies suggest the existence of a yearly cycle of coastwise water movement controlled primarily by seasonal winds. Uniformly southward winter drift and uniformly northward summer drift define the extremes of seasonal variation, but these extreme conditions may not occur every year due to winds atypical of the season.

During some seasons, a drift convergence may occur in the study area. Its position tends to shift northward during the spring and southward during the fall resulting in the net development of migrating surface and bottom convergence zones centered along the south-central Texas coast. The convergences are complex in structure both in the horizontal and in vertical sections.

METHODS

A Smith-MacIntyre grab sampler was used to collect bottom samples from fifty stations (Fig. 1). After removing subsamples for textural analyses, the enclosed sediments (14.5 liters per sample) were washed through a 0.5 mm mesh sieve. Organisms recovered were fixed in 10 percent formalin, preserved in 45 percent isopropyl alcohol, and later identified and counted in the laboratory. Because the study area was sampled during October 25 to December 22, 1974, this study represents only a "snapshot" picture of the benthic biological conditions that prevailed during that time. It must also be stressed that only one grab sample (1096 cm^2; 15 liters) was taken at each station because of time and logistical constraints.

Eleven relatively undisturbed box cores (30 x 30 x 50 cm) and thirty pipe cores as much as 2.0 m long were collected for analysis of physical and biogenic sedimentary structures. In the laboratory, x-ray radiographs were made of half-rounds and slabs using radiographic scanning techniques (Hill and others, 1979).

Textural data are from Berryhill and others (1976) and are part of a larger study by Shideler (1977). The silt/mud fraction was analyzed by a 16 channel TA Coulter Counter and the sand-size fraction by use of a Rapid Sediment Analyzer (RSA). A detailed description of analytical methods for the textural analysis is in Berryhill and others (1976).

DISCUSSION OF RESULTS

Biota

Number of Species and Individuals

The 50 samples examined yielded 952 individuals representing several taxonomic groups (Table 1) and 74 species (Table 2). The taxonomic groups having the greatest number of species were Polychaeta (53 percent), Mollusca (23 percent), and Crustacea (16 percent). The greatest number of individuals collected belong to Crustacea (50 percent), Polychaeta (32 percent), and Mollusca (8 percent). Other taxonomic groups accounted for less than 10 percent of the total number of species and individuals.

The number of species per sample (= species richness component) ranged from zero to 13 with a mean of 6.5 (Fig. 2). Species richness generally decreases with increasing water depth to about 70-100 m and then gradually increases again offshore. Variation in species richness across the study area is relatively small.

The number of individuals per sample (= density) ranged from zero to 143 with a mean of 20.3 (Fig. 3). Density decreased sharply in a seaward direction to about 40-50 m and then, on the average, slightly increases with increasing water depth. Variation in density is small on the mid-shelf and relatively larger at depths shallower than 50 m and greater than 150 m. The greatest number of individuals were in water depths shallower than 30 m.

Species Distribution

Distribution of the infaunal invertebrates exhibits distinct patterns relative to water depth with various taxonomic groups (Figs. 2 and 3) and species (Table 3) having apparent spatial limitations. The number of crustacean and polychaete species per sample are about the same across the shelf with both groups showing perhaps a slight decrease seaward. The molluscs increase offshore. Like diversity, density of various taxonomic groups changes systematically offshore. Numbers of crustaceans significantly decrease in water depths greater than about 30 m. On the average, molluscs are more numerous on the outer shelf (>150 m) than in shallower water. Polychaete density decreases with increasing water depth; at the shelf's eastern edge, average polychaete density per sample slightly increases due to greater sample variability with a few samples having relatively high densities.

Based on distribution the macrobenthic infauna (Table 3) can be divided into three basic groups. Group one consists of several species that are found across the entire shelf. They were very common at many stations and include nemerteans, ophiurids, echiurids, the mollusc *Corbula* sp., the amphipod *Ampelisca cristoides*, and the polychaetes *Cossura delta*, *Paraprionspio pinnata*, *Lumbrineris* sp., a cirratulid, a pilargid, *Onuphis* sp., and *Ninoe nigripes*. A second major group includes a few species divided into two smaller subgroups - species only in the inner (20-120 m) half of the shelf (e.g., *Ancistrosyllis papillosa*) or only on the outer (90-200 m) shelf (e.g., *Glycera* sp.). The majority of the infauna are in a third general group of species which are restricted in their distribution to the inner, mid or outer third of the Texas shelf. Twenty-four species (e.g., *Diopatra cuprea*) were only found on the inner shelf (20-60 m). *Sigambra tentaculata* is an example of some twelve species which were collected only from the mid-shelf (60-120 m). Distribution of eleven species (e.g., *Terebellides stroemi*) was restricted to the outer shelf (120-200 m).

Before the above results can be interpreted in terms of what factors control the observed regional distribution patterns, a fair question is how valid are the results considering the facts that the sampling was done only in the winter and that only one grab sample was taken at each station? A study of the benthic invertebrates on the south Texas shelf during 1975 by Holland (1976) included two transects (6 stations) in or immediately adjacent to my study area. Evaluation of sampling precision using the Smith-MacIntyre grab sampler indicated that one grab sample per station obtains approximately 30 percent of the species while four grab samples per station will collect about 60 percent of the species. Holland estimated that 50 or more samples at an individual station might be required to adequately sample total infaunal population.

Holland (1976) took four grab samples at each station during the winter, spring, and summer seasons. His results (Table 4) indicate the same regional patterns I found, i.e., number of species and individuals per sample generally decrease in a seaward direction regardless of season. Quantitatively, his winter results are very similar to mine. Holland's sampling did not exceed 131 m of water depth, and therefore his data do not document the gradual increase in a number of species and individuals at depths greater than 150 m that I observed. I conclude that my overall sampling density in the study area helps overcome the variability associated with taking a single grab per station and that the regional patterns observed for distribution of numbers of species and individuals are valid.

In the northwestern Gulf of Mexico, a number of investigators (Parker, 1956, 1960; Boyer, 1970; Stanton and Evans, 1971, 1972; Hill, 1975; Holland, 1976) have noted the close relationship between the distribution of macroinvertebrates and variations in sediment type and water depth. The general correlation of decreasing numbers of species and individuals with increasing water depths has already been noted (Figs. 2 and 3). A similar correlation is evident when the distribution of species and of individuals (Figs. 2 and 3) is compared to sediment distribution (Fig. 4).

In contradiction to the general trends discussed above are the increase in both numbers of species and individuals at the eastern edge of the shelf (Figs. 2 and 3). The higher diversity and density there probably reflects a response to a sedimentological characteristic not indicated by figure 4. The bottom sediments in the outer shelf area contain large numbers of foraminiferal tests, among which Orbulina sp. is the most conspicuous. The numerous forams in otherwise muddy sediments increase the sediment diversity and thus affect the number and types of infauna.

Overall, the density of species and individuals in the study area is low compared to coastal waters adjacent to the shelf and to parts of the continental shelf further north. For example, Holland and others (1974) reported 338 benthic taxa from Corpus Christi Bay with maximum standing crops as high as 11,856 individuals/0.5 ft^3. Manheim (1975) reported 190 species of polychaetous annelids alone from the shelf off Mississippi, Alabama, and the Florida panhandle. I believe that major factors influencing the pattern of species richness and infauna abundance in this study are sediment type and water depth.

Grain Size

Results of the grain size analyses of surficial sediments are synthesized (Fig. 4) to demonstrate two types of textural interrelationships: (1) single component percentages (gravel, sand, silt, clay), each with a unique distribution pattern; and (2) mean grain size (Ø). These aspects of the sediment properties most clearly demonstrate the regional patterns of sediment distribution.

Gravel (detritus >2mm) is a very minor constituent representing a maximum of one percent in an occasional sample but totally absent in most samples. The gravel is mostly biogenic shell detritus; lithic fragments are very rare (two samples). Shell material is found throughout the study area but is more common is water depths shallower than 30 m.

The sand-size fraction (63 µm - 2mm) is largely terrigenous with some biogenic detritus. Relative to regional distribution, sand is the predominant constituent nearshore (in water depths shallower than 20 m) and quickly diminishes to less than 10 percent seaward.

The most common constituent of bottom sediments in the study area is silt-sized detritus (3.9 - 63 µm ; Fig. 4). The amount of silt increases from less than 10 percent in shallow water (approximately 10 m) to a maximum of 70-80 percent in water depths of 20-30 m. As water depth continues to increase, the amount of silt gradually decreases toward the outer shelf edge.

The clay-sized fraction (<63 µm) of the sediment has a distribution pattern unlike the other constituents. Clay detritus shows a relatively sharp but minor increase in abundance between 10 and 30 m and gradually increases with increasing water depth. Only at the shelf edge does clay represent about 50 percent of the sediment. In the 3.0 to 0.45 µm size fraction, the predominant clay mineral is an expandable type, probably calcium montmorillonite (Berryhill and others, 1976). This clay mineral represented 40-90 percent of the material in the stated grain size. Illite was the second most common clay with only trace amounts of a chlorite-type mineral.

The mean grain size (Fig. 4) ranged from fine sand (3.0 Ø) to clay (7.9 Ø). Most of the study area is covered by fine to very fine silt (6.00-7.90 Ø). The coarser sediment (<6.0 Ø) is limited in distribution to water depths generally shallower than about 20 m. Overall, the mean grain size decreases with increasing water depths with the most pronounced change between 10-30 m.

The mean grain size pattern shows size gradients and indicate that the surficial bottom sediments are in equilibium with the hydraulic regime. General decreases in grain size seaward largely reflects increasing distance from coastal source areas and decreasing wave energy. Overall, the sediment distribution pattern meets the definition of a graded shelf as defined by Swift (1969).

Sedimentary Structures

Biogenic Sedimentary Structures

Frey (1975) defines biogenic sedimentary structures as "structures produced in the sediments by the activity of organisms upon or within an unconsolidated particulate substrate." On the south Texas shelf, these structures vary in type, size, and orientation. Some larger biogenic structures are indicated by textural differences or changes in sediment color; most small traces, however, commonly show only on X-ray radiographs.

Traces are classified below as burrow, tube, or locomotion trace. Definition of these terms follow Hertweck (1972). Burrows are open biogenic structures made in unconsolidated sediments by dwelling or locomotion activities of organisms; the main feature of burrows is that their walls are not cemented structures capable of supporting themselves when removed from the sediment. Tubes, which maintain their physical integrity when removed from the sediment, are animal dwelling structures constructed by direct secretion or agglutination. Subsurface biogenic structures resulting from organisms pushing through sediment without leaving cavities are termed locomotion traces. In this study, very few organisms were collected directly from a biogenic sedimentary structure thereby making it difficult to associate specific structures with specific species.

Trace A (Fig. 5A)

Burrow: tight vertical spiral; 4-6 mm tube diameter, 1-1.5 cm spiral diameter, 1-1.5 cm between spiral loops; burrow unlined with mucus-lined smooth walls; observed lengths to 35 cm.

Environment: outer continental shelf, water depth 90-200 m (Table 5); clayey-silt sediment.

Animal: unknown.

Trace B (Fig. 5B)

Tube: 3 mm overall diameter, 1-1.5 mm tube, 1 mm mucus agglutinated thin walls; straight to irregular, no branching; subhorizontal to subvertical; observed lengths up to about 20 cm.

Environment: all water depths throughout the study area (Table 5); common in sandy to clayey-silt sediments.

Animal: unknown.

Trace C (Fig. 5C)

Burrow: 4-7 mm diameter, occasional thin (0.1 mm) mucoid lining; diameter constant but the shape is variable - straight sections (few cm long) sub-vertical, possible U-shaped, rarely branched?; observed lengths to 15 cm.

Environment: found at all water depths (Table 5); in shallower coarser sediments, this trace is confined to the muddy beds. (Note: In this report, mud is a collective form referring to detritus less 63 µm large, i.e., silt + clay detritus.)

Animal: *Glycera* sp., Polychaeta.

Trace D (Fig. 5D)

Tube: 0.2-1.0 cm diameter, most with agglutinated walls up to 3 mm thick; tubes mostly mud filled with walls of slightly coarser material than fill material; horizontal orientation, cross to oblique sections common in radiographs; observed lengths to 12 cm.

Environment: commonly found at all water depths (Table 5) in coarse to fine grained sediments.

Animal: unknown.

Trace E (Fig. 5E)

Tube: 3-8 mm overall diameter, walls 1-3 mm thick, shaft 0.5-2.0 mm wide; agglutinated walls of coarser grained material usually containing some sand; vertical to subvertical unbranched shafts; extending from sediment-water interface to depths of 35 cm.

Environment: inner to mid-continental shelf, water depths less than 120 m (Table 5); common in sandy to silty sediments.

Animal: unknown.

Trace F (Fig. 5F)

Burrow: 1-3 mm overall diameter, shaft 1-2 mm, thin mucus impregnated walls (0.2-0.5 mm); branched, subvertical shafts; branching at 25-45° angles; observed lengths to about 5 cm.

Environment: inner shelf, water depths less than 60 m (Table 5); rare and found only in heavily bioturbated fine-grained beds.

Animal: unknown.

Trace G (Fig. 5G)

Burrow: loosely wound spiral; tube diameter 5-7 mm, spiral diameter 1.5 cm; loop spacing slightly irregular (1-3 cm); burrow winds upward subvertically; smooth mucus-lined walls; observed lengths to 15 cm.

Environment: inner shelf at depths less than 30 m (Table 5); rare in muddy sand or sandy mud deposits.

Animal: unknown.

Trace H (Fig. 5H)

Locomotion trace: long series of U-in-U backfill structures, 3-6 cm diameter; laminae defined by alternating sand and finer grained layers; x-section tends to be hemispherical but poorly defined; horizontal orientation; observed lengths up to 30 cm.

Environment: distinct traces were only found on the inner shelf in water less than 30 m deep (Table 5); however, the organism producing this trace was collected in deeper water (up to 120 m); rare in sandy substrates.

Animal: *Moira atropos* (Lamarck), Echinodermata, Echinoidea.

Trace I (Fig. 5I)

Burrow: 1-2 cm diameter; thin lining (0.1-0.2 mm); unbranched, vertical; occasionally filled with shell debris in otherwise shell free sediment; observed length to 20 cm.

Environment: inner shelf, water depths less than 30 m (Table 5);

penetrates bedding types ranging from sandless mud to clean sand; rare.

Animal: unknown.

Trace J (Fig. 5K)

Burrow: 2-5 mm diameter; no wall, no lining; filled with sand and/or shell material; sinuous; oblique orientation.

Environment: inner shelf, water depths less than 30 m (Table 5); common in relatively thin (few cm) mud beds.

Animal: unknown.

Trace K (Fig. 5L)

Burrow: tight horizontal spiral; 3-4 mm tube diameter, spiral diameter 2.5 cm; smooth walls not reinforced; observed lengths up to 20 cm.

Environment: inner shelf, water depths less than 30 m (Table 5); common in intensely bioturbated sandy mud or muddy sand.

Animal: unknown.

The preservation potential of these traces is worth noting. All of the traces were found in upper (0-50 cm) and lower (greater than 100 cm) sections of cores - well below erosion depth and, therefore, have good potential for being incorporated into the rock record. Secondly, all the traces were often found in a "filled" condition, that is when the animal departed, the trace didn't simply collapse and disappear. The overall low diversity of traces in the cores was not surprising considering earlier studies have shown that few organisms produce traces which are actually preserved. Off Georgia, for example, Hertweck (1972) calculated that of 269 living species collected on the beach-shelf area, only 19 (7.1 percent) produced biogenic sedimentary structures capable of being preserved. Surprising, however, was the lack of more traces near the sediment-water interface in this study - traces which are usually present in other environments (e.g., nearshore zone; Hill and Hunter, 1976) but which ultimately get destroyed by further bioturbaton, subsequent sediment compaction, or erosional events. The underconsolidated nature (due to very high water content) of the uppermost sediment apparently precludes any preservation of these near surface traces. Only "long" traces with a vertical to subvertical orientation or horizontal traces produced at depth survive both erosional events and sediment liquifaction processes near the sediment-water interface.

Hertweck (1972) defines characteristic traces as conspicuous, preservable traces occurring principally in one environment and found in most samples in some abundance. Only two traces in this study fit this definition: trace A (Fig. 5A) is the characteristic lebensspuren (= life trace) in sediments on the outer shelf (water depths greater than about 100 m; Table 5); trace E (Fig. 5E) is characteristic of inner shelf sediment (approximate water depths 20-100 m; Table 5).

Differences in the distribution, diversity and density of traces across the shelf have environmental significance. Most of the traces (greater than 70 percent) are limited to specific ranges in water depth (Table 5). Additionally, shallower water sediments tend to have a greater diversity (Table 5) and density (Fig. 6) of traces than sediments on the outer shelf. Overall, detail ichnocoenosis analysis is useful in defining shelf environments.

The generally parallel relationship between animal and trace diversity and abundance across the shelf is interesting considering that only a few organisms produce preservable traces. Both the biological and ichnological aspects of this study have demonstrated the zonation of the above parameters. Shallower water sediments have assemblages of organisms and traces which have high numbers of individuals and species (several limited in distribution to this environment) relative to outer shelf sediments.

Physical Sedimentary Structures

Several bedding types (Fig. 7) characterize the south Texas shelf. They are classified on texture and structure as seen in slabs and X-ray radiographs of box cores and gravity cores. Distribution of each bedding type is important in developing a suite of facies characteristic of the graded shelf environment from the lower shoreface to the outer shelf.

Sand

Laminated sand beds (Fig. 7A) - thinly bedded sand; horizontal stratification; laminations generally parallel to subparallel. The structures are present out to water depths of about 100 m (Table 6). They are, however, more abundant, and generally thicker on the lower shoreface (less than 30 m water depth). Based on close examination of subtle structures, many of the beds indicated in figure 6 as bioturbated sand were probably originally laminated beds.

Bioturbated sand beds (Fig. 7B) - sand beds generally lacking distinct physical structures due to reworking by organisms. These beds are distributed thoughout the study area at all water depths (Table 6). Bed thickness varies from 1 to 30 cm with the thickest beds on the lower shoreface. These beds are very common in shallower water deposits but decrease in abundance with increasing water depth.

Taking both sand bed types above as a single unit (= "mudless" sand; i.e., sand bed containing less than 25% particles smaller than 63 um), distribution, abundance, and thickness of this unit vary across the shelf (Fig. 8). Relative to sandless mud beds, mudless sand beds on the average are more abundant, thicker, and represent a greater proportion of cored sediments on the lower shoreface. The variability in these parameters of mudless sand units is also greater in shallower water. With increasing water depths, mudless sand units become less abundant, thinner, are a minor component of the total cored sediment, and show less variability in parameters.

Sand and Mud

Interlaminated sand and mud beds (Fig. 7C) - thinly interlaminated layers of sand and mud; individual laminae 0.2-2.0 cm thick. The distribution of these beds are limited to water depths less than 30 m (Table 6). From close study of the cores, it appears that this bed type is the "nonbioturbated" counterpart of the heavily bioturbated muddy sand beds with mottled textures. Bed thickness ranges from 2 to 15 cm.

Graded beds (Fig. 7D) - sand (with sharp basal contact) grading upward into silt and clay. This bed type was only observed once, in a core taken at water depths of 19 m (Table 6). The bed was 11 cm thick.

Bioturbated sandy mud or muddy sand layers (Fig. 7E) - beds of biogenically reworked sediments which lack or nearly lack any physical sedimentary structures. Mottled textures are particularly distinctive and result from bioturbation of thinly interbedded sand and mud beds in shallow water. As water depth increases, the sand content diminishes and the distinctive mottled texture disappears. Overall, bioturbated sandy mud or muddy sand beds are generally found in water depths less than 150 m. Muddy sand beds with mottled texture were found only in water depths less then 30 m (Table 6). Bed abundance and thickness increases in shallower water, particularly on the lower shoreface.

Mud

Mud beds (Fig. 7F) - layers of sandless mud (>1 cm) are individual beds which appear to be unrelated to overlying and underlying beds; as opposed to interlaminated sand and mud beds (Howard and Reineck, 1972). These beds which contain very thin (1 mm) horizontal laminations, are common from the lower shoreface to the seaward edge of the shelf (Table 6). In shallow water, mud beds are relatively thin (few cm) amd numerous compared to mud beds on the mid to outer shelf (Fig. 8). On the outer shelf the mud beds can be a meter or more thick. The amount of cored material represented by sandless mud beds increases on the average from about 30 percent on the lower shoreface, to 89-90 percent on the mid shelf, and finally to greater than 90 percent on the outer shelf. Variability in mud bed parameters generally decreases with increasing water depth.

Shells

Shell beds - beds of shells only occur as part of sand beds; generally near the basal contact. Those shell beds are 0.5-1.0 cm thick and are always associated with sand beds on the lower shoreface. Thicker shell accumulations occur locally associated with biogenic sedimentary structures, principally as burrow fill.

Except for bioturbated sand beds and bioturbated sandy mud/muddy sand beds, the above bedding types are primary physical sedimentary structures. All beds, however, are bioturbated to some degree. Examples of degrees of bioturbation are shown in figure 9. Variation in the degree of bioturbation for each bedding type represents constructional and destructional aspects of structures across the shelf. A graded scale next to each graphic core display (Fig. 6) illustrates the degree of bioturbation on the shelf.

Bioturbation generally decreases in a seaward direction. As pointed out by Howard and Reineck (1972), it might be assumed that under ideal conditions bioturbation would gradually increase with increasing water depth. However, this is not the case in this study area as even the finest of laminations are clearly evident in deeper water cores (Fig. 10). Changes in sediment texture and infaunal assemblages might explain the variation in bioturbation intensity. With increasing water depth, the sediments become almost uniform in grain size and benthic assemblages exhibit extremely low densities and diversity. Average sedimentation rates in the study area, calculated from data of Holmes and Martin (1977), indicate a relatively high rate of approximately 2 mm/yr for mid to outer shelf and no sedimentation for the lower shoreface. Uniformly fine-grained sediments contributing to low animal density and diversity, and relatively high sedimentation rates would probably result in a decrease in bioturbation on the outer shelf.

Bed Sequences and Facies Zonation

The relationship of beds to each other is important in (1) understanding the genesis of each bed type by reference to its neighbors, and (2) defining bedding associations which are considered genetically or environmentally related (Reading, 1978).

To determine whether bedding types described earlier are interbedded randomly or lie in a preferred order (= a sequence) with vertical transitions and whether such a sequence is cyclic, a statistical technique reviewed and modified by Walker (1979) was used to generate observed and random transition probabilities from which bedding relationship diagrams were constructed. The application of this method was to cores taken on the lower shoreface (<30 m water depth) because of the greater bedding diversity. For the purposes of the statistical technique, four bedding types (= units within sequences) were used (1) mudless sand (laminated + bioturbated sand beds); (2) sandless mud beds; (3) interlaminated mud and sand beds; and (4) mottled muddy-sand beds. Because of their rare occurrence, graded beds and shell beds were omitted from the calculations.

Lower shoreface facies: The test results (Table 7) indicate two major vertical bedding sequences comprised of three units each (Fig. 11A): (1) basal sand ⟶ interlaminated mud and sand ⟶ muddy sand; and (2) basal sand ⟶ sandless mud ⟶ muddy sand. Both depositional sequences are cyclic and both are the result of storm sedimentation based on the interpretation of (1) the processes generating each unit and (2) the relationship between units within a sequence.

Unit one is a basal mudless sand which may or may not show stratification due to the intensity of bioturbation (basal unit in both sequences). Where bioturbation is low, a sharp, erosional basal contact (Fig. 12A) is common. Stratification consist of very thin horizontal laminations. These structures in shelf deposits have been interpreted by Kulm and others (1975) to be the result when sand is deposited during storms. In the study area, two other lines of evidence indicate the sand beds to be storm deposits. The decay patterns for ^{210}Pb in cores from the study area suggest the sand layers represent single sedimentological events of short duration which disrupted the normal ^{210}Pb decay pattern (Holmes and Martin, 1977). Berryhill (1977) also concluded the sand beds resulted from storm activity from his incremental analyses of shelf cores which show the sand beds are laterally persistent for several kilometers. Sand beds with these characteristic have been called storm lag deposits by Brenner and Davies (1973) and sublittoral sheet sands by Goldring and Bridges (1973).

Unit two (middle unit in sequence two) consists of sandless mud layers. This layer is probably rapidly deposited as a storm subsides and the capacity of the water to carry large volumes of suspended material diminishes. Evidence relating this unit to storm activity include (1) sharp basal contacts with underlying beds when unit one is missing, (2) where a thin basal laminated sand is present, it always grades upward into the mud layer, (3) homogeneity of the mud layer, (4) general lack of bioturbation, and (5) indistinct but perceptable laminations. The general lack of bioturbation in these beds is probably the result of the destruction of infaunal assemblages by the storm. Deeper burrowing organisms that survive the initial erosion burrow upward through the storm deposits until they reach their normal position relative to the sediment-water interface. Evidence for this are the escape structures (Frey, 1975) which are relatively common in the mud layers. Thickness of this unit probably depends on the amount of shelf mud resuspended and coastal mud discharged during the storm.

Beds characterized by interlaminated muds and sand constitute unit three (middle unit of sequence one). Interbedding of two distinct sediments reflects fluctuations in the intensity and periodicity of hydrodynamic conditions and in the supply of sediment (Johnson, 1978), i.e., changing depositional conditions. Lower units grade into this unit which in turn normally grades into bioturbated sand above. Bioturbation varies from less than 30 percent to 60-90 percent; escape structures are occasionally present. Based on evidence of fluctuating depositional conditions, stratigraphic relationships with adjacent beds, and increased bioturbation, the interlaminated mud and sand unit probably represents a readjustment period following a storm. During this time, the balance between physical and biogenic assemblages and processes begins to return to fair weather conditions.

Muddy sand beds with mottled textures constitute unit four (uppermost unit is both sequences). This unit grades into the unit below but has a sharp upper contact (Fig. 12B). The original presence of interbedded sand and mud laminae indicates fluctuating depositonal non-storm conditions. Intense bioturbation indicates, however, that biogenic reworking of the sediment exceeds the depositional processes. The intensity of bioturbation, diversity of traces, and type of behavior represented by the traces (e.g., feeding traces) suggest the infaunal assemblages have been reestablished to "normal" conditions. If the bedding sequence is complete, unit four is the uppermost bed in a sequence and the beginning of a new sequence is marked by the sharp upper contact.

Complete sequences are rare (Fig. 6). Beginning with the basal contact, a sequence may be terminated at any point within the sequence depending on the depth of erosion due to the next storm. Bioturbation of storm deposited sands often obscures the sharp contact between two sequences making it difficult to distinquish between cycles especially in pipe cores with small diameters (Fig. 12C). Subtle evidence in the cores also indicates that some storm cycles are not very thick (few cm) and are completely bioturbated with time.

Why two major sequences in the lower shoreface facies? Among the major factors influencing the type of bed deposited during a storm are (1) energy level, (2) sediment type available, (3) location of sediment source, and (4) distance from shoreline combined with water depth

(Johnson, 1978). The study area is affected by storms of different energy levels (e.g., tropical storms to hurricanes), and duration (e.g., hours to days). The principal source of sand is the barrier island system whereas mud is derived from the outer shelf and coastal sources - some as far away as the Mississippi River (Berryhill, 1977). Most storms probably stir up enough bottom sediments to suspend large quantities of mud. Few storms would generate the necessary energy in the water column to move large amounts of sand from coastal systems seaward. Therefore, the hydraulic energy generated by a particular storm determines the quantity of sand eroded and distributed across the shelf resulting in the different bedding sequences.

Mid-shelf facies: On the midshelf (30-120 m), the bedding sequence is relatively simple with mud beds separated by either mudless sand beds or muddy sand beds (Figs. 6 and 11B). The sand beds are less abundant, thinner, and are more bioturbated than lower shoreface sand beds; the mud beds much thicker (Figs. 6 and 8). Sands have a sharp basal contact and grade into the overlying mud unit. Interlaminated mud and sand beds are absent. This distribution pattern results because (1) deposition of suspended muds dominate fair weather processes, and (2) storms of sufficient energy and duration to stir bottom sediments or transport sand greater distances offshore into deeper water are probably not as common as lesser storms which only affect shallower water deposits.

Outer shelf facies: The bed sequence on the outer shelf (120-200 m) is simple (Figs. 6 and 11C). Suspension deposited mud alternates with periodic sand influxes (distal storm layers). Mud beds are predominant and very thick while sand beds are thin and rare (Figs. 6

and 8). The sands are totally bioturbated but somewhat surprisingly show little mixing with adjacent mud beds. Therefore, sandy mud beds are not observed in this environment. Storms with the capacity to distribute sand to these water depths must be very rare.

Overall, bedding relationships across the shelf indicate storm-dominated sedimentation in the study area. The main source of energy is strong currents which are most intense during large storm conditions. Bedding sequences and facies distributions are therefore interpreted as reflecting a progressive decrease in energy across the shelf in response to increasing water depth and decreasing intensity and frequency of storm disturbances.

CONCLUSIONS

The low energy, microtidal, continental shelf off south-central Texas is characterized by specific facies defined by macrobenthic infauna, grain size, biogenic sedimentary structures, physical sedimentary structures, bedding types, and bedding sequences (Fig. 13).

Lower Shoreface (10-30 m): relatively dense and diverse infaunal assemblage characterized by large number of amphipods. The sediment has a significant fine sand component with occasional thin shell beds. Bioturbation is generally high with a diverse assemblage of traces. Long, straight vertical tubes with agglutinated coarse grained walls (trace E) are characteristic of this environment. Clean sand beds occur in parallel to subparallel laminated sets. Erosional contacts at the base of the sand beds are common. Bedding relationships define two major sequences, both of which are cyclic: (1) thin, clean laminated sand ⟶ thick sandless, nonbioturbated mud ⟶ heavily bioturbate muddy sand with mottled texture, and (2) thick, clean laminated sand ⟶ interlaminated mud and sand with varying degrees of bioturbation ⟶ muddy sand with mottled texture. Both sequences result from variation in hydraulic energy related to storm disturbances.

Midshelf (30-120 m): polychaete dominated, infaunal assemblages characterized by very low diversity and abundance. The clayey-silt sediment contains much less sand than the lower shoreface and shell beds are totally missing. Mixed mud and sand beds are best described as sandy mud layers. Sediments are moderately bioturbated. Trace diversity is less than the lower shoreface but greater than the outer shelf. No specific biogenic structure characterize this area where the trace assemblage is a composite of structures found in both shallower and deeper water. The only physical structures are occasional parallel laminated clean sand beds. Bedding diversity is less than the lower shoreface but greater than the outer shelf. Moderately thick mud beds (deposited during fair weather) are separated by various types of storm related sand beds including relatively thin laminated sand beds, bioturbated sand beds, or sandy mud beds.

Outer Shelf (120-200 m): infaunal assemblage exhibits relatively low species richness and abundance compared to the lower shoreface but slightly higher than the midshelf. An increase in mollusc diversity and abundance characterize this environment. Like the midshelf, the sediment is a clayey-silt but the clay content is greater. Bioturbation and trace diversity is low. The characteristic trace is a burrow best described as a tight looped vertical spiral with mucus-lined walls. Bedding diversity is very low and bedding relationships very simple. Thick, faintly laminated, slightly bioturbated mud beds (deposited between storms) are separated by thin, heavily bioturbated, relatively clean sand beds (distal storm layers).

Overall, surficial sediments are in equilibrium with the hydraulic regime during fair weather conditions. However, the stratigraphic record indicates storm-dominated shelf sedimentation resulting in zonation of sedimentary structures, bedding types and bedding sequences from the lower shoreface to the outer shelf.

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TABLES

Table 1. Number of species and individuals collected from 50 stations.

Taxon	No. of Species	No. of Individuals
Polychaeta	39 (53 percent)	309 (32 percent)
Crustacea	12 (16 percent)	474 (50 percent)
Mollusca	17 (23 percent)	72 (8 percent)
Others	6 (8 percent)	97 (10 percent)
Total	74 (100 percent)	952 (100 percent)

Table 2. Species represented in the study area.

- PHYLUM
  - Class
    - Order
      - Family
        - Species

- COELENTERATA
  - Anthozoa
    - Pennatulacea
      - Renillidae
        - *Renilla mulleri*

- NEMERTINEA
  - unidentified nemerteans

- ANNELIDA
  - Polychaeta
    - Phyllodocida
      - Sigalionidae
        - *Sthenelais* sp.
      - Glyceridae
        - *Glycera* sp.
      - Goinadidae
        - *Glycinde* sp.
        - *Goniada* sp.
      - Nephytyidae
        - *Nephtys picta*
        - *Nephtys* sp.
      - Pilargidae
        - *Ancistrosyllis papillosa*
        - *Sigambra tentaculata*
        - undentified pilargid
      - Nereidae
        - *Nereis* sp.
    - Capitellida
      - Capitellidae
        - *Notomastus latericeus*
      - Maldanidae
        - unidentified maldanid
      - Opheliidae
        - *Armandia agilis*
        - *Armadia maculata*
        - *Polyophtalmus pictus*
    - Spionida
      - Spionidae
        - *Malacoceros indicus*
        - *Malacoceros* sp.
        - *Paraprionospio pinnata*
        - *Scolelepis* sp.
        - *Spiophanes* sp.
        - unidentified spionid

(Table 2 continued)

- ANNELIDA (con't)
  - Polychaeta (con't)
    - Spionida (con't)
      - Heterospionidae
        - unidentified heterospionid
      - Paraonidae
        - *Aricidea* sp.
        - *Paraonis* sp.
        - unidentified paraonid A
        - unidentified paraonid B
    - Eunicida
      - Onuphidae
        - *Diopatra cuprea*
        - *Onuphis* sp.
      - Lumbrineridae
        - *Lumbrineris* sp.
        - *Ninoe nigripes*
    - Amphinomida
      - Amphinomidae
        - *Amphinome rostrata*
        - *Pseudeurythoe* sp.
    - Magelonida
      - Magelonidae
        - *Magelona* sp.
    - Ariciida
      - Orbiniidae
        - unidentified orbiniid
    - Cirratulida
      - Cirratulidae
        - unidentified cirratulid
      - Cossuridae
        - *Cossura delta*
    - Terebellida
      - Terebellidae
        - *Terebellides stroemi*
    - Flabelligerida
      - Flabelligeridae
        - unidentified flabelligerid
        - unidentified polychaete

- MOLLUSCA
  - Gastropoda
    - Melanellidae
      - *Strombiformis* sp.
    - Retusidae
      - *Volvulella texasiana*
      - *Pyrunculus caelatus*
      - undentified gastropod
  - Scaphopoda
    - Dentaliidae
      - *Dentalium* sp.

(Table 2 continued)

- MOLLUSCA (cont'd)
  - Bivalvia
    - Nuculanidae
      - *Nuculana acuta*
      - *Nuculana concentrica*
      - unidentified nuculanid
    - Diplodontidae
      - *Diplodonta* sp.
    - Carditidae
      - *Cycolcardia* sp.
    - Veneridae
      - *Cyclinella tenuis*
    - Tellinidae
      - *Macoma pulleyi*
    - Corbulidae
      - *Corbula* sp.
    - Verticordiidae
      - *Verticordia ornata*
      - *Verticordia* sp.
    - Leptonidae
      - *Mysella* sp.
      - unidentified bivalve

- ARTHROPODA
  - Crustacea
    - Cumacea
      - Leuconidae
        - *Eudorella monodon*
    - Tanaidacea
      - Apseudidae
        - *Leptognatha gracilis*
      - Tanaidae
        - unidentified tanaid
      - Stomatopoda
        - Squillidae
          - *Squilla empusa*
      - Amphipoda
        - Ampeliscidae
          - *Ampelisca cristoides*
          - *Ampelisca* cf. *cucullata*
        - Gammaridae
          - *Gammarus* sp.
        - Lysianassidae
          - *Tmetonyx* sp.
      - Decapoda
        - Pinnotheridae
          - *Pinnixa retinens*
          - *Pinnixa* sp.
        - Goneplacidae
          - *Speocarcinus* sp.
          - *Chasmocarcinus mississippiensis*

(Table 2 continued)

- ECHIURIDA
  - unidentified echiurid A
  - unidentified echiurid B
- ECHINODERMATA
  - Echinoidea
    - Spatangoida
      - Schizasteridae
        - *Moira atropos*
  - Ophiuroidea
    - Ophiurida
      - unidentified ophiurid

Table 3. Distribution of infaunal species.

Species	Water Depth (m) 60	 60-120	 120
Cossura delta	----------	----------	----------
nemerteans	----------	----------	----------
Paraprionspio pinnata	----------	----------	----------
Nephtys picta	----------	----------	----------
ophiurid	----------	----------	----------
echiurid B	----------	----------	----------
Lumbrineris sp.	----------	----------	----------
cirratulid	----------	----------	----------
Onuphis sp.	----------	----------	----------
pilargid	----------	----------	----------
Corbula sp.	----------	----------	----------
Ampelisca cristoides	----------	----------	----------
Ninoe nigripes	----------	----------	----------
Nuculana concentrica	----------	----------	
Scolelepis sp.	----------	----------	
unidentified polychaete	----------	----------	
Aricidea sp.	----------	----------	
Magelona sp.	----------	----------	
nereid	----------	----------	
Ampelisca cf. cucullata	----------	----------	
paraonid	----------	----------	
unidentified gastropod	----------	----------	
Ancistrocyllis papillosa	----------	----------	
Glycera sp.		----------	----------
echiurid A		----------	----------
Nuculana acuta		----------	----------
Renilla mulleri	----------		
Macoma pulleyi	----------		
Squilla empusa	----------		
Gammarus sp.	----------		
Diopatra cuprea	----------		
Pseudeurythoe sp.	----------		
Nephyts sp.	----------		
paraonid	----------		
Amphinome rostrata	----------		
Malacoceros sp.	----------		
Armandia maculata	----------		
Malacoceros indicus	----------		
Pinnixa retinens	----------		
Chasmocarcinus mississippiensis	----------		
Eudorella monodon	----------		
Armandia agilis	----------		
Leptognatha gracilis	----------		
Speocarcinus sp.	----------		
Sthenelais sp.	----------		
Notomastus latericeus	----------		
Goniada sp.	----------		
spionid	----------		
Paraonis sp.	----------		
Polyophthalmus pictus	----------		
Cyclinella tenuis		----------	
Volvulella texasiana		----------	
Diplodonta sp.		----------	
Pyrunculus caelatus		----------	
Pinnixa sp.		----------	
heterospionid		----------	
Sigambra tentaculata		----------	
maldanid		----------	
Moira atropos		----------	
Dentalium sp.		----------	
tanaid		----------	
Glycinde sp.		----------	
flabelligerid			----------
Spiophanes sp.			----------
orbiniid			----------
Terebellides stroemi			----------
Tmetonyx sp.			----------
Cycolcardia sp.			----------
nuculanid			----------
Verticordia sp.			----------
Verticordia ornata			----------
unidentified bivalve			----------
Mysella sp.			----------

Table 4. Total number of species and individuals for the four replicates at each station of Holland (1976).

Transect Number	Station No.	Latitude	Longitude	Water Depth (m)	Winter		Spring		Summer	
					No. of Species	No. of Individuals	No. of Species	No. of Individuals	No. of Species	No. of Individuals
II	1	27°40'	96°59'	22	22	228	43	1481	27	116
II	2	27°30'	96°44.5'	49	14	29	27	66	19	33
II	3	27°17.5'	96°23'	131	7	12	13	18	11	15
III	1	26°57.5'	97°11'	25	13	133	34	301	23	116
III	2	26°57.5'	96°48'	65	7	14	25	53	19	30
III	3	26°57.5'	96°32.5'	106	11	16	13	21	26	65

Table 5. Distribution of traces. See text for description of each trace; trace designation corresponds to text.

Water Depth Interval (m)	Trace A	 B	 C	 D	 E	 F	 G	 H	 I	 K	 L
<30		X	X	X	X	X	X	X	X	X	X
30-60		X	X	X	X	X					
60-90		X	X	X	X						
90-120	X	X	X	X	X						
120-150	X	X	X	X							
>150	X	X	X	X							

Table 6. Distribution and abundance of bedding types.

Water Depth Interval (m)	Bedding Type[1] 1	2	3	4	5	6	7
<30	31	20	14	19	6	1	10
30-60	51	26	8	15	-	-	-
60-90	55	25	10	10	-	-	-
90-120	52	19	14	14	-	-	-
120-150	75	25	-	-	-	-	-
>150	70	30	-	-	-	-	-

[1] % occurrence in given depth interval

Bedding Types
1. mud bed
2. bioturbated sand bed
3. laminated sand bed
4. sandy mud
5. interlaminated mud and sand
6. graded bed
7. muddy sand, mottled texture

Table 7. Tabulation of bedding relationships using Walker's (1979) method. (IMS = interlaminated mud and sand; MS = muddy sand)

A. Observed number of transitions between beds.

	Sand	Mud	IMS	MS
Sand	--	33	1	19
Mud	35	--	6	23
IMS	4	3	--	23
MS	20	21	5	--

B. Observed transition probabilities (%).

	Sand	Mud	IMS	MS
Sand	--	62	2	36
Mud	55	--	9	36
IMS	33	25	--	42
MS	44	46	10	--

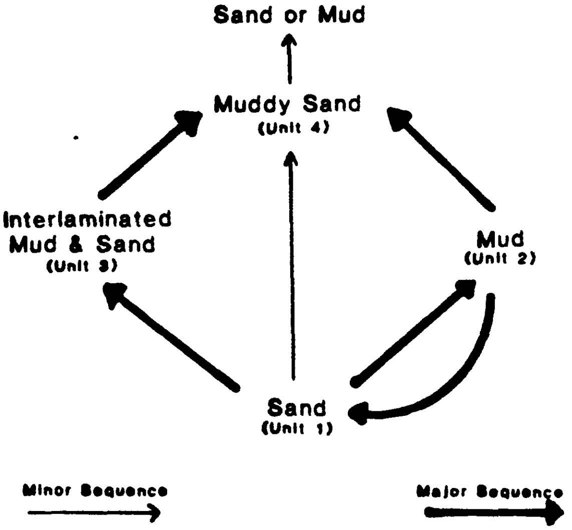
C. Transition probabilities for random sequence (%).

	Sand	Mud	IMS	MS
Sand	--	49	9	42
Mud	48	--	10	43
IMS	34	36	--	31
MS	44	47	9	--

D. Observed minus randum transition probabilities (%).

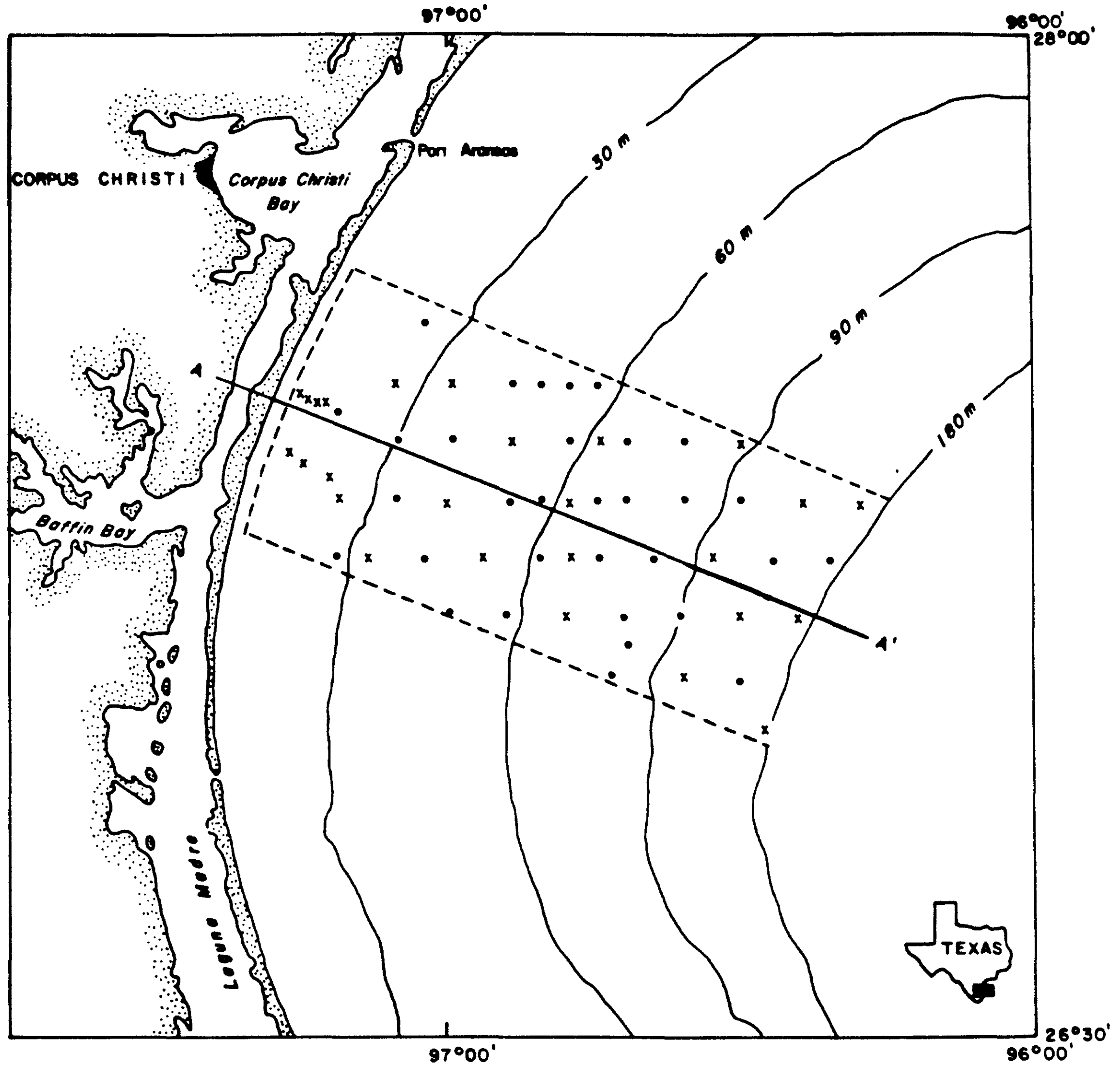
	Sand	Mud	IMS	MS
Sand	--	+13	+7	-6
Mud	+7	--	-1	+7
IMS	-1	-11	--	+11
MS	0	-1	+1	--

E. Preferred bedding relationships (i.e., unit sequences) if such relationships are not random.



FIGURES

Fig. 1. Index map of study area and sample locations. Biological and grain size analyses made of all samples; cores taken at stations indicated by crosses.


97°00'
96°00'
28°00'
Port Aransas
CORPUS CHRISTI
Corpus Christi Bay
30 m
60 m
90 m
180 m
A
A'
Baffin Bay
Laguna Madre
TEXAS
97°00'
26°30'
96°00'

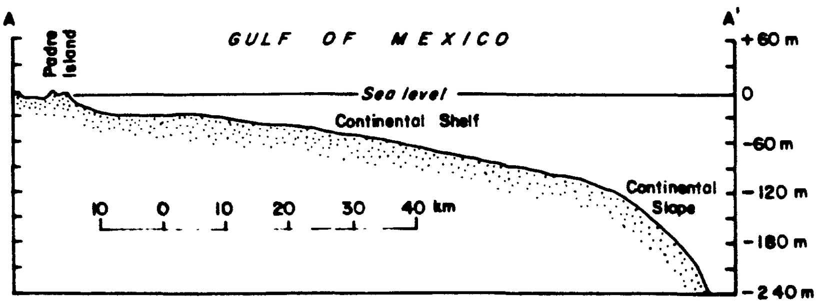

A
A'
Padre Island
GULF OF MEXICO
+60 m
Sea level
0
Continental Shelf
-60 m
Continental Slope
-120 m
-180 m
-240 m
10 0 10 20 30 40 km

Fig. 2. Distribution of taxonomic diversity (species richness component). Average value represented by solid line.

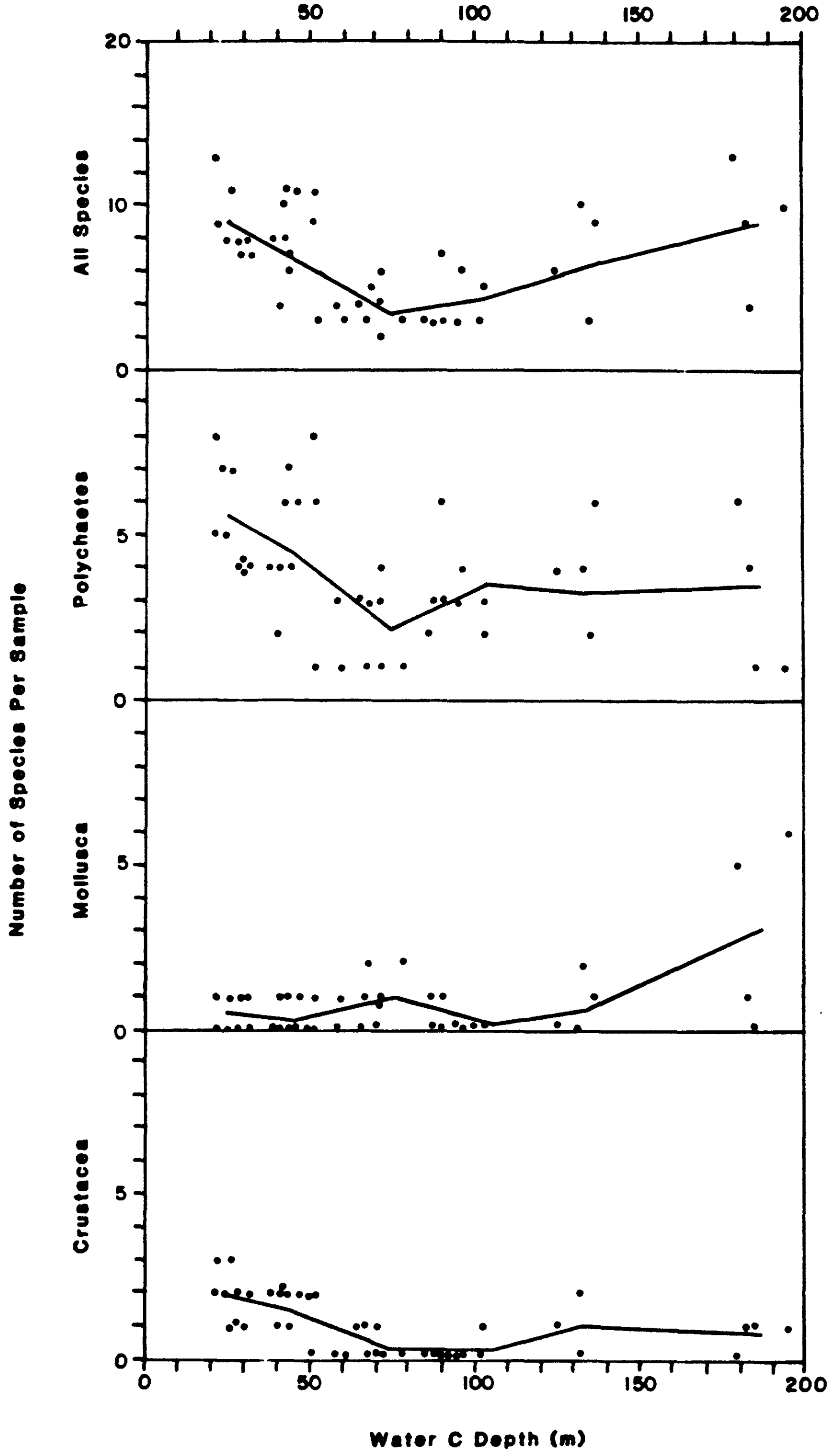

50
100
150
200
20
10
0
All Species
5
0
Polychaetes
5
0
Mollusca
5
0
Crustacea
Number of Species Per Sample
0
50
100
150
200
Water C Depth (m)

Fig. 3. Distribution of taxonomic abundance. Average values represented by solid line.

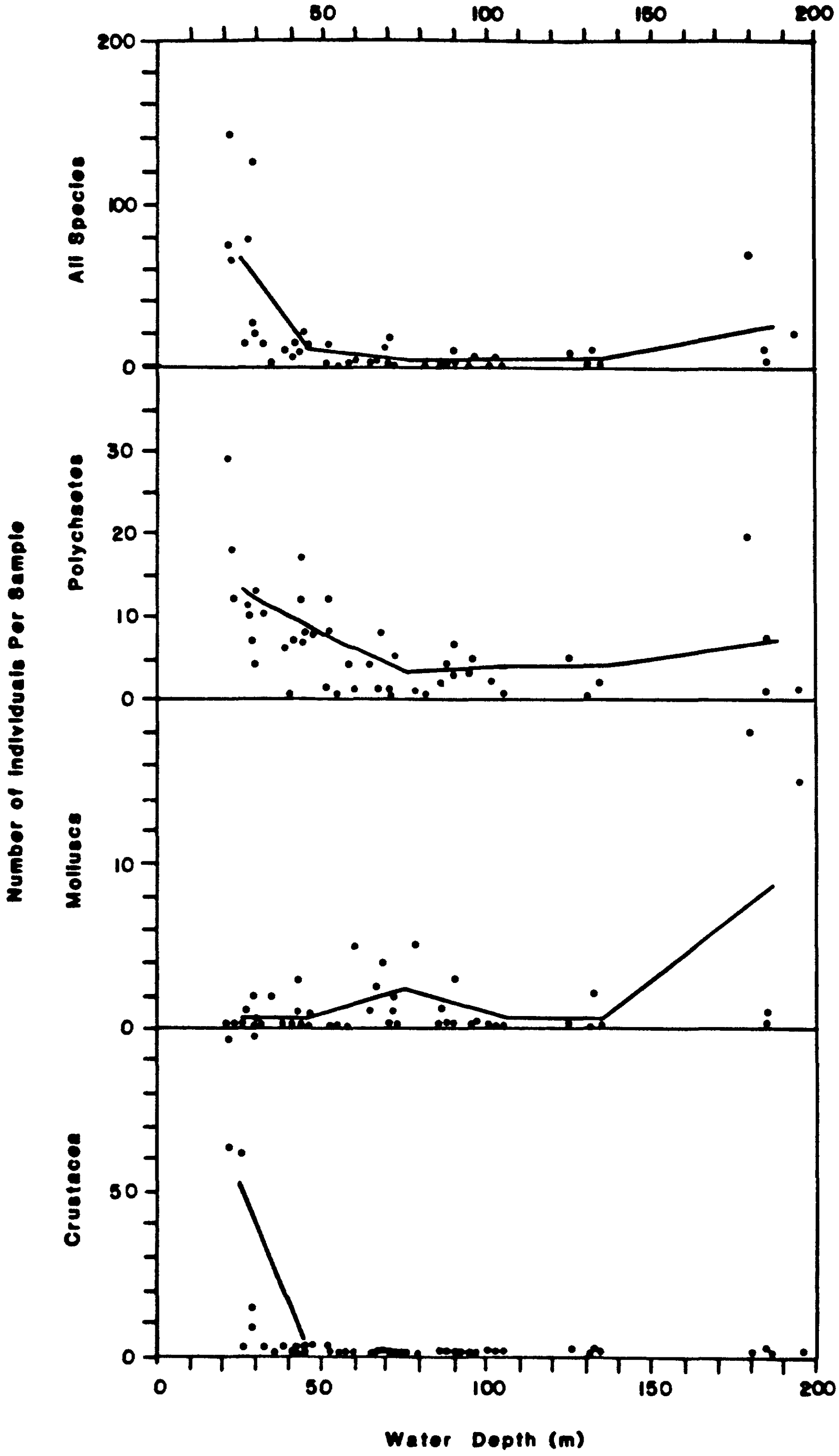

50
100
150
200
200
100
0
All Species
30
20
10
0
Polychaetes
Number of Individuals Per Sample
10
0
Molluscs
50
0
Crustacea
0
50
100
150
200
Water Depth (m)

Fig. 4. Distribution of sediment components within the study area.

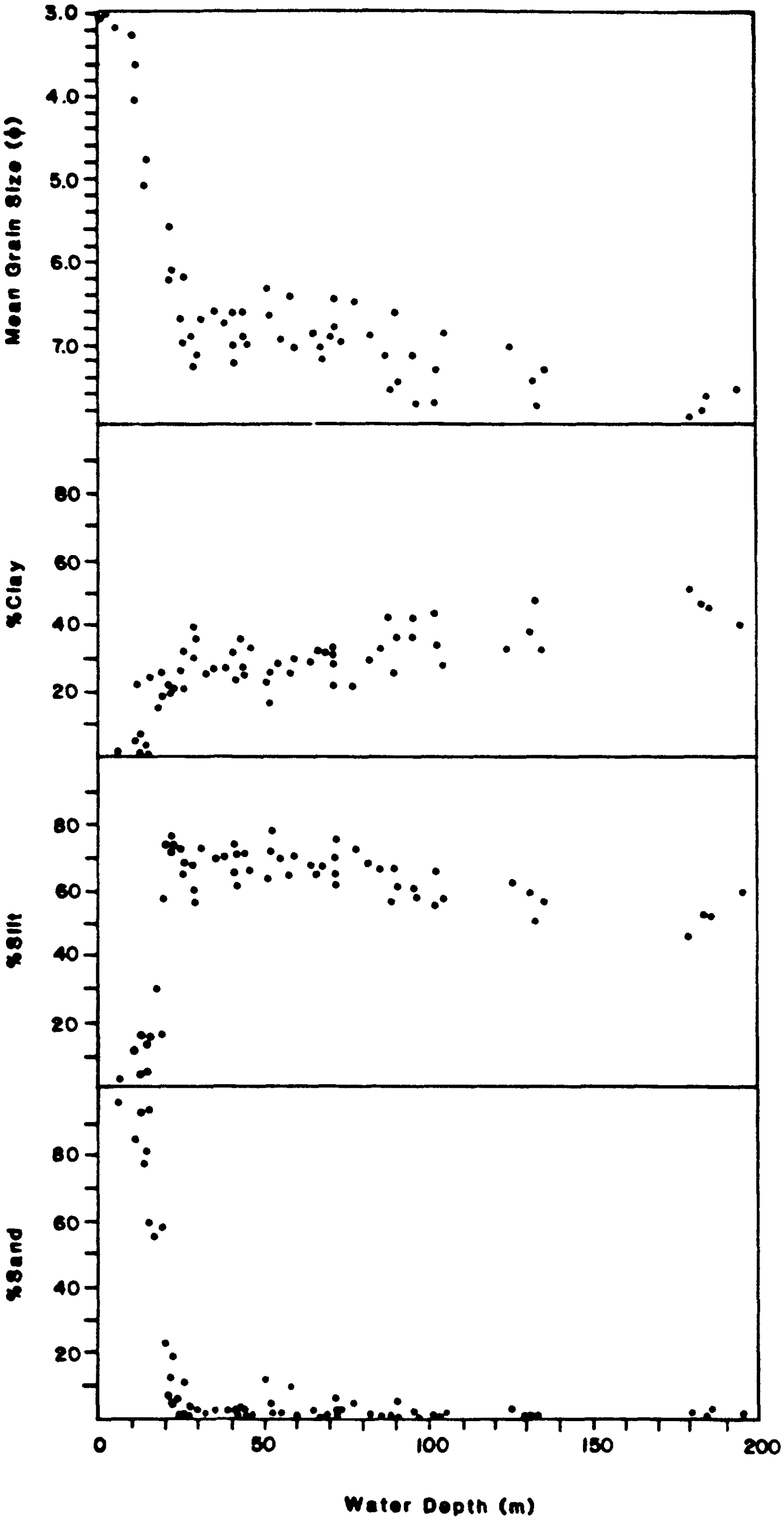
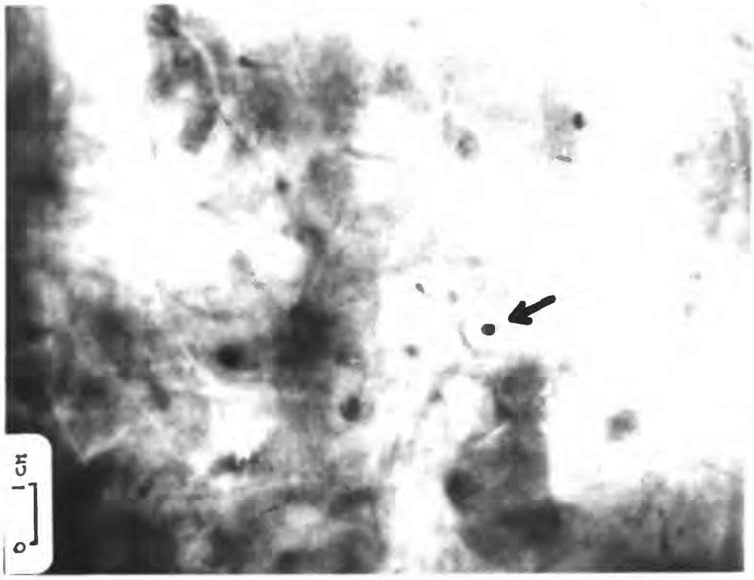

Mean Grain Size (ϕ)
3.0
4.0
5.0
6.0
7.0
%Clay
80
60
40
20
%Silt
80
60
40
20
%Sand
80
60
40
20
0
50
100
150
200
Water Depth (m)

Fig. 5. Examples of specific biogenic sedimentary structures observed in cores (sections perpendicular to bedding). These are x-ray negatives where mud is black, sand is white, and sandy mud is a mottled grey. See text for descriptions.

A

B

D

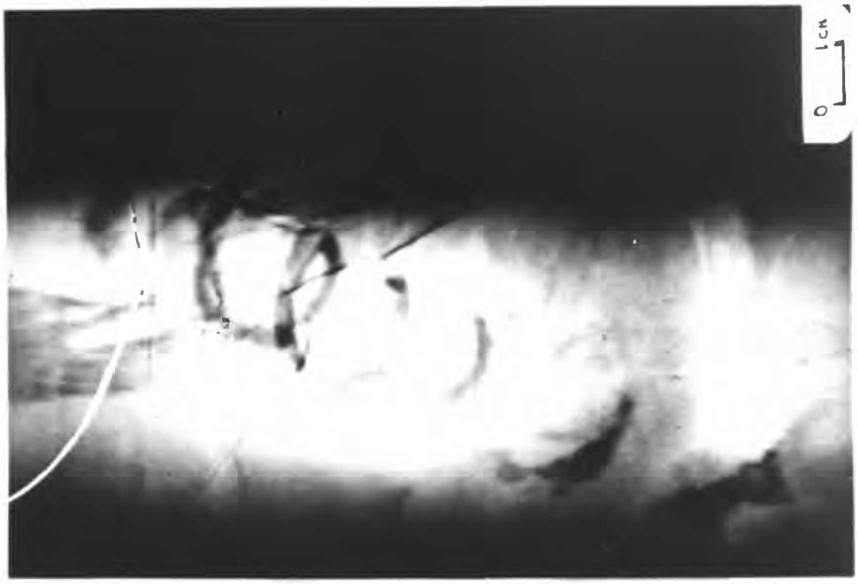


C

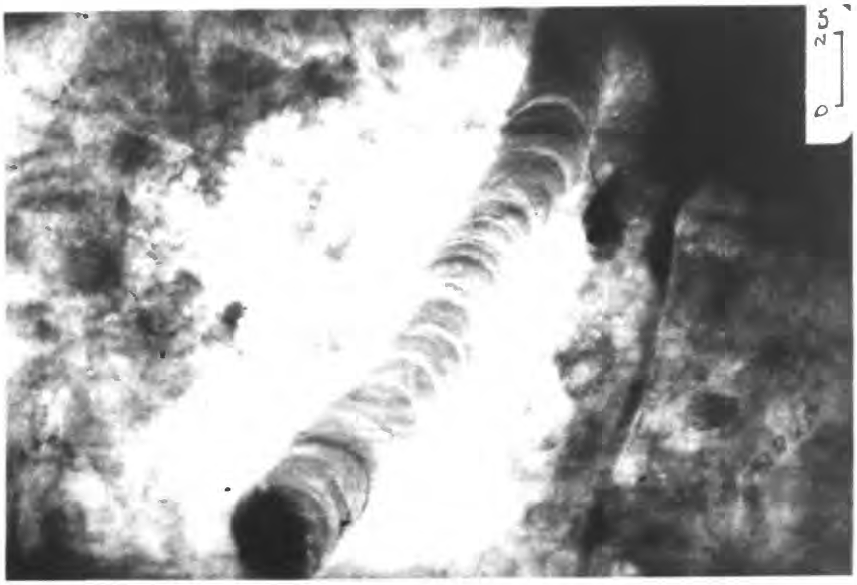
J

I

G

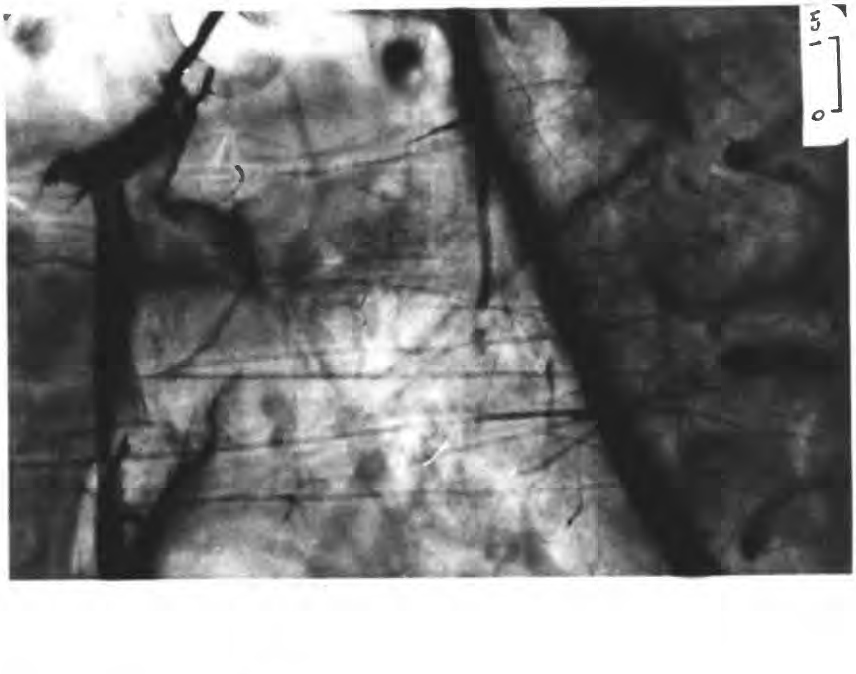


H

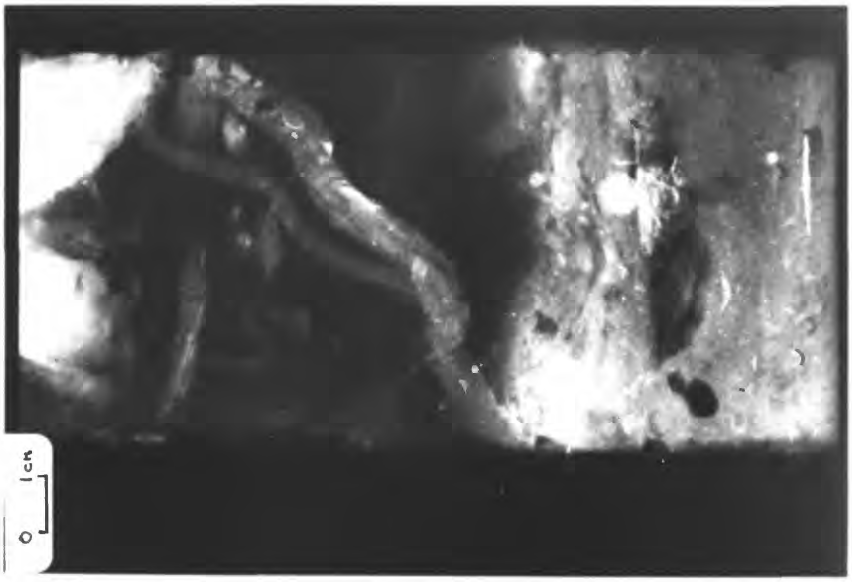


F

E



K



L

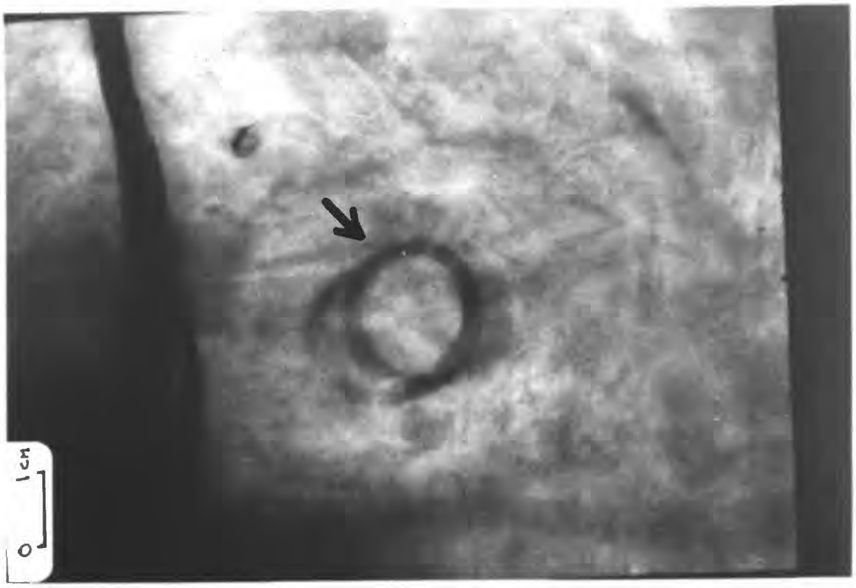
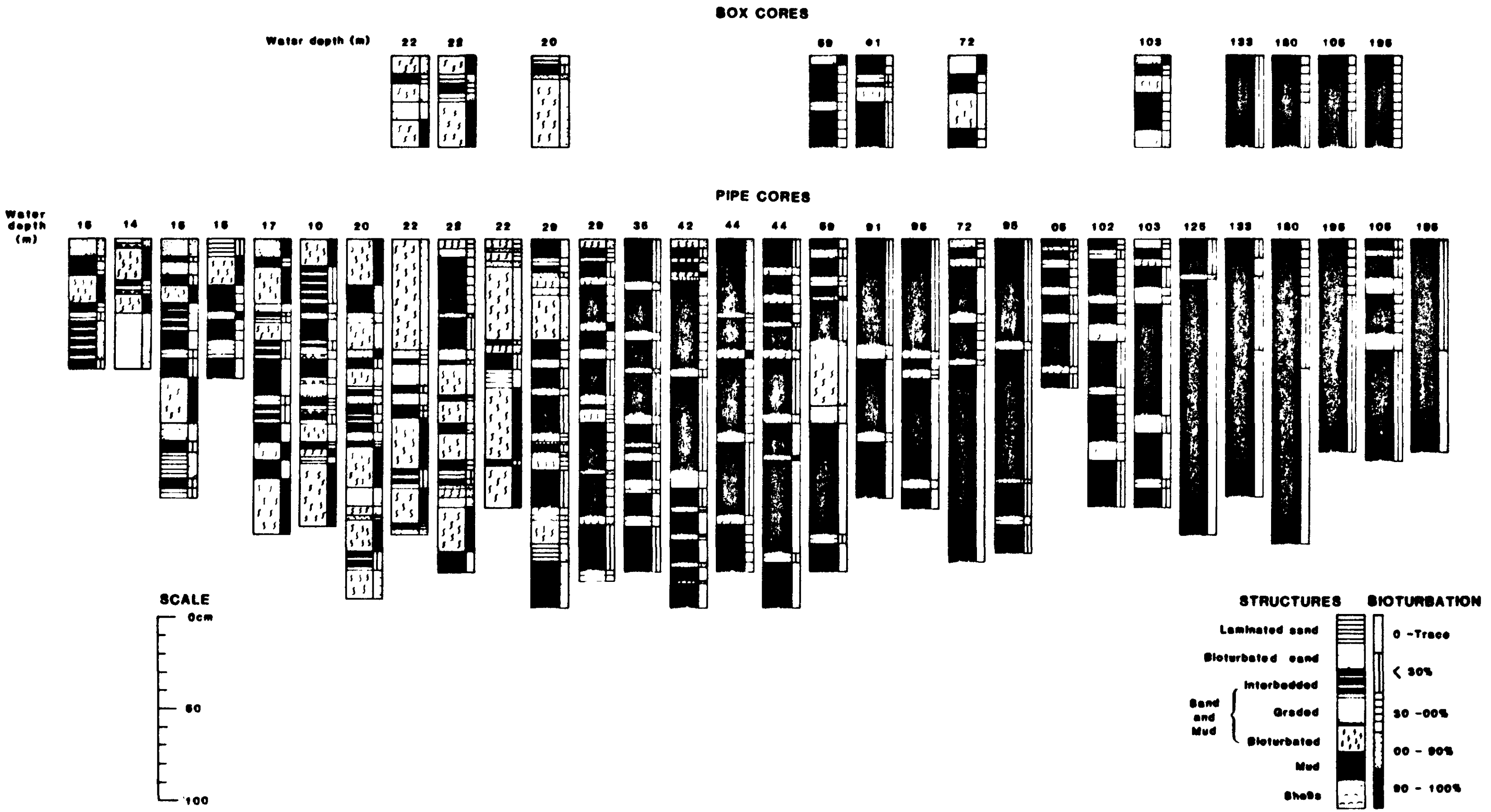
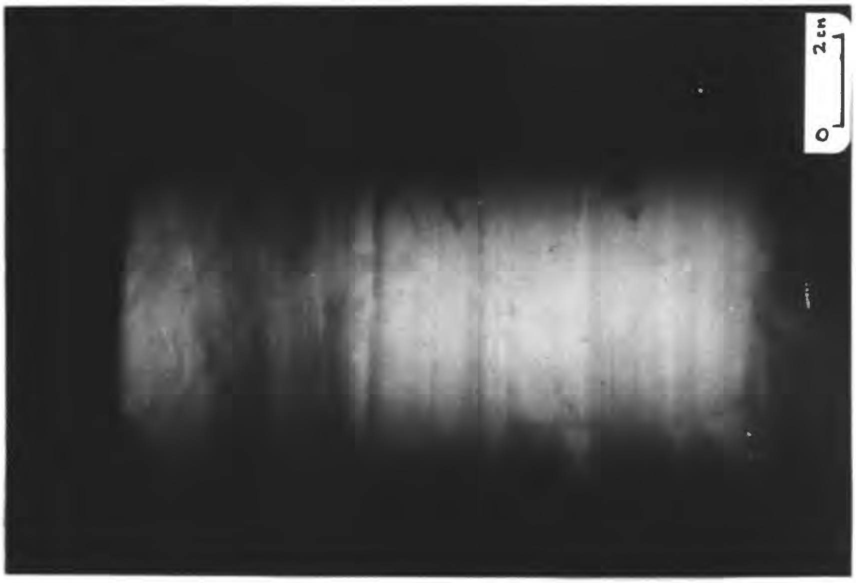


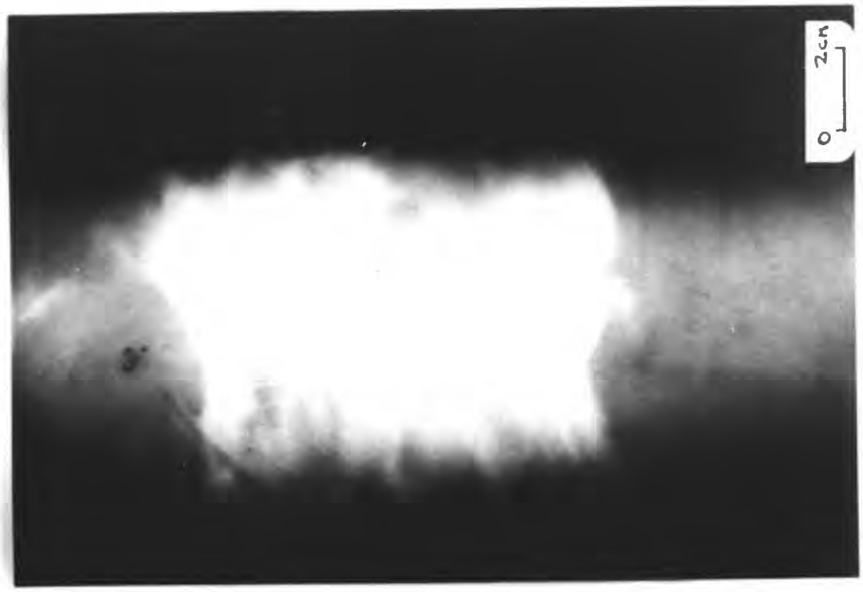
Fig. 6. Graphic display of cores. Symbols indicate various sedimentary structures. Degree of bioturbation is shown in the right-hand column (see also figure 9).


BOX CORES
Water depth (m)
22
28
20
59
61
72
103
133
150
165
185
PIPE CORES
Water depth (m)
15
14
15
15
17
19
20
22
28
22
29
29
36
42
44
44
59
61
66
72
85
96
102
103
125
133
150
165
165
185
SCALE
0cm
50
100
STRUCTURES
Laminated sand
Bioturbated sand
Sand and Mud
Interbedded
Graded
Bioturbated
Mud
Shells
BIOTURBATION
0 - Trace
< 30%
30 - 60%
60 - 90%
90 - 100%

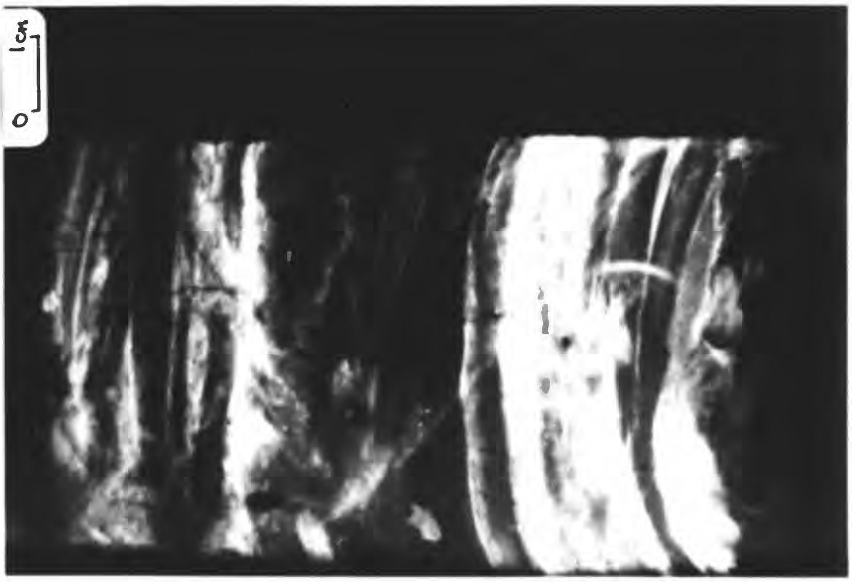
A



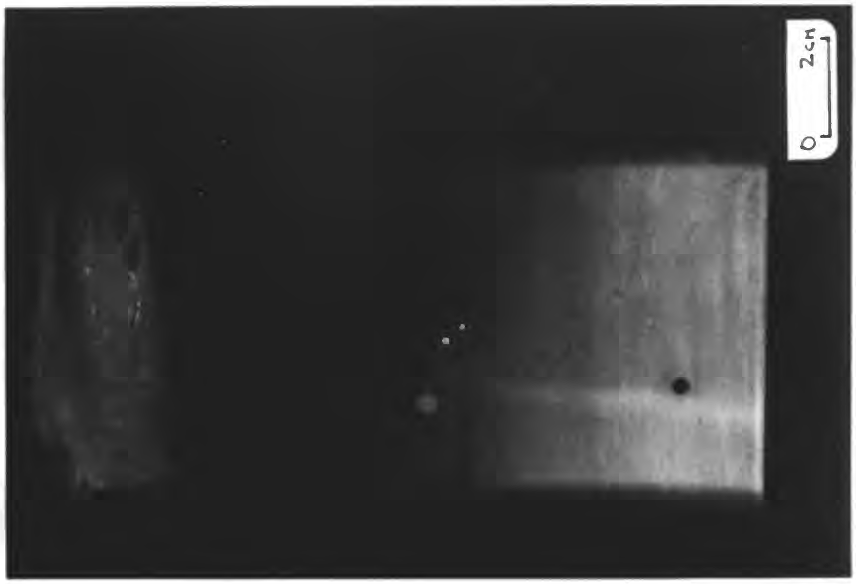
B



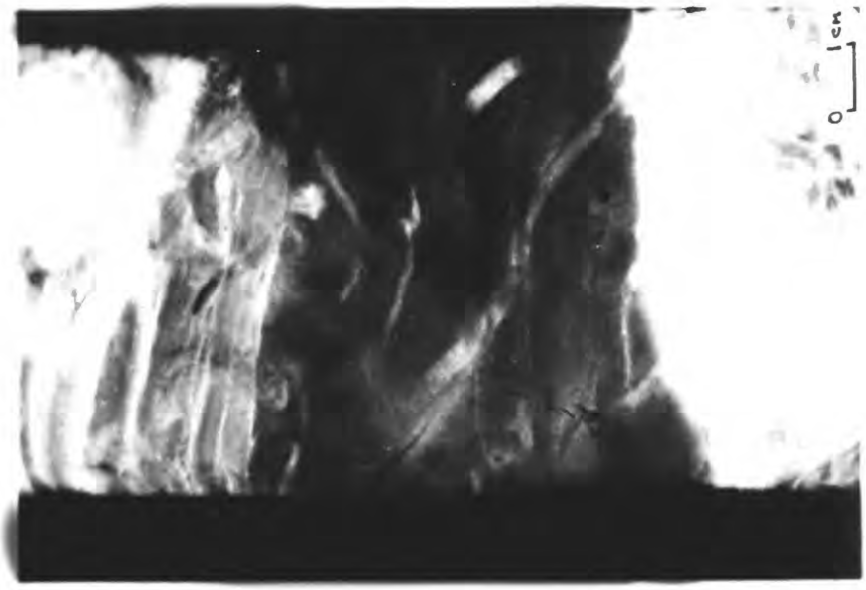
C



D



F



E

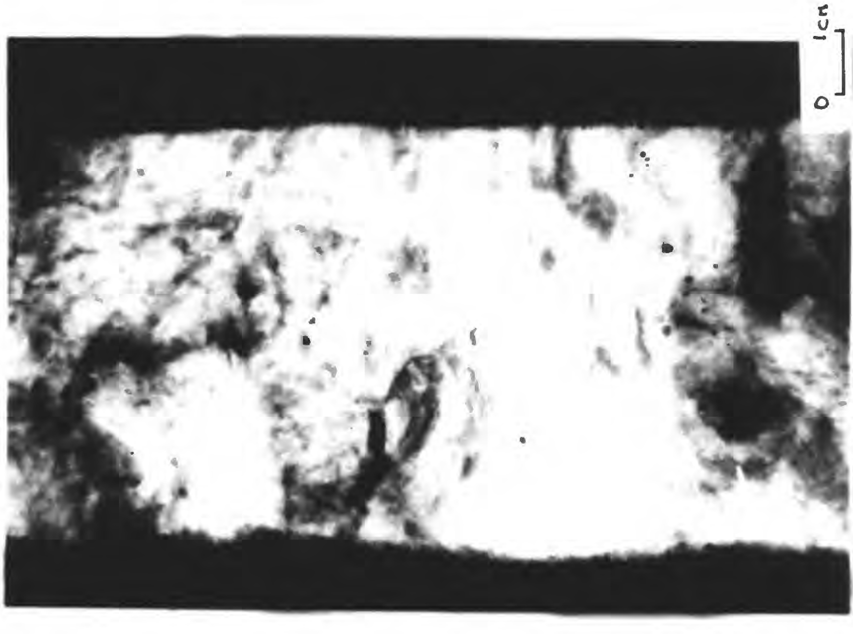


Fig. 8. Distribution of clean sand beds and sandless mud beds comparing bed thickness and abundance.

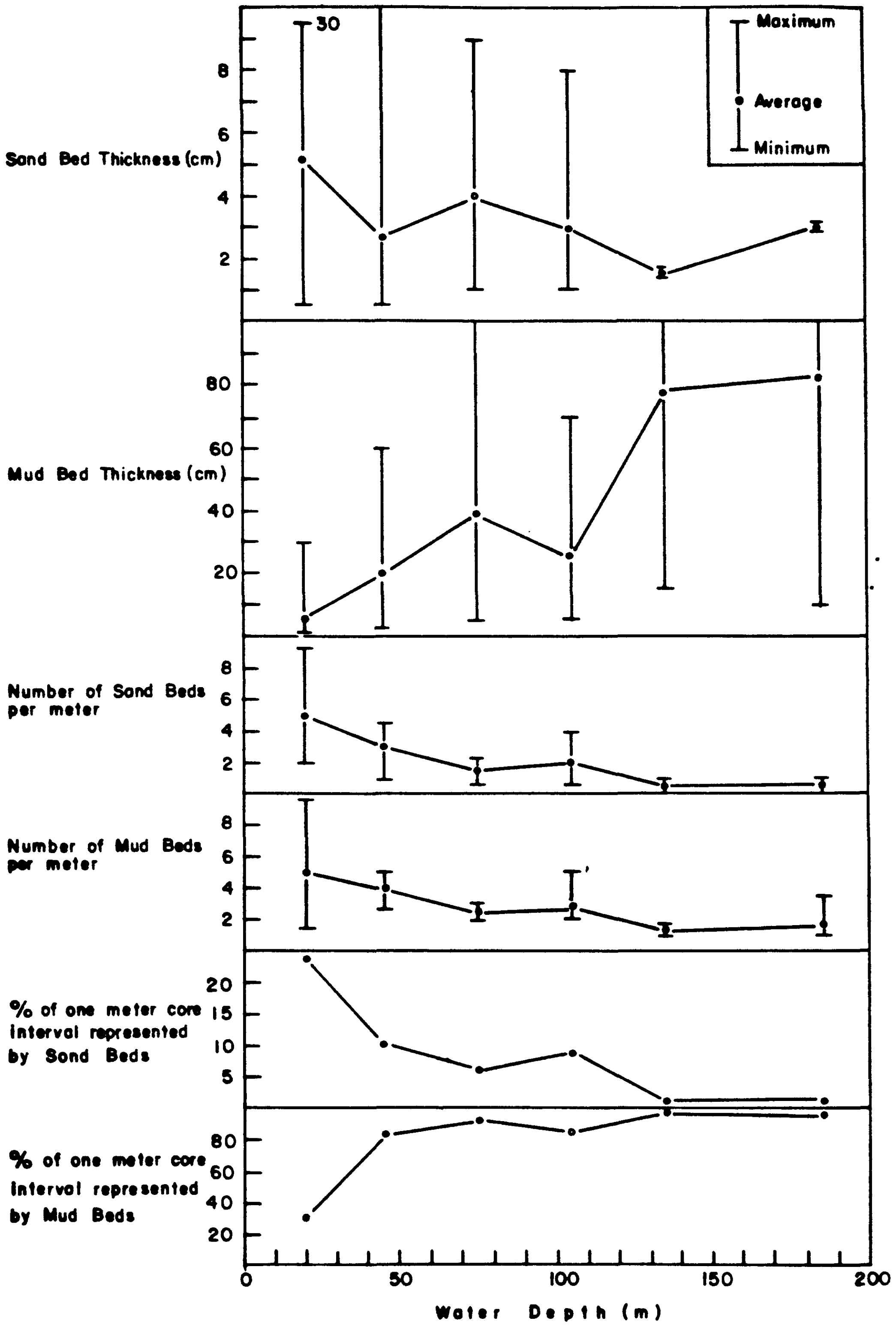

30
Maximum
Average
Minimum
Sand Bed Thickness (cm)
8
6
4
2
Mud Bed Thickness (cm)
80
60
40
20
Number of Sand Beds per meter
8
6
4
2
Number of Mud Beds per meter
8
6
4
2
% of one meter core interval represented by Sand Beds
20
15
10
5
% of one meter core interval represented by Mud Beds
80
60
40
20
0
50
100
150
200
Water Depth (m)

Fig. 9. Scale showing different degrees of general bioturbation. These are x-ray negatives where the mud is black and sand is grey.

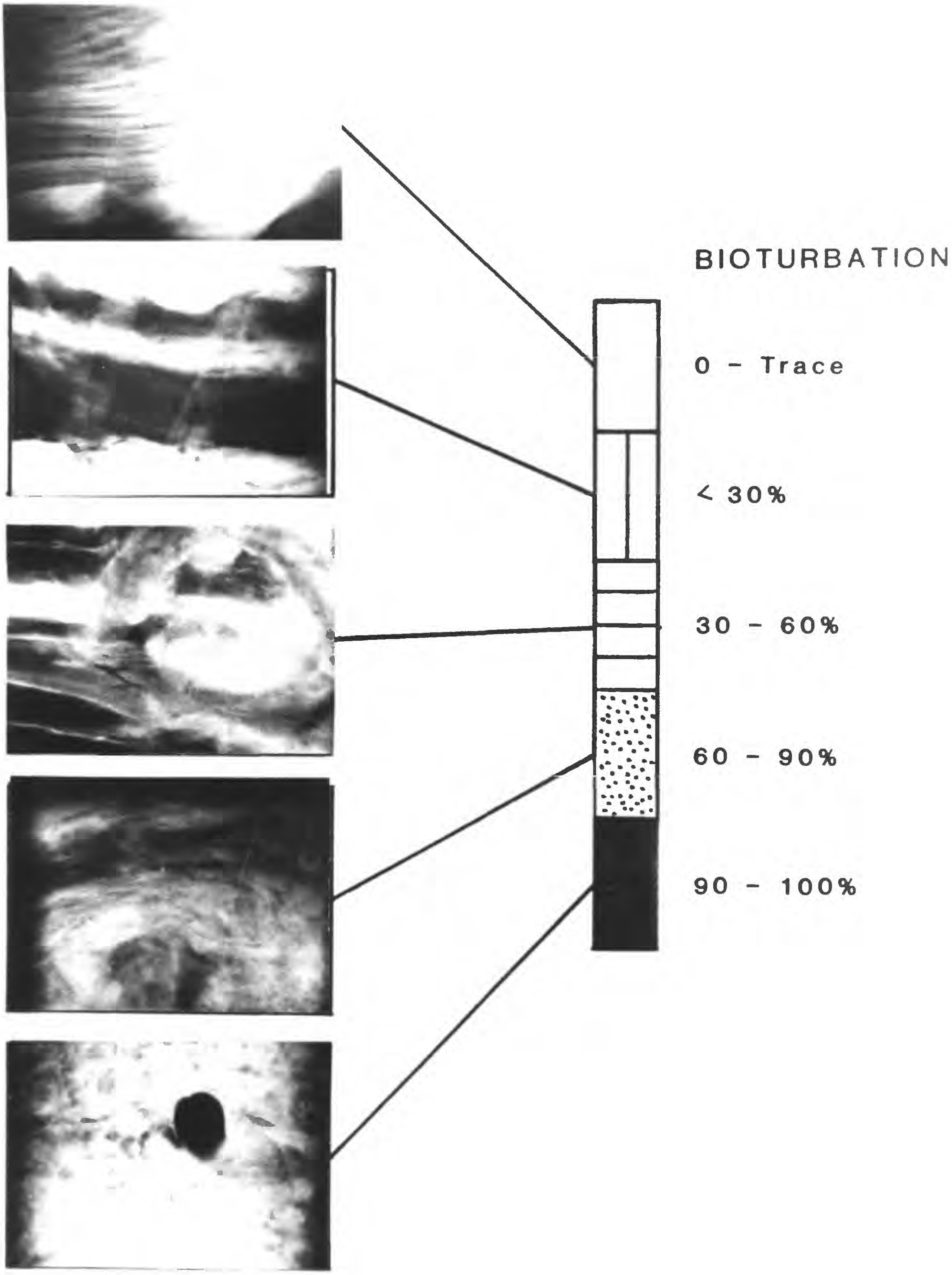

BIOTURBATION
0 - Trace
< 30%
30 - 60%
60 - 90%
90 - 100%

Fig. 10. X-ray negative showing very fine parallel laminations in a mud bed cored at 195 m of water depth.

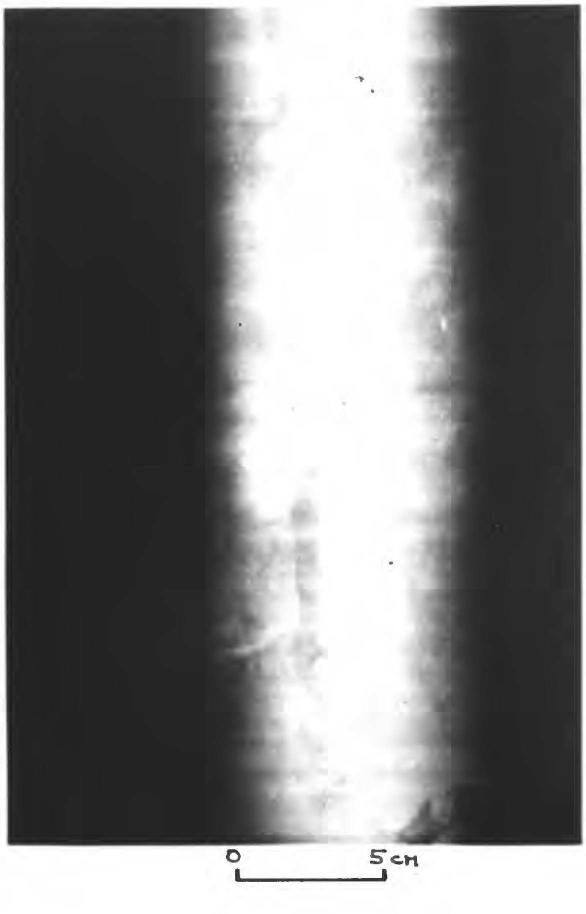

0
5 cm

Fig. 11. Relative thickness and vertical distribution of sedimentation units within major bed sequences of the (A) lower shoreface facies, (B) mid-shelf facies, and (C) outer shelf facies.

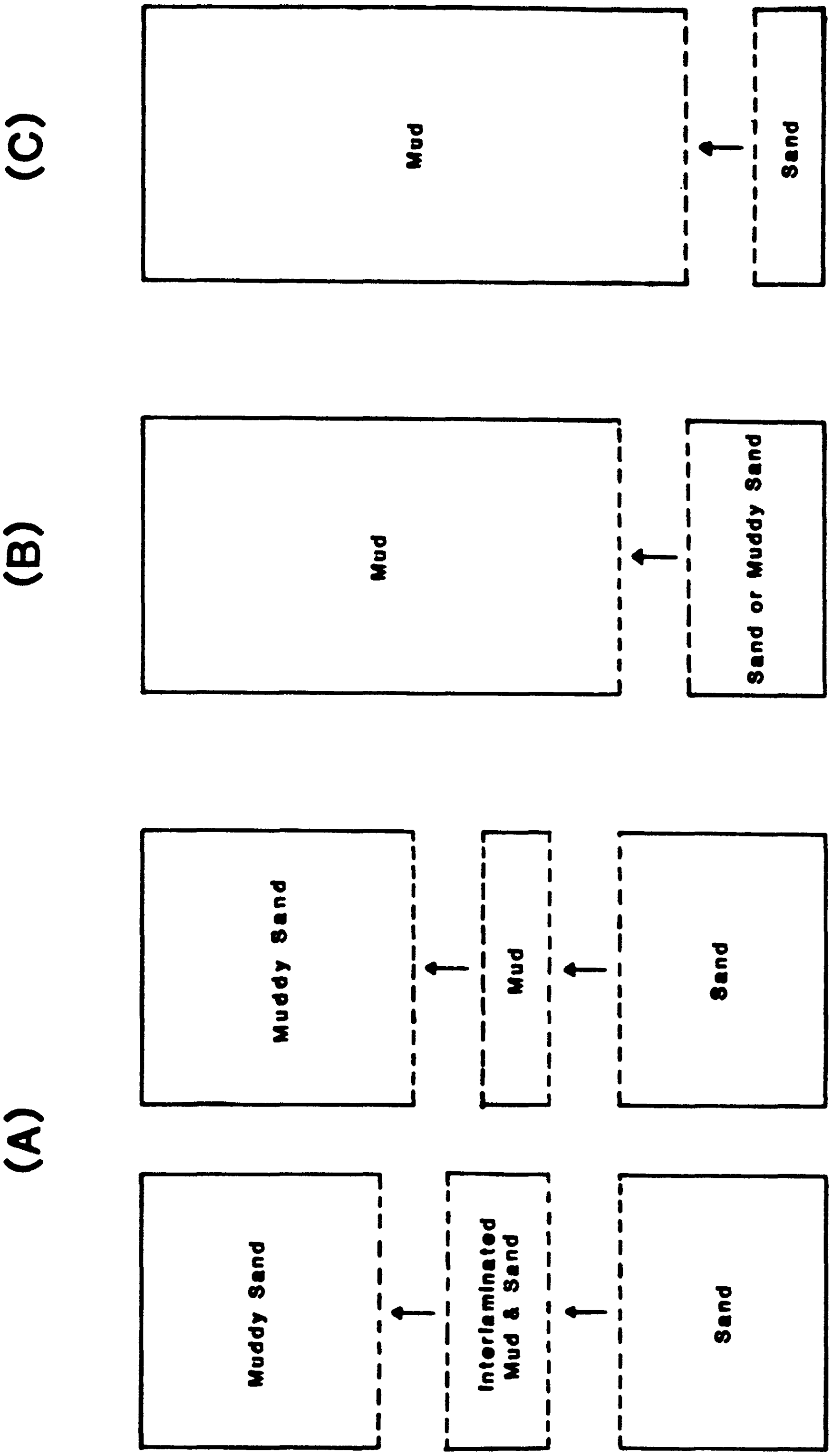
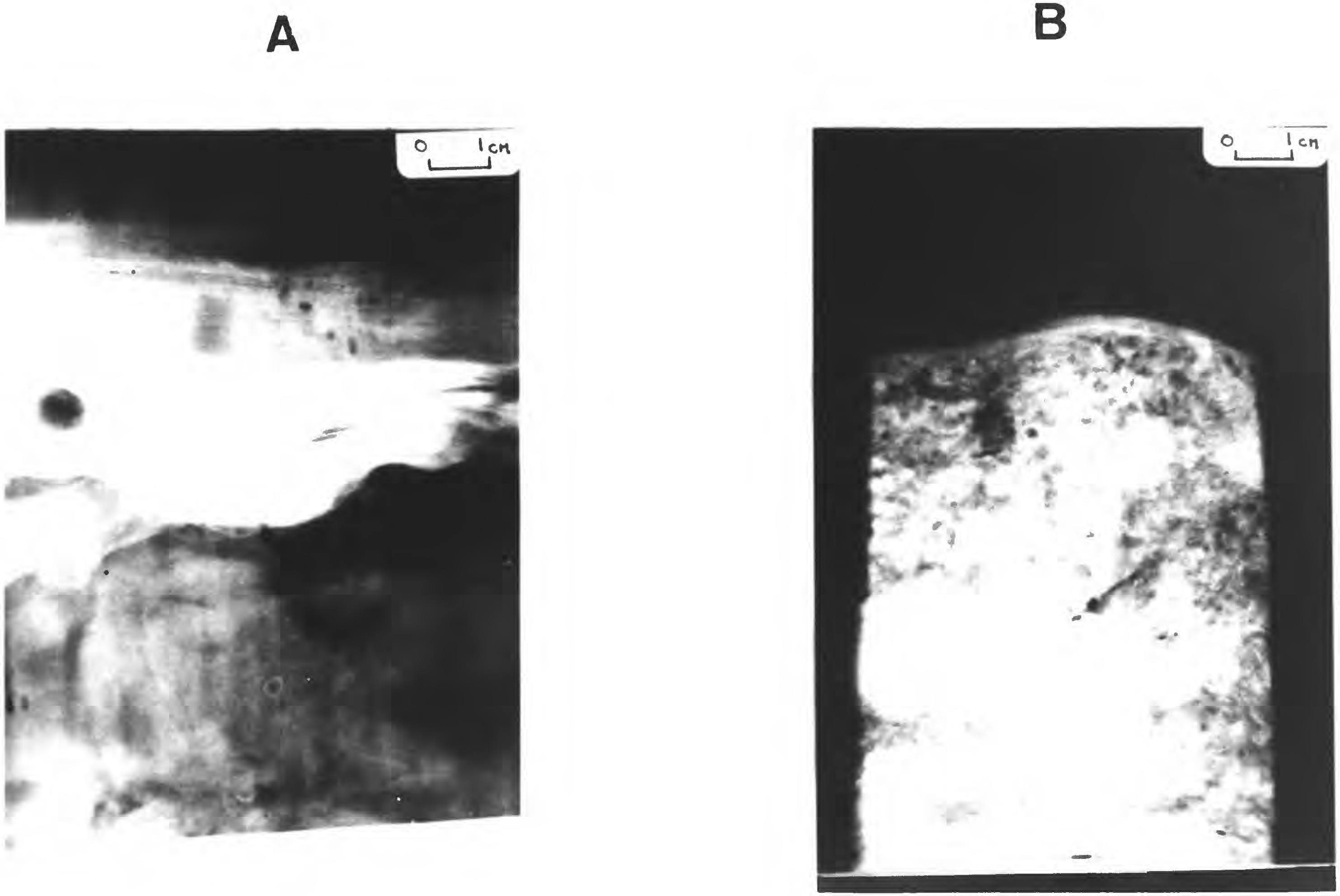

(A)
Muddy Sand
Interlaminated Mud & Sand
Sand
Muddy Sand
Mud
Sand
(B)
Mud
Sand or Muddy Sand
(C)
Mud
Sand

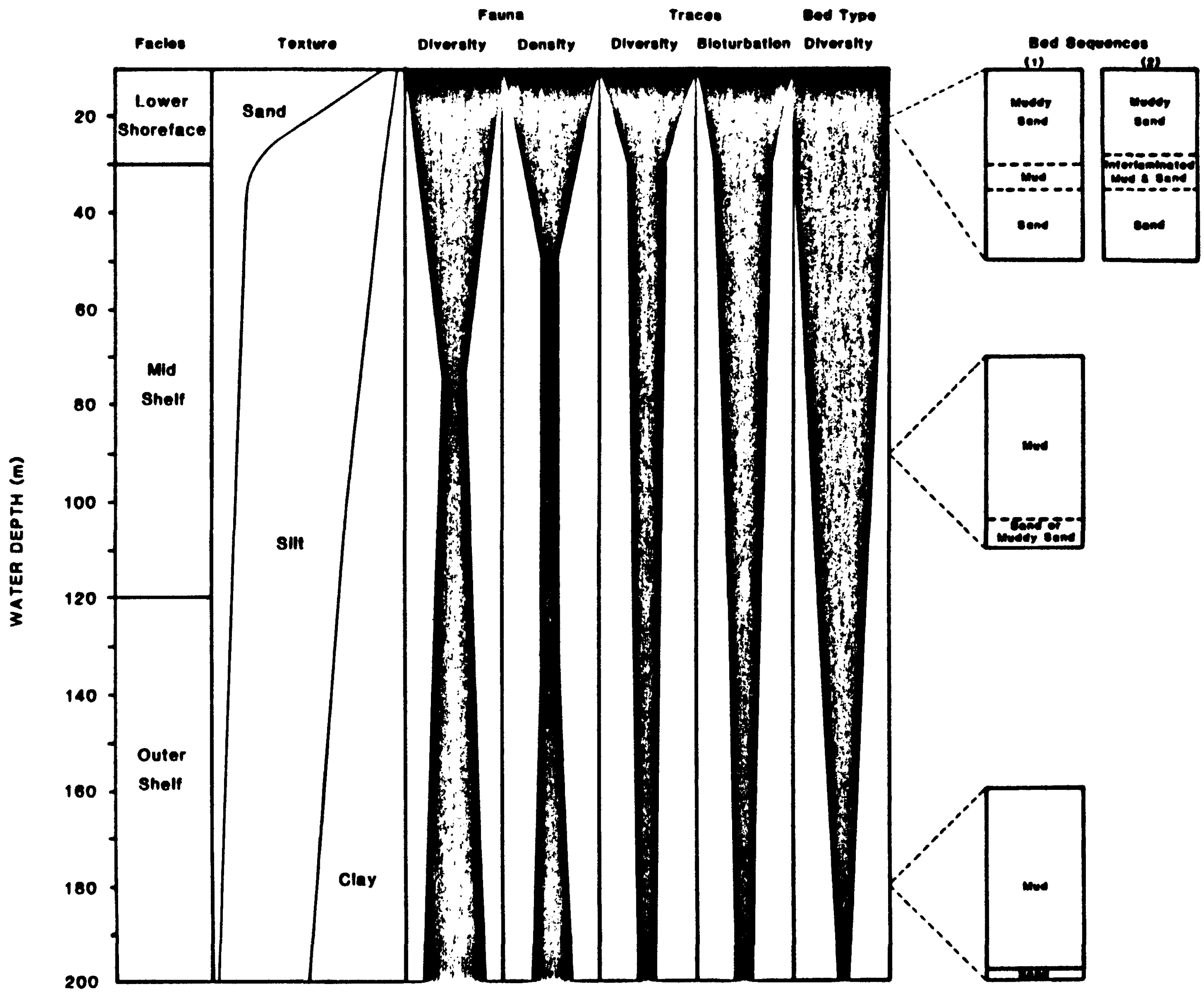
Fig. 12. Examples of bed contacts in cores. These are x-ray negatives where mud is black and sand grey.(A) sharp, irregular erosional contact;(B) sharp, smooth upper contact of a muddy sand bed;(C) variability along a single bed from a laminated bed with diffuse basal contact.



3a

C

Fig. 13. Vertical sequence of biological and geological characteristics in a lower shoreface to outer shelf sequence within the study area.


Facies
Texture
Fauna
Diversity
Density
Traces
Diversity
Bioturbation
Bed Type
Diversity
Bed Sequences
(1)
(2)
Lower Shoreface
Mid Shelf
Outer Shelf
Sand
Silt
Clay
Muddy Sand
Mud
Sand
Muddy Sand
Interlaminated Mud & Sand
Sand
Mud
Sand or Muddy Sand
Mud
WATER DEPTH (m)
20
40
60
80
100
120
140
160
180
200