

# **Deltaic Sand Bodies**

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DELTAIC SAND BODIES

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## Introduction

Deltaic depositional facies result from interacting dynamic physical processes (wave energy, tidal action, climate, etc.) which modify and disperse riverborne clastics. Since ancient times, river deltas have been of fundamental importance to civilization. Owing to their early significance as agricultural lands, deltas received considerable attention from scholars such as Homer, Herodotus, Plato, and Aristotle. More recently, subsurface deltaic facies have played a paramount role in accommodating the world's energy needs; ancient deltaic sediments have provided source beds and reservoirs for a large percentage of the known petroleum reserves. The facies relationships and mechanisms responsible for development and distribution of deltaic sand bodies must be understood before they can be explored efficiently.

Deltaic environmental settings normally exhibit many of the characteristics required of a potential hydrocarbon-producing basin--multiple types of reservoir rocks, immediate or nearby source beds, a wide variety of structural and stratigraphic traps, and a buildup of considerable thickness of clastic rocks that are rapidly varied.

This short course will cover three major aspects of deltaic sediments: (a) the main processes responsible for the formation of sand bodies; (b) the sedimentary characteristics of the deposits (both sub-

aerial and subaqueous delta sequences); and (c) the variability of delta sediments that are deposited under a wide range of depositional facies. The modern Mississippi River will be used to illustrate the first two aspects. A considerable amount of subsurface data is available, and a large number of process studies provide the basis for this portion of the course. The discussion of the variability of deltaic deposits is based on the study of a considerable variety of depositional settings that has been conducted by personnel of the Coastal Studies Institute, Louisiana State University, during the past 20 years.

### Deltaic Settings

The term "delta" was first applied by the Greek historian Herodotus in approximately 450 B.C. to the triangular alluvial deposits at the mouth of the Nile River. In broader terms, deltas can be defined as those coastal and nearshore features that have been built by riverborne sediments. Included in this definition are those sediments that have been sorted by various marine agents such as waves, currents, and tides and redeposited in the delta plain and its nearshore waters. The various physical, chemical, and biological processes that control delta development vary appreciably on a global scale, and hence the landforms in deltaic regions span nearly the entire spectrum of coastal features and include distributary channels, rivermouth bars, interdistributary bays, tidal flats, tidal ridges, beach dune complexes, swamps, marshes, and evaporite flats.

Deltaic deposits are found where a stream debouches into a receiving basin, whether the receiving basin is an ocean, inland sea, bay, estuary, or lake. Despite the various environmental contrasts, all actively prograding deltas have at least one common attribute: a river

supplies clastic sediment to the coast and inner shelf more rapidly than marine processes can remove it. A river system generally consists of four primary components: drainage basin, alluvial valley, delta plain, and receiving basin (Fig. 1). The drainage basin basically is the source of the water and sediments, and processes within this component determine the sediment-water supply and the initial size and composition of the sedimentary load. The tributaries within the drainage basin act as a gathering point for the sediments and waters that begin the journey toward the sea. Eventually the tributaries merge into one or more major channels, and the alluvial valley is formed. The alluvial valley is essentially a conduit in which the river flows over and through its own deposits. As a result of migration of alluvial channels, there is often continuous sorting of the sediments and alterations to the size and composition of the sediment suite entering the valley from the drainage basin. At some point along its length the river ceases to function primarily as a transporting agent and becomes a dispersal system. Sediments accumulate and begin the formation of the delta plain. This component of a river system results primarily from interaction between riverine and marine processes. The morphology and geometry of the deltaic deposits reflect the hydraulic regime, sediment load, geologic structure and tectonic stability, climate, tides, winds, waves, water density contrast, coastal currents, and the innumerable interactions of all these factors. The receiving basin is the recipient of the riverborne clastic sediments. The characteristics of the receiving basin are among the most important process controls in the development of a delta, and the various oceanographic nearshore processes on a delta coast are crucial to the shaping and remolding of the riverborne sediments.

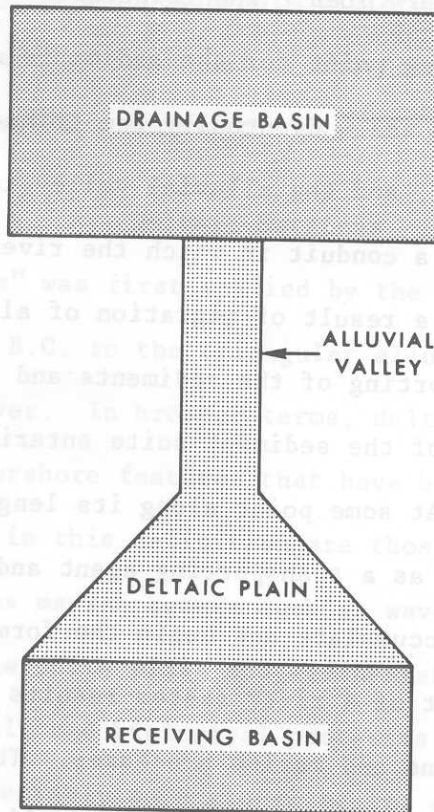


Figure 1. Components of a river system.

A delta plain can generally be subdivided into basic physiographic zones, which commonly include rather restrictive environmental settings and to a large degree control the types of deposits that are present within these zones. Figure 2 illustrates the major components of a delta plain. The subaerial component of a delta is usually divided into the upper and lower delta plains. The upper delta plain is normally the oldest part of the subaerial delta and exists above the area of significant tidal or marine influences. Unfortunately, in ancient rock sequences only faunal evidence can be used to separate these two aspects of the delta. Commonly the upper delta is essentially the continuation of the alluvial valley and is dominated by riverine processes. The lower delta plain lies within the realm of river-marine interaction and extends landward from the low-tide mark to the limit of inland tidal influence. The lower delta plain is most extensive in areas where tidal ranges are large and seaward gradients and topographic relief are low. The subaqueous delta plain is that part of the delta that lies below the low-tide level and contains a relatively open marine fauna. The extent of the zone of influence of the delta into its receiving basin varies considerably from delta to delta; in some deltas, sediments derived from the river mouth are carried offshore to water depths beyond the edge of the continental shelf. Most commonly, the subaqueous delta is characterized by seaward fining of the sediments. The sands and the coarser clastics are deposited near the river mouths, and the finer grained sediments are dispersed farther seaward.

Figure 3 shows the location of the major modern world deltas. As can be seen, they span the climatic zonation from the cold Arctic through the temperate zones to the tropics and along arid coastlines.

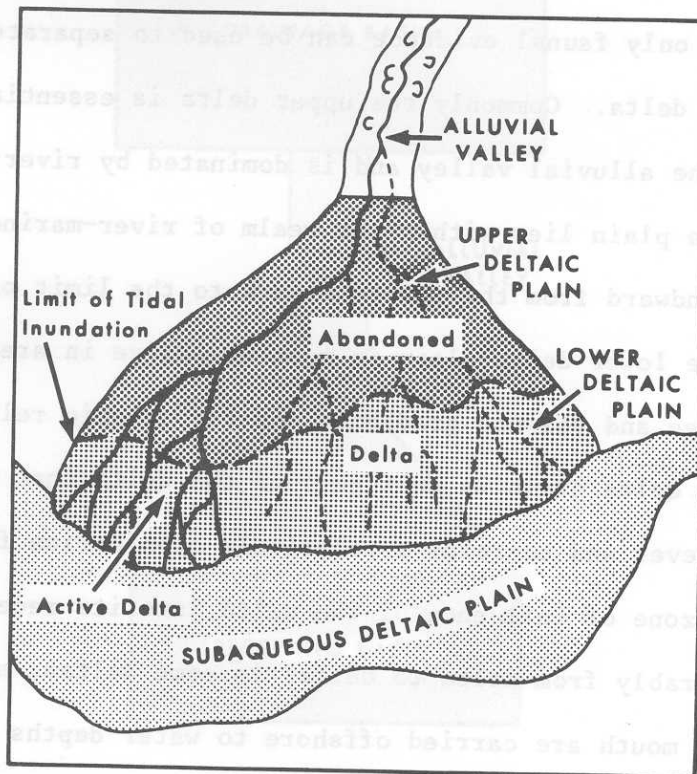


Figure 2. Components of a delta plain.

Thus modern deltas provide a fairly good sampling of the role that climate plays in controlling depositional processes. Modern deltas debouch their sediment-water discharge into a large variety of receiving basins. They range from extremely small inland settings such as the Black Sea to larger semi-interior basins such as the Mediterranean and the Gulf of Mexico and on to broad continental shelves that front major oceanic basins such as the Pacific and Atlantic. In addition, a large number debouch into narrow seaways and semi-enclosed tectonic graben structures. Marine processes are also highly variable along modern delta coasts, which range from those that have extremely low wave energy, such as the deltaic coasts of the Nile, Mississippi, and Danube Rivers, to those that have extremely high wave energy such as the Senegal and the Sao Francisco, which debouch onto continental shelves fronting the major South Atlantic stormy seas. Tidal variation also shows considerable ranges into which the deltas must prograde. Low-tide deltas such as the Mississippi, the Nile, and the Danube contrast strongly to those deltas where tidal range can be extremely high (up to 10-15 m), such as the delta plains of the Ord River, in Western Australia, and the Ganges-Brahmaputra, in Bangladesh. Thus, although modern deltas all display common components, their size, shape, and subsurface relationships vary from delta to delta. In order to interpret and exploit efficiently ancient deltaic sequences, it is of fundamental importance to understand the mechanisms controlling the formation and distribution of deltaic sand bodies.

#### Deltaic Processes

Interacting physical, biological, and chemical processes during the time of deposition exert significant control over the distribution,

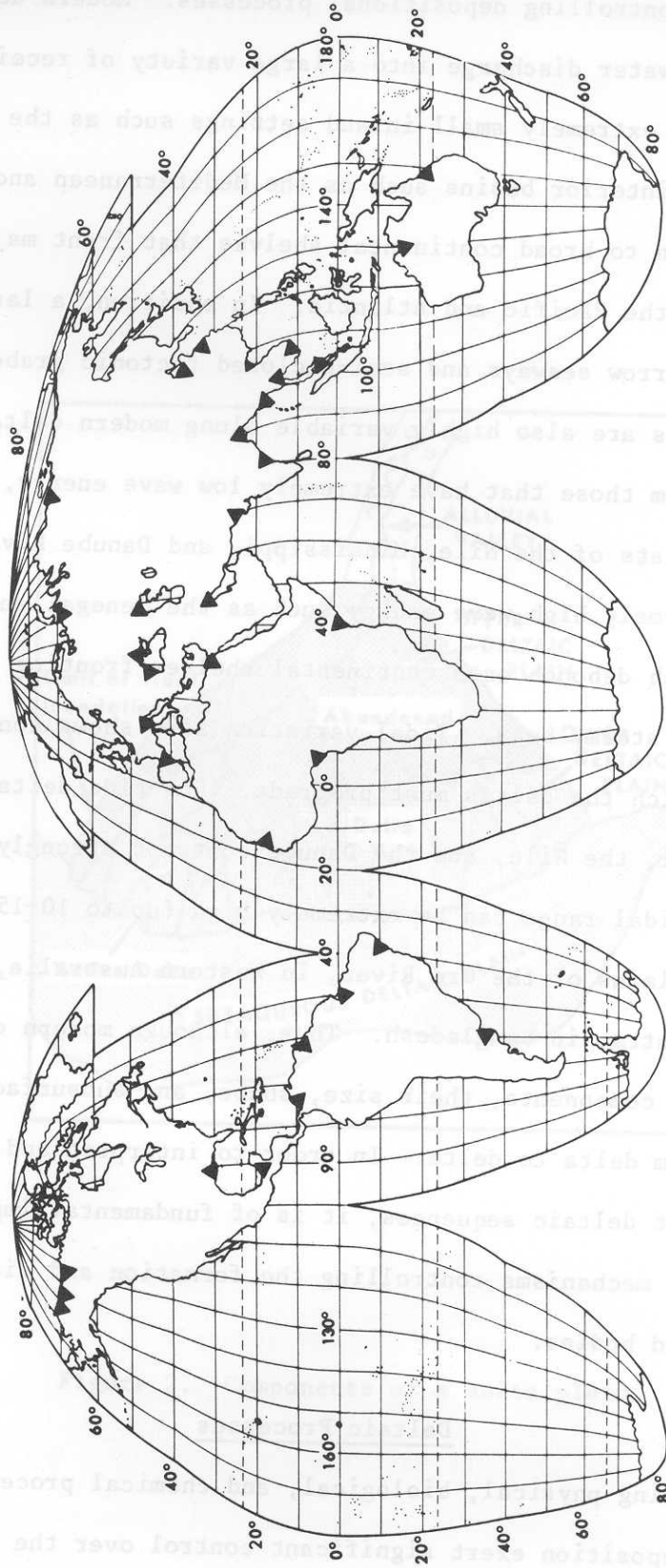


Figure 3. Location of major modern delta plains.

orientation, and internal geometry of deltaic sand bodies. Figure 4 illustrates schematically some of these major process variations that exist within the drainage basin, alluvial valley, delta plain, and receiving basin. Factors such as climate, vegetation, and soil and the geology and tectonic history of the receiving basin play an important role in controlling the size and composition of the sediments that are debouched into the alluvial valley. Within the alluvial valley, climate and morphology control the degree to which sediments are traded and exchanged on their journey toward the delta. Factors such as wave energy, tidal processes, and tectonics of the receiving basin play a major role in the development of the sand bodies. A considerable amount of effort has been directed toward attempting to understand and quantify the processes operative in modern world deltas so that assessment can be made as to the direct role they play in shaping delta environments. These studies have indicated that the most important processes are climate, water and sediment discharge and its variability, sediment type and yield, river-mouth processes, nearshore wave power, tides and tidal regime, nearshore currents, shelf slope, and tectonics and geometry of the receiving basin.

### Climate

More than any other single factor, climate determines the variation in intensity of the physical, chemical, and biological processes active within all components of river systems. The major control it exerts is as follows:

A. Runoff is a function of precipitation, which is controlled by weather systems operative within the drainage basin. In large tropical basins, precipitation is normally high and the result is a continual

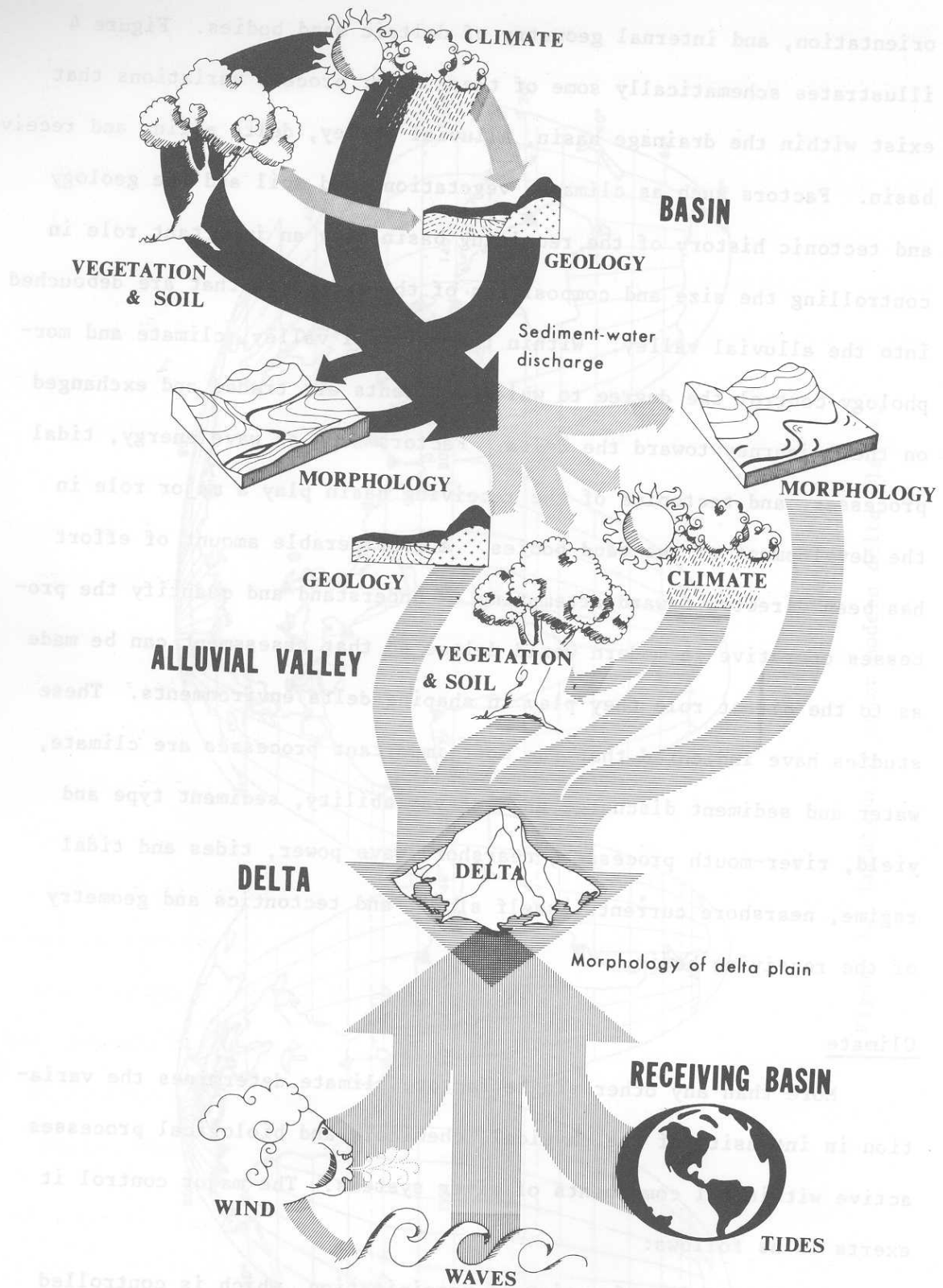


Figure 4. Major process controls on river systems.

supply of sediments and water to the alluvial valley. The volume of sediment-water mixture is not extremely erratic under these conditions, and the channels normally display rather stable patterns. In contrast, in arid or arctic drainage basins precipitation is normally erratic. Channels in such systems tend to migrate considerably and to be extremely unstable. Braided channel patterns are the most common, and in most instances the ratio of bed load to suspended load is quite high.

B. Climate controls the composition and quantity of in situ deposits. Tropical and arctic environments are conducive to the production and preservation of organic material, and commonly peat forms the bulk of the subaerial deposits. High bioturbation is common in all of the subaerial environments. The abundance of organic detritus, combined with a favorable environment for preservation, results in accumulations of thick in situ and transported organic debris, both within the sand body and encasing sand bodies. In temperate and arid climates organic production can be high, but preservation is generally less efficient than in tropical areas. The rapid degradation of in situ organics releases complex chemical solutions to the water column and to the pore waters. As a result, diagenetic products are produced rapidly, and in many instances prevent excessive compaction of the deltaic sequences. In arid conditions evaporation plays a significant role. Evaporites and chemical precipitants form the major deposits that cap delta sand bodies.

### Discharge Regimes

Temporal discharge tendencies and variation in discharge throughout a hydrologic year exert a great influence on alluvial valley and deltaic sand geometries. The major controls exerted are:

A. Formation of alluvial valley channel patterns. When discharge variations are small, channels are better able to adjust to an equilib-

rium configuration, and in these instances primarily meandering channels result and sand bodies are of the elongate shoestring type. When discharge is highly erratic, channels do not have sufficient time to adjust to any given flow, and as a result may be unstable much of the year.

Braided patterns often result, as the river tends to change its course frequently and migrate rapidly and erratically. This type of channel migration often produces sheet sands, which are associated with broad, constantly shifting braided channels.

B. Size and sorting of the sediment load. Extremely erratic discharge in rivers results in relatively coarse and poorly sorted sediments. Sand bodies are often clay bound and show little or no permeability. Under less erratic but constant discharge sand bodies normally display better sorting both vertically and laterally. Meander-belt sand bodies, produced by regular discharge patterns, tend to show a fining-upward sequence, whereas braided channel sands produce more erratic grain-size variations both laterally and vertically within the alluvial sand bodies.

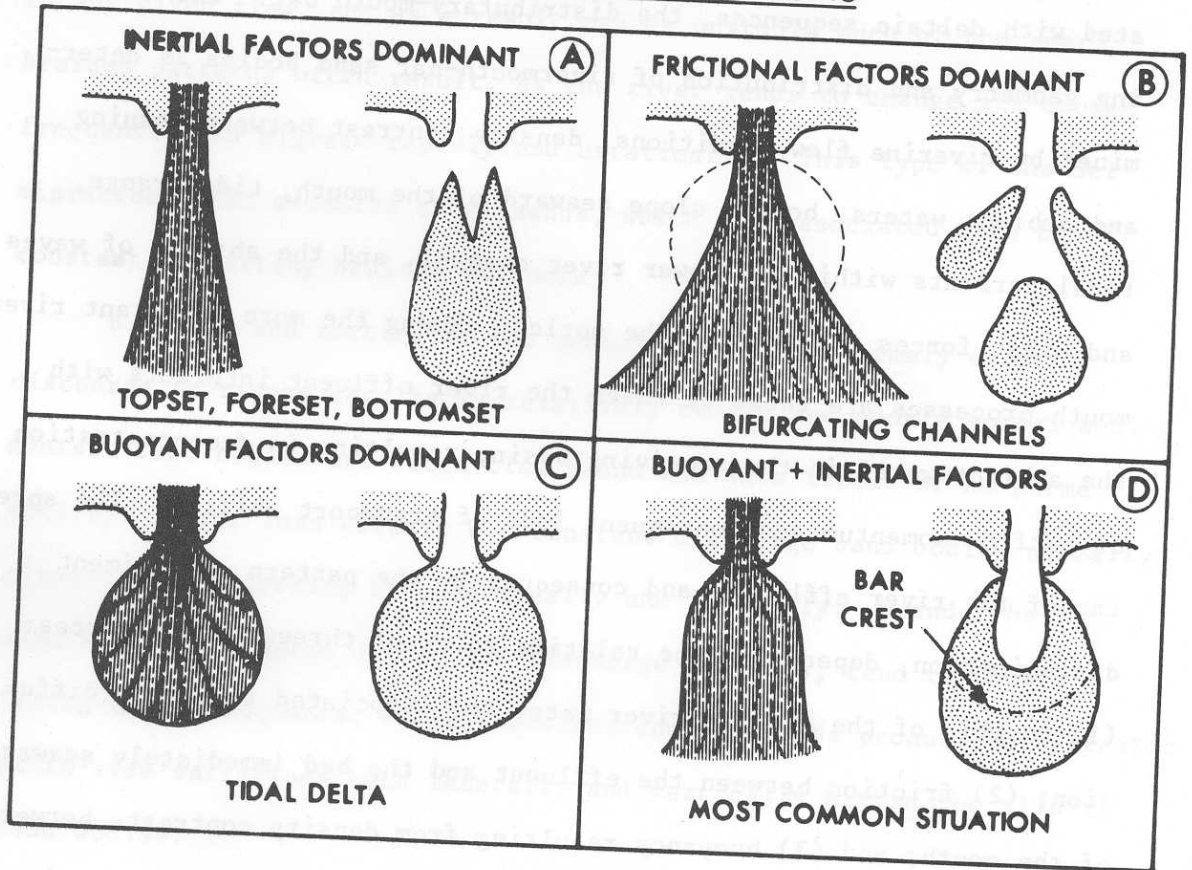
C. Rate and pattern of delta growth. In river systems where sediment-water discharge is constant and high all year, long, linear sand bodies commonly trend at high angles to the coast. In cases in which sediment yield and water discharge are extreme throughout the year, marine processes have ample opportunity to rework sands delivered to the coast, and often linear sand bodies form more parallel to the shoreline.

#### Rivermouth Processes

The river mouth is the point at which the seaward-flowing water leaves the confines of the channel banks and spreads and mixes with

ambient waters of the receiving basin. It is the dynamic dissemination point for sediments which contribute to continuing delta progradation and is responsible for forming one of the major sand bodies associated with deltaic sequences, the distributary-mouth bar. The resulting geometry and distribution of rivermouth-bar sand bodies is determined by riverine flow conditions, density contrast between issuing and ambient waters, bottom slope seaward of the mouth, tidal range, tidal currents within the lower river channel, and the ability of waves and other forces to obstruct the outlet. Among the more important rivermouth processes are those by which the river effluent interacts with the ambient water in the receiving basin, resulting in deconcentration of outflow momentum and consequent loss of transport ability. The spreading of the river effluent, and consequently the pattern of sediment dissemination, depends on the relative roles of three primary forces: (1) inertia of the issuing river water and associated turbulent diffusion; (2) friction between the effluent and the bed immediately seaward of the mouth; and (3) buoyancy resulting from density contrasts between issuing and ambient fluids. Figure 5 shows schematically these major rivermouth mechanisms. When outflow velocities are high, depths seaward of the river mouth are relatively large, and density contrasts are negligible, inertial forces will dominate and the effluent will spread and diffuse as a turbulent jet. When this force is dominant, the distributary-mouth bars are generally linear in nature and spread laterally a minimal distance. Such deposits are often quite thick. Coarse sediments fall out immediately in the vicinity of the river mouths, and quite commonly the vertical sequence in such deposits changes rapidly from fine-grained marine clays upward into coarser rivermouth-bar sands. Lateral continuity of sand deposits is normally low.

## RIVER MOUTH MECHANISMS



### LEGEND

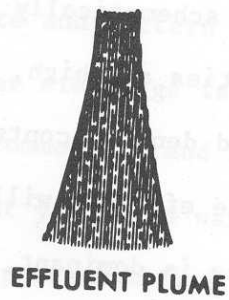


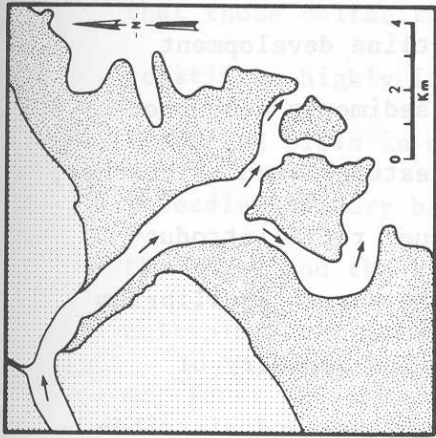
Figure 5. River-mouth mechanisms.

In regions where the water seaward of the mouth is shallow, turbulent diffusion becomes restricted to the horizontal and bottom friction plays a major role in causing effluent deceleration and expansion. Initially the rapid rate of effluent expansion characteristic of this type of river mouth produces a broad, arcuate radial bar; however, as deposition on the bar continues, natural subaqueous levees develop beneath the lateral boundaries of the expanding effluent, where velocity gradients are steepest. Development of the levees tends to inhibit further increases in effluent expansion, so that with continuing bar accretion continuity can no longer be maintained simply by increasing effluent width. As the central portion of the bar grows upward, channelization develops along the thread of maximum turbulence, which tends to follow the subaqueous levees. This process results in a bifurcated channel pattern, which has a triangular middle-ground shoal separating the diverging channel arms. This type of distributary-mouth bar is extremely common in many modern river deltas.

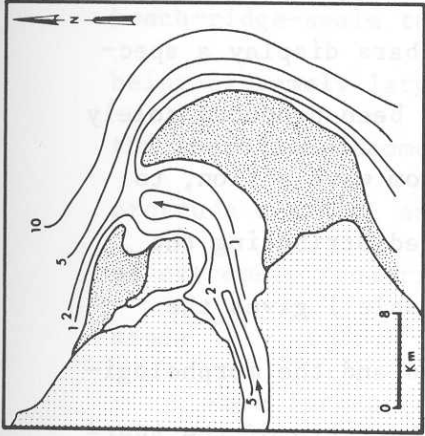
A third process results from density differences between effluent waters and receiving-basin waters. Most of the world's major rivers debouch into saltwater basins, and a density difference exists between the fresh river water and the normal oceanic basin water. Although suspended material increases the density of fresh water slightly, suspended load in most rivers creates a density difference that is extremely small in comparison to that created by the salt content of marine water. In such cases turbulent diffusion tends to be generally suppressed, and lateral effluent expansion occurs, largely as a result of buoyant spreading of the fresh water as a relatively homogeneous layer. The outflowing and spreading freshwater effluent decelerates radially away from the river mouth. Coarse sands are deposited in the immediate vicinity

of the river mouth, and fine-grained sediments are deposited seaward. In such cases the distributary-mouth bars are relatively thin and tend to show high lateral continuity.

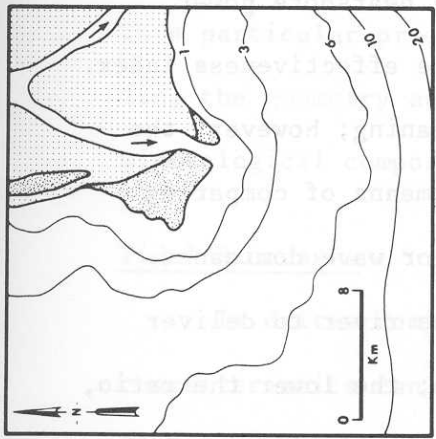
In most natural situations, however, it is the combination of these three major forces that controls the major geometry of the resulting sand bodies. Figure 6 shows in plan view the major types of river-mouth bars, as seen on a hydrographic map. This figure shows that there are large variations in the plan-view geometry of distributary-mouth bars, most of which occur primarily because other forces begin to play important roles. Processes such as waves, tides, and tidal currents resuspend and rework sediments and carry them to downdrift areas, and thus change the configuration of the rivermouth bars. Although details of these types of patterns can be assessed in modern river deltas, it is highly probable that in ancient rock sequences and in bore holes little or no major change can be detected in the basic plan-view geometry. The major differences that would be seen are between those distributary-mouth bars that are deposited in rather low-tide regions, where little or no evidence of tidal reworking can be found, and distributary-mouth bars deposited in areas dominated by high tide, in which internal sedimentary characteristics can normally be discerned in cores and serve as a clue to the changing geometry of the rivermouth bar. The geometry of distributary-mouth bars and high tidal ridges results primarily from strong bidirectional sediment transport. This process leads to the formation of large, linear tidal ridges immediately seaward of the river mouth (Fig. 6E). These ridges are commonly composed of coarse river-borne sand and vary considerably in size. Often the ridges are oriented parallel to the river channel. Such sand bodies are common in a number of modern world deltas, and it is suspected that they are present in



C- Middle ground



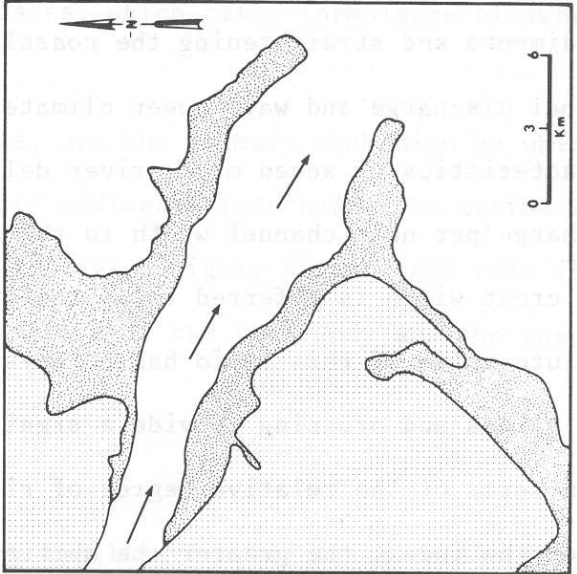
B- Lunate



A- Radial



E- Tidal ridges



D- Subaqueous jettied

Figure 6. Types of river-mouth bars.

many ancient sequences but have not been recognized to date.

### Wave Energy

No single factor plays a greater role in coastline development than wave regime. Waves sort and redistribute the sediments debouched by rivers and mold these sediments into shoreline features such as beaches, barriers, and spits. In deltaic regions the continued rapid introduction of sediments by a riverine source interrupts the normal equilibrium between a wave regime and depositional topography. The geometry of many deltaic sand bodies depends not only on the magnitude and distribution of wave forces but also on the ability of the river to supply sediments. In a worldwide setting, distributary-mouth bars display a spectrum of configurations ranging from those that have been produced solely by debouchment of the river without interference from wave action, to those that reflect complete dominance by waves in redistributing the river sediments and straightening the coastline. Table 1 gives the mean annual discharge and wave power climate indices and the morphological characteristics of seven major river deltas. The ratio of the average discharge per unit channel width to the average nearshore power per unit crest width is referred to as the discharge effectiveness index. The absolute value of this ratio has no physical meaning; however, the relative values and ordering provide a significant means of comparing deltas in terms of the relative degree of riverine or wave dominance. The higher the index, the greater the ability of the river to deliver sediments to the shoreline unimpeded by wave action; the lower the ratio, the greater the dominance of extreme wave energy over deltaic-riverine processes. In the latter case wave processes contribute significantly to reworking of the river-derived sediments. The attenuation ratio

shown in the table indicates the extent to which wave power is lost through friction between deep water and the shoreline. The table shows that those deltas that are primarily river-dominated tend to display coastlines highly indented by multiple extended digitate distributaries. The delta plain in many cases consists of marsh and closed and shallow interdistributary bays. In intermediate-wave-energy deltas, such as the Niger and the Nile, the shoreline may be smooth and arcuate, and multiple river mouths protrude slightly from the shoreline. Sand beaches may front the shoreline, and small ridge-and-swale topographies may exist behind the major beach-ridge systems. Within the delta plain beach-ridge-swale topography is most common, the swales in many cases being extremely large. As wave energy attains higher and higher levels, the shoreline becomes extremely straight. The river mouths no longer protrude seaward, and most of the interior delta plain consists primarily of extremely sand-rich deposits, which often form large blanket-type sands.

Wave forces, therefore, are the primary mechanism by which the sea reworks and molds deltaic sediments into nearshore marine sand bodies. This particular process thus plays a highly significant role in controlling the geometry and orientation of the sand body and the resulting mineralogical composition.

### Tidal Processes

In deltas dominated by tidal action, at least three important characteristics can be identified: (a) water-mass mixing by tidal activity destroys vertical density stratification, so that the effects of buoyancy at river mouths are negligible; (b) for part of the year tides account for the highest percentage of sediment-transport energy,

and flow both in and seaward of the river mouths is subjected to reversals over a tidal cycle that cause bidirectional sediment transport; and (c) the zone of marine-riverine interactions is greatly extended both vertically and horizontally. Tidal amplitudes in macrotidal rivers tend to be relatively large compared to water depths over rivermouth bars, and the tidal wave is significantly deformed. In and seaward of the mouths of macrotidal rivers bidirectional tides commonly rework the sediment supplied by the river into linear subaqueous sand ridges, often referred to as tidal ridges. These large ridges parallel tidal currents and separate zones of flood- and ebb-dominated sediment transport. Because of deformation of the tidal wave, average flood velocities significantly exceed average ebb velocities, and the result is a tide-induced bed shear that produces a net upstream effect over the bed, and hence there is appreciable upstream transport of bed load. The largest and most prominent bed forms found in the lower distributaries thus are flood oriented. This upstream transport of bed load causes extensive sand accumulations within the channels, and as the channel is abandoned it would normally be sand clogged; thus, sand-filled channels are of major significance in tide-dominated deltas.

Macrotidal distributaries commonly have tidal intrusion far upstream. Flood-dominated or upstream bed-load transport augments point-bar growth and necessitates lateral channel migration in order to maintain sufficient depth. In many cases intense meandering patterns are found just upstream of maximum tidal influence, and well-developed sand bodies tend to develop within the delta plain. This pattern contrasts sharply with channel patterns in river deltas where tide range is low. In most instances macrotidal-range deltas also display considerable overbank crevassing. During flood tide, current velocities and maximum

turbulence are attained when the channel is at mid-tide level, and large amounts of sediment are put in suspension. A strong flood tide, combined with a high tide range, causes a backwater effect on seaward-flowing riverine water, and very commonly the river will top its bank, causing extensive crevasse splaying. The movement of tidal waters in and out of the channel and over the lower delta plain is also of basic importance to depositional patterns in interdistributary- and distributary-margin regions. Intricate networks of tidal channels are common features of many deltas having high tide range. In tropical humid regions where abundant vegetation is present, the tidal plain is often characterized by extremely heavy growth of mangroves and other salt-tolerant plants. In more arid macrotidal regions, interdistributary flats are composed of silts and clays deposited from suspension and overbank flows, and in many instances these splays interfinger with evaporite layers that form in the more interior parts of interdistributary regions.

#### Offshore Currents

Currents offshore of the delta plain are driven by several forces: deep oceanic currents impinging against the continental margin, tidal propagation, wind stress, wave action, and density gradients. In low-tide regions wind stress is often the dominant driving force. In areas where tide ranges are high, tide-driven coastal currents may transport sediment alongshore away from the river mouths. Such currents are found in narrow seaways and semi-enclosed basins that have broad continental shelves. During hurricanes, bottom currents sort and rearrange a considerable amount of sediment in a short time. In addition, as storm waves propagate over extremely soft bottoms, interactions between surface waves and bottom sediments become an important driving force in

a variety of downslope mass movements of sediments. These produce a variety of types of deformational features within the sedimentary column, and in some cases are responsible for large-scale subaqueous instability processes.

The major role played by all types of currents is in orienting sand bodies subparallel or parallel to depositional strike. In many cases these sand bodies can be found far offshore seaward of the river-mouth regions. The sand bodies often parallel the shoreline and display low-angle, large-scale internal cross-bedding.

### Shelf Slope

High rates of sediment accumulation and rapid progradation associated with river deltas result in lower slope angles than those found in most other coastal environments. Slopes off modern deltas vary from a low of  $0.003^\circ$  off the Parana River to as high as  $0.48^\circ$  off the mouth of the Senegal River. It is this subaqueous part of the continental shelf that primarily influences frictional attenuation of incoming deep-water waves, and therefore it can be regarded as the control that determines the nearshore wave power. Because of the high sediment yield of many river deltas, modern continental shelves and often upper continental slopes are purely depositional in nature and are formed in a rather short time; most of these shelves show direct evidence of progradation during modern times. This situation contrasts sharply with that of shelves fronting other coastal environments, where in many cases the shelf deposits are largely residual or lag accumulations formed during lower sea-level fluctuations or are of tectonic origin.

The slope of the continental shelf plays an important role in determining the pattern of delta switching, which happens over geologi-

cally longer periods of time. The first type of switching is lobe switching, a condition in which the delta progrades as a series of distributary channels and after a time abandons the entire system or locus of deposition and forms a new lobe in an adjacent region. Successive lobes overlap one another, forming stacked multiple regressive sand sequences. This pattern is found where offshore slope is extremely low and where wave power is low and tidal range is generally below 2 m. In such instances the distributary-mouth-bar deposits associated with each delta lobe merge with one another to form a large sheet of sand. A second type of delta switching occurs when a channel makes major shifts far upstream in the delta plain and a corresponding new course develops for the river and its deltas. This pattern is characterized by intermediate shelf slopes, high, persistent wave energy, and generally a high tide range. A third type that is commonly displayed in modern world deltas is referred to as alternate channel extension. Two or more distributaries break off at a nearly common point at the head of the delta and continue unbranched to the present river mouths. Commonly one of the distributaries will carry the majority of the sediment-water discharge at any given time. As a result, this channel will actively prograde seaward, but the other distributaries will show little or no progradation and will commonly be wave reworked along the margins. Eventually the prograding distributary will lose its gradient advantage by overextending itself, and the discharge will flow through one of the shorter distributaries. With its increased sediment load, the new channel will rapidly prograde, leaving behind a series of stranded beach ridges. This process will be repeated multiple times, forming a delta plain characterized by multiple sequences of beach ridges.

## Receiving Basin Geometry and Tectonics

The geometry of the receiving basin appears to exert strong control on delta configuration and delta switching patterns. Numerous types of depositional basins can be identified but are extremely difficult to quantify. Figure 7 illustrates schematically major configurations of various types of receiving basins. The first type consists of a narrow trough open at both ends which normally provides a passage connecting two larger bodies of water. Structural downwarping has occurred within the basin, and sediments delivered by the river are fed from the sides of the basin into the central axis of the seaway. The narrow restriction causes tidal currents to be extreme, and many deltas display skewed alongshore configurations and are tide- and current-dominated. The second type basin consists of a closed-end, narrow structural trough, with the river supplying sediment at the closed end of the trough. The tidal wave in this type of basin is significantly modified by the basin shape, and currents tend to move in and out of the narrow, elongate basin rather than displaying strong alongshore components. In many cases the lower end of the deltaic distributaries are totally tide dominated. Large, linear offshore tidal ridges and sand-filled channels dominate the deltas deposited into this type of basin. The third type consists of a downwarped area that lies inland of the shoreline, yet the site of active deltaic deposition is seaward of this point and the delta progrades onto a rather stable platform. In such instances large inland freshwater deltas and large swampy areas are common within the upper delta plain and alluvial valley. In the fourth type, an area of active subsidence lies seaward of the present shoreline, and this type of basin is normally found fronting major open-ocean basins. Numerous deltas are found alongshore and alongstrike and generally are attempt-

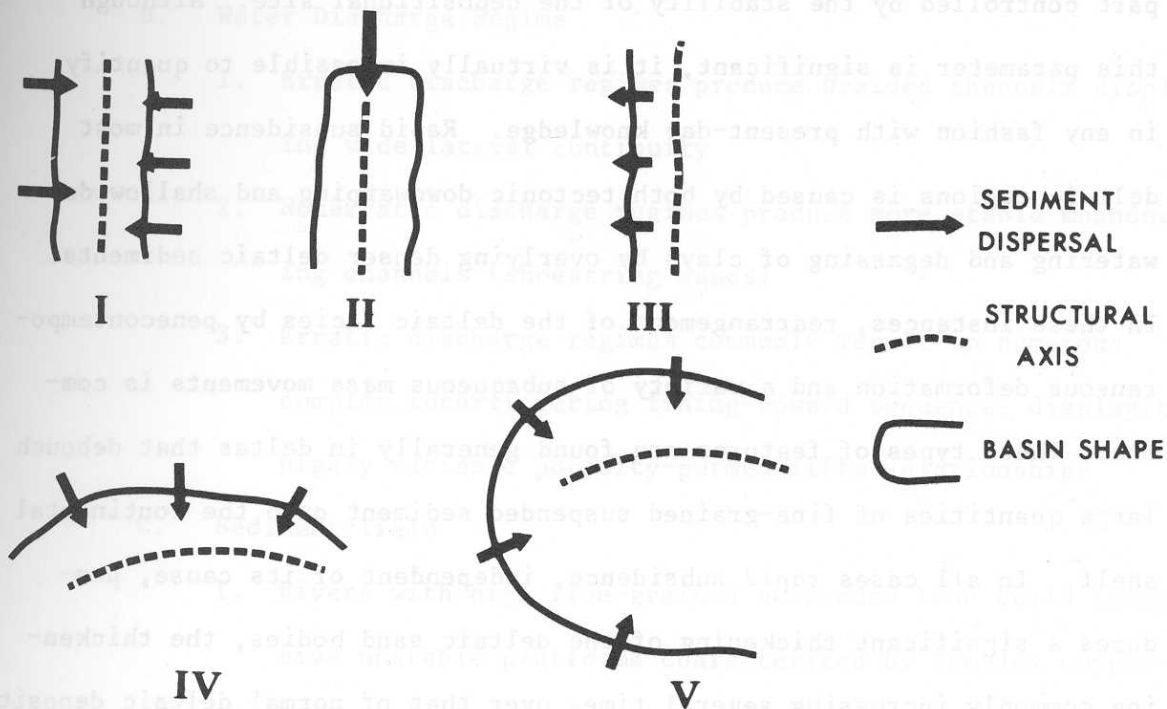


Figure 7. Major configurations of receiving basins.

ing to infill the rapidly subsiding basin. The fifth type is characteristic of semi-enclosed or enclosed basins such as the Gulf of Mexico. A zone of rapid subsidence lies close to one side of the basin. Rivers emptying into this type of basin commonly display features characteristic of rapid continuing subsidence, and deposits can attain relatively large thicknesses in a short time.

The third-dimensional aspect of deltaic sequences is in large part controlled by the stability of the depositional site. Although this parameter is significant, it is virtually impossible to quantify in any fashion with present-day knowledge. Rapid subsidence in most deltaic regions is caused by both tectonic downwarping and shallow dewatering and degassing of clays by overlying denser deltaic sediments. In these instances, rearrangement of the deltaic facies by penecontemporaneous deformation and a variety of subaqueous mass movements is common. These types of features are found generally in deltas that debouch large quantities of fine-grained suspended sediment onto the continental shelf. In all cases rapid subsidence, independent of its cause, produces a significant thickening of the deltaic sand bodies, the thickening commonly increasing several times over that of normal deltaic deposits. In those receiving basins that display low subsidence rates and relatively high stability, thin deltaic sequences are more common. The sand bodies are normally widespread and tend to show high lateral continuity.

#### Summary of Process Characteristics

Various interacting dynamic processes acting on sediment produce the wide variety of deltaic sand body geometries and distributions in modern deltas. The following list summarizes the major control exerted

on deltaic facies by each process discussed in the previous section.

A. Climate

1. Controls sediment-water yield
2. Controls in situ delta deposits; tropical: large, thick accumulations of peat; temperate: thin, high, laterally continuous peat layers; arid: complex interfingering supratidal and evaporite deposits

B. Water Discharge Regime

1. Erratic discharge regimes produce braided channels displaying wide lateral continuity
2. Nonerratic discharge regimes produce more stable meandering channels (shoestring sands)
3. Erratic discharge regimes commonly result in numerous complex interfingering fining-upward sequences displaying highly variable porosity-permeability relationships

C. Sediment Yield

1. Rivers with high fine-grained suspended load build extensive unstable platforms characterized by complex compactional and deformational features

D. Rivermouth Processes

1. Distributary-mouth-bar sand-body geometry and distribution controlled by three major forces: inertial (narrow, linear sand bodies); buoyant (thin, widespread, coalescing sand bodies); and frictional (bifurcated channels with middle-ground sand bars capped by subaqueous natural-levee deposits)
2. All distributary-mouth-bar deposits display coarsening-upward sequences

E. Wave Power

1. High, persistent wave power produces straight delta shorelines; sand bodies display marine characteristics and are oriented parallel to depositional strike or form clean, well-sorted sheet sands; sand bodies display high quartzose content independent of parent material
2. Low wave power results in irregular indented delta shorelines and sand bodies oriented at high angles to depositional strike; sand bodies often clay bound and poorly sorted

#### F. Tidal Processes

1. High-tide-range deltas have sand-filled channels; numerous sandy overbank crevasse splays; large, complex meander belt sand bodies in upper delta plain
2. Macrotidal ranges in narrow seaways, straits, etc., result in formation of major linear offshore tidal ridges and bars that often attain lengths of tens of kilometres and thicknesses that approach 20-30 m

#### G. Wind Processes

1. Directional variability in coastal wind systems often produces multidirectional cross bedding to coastal sand dunes
2. In microtidal regions wind stress on nearshore water masses usually controls currents that shape and orient offshore sand bodies

#### H. Nearshore Currents

1. Sediment transporting currents in delta regions are driven by several forces: permanent deep oceanic currents impinging on the shelf, tidal propagation, wind- and wave-driven

and complex density currents

2. Currents are responsible for orienting offshore sand bodies parallel or subparallel to depositional strike; sand bodies are in many cases located considerable distances offshore or downcurrent from active delta lobe; sand bodies commonly display strong marine bedding characteristics

#### I. Shelf Slope

1. Subaqueous slope controls offshore wave dissipation, which strongly influences sorting and hence porosity of near-shore sand bodies
2. Low offshore slopes are commonly associated with multi-channel distributary patterns, which can form complex sand body relationships
3. Shelf topography, especially presence of submarine canyons, plays major role in topping of delta sediments and formation of deep marine sand bodies

#### J. Tectonics of Receiving Basin

1. Rapidly subsiding basins result in overthickening and localization of deltaic sand bodies, whereas relatively stable basins display widespread and laterally continuous delta sand facies
2. Localized differential weighting and dewatering of sediments in receiving basin results in formation of large-scale penecontemporaneous structures, and sediments often display evidence of subaqueous mass sediment movements, displaced sediment, and complex slumping

#### K. Receiving Basin Geometry

1. Large-scale geometry of receiving basin exerts significant

- control on delta configuration and delta switching patterns
2. The large-scale geometry of most receiving basins results in formation of similar delta relationships for large distances in an alongshore direction

## Characteristics of Deltaic Depositional Environments

### Introduction

This section of the short course will deal primarily with the processes of deposition responsible for developing the various depositional environments within the delta plain and will attempt to characterize some of the internal structures of the deposits. Because of the data base available, the vast majority of the data will be drawn from the modern Mississippi River delta. The major environments described are as follows:

#### A. Subaerial Delta Plain

1. Distributary Channel Fill
2. Interdistributary Bay
3. Marsh Environment
4. Crevasse Splays and Bay Fills

#### B. Subaqueous Deltaic Environments

1. Distributary-Mouth Bar
2. Distal Bar
3. Prodelta Clays
4. Offshore Slump Deposits

### Mississippi Delta Setting

The Mississippi, the largest river system in North America, drains an area of 3,344,560 km<sup>2</sup>. Average water discharge at the delta apex

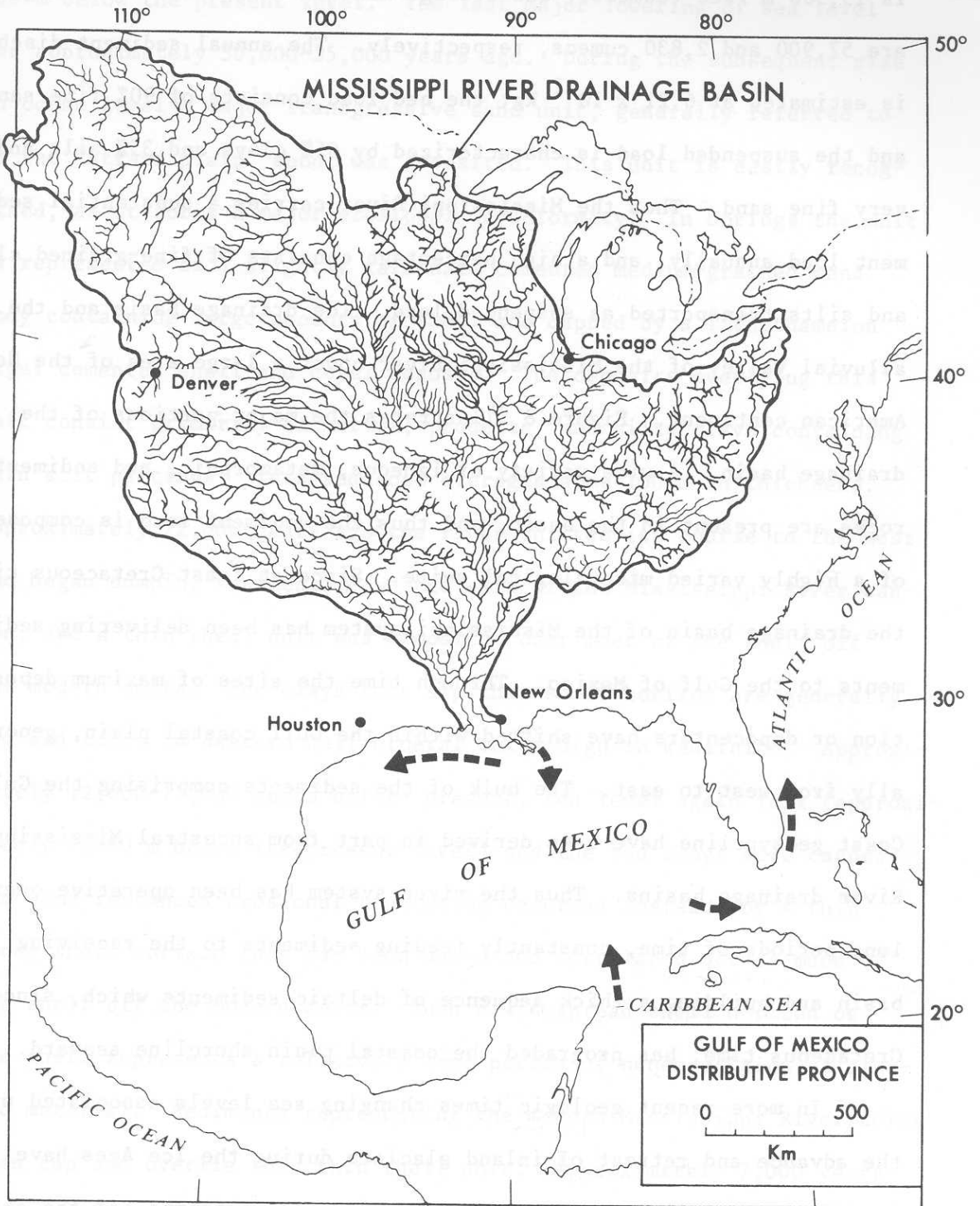


Figure 8. Drainage basin of Mississippi River delta.

is  $15,360 \text{ m}^3/\text{sec}$  (cumecs), and average maximum and minimum discharges are 57,900 and 2,830 cumecs, respectively. The annual sediment discharge is estimated at  $6.21 \times 10^{11}$  kg; the bed load consists of 90% fine sand and the suspended load is characterized by 65% clays 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 clays and silts transported as suspended load. The drainage basin and the alluvial valley of the Mississippi River cover a large area of the North American continent. Figure 8 illustrates the major portions of the drainage basin. A wide variety of igneous, metamorphic, and sedimentary rocks are present in the basin, and thus the sediment load is composed of a highly varied mineralogical suite. Since at least Cretaceous times the drainage basin of the Mississippi system has been delivering sediments to the Gulf of Mexico. Through time the sites of maximum deposition or depocenters have shifted within the Gulf coastal plain, generally from west to east. The bulk of the sediments comprising the Gulf Coast geosyncline have been derived in part from ancestral Mississippi River drainage basins. Thus the river system has been operative over long periods of time, constantly feeding sediments to the receiving basin and building a thick sequence of deltaic sediments which, since Cretaceous time, has prograded the coastal plain shoreline seaward.

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 150-

200 m below the 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 unit is easily recognized, as it forms a major erosional unconformity. In borings the unit is represented as a slightly carbonate cemented medium-grained sand body containing large amounts of shell and capped by a lithothamnion algal cemented shell and coral deposit. The deposits overlying this unit consist primarily of marine, prodelta, and silty clays containing thin silt partings. This sequence averages some 100 m in thickness. Approximately 22,000 years ago the river shifted its course to the west and 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 delta. The clays that cap this shell horizon are generally red and carry an eastern Gulf mineral suite high in kaolinite. Approximately 12,000-15,000 years before present, sea level again fell (approximately 70-80 m below its present level) and the red clays were capped (in some instances erosional truncation occurred instead) by a thin sandy shell horizon that has been dated and correlated across much of the shelf off the modern delta. Such a widespread shell horizon on the shelf represents a relatively long period of nondeposition of clastic material. Sediments representing the modern Mississippi River delta then cap and overlie this thin shell unit. Approximately 7,000 years ago the delta began a series of progradations and development of its modern Mississippi delta lobes. Figure 9 illustrates the various switching lobes during the past 7,000 years. Each of the deltaic lobes generally lasts from 1,000 to 1,500 years at an individual site. The modern bird-foot delta or Balize Delta began its progradation some 600-800

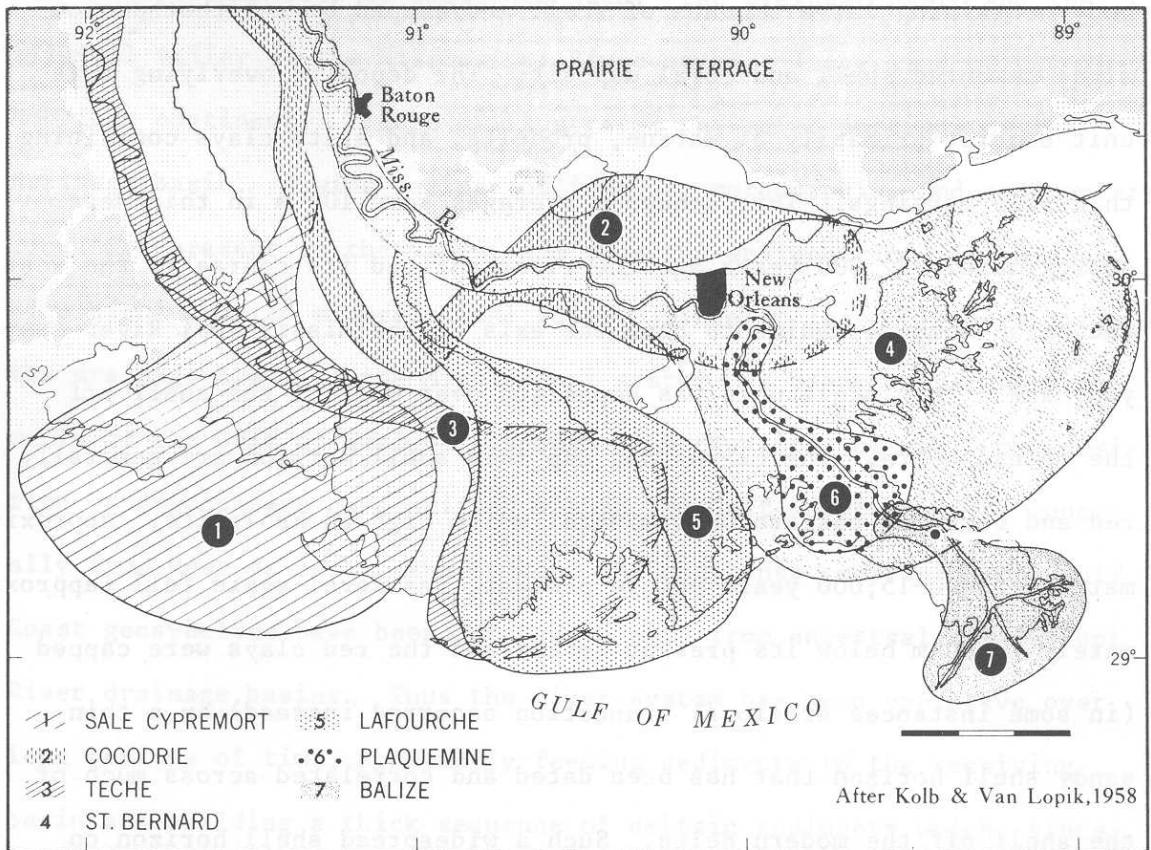


Figure 9. Deltaic lobes of the modern Mississippi River.

years ago. During this time a thick sequence of prodelta clays accumulated on the shelf off the modern delta. As the delta continued its progradation, silt and clay units, represented by the distal bar, began to be deposited, and off the modern delta these sequences range from 10 to 20 m in thickness. The final episode was the deposition of the modern distributary-mouth bars of the Balize Delta. Although they are highly variable, the average thickness across most of the delta plain is 20 m. Figure 10 shows the typical vertical sequence of deposits beneath the modern bird-foot delta.

The modern bird-foot or Balize Delta represents the present-day locus of active sedimentation. It is a very young delta, having formed within the past 600-800 years. The area of this subaerial bird-foot delta is approximately  $600 \text{ km}^2$ , compared with an average areal extent of  $2,700 \text{ km}^2$  of the older delta lobes (each of which had an active life of 800-1,500 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 approximately 20 m, whereas the average thickness of the modern Balize Delta is 100-120 m. Seaward progradation rates in the distributary mouths range from in excess of 100 m per year to less than 50 m per year, depending on the specific distributary monitored. Sedimentation rates seaward of the river mouth are extremely high, averaging slightly less than 1 m per year. During high floods, however, accumulations of 3-4 m of sediment over 2-4 months have been documented. In adjacent interdistributary bays, accumulation rates rarely exceed a few centimetres per year, and in some places the bay bottoms are being eroded.

Offshore slopes of the entire delta front are extremely low, rarely exceeding  $1.5^\circ$ , and in the interdistributary bays bottom slopes are

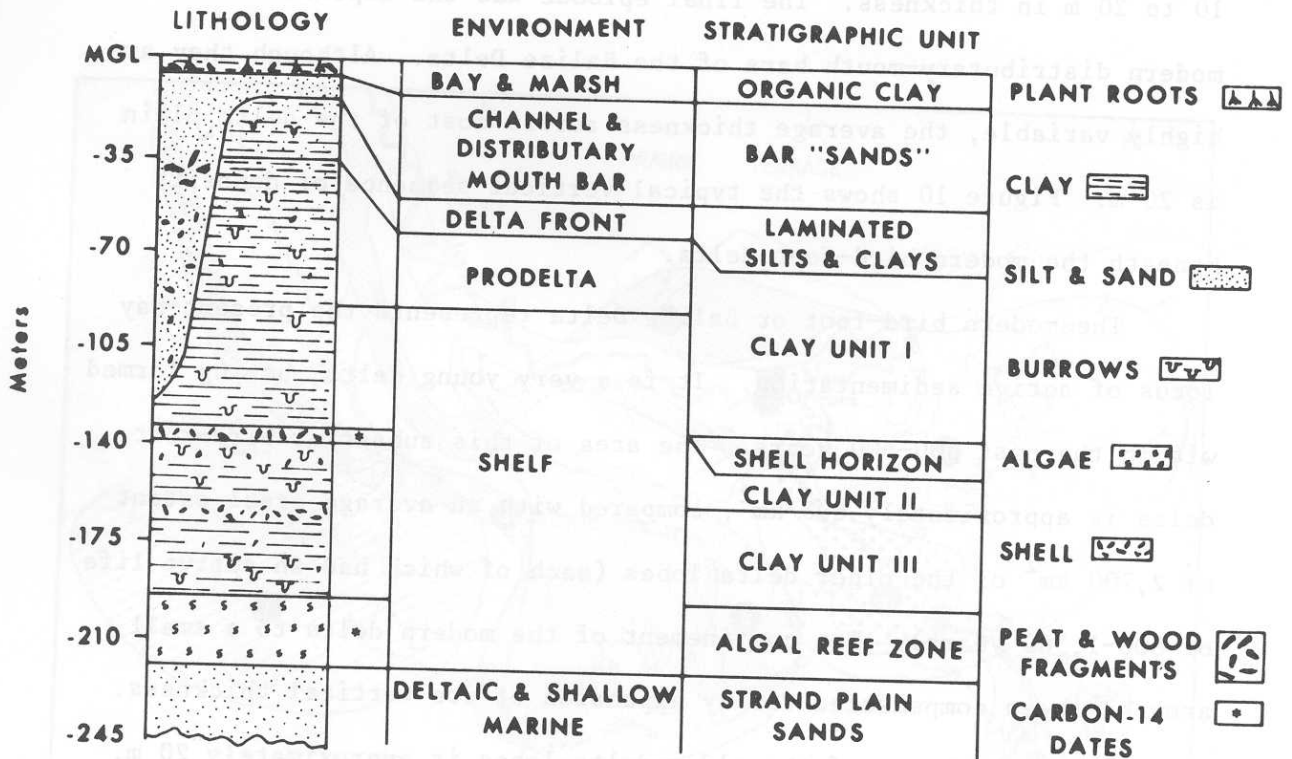


Figure 10. Vertical sequence of deposits in modern Mississippi River delta.

generally less than  $0.5^{\circ}$  and rarely greater than  $0.2^{\circ}$ . At the shelf break, which generally is in water depths of 200 m, the slope increases slightly, averaging  $1.7-2.2^{\circ}$ . In localized areas scarps caused by active faulting display heights as great as 50-60 m and slopes approaching  $2.5-3^{\circ}$ .

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. Many radiocarbon dates from borings in the delta, however, suggest general subsidence ranges of 30-100 cm per century. This range of regional subsidence rate computed from the delta is in general agreement with present published rates of other areas in the Gulf Coast geosynclinal system. Of greater significance in the modern deltaic lobes is the response of the weak, plastic sediments to rapid sedimentary loading. Consolidation by dewatering and degassing and underlying sediment flowage beneath rapidly localized sediment loading can be significant. In the region of the immediate river mouths, where denser distributary-mouth-bar sands prograde over weak underlying clays, local subsidence rates can be as high as 200 cm per year, an extremely rapid subsidence rate.

The orderly repetition of depositional events and shifting sites of sedimentation in modern Mississippi River deltas results in numerous interfingering and overlapping regressive deltaic sequences, which are separated by shallow-water marine deposits of a transgressive nature. The initiation, growth, and abandonment of various delta lobes results in cyclic alternation of detrital deposits. The major regressive detrital

lens is characterized by high percentages of relatively coarse clastics, sands and silts, abrupt facies changes, and rapid accumulation and burial sites. The bounding sediments, which tend to be generally richer in organic constituents and chemical precipitants, show a slower depositional rate and tend to be tabular accumulations with considerable lateral continuity. The cyclic concept provides a framework for organizing the complex environmental relationships and facies distributions resulting from delta building.

### Environments of Deposition

The first set of subenvironments to be described consists of those that form the subaerial delta plain. Figure 11 shows a high-altitude photograph of part of the subaerial delta plain of the modern bird-foot delta. From this altitude many of the subenvironments can be readily discerned. The major environments include distributary channels, interdistributary bays, marshes, and numerous overbank splays and bay-fill units (characterized by numerous small bifurcating distributaries).

Abandoned distributary-fill deposits. The distributary channels of the modern river delta display a wide variety of sizes and shapes. They range in width from 1 km to a few metres. Depths range from 30 m in the larger distributaries to 1-2 m in the smaller channels. The distributary channel is a natural flume which accommodates and directs part of the water and sediment discharged from the parent river system to the receiving basin. In most deltas, and particularly those of the Mississippi River, the distributary channels are rather stable and do not tend to migrate laterally, preventing the formation of point bars or meander belts in the active delta region. In other deltas, for example high-bedload streams or those environments where tidal range is



Figure 11. High-altitude photograph of the subaerial delta plain of the Mississippi River delta.

Figure 12. Oblique aerial view of abandoned channel of Kallire Bayou, Mississippi River delta.

high, migration of the distributary channel can take place, resulting in formations similar to the channel deposits commonly described as sand-filled channels in the ancient-rock literature. Although little research has been conducted, the lack of channel migration in the modern lower delta plain of the Mississippi is undoubtedly due to the fact that most of the river channels scour through their distributary-mouth-bar deposits into the underlying marine clays, providing an entrenchment of the distributary channel with minimal tendencies to migrate laterally. Depths within most of the distributary channels decrease rapidly as the river-mouth bar is approached, and water depths over most of the distributary-mouth bars rarely exceed 3 m. Abandonment of a distributary channel is an extremely complex process and in many areas is simply an accident. Log jams, loss of gradient advantage, infilling during a catastrophic period such as hurricanes, or changes upstream in the river channel will cause the channel to deteriorate and infill. Deprived of an active influx of sediment and water, the channel will undergo an infilling process. Only local sediments derived from both upstream and downstream will begin to infill the abandoned channel. Figure 12 is an oblique aerial photograph of an abandoned channel within the Mississippi River delta plain. This channel was formerly Balize Bayou, one of the major distributaries of the modern Mississippi Delta in the early 1800s. By the 1860s the channel was being abandoned and virtually would not accommodate deep-draft sailing ships. The original channel was 180-240 m wide and had water depths on the order of 12-15 m. By the mid-1900s the channel had completely infilled over a distance in excess of 20 m. One of the old pilot towns located along its banks, which was abandoned in the late 1860s, now lies buried approximately



Figure 12. Oblique aerial view of abandoned channel of Balize Bayou, Mississippi River delta.

3-4 m below the present marsh surface. During channel abandonment the lower part of the channel is commonly filled with poorly sorted sands and silts containing an abundance of transported organic debris. As the channel shoals, the water becomes more stagnant and lower current velocities are maintained. Fine-grained materials begin to infill the channel proper. With time and continued subsidence, the channel is often entirely filled with fine-grained, poorly sorted sediments. Organic debris, logs, and clays with extremely high water contents often form the upper part of the channel fill. Thus in many deltaic regions where tides are low and suspended-sediment load is high no process exists by which to infill the channels with sand or other coarse debris. This aspect of the infilling of a distributary channel is schematically illustrated in the upper left diagram of Figure 13, which illustrates the infilling of two distributary channels and shows that the channel deposits themselves cut through the major sand body, which is the distributary-mouth bar. The upper right diagram, based on numerous cores through abandoned channels, illustrates a typical vertical sequence. The major characteristic is the erratic nature of the thin sand and silt layers that alternate with fine-grained clastic detritus, which forms the bulk of the deposits. Numerous core holes indicate that there is no orderly plan to the infilling process. About the only common attribute is that if there is any substantial amount of sand there is a general tendency for the sand to be concentrated near the base of the channel, or at points where the channel bifurcates. Because of this lack of organized infilling, it is often difficult to pick the base of the channel itself. Generally the only applicable method is the use of faunal remains, because most of the distributary channels scour down into underlying marine

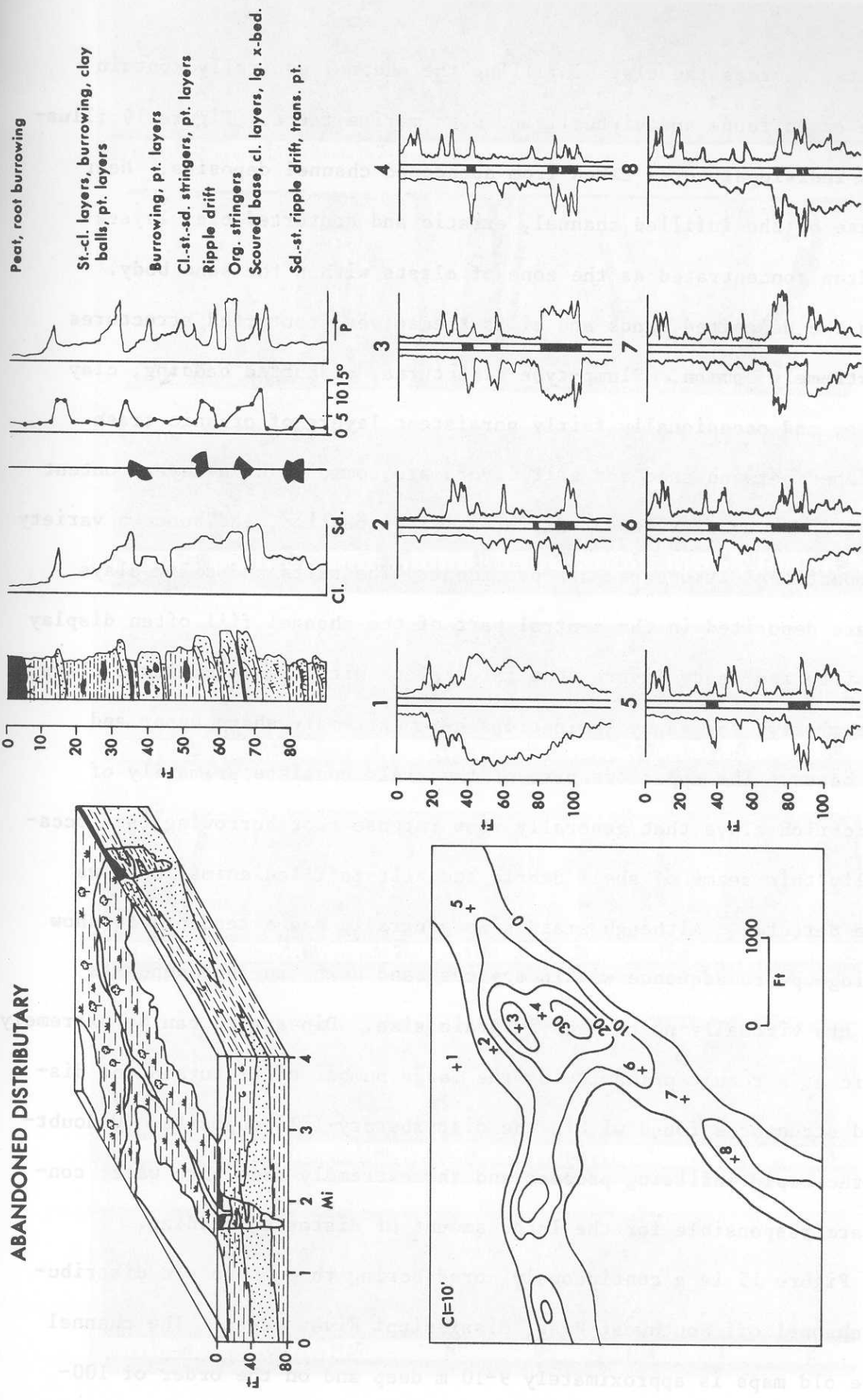


Figure 13. Diagram illustrating characteristics of distributary channel-fill deposits.

deposits, whereas the clays infilling the channel generally contain little or no fauna and virtually no open marine fauna. Figure 14 illustrates individual cores taken from abandoned channel deposits. Near the base of the infilled channel, erratic and contorted clay layers are often concentrated as the zone of clasts within the sand body. Within the deposited sands and silts themselves, contorted structures are extremely common. Slump-type structures, distorted bedding, clay infills, and occasionally fairly persistent layers of organic trash sandwiched between sand and silt layers are common. High water content results in numerous types of differential compaction, and hence a variety of compactional structures are prominent. The silts and silty clays that are deposited in the central part of the channel fill often display thin silty and sandy layers that intercalate with highly burrowed clays. Most commonly, the sandy laminations have extremely sharp upper and lower bases. The uppermost part of the field consists primarily of organic-rich clays that generally show intense root burrowing, and occasionally thin seams of shell debris and silt-infilled animal burrows can be detected. Although grain size generally has a tendency to show a fining-upward sequence within any one sand unit, in some deposits there are virtually no changes in grain size. Dip angles can be extremely erratic as a result primarily of the large number of disturbed and distorted structures found within the distributary-fill deposits. Undoubtedly the rapid infilling process and the extremely high pore water content are responsible for the large amount of distorted bedding.

Figure 15 is a continuously cored boring through an old distributary channel off Southwest Pass, Mississippi River delta. The channel on the old maps is approximately 9-10 m deep and on the order of 100-110 m wide. The base of the channel in the cored boring is identified

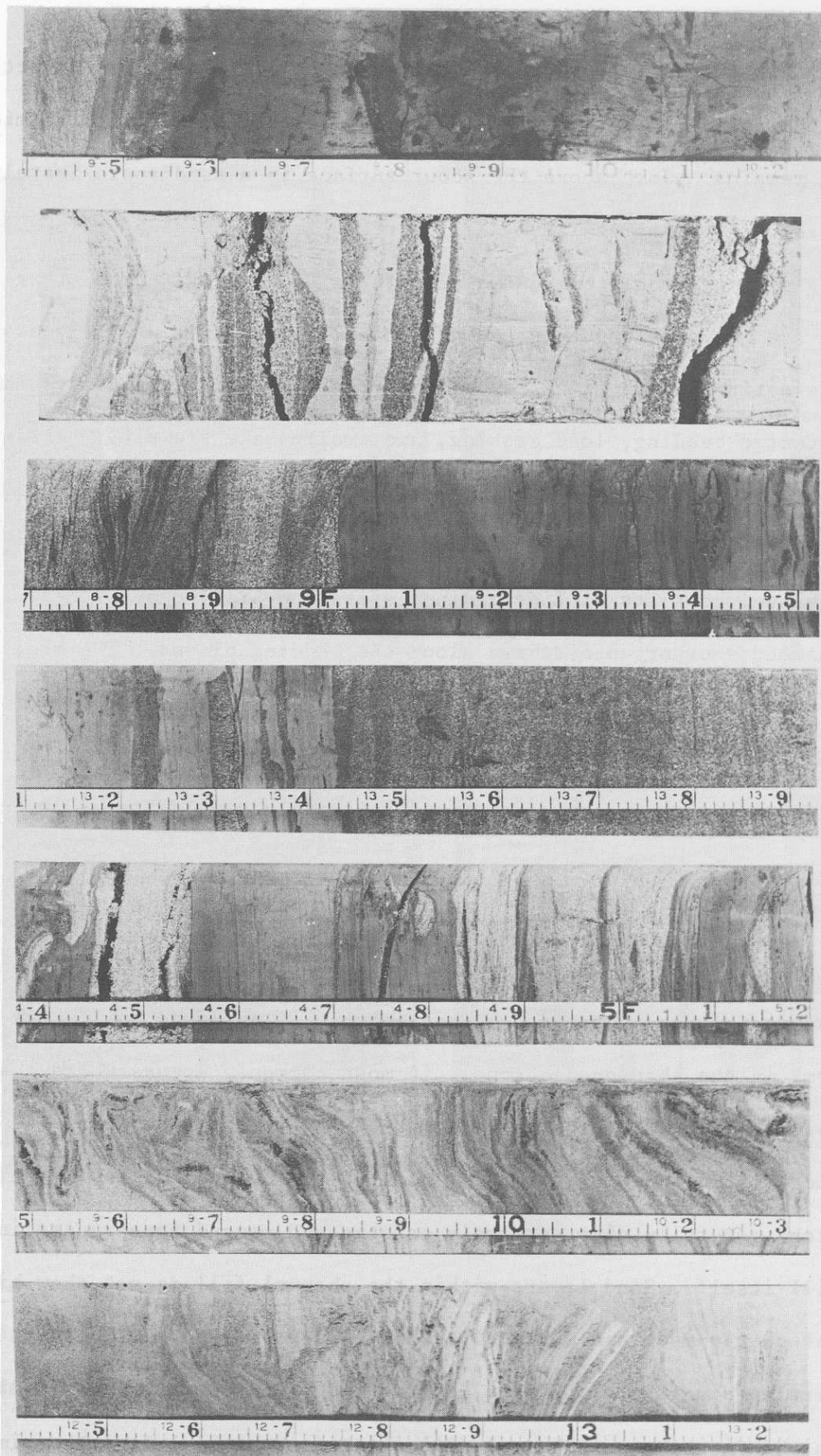


Figure 14. Cores from abandoned channel-fill deposits.

by the letter A and occurs 10.5 m below sea level. The clays directly below the scour plain, where burrowing is present, contain marine microfaunal remains. Just above the scour surface is a sand approximately 1 m thick. It contains fairly well sorted fine- to medium-grained sands displaying small-scale current structures. Organic trash and other debris are common along the bedding planes. Above this unit are a series of alternating sands, silty clays, and clays that display a large amount of contorted bedding, load casting, and small-scale slumping. The central part of the field consists of silty clays alternating with thin silt laminations. The uppermost section of the fill in this distributary channel consists of fine-grained silts and silty clays containing large amounts of organic debris along the bedding planes. The uppermost metre of this abandoned channel consists primarily of organic-rich clays and peats which, because of their extremely high water content, cannot be preserved and adequately cored and thus are not illustrated in the boring.

The lowermost two diagrams in Figure 13 illustrate an isopach map and variations in electric log response across an abandoned channel-fill sequence. As shown in the isopach map, if any sand buildup is apparent in the abandoned channel, it most commonly occurs where the channel displays a bifurcating nature, and often 5-8 m of sand will be concentrated in this particular part of the channel fill. The electric logs generally give extremely erratic and ragged appearances in the fill itself. Sand layers within the channel fill do not show high lateral continuity, and logs only a few hundred metres apart cannot be correlated accurately. Thus, in low-tide, low-energy, river-dominated deltas the distributary-channel fill often forms a seal for other impor-

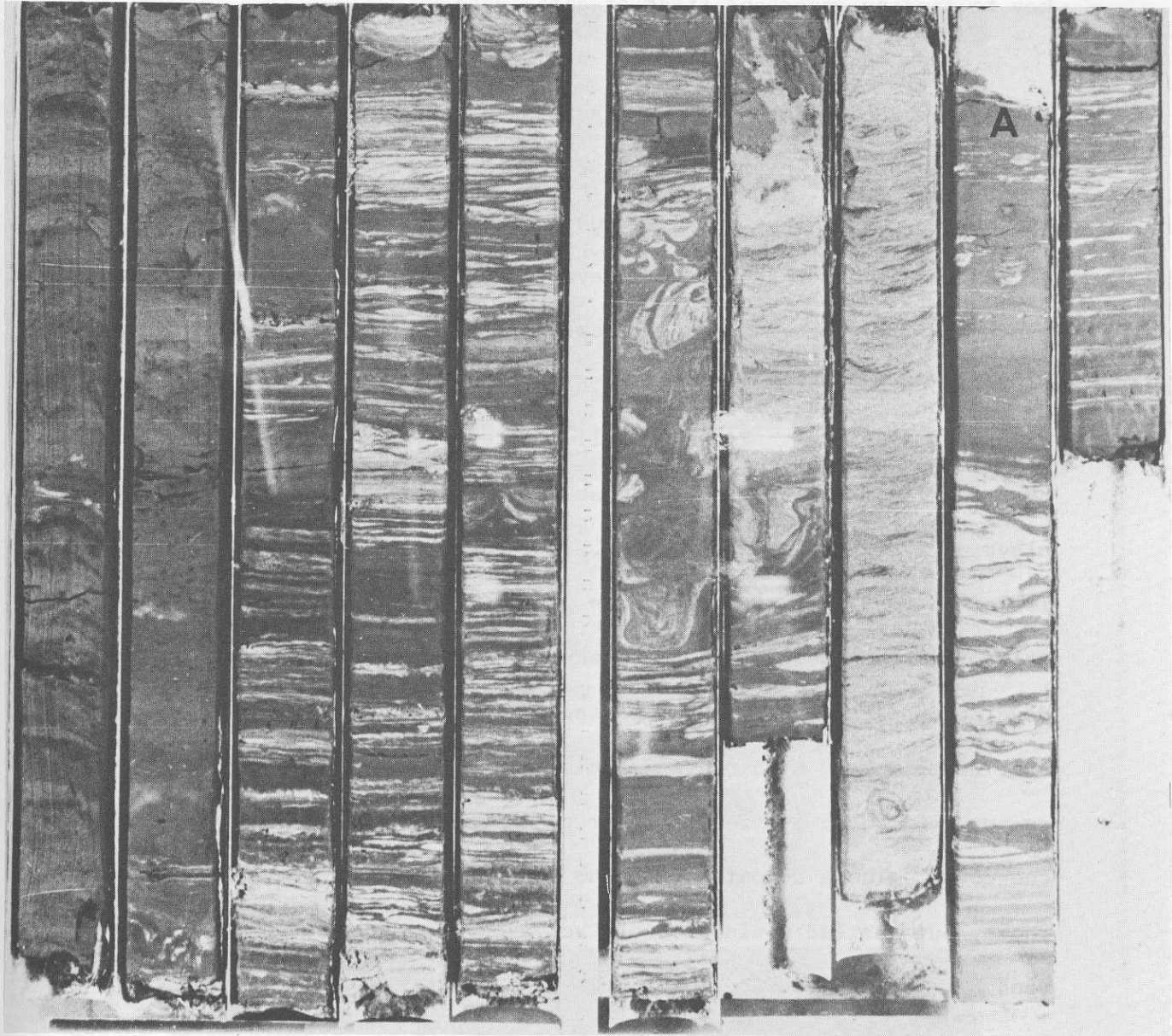


Figure 15. Continuous cored boring through a distributary channel-fill deposit.

Figure 16. Cores from marsh deposits.

tant sand bodies such as the distributary-mouth bar. The location and mapping of these clay-filled channel sequences is in many cases the key to finding important stratigraphic traps.

Marsh environment. Marshes are low tracks of periodically inundated land supporting nonwoody plants such as grasses, reeds, and rushes. The marsh surface in the delta approximates the mean high-tide level, and within the Mississippi River delta this level is only a fraction of a metre higher than mean sea level. Within the active deltas marshes generally range from fresh to brackish. The marsh's most notable feature is the abundance of plant life and the production and preservation of organic material. Figure 16 illustrates several cores taken within the marsh environment. Notice that organic debris and high organic clays dominate the cored sections. Evidence of active plant rooting is common in all of the cores. In general in the Mississippi River delta inorganic content of the discharged water is so high that well-developed peats do not form. Instead, most of the marsh deposits consist of extremely high organic clays. Early diagenetic products are common, and often pyrite and siderite are found in abundance within the cores. These deposits offer no possibility for reservoir-quality rocks, but instead would probably act as source beds for gas production. Upon burial and maturation, much of the organics could be converted to gases and would provide a nearby source bed for other types of reservoir rocks within the subaerial delta.

Interdistributary-bay deposits. The interdistributary-bay environment includes areas of open water within the active delta which may be completely surrounded by marsh or distributary levees but which are more often partially open to the sea or connected to it by small tidal

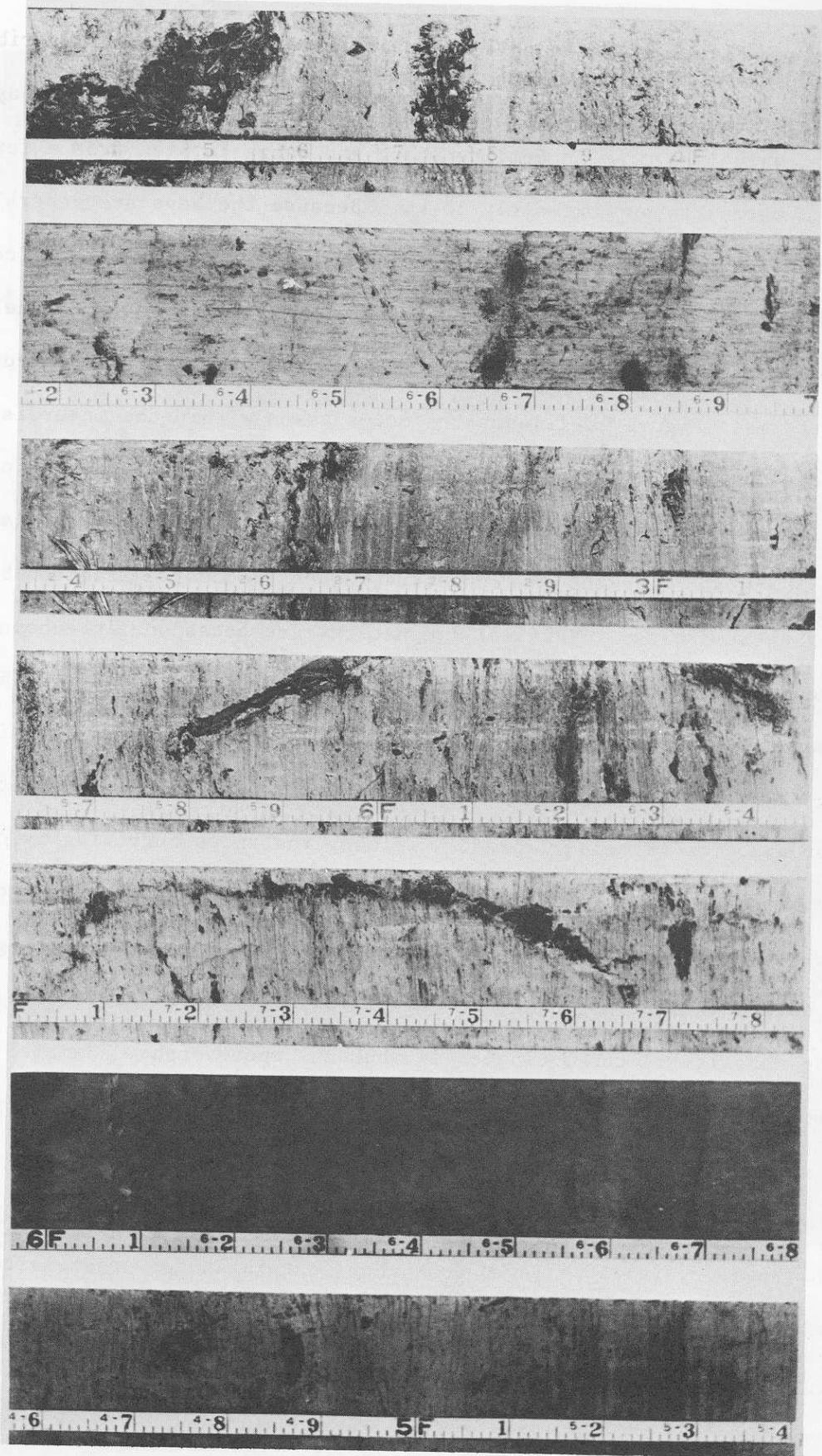


Figure 16. Cores from marsh deposits.

channels. Figure 17 is an oblique aerial view of small interdistributary bays within the active delta of the Mississippi River. The bays are commonly irregular in outline shape and range in size from a few hundred metres to approximately 15 km. Because the bays are generally bypassed by active coarse clastic sedimentation, the deposits are composed primarily of fine-grained sediments that are brought into the bays during periods of high flood or abnormal high tides associated with storms. Figure 18 illustrates cores taken within the interdistributary-bay deposits of the Mississippi River delta. The most abundant single sedimentary structure in the bay deposits consists of lenticular laminae, the product of reworking and concentration of the coarse fraction by wind-generated waves. Parallel laminations are occasionally encountered and consist of alternating zones of fine silts and silty clays. These laminae are probably formed during times of high flooding in the Mississippi River delta. In nearly all the interdistributary-bay deposits bioturbation is extremely common. In many instances burrowing by organisms obliterates nearly all the primary sedimentary structures, and even in those deposits where some stratification exists the cores generally have a modeled appearance. One of the more characteristic features of bay deposits is the inclusion of abundant sporomorphs. Samples from the active interdistributary regions of the modern delta show an extremely high content of reworked spores and pollen, ranging in age from Cretaceous through modern. These deposits would not provide reservoir-quality rocks; however, it is believed that they contain enough organics to become an important source rock for many of the deltaic reservoir sands.

Crevasse or bay-fill deposits. One of the major facies associated with many deltas is the large areal extent of the bay fills or crevasses that break off main distributaries and infill the numerous interdistribu-



Figure 17. Oblique aerial view of inter-distributary bays and marsh.



tary bays in the lower delta plain. These sequences form the major land areas in the lower delta. Crevasses build into shallow bays between or adjacent to the major distributaries and extend themselves seaward through a system of radial bifurcating channels similar in plan to the veins of a leaf. The interdistributary bays into which the crevasses prograde are normally open bodies of water which are often completely surrounded by marsh or distributary channels. Most of the bays are shallow water bodies, rarely exceeding 7-10 m in depth, and contain brackish to marine waters. The bays are commonly elongate, with their longest dimension ranging from a few hundred metres to approximately 15-20 km. Figure 19 illustrates the historic sequence of bay fills that have formed within the modern delta during the past few hundred years. Of the six crevasses shown in Figure 19, four have been dated historically, and much of their development can be traced by historic maps. Each bay fill forms initially as a break in the major distributary channel during flood stage, gradually increases in flow through successive floods, reaches a peak of deposition, wanes, and becomes inactive. As a result of subsidence, the crevasse system is inundated by marine waters, reverting to a bay environment, and thus completing a sedimentary cycle. The mass of sediment resulting from the process of crevassing varies in thickness from 3 to 15 m, and this sequence forms in a period of approximately 100-150 years. Although many of the individual bay fills are relatively thin, continuing subsidence and repetition of similar processes results in stacking one bay fill on top of another, thus building up a thick sequence of lower delta plain deposits. Figure 11 shows from a high altitude one such bay-fill pattern. This particular pass, Cubits Gap crevasse, was formed in 1862,

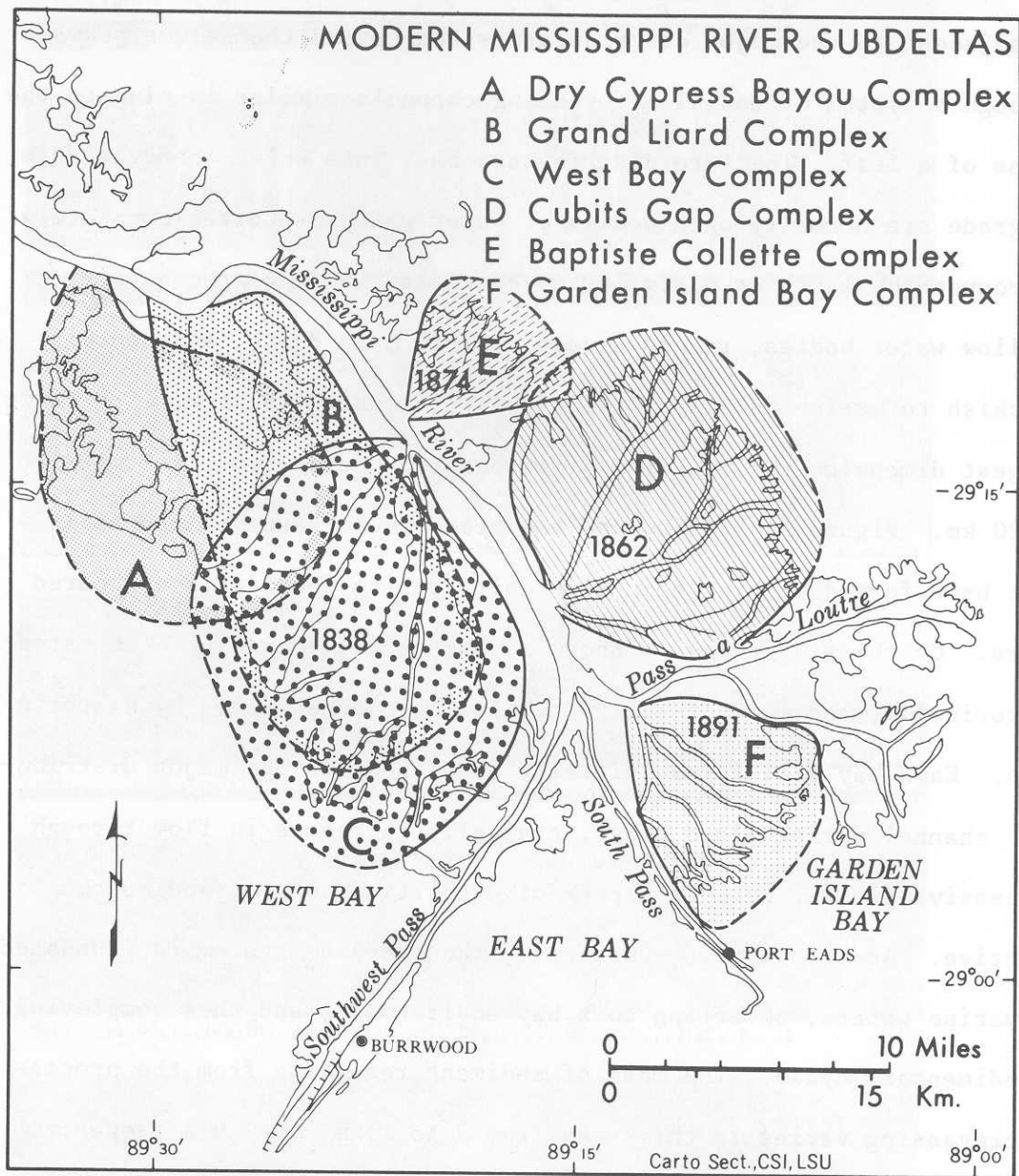


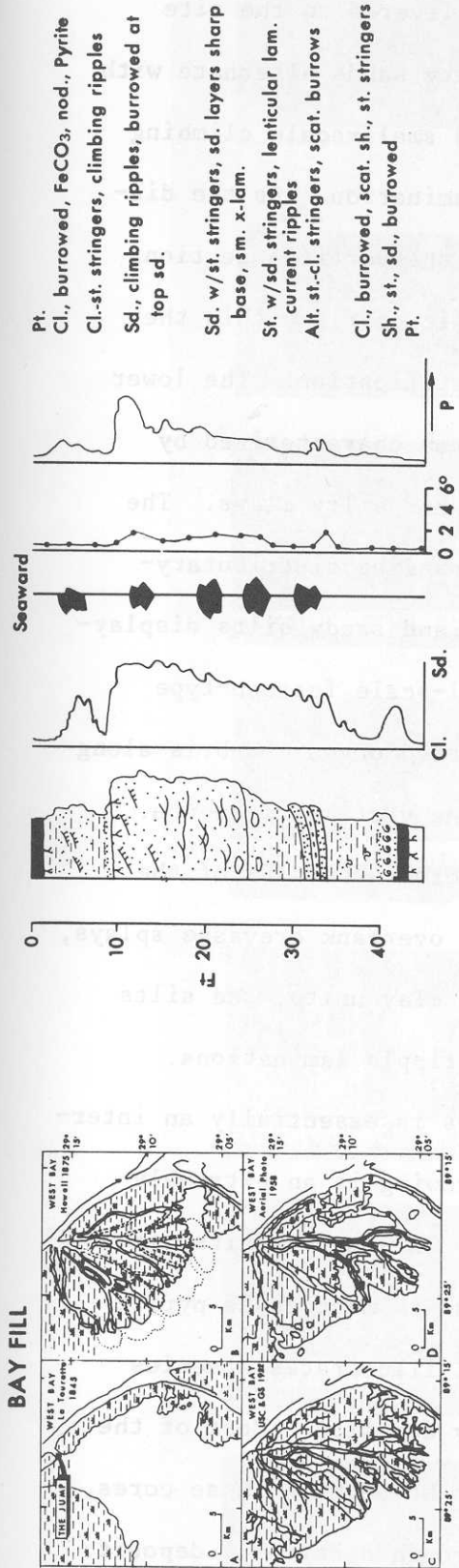
Figure 19. Crevasses or bay fills of the modern bird-foot delta of the Mississippi River.

when a break in the levee occurred and some 6-8% of the Mississippi water was diverted through the crevasse opening. By 1870 only a small number of low shoals were visible on maps; however, by 1903, some 30 years later, essentially the entire bay area had been infilled with crevasse-splay or bay-fill sediments. Since that time subsidence and deterioration have resulted because of lack of clastic sedimentation, and presently only the major distributary patterns are obvious on the high-altitude photograph. Most of the former land surface has now reverted to extremely shallow-water bays, and in approximately another 40 years the entire land mass will have subsided below sea level and the environment will have reverted to an interdistributary bay.

The upper left diagram of Figure 20 illustrates, by a series of historic maps, the development of the West Bay fill. The break in the major Mississippi channel occurred in 1839, and maps from that time show water depths on the order of 7-10 m in the adjacent bay. After the initial break in the major levee of the Mississippi River, coarse sediment was dumped subaqueously in the vicinity of the break and no new subaerial land developed. However, with continued deposition and a general shoaling in the bay near the break, a bifurcated channel pattern commenced, and infilling of the bay sequence developed rapidly. This stage of development is illustrated by the map of 1875; most of the channels were still actively prograding, and nearly the entire bay had been filled with sediments or a regressive sequence of deltaic deposits. The map from 1922 shows that many of the channels had been abandoned; they had prograded far enough seaward to lose their gradient advantage, and only a few of the major channels were continuing to deliver sediments into the bay. Much of the newly exposed land had been converted

to luxuriant fresh marsh growth, and organic-rich clays were capping the top of the regressive sequence. With time, plant growth could no longer maintain its productivity because of encroaching marine waters, and slowly the marsh began to break into numerous small lakes and bays. Wind-generated waves in the shallow bays, coupled with subsidence, began to destroy the marsh surface, and by 1958 much of the original land buildout had subsided below sea level and the area reverted to a bay environment. By 1980 the entire region had been inundated by marine waters, and the West Bay complex has now reverted to a shallow marine interdistributary environment. Given time, eventually another crevasse will form on the bank of the Mississippi, and another period of infilling will ensue, again filling the interdistributary bay with detrital sediments. It is this process of repeated filling, alternating with periods of marsh destruction, subsidence, and reversion to open bay conditions, that forms the bulk of the cyclic deposits in the lower delta plain.

The upper right-hand diagram of Figure 20 illustrates a typical vertical sequence that results from bay infilling. As can be seen, it is a coarsening-upward sequence, with shallow brackish water clays and organic debris forming the lower part and well-sorted clastics forming the upper sand body. The upper unit is essentially the distributary-mouth-bar deposits associated with the prograding distributary. The lowermost part of the bay fill generally consists of alternating silts and silty clays, and the clays often show silt- and sand-infilled burrows. With continued and increasing sedimentation in the interdistributary bay, coarser particles and more rapid deposition occur. Silty and sandy stringers begin to intercalate with silty clays. Burrowing is generally reduced. As the distributary system advances farther into



Pt.  
Cl., burrowed, FeCO<sub>3</sub> nod., Pyrite  
Cl.-st. stringers, climbing ripples  
Sd., climbing ripples, burrowed at top sd.

Sd. w/st. stringers, sd. layers sharp base, sm. x-lam.  
St. w/sd. stringers, lenticular lam. current ripples  
Alt. st.-cl. stringers, scat. burrows

Cl., burrowed, scat. sh., st. stringers  
Sh., st., sd., burrowed  
Pt.

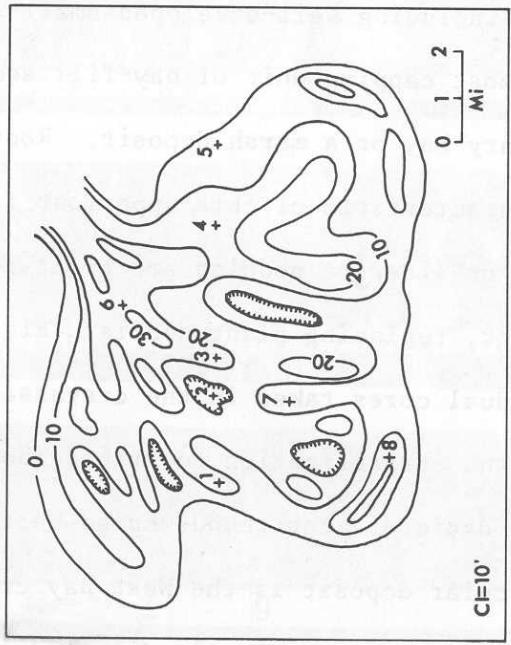
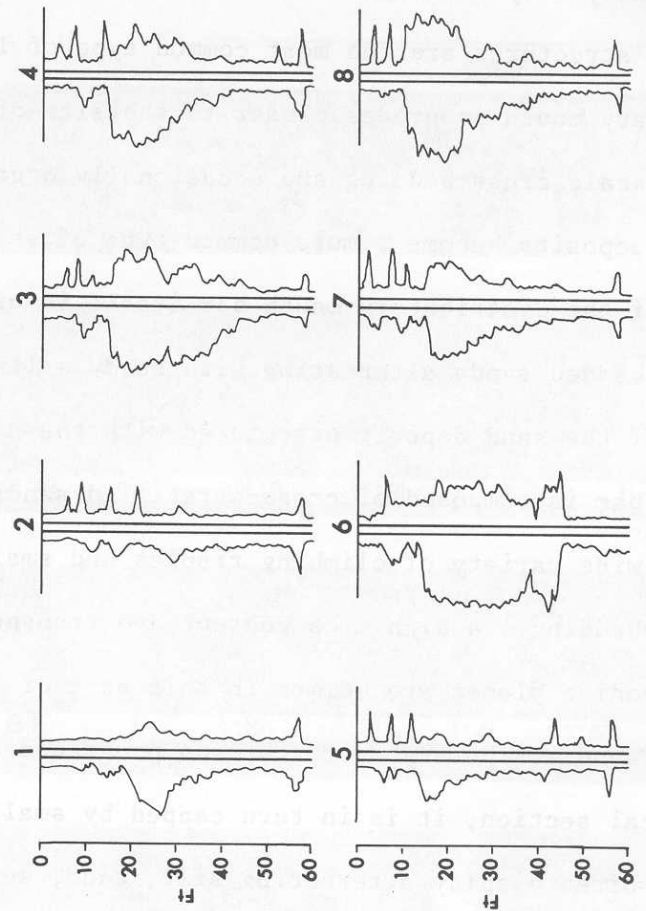


Figure 20. Diagram illustrating sedimentary characteristics of the bay-fill deposits.

the bay, coarser grained clastics begin to be delivered to the site of the vertical section, and often sands and silty sands alternate with thin silty clay laminations. Graded bedding and small-scale climbing ripple structures are the most common type of lamination. As the distributary mouth progrades closer to the site of the vertical section, small-scale cross-bedding and occasionally organic debris within the sandy deposits become a more common type of stratification. The lower part of the distributary-mouth bar itself is often characterized by cross-bedded sands alternating with sandy silts and silty clays. The bulk of the sand deposit associated with the advancing distributary-mouth bar is composed of cross-stratified sands and sandy silts displaying a wide variety of climbing ripples and small-scale festoon-type cross-bedding. A high mica content and transported organic debris along the bedding planes are common in this part of the vertical sequence. Once the distributary-mouth bar has prograded across the site of the vertical section, it is in turn capped by small overbank crevasse splays, which often display alternating silt, sand, and clay units, the silts and sands including well-developed small-scale ripple laminations. The uppermost capping unit of bay-fill sequences is essentially an interdistributary-bay or a marsh deposit. Root burrowing is an extremely common characteristic of this uppermost field. In some deposits, iron carbonate or siderite nodules are plentiful, and in most cases pyrite is abundant, replacing plant debris. Figure 21 illustrates a series of individual cores taken in the crevasse-splay deposits. Most of the types of the stratification described above can be seen in these cores. Figure 22 depicts a continuous cored boring through a bay-fill deposit. The particular deposit is the West Bay crevasse, which broke through in 1839. The cores are 9 m in diameter and are essentially continuous.

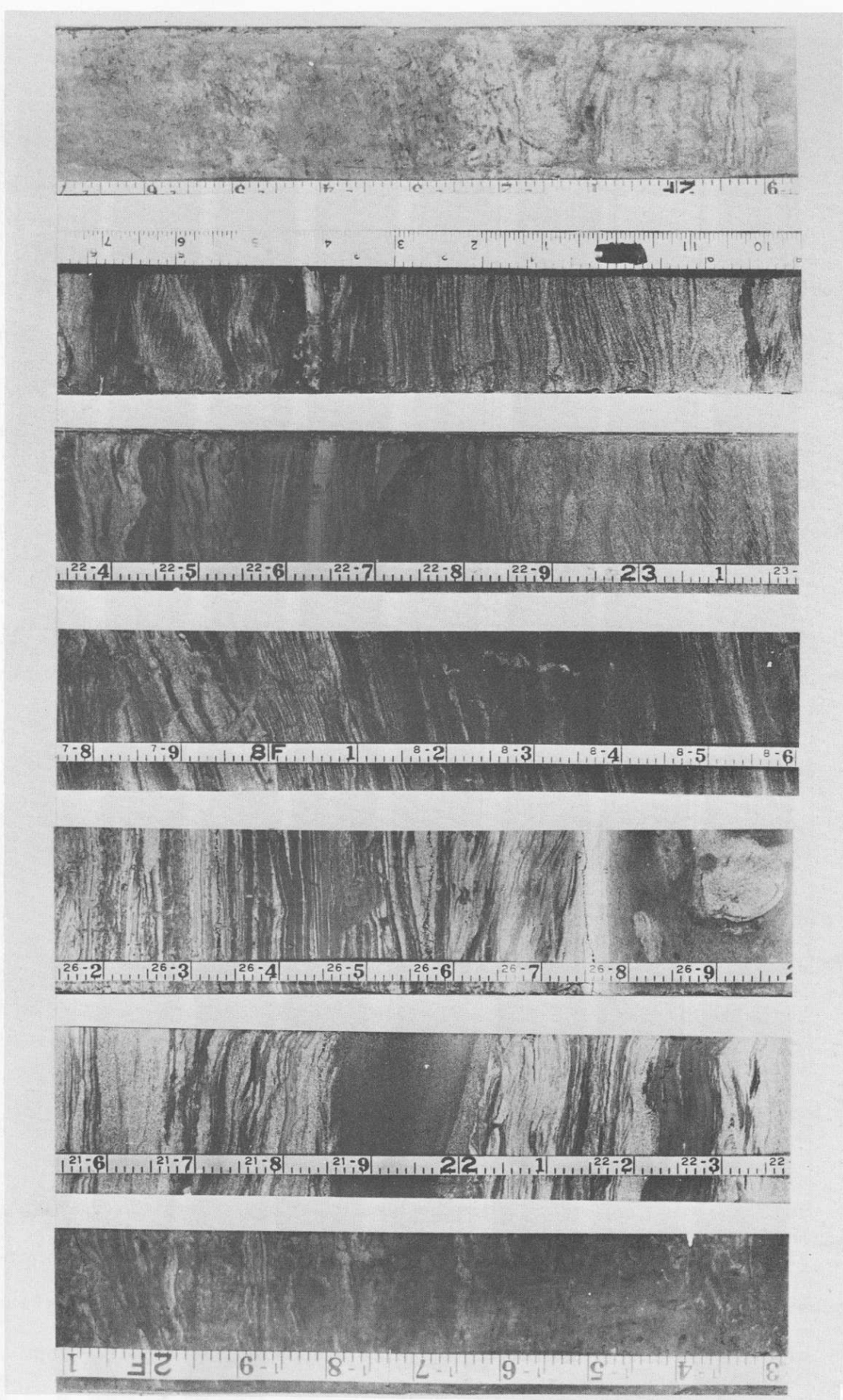


Figure 21. Cores from the bay-fill environment.

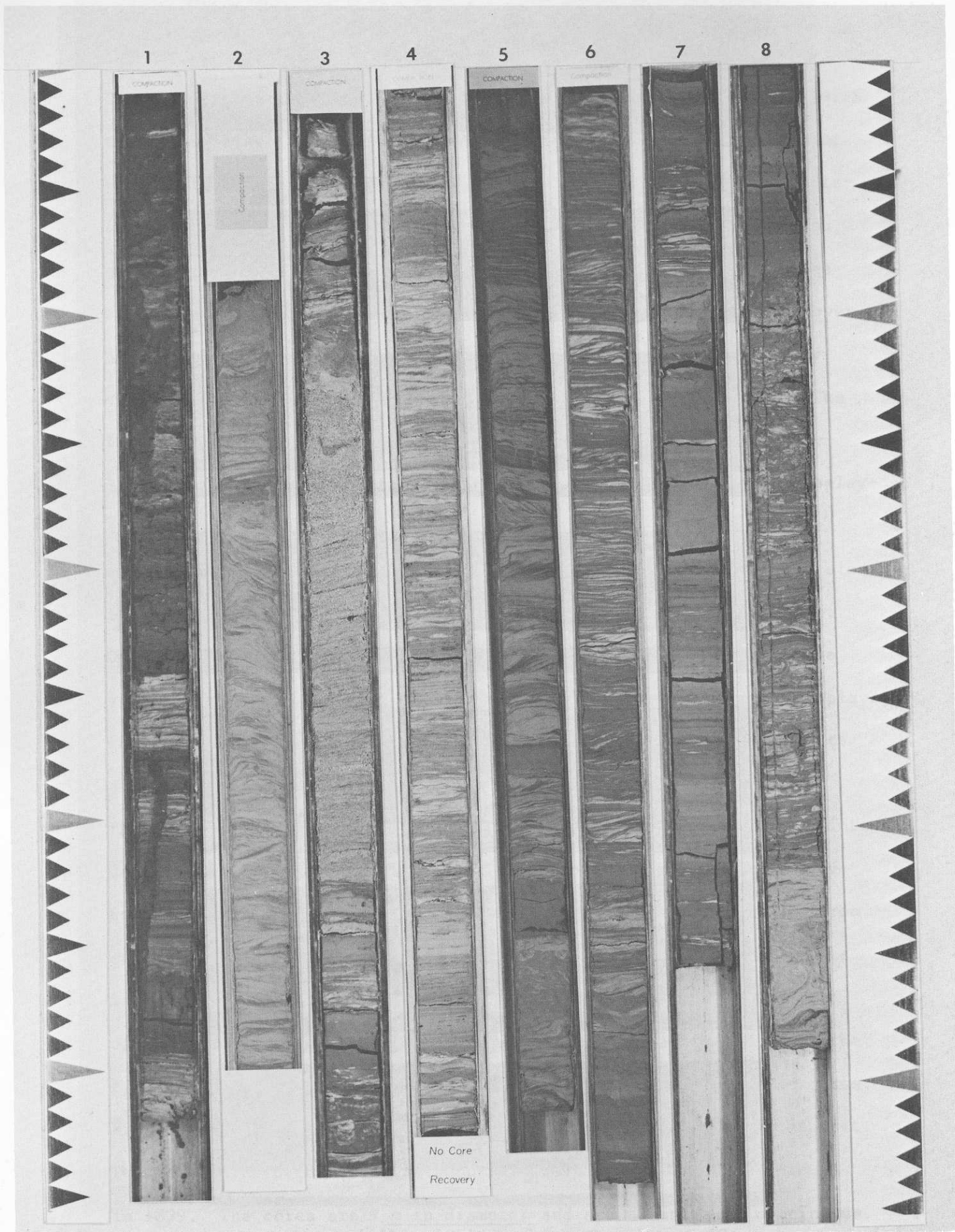


Figure 22. Continuous core through a bay-fill deposit.

The bottom of the core is shown in the lower right-hand corner, and the present marsh surface is in the upper left-hand corner. The core is approximately 10 m long. Burrowed sediments of the original bay bottom can be distinguished in core 8. Core 7 shows the infilling of the bay by fine-grained clays; it is essentially a prodelta clay environment. Cores 5 and 6 show the alternating silts, sands, and silty clays that comprise the middle part of the field, which is generally termed the distal bar. The distributary-mouth bar itself is characterized by cores 2, 3, and 4, with the upper part being essentially nearly continuous sand deposition. The small overbank crevasses or natural levees that cap the small distributaries are illustrated in the lower part of core 1, while the upper part represents the presently accumulating marsh.

The lower two diagrams of Figure 20 illustrate an isopach map of a bay-fill sequence and variations in log response that can occur within such a sand body. The isopach sand body generally displays a fan-shaped wedge, with the thickest sands generally being found near the initial break in the distributary channel. Often the sands in this vicinity display sharp-based scouring into the underlying new distributary-bay and marsh deposits. Away from the initial break, however, the typical coarsening-upward sequence (or inverted bell-shaped logs) becomes the most common type of log response. Within the overall sand body, there are areas where sands have not accumulated to any great thickness, and thus there are zones in which virtually no sand can be found and the entire sequence consists of interdistributary-bay silts and clays grading upward into marsh deposits. Comparing these log responses and the typical boring sequence with the continuously cored boring in

Figure 22 shows many similarities.

### Subaqueous Delta Environments

The subaqueous delta is the part of the delta plain that lies below low-tide level and extends seaward to the area actively receiving riverborne sediment. It is the foundation across which progradation of the subaerial delta must proceed. Most commonly the subaqueous delta is characterized by seaward fining of sediments, sands and coarser clastics being deposited near the river mouths and finer grained sediments settling farther offshore from suspension or as a result of downslope mass-movement processes. Figure 23 is a high-altitude photograph of the distributary mouths of the eastern part of the Mississippi River delta. Note the bifurcated channel pattern of the major distributary, Pass a Loutre. The highly turbid freshwater effluent plume can be seen to extend out considerable distances offshore. Note especially that the plume expands considerably as it leaves the confines of its channel and spreads seaward under the influence of bottom friction, buoyancy, and inertial effects. It is the spreading of this effluent plume that controls the distribution of the major subenvironments of the subaqueous delta plain. The seawardmost section of the subaqueous delta commonly is referred to as the prodelta environment and is composed of the finest material deposited from suspension. The prodelta silts and clays grade landward or upward vertically into the coarser silts and sands of the distal bar. Directly at the mouths of the active distributaries are found the coarsest sand deposits. These deposits are referred to as the distributary-mouth bar. If the sediments deposited seaward of the river mouth accumulate faster than subsidence or removal of sediments by marine processes, the subaerial deltaic deposits will prograde and overlies the uppermost parts of the subaqueous delta, forming a complete

delta sequence. The distribution of these environments of the subaqueous delta is shown schematically in Figure 24.

A general understanding of the processes and mode of formation of the distributary-mouth bar is critical to understanding the evolution and vertical relationships in a delta sequence. Figure 25, modified from an original diagram by Secaton (1960), illustrates the process

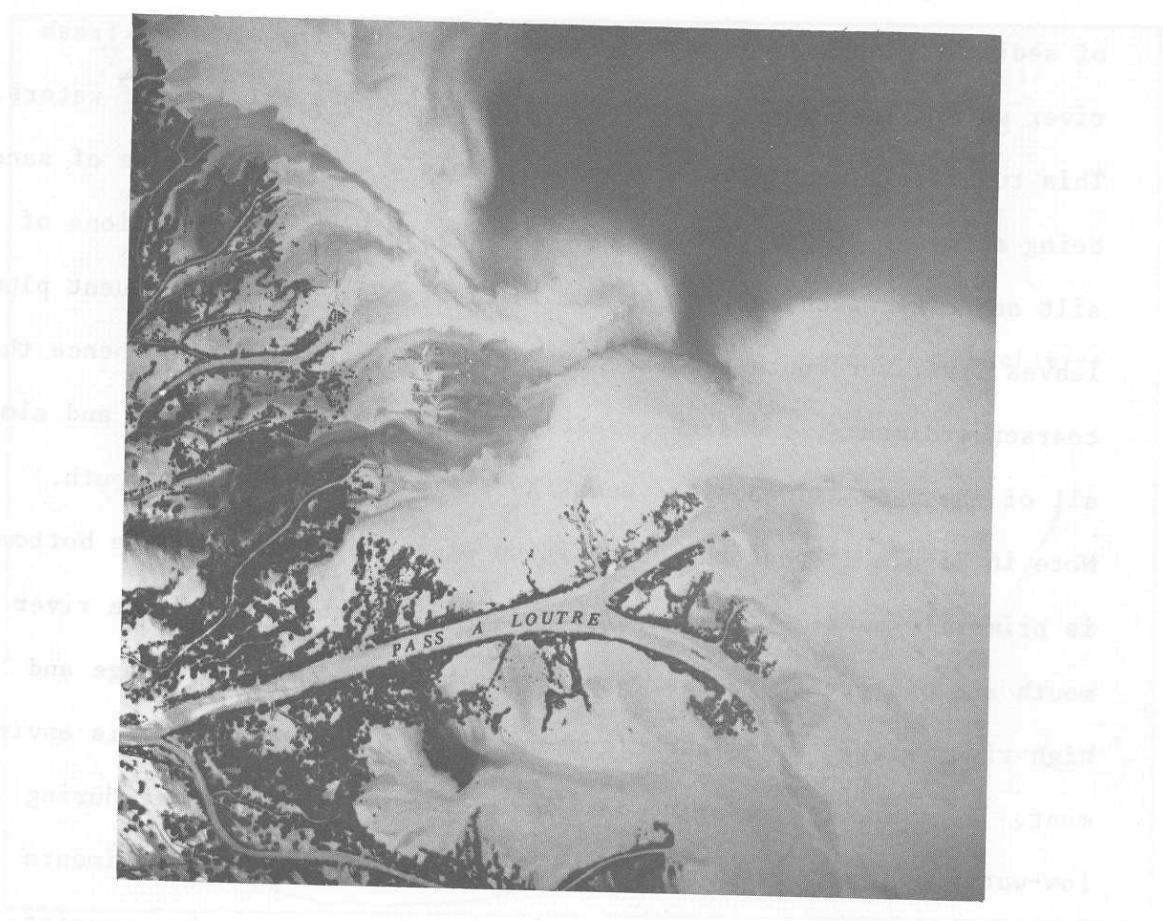


Figure 23. High-altitude photograph of the distributary mouths of the Mississippi River delta.

delta sequence. The distribution of these environments of the subsequent delta is shown schematically in Figure 24.

A general understanding of the processes and mode of formation of the distributary-mouth bar is critical to understanding the evolution and vertical relationships in a deltaic sequence. Figure 25, modified from an original diagram by Scruton (1960), illustrates the process of sediment dispersal at a river mouth. Low-density, turbid, fresh river water flows via the distributary over denser saline Gulf waters. This turbid effluent plume may contain only a small percentage of sand being actively transported by the river, with high concentrations of silt and clay, such as illustrated in Figure 25. As the effluent plume leaves its river mouth and expands, velocity decelerates and hence the coarser sediments, the sands, settle rapidly from suspension, and almost all of the sand is deposited near the vicinity of the river mouth. Note in Figure 25 that the composition of the sediments on the bottom is primarily sand. Because of variations in turbulence at the river mouth and different process intensities between low river stage and high river stage, silts and clays can also be deposited in this environment. However, reworking by marine processes (predominantly during low-water periods) results in cleaning and sorting of the sediments by wave processes. As a result, the distributary-mouth bar consists commonly of clean, well-sorted sands that have been delivered by the river to its mouth. The remaining fine-grained suspended load carried by the river is distributed widely as the river effluent continues to expand and is constantly decreasing in velocity seaward. Larger amounts of silts, sands, and clays fall out progressively seaward. As the sediment load is constantly diminishing within the water column and is being spread in an ever increasing area, the rate of clastic deposition gradually

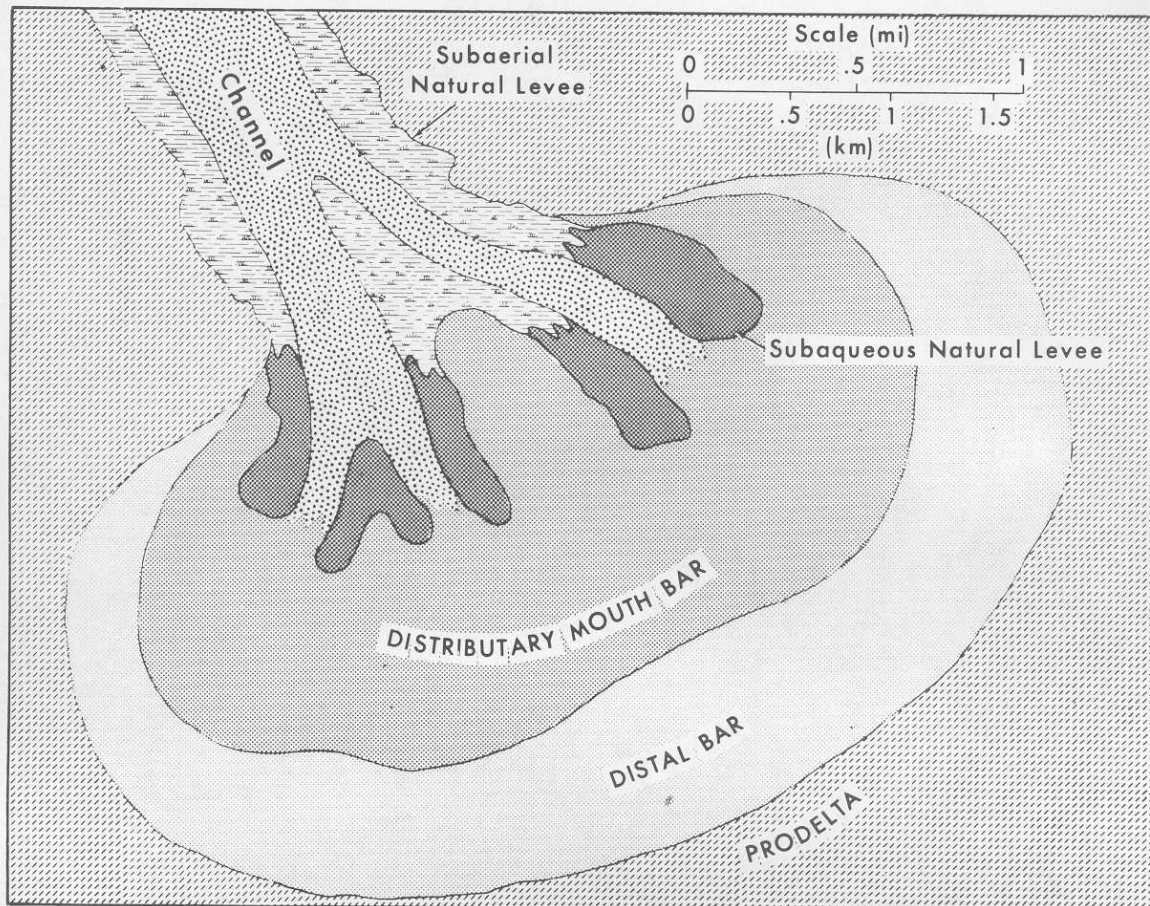


Figure 24. Depositional environments at a river mouth.

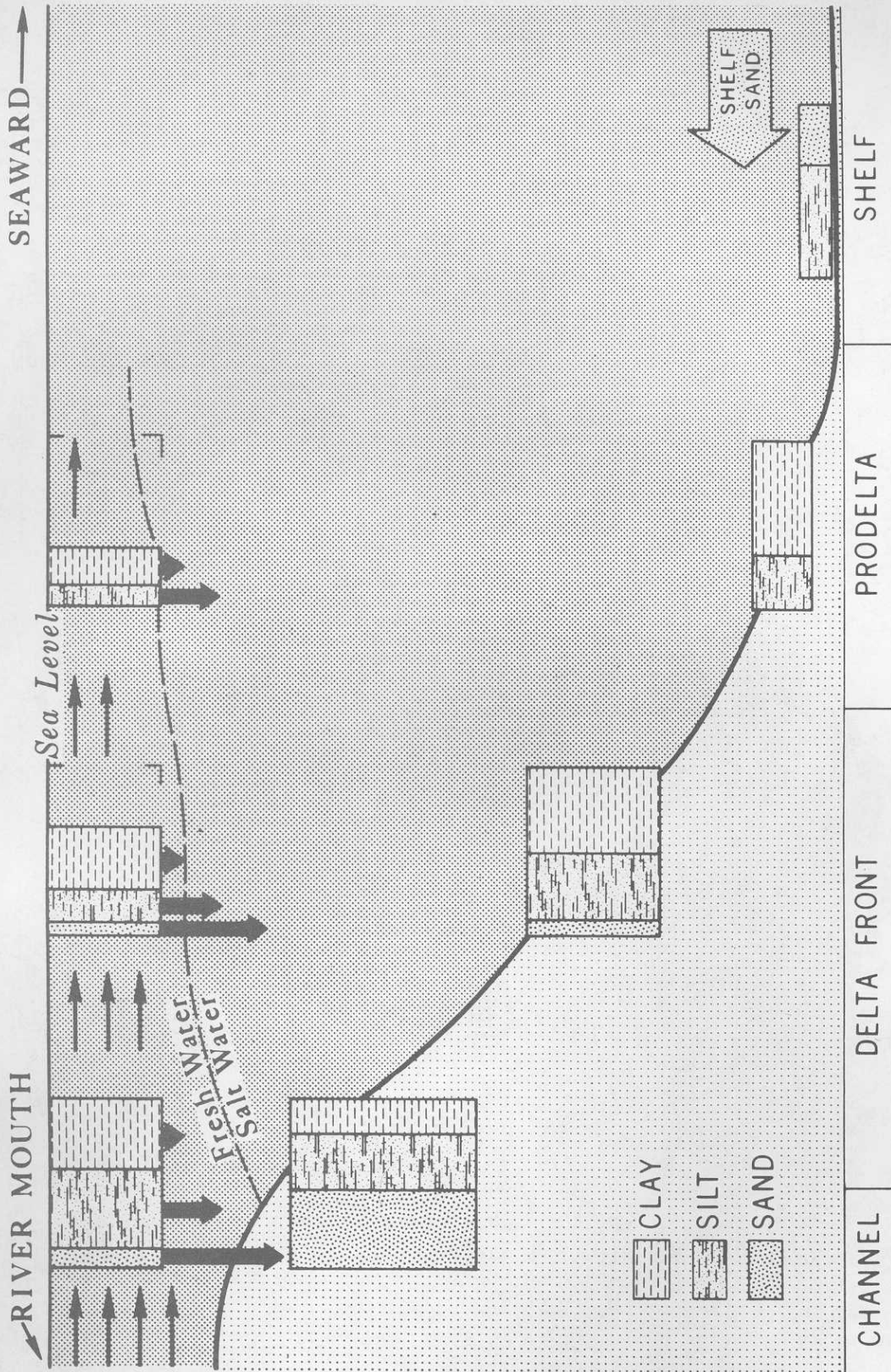


Figure 25. Sediment dispersal at a river mouth (from Scruton, 1960).

ally decreases seaward from the distributary mouths. Thus the silts and some of the clays fall out and form what is commonly termed the distal bar, or delta front (Scruton, 1960). With continued expansion and ever-decreasing velocity, finally only the finest grained deposits remain within the water column, eventually settle out to the bottom, and are incorporated as prodelta clays, which contain fine silts and clays deposited completely from suspension. Thus by this process of effluent expansion and the consequent loss of transporting power, a series of subenvironments is progressively laid down around the river mouths. Bottom samples would show that the coarsest sands are found in the immediate vicinity of the river mouth. As greater water depths were encountered, and farther offshore, fine sands, silts, and clays would alternate, depending upon the extent of each flood. In the Mississippi River delta, silts and fine sands can be laid down in water depths as great as 75-100 m. Farthest offshore and spread laterally the greatest are the fine-grained silts and clays (prodelta deposits); these fine-grained sediments can move seaward great distances, and it is not uncommon to find clays beyond the shelf edge and deposited from suspension in the upper slope environment. Note in Figure 25 that Scruton (1960), as he moved out onto the shelf environment, encountered sands. At the time of his interpretation, he envisioned that these sands were being worked onshore from the shelf by submarine currents. Recent evidence, to be discussed later, will indicate that these sands found in the outer shelf and upper slope result from mass-movement processes by which large parts of the river-mouth-bar deposits are mass moved seaward and incorporated in the shelf-edge and upper-slope deposits.

Figure 25 illustrates the development of a facies in a single instant of time. However, because of the continued influx of sediment

to the distributary mouth, these facies prograde seaward with time. Figure 26 illustrates a series of depositional surfaces through time. As can be seen, the entire delta-front progrades seaward. However, because of the continuing processes of hydraulic sorting and deposition of the sediment, the sands remain in and near the river mouth, with the silts and silty clays moving seaward and prodelta settling farthest offshore. As a result, the lithofacies follow essentially horizontal to the sea level surface, and thus the time lines, which represent depositional surfaces, cross the lithologic boundaries. In a sense the sand body represented by the distributary-mouth bar is a time transgressive unit. Figure 27, modified from Gould (1970), shows the progradation of the distributary-mouth bar of Southwest Pass during the period 1764 to 1959. During this 200-year period the distributary prograded 10 km seaward and formed a distributary-mouth-bar deposit that ranges in thickness from 20 m to 80 m and is in excess of 6 km wide. The formation of a sand body of this dimension within a 200-year period indicates the extremely rapid deposition of distributary-mouth-bar sands. Historic hydrographic maps indicate that the average progradation rate approximates 100-110 m per year.

Prodelta deposits. The basal portion of the actively prograding delta is commonly referred to as the prodelta deposits. This facies is characteristically a blanket of clays and fine silts deposited from suspension, having high lateral continuity and low lithologic variation. Because deposition is entirely from suspension, parallel laminae are by far the most common primary structure. Parallel laminations are detected by slight color changes, which depend on the amount of transported fine-grained organics incorporated, and by alternations of fine graded silt layers within an otherwise fine-grained clay. High

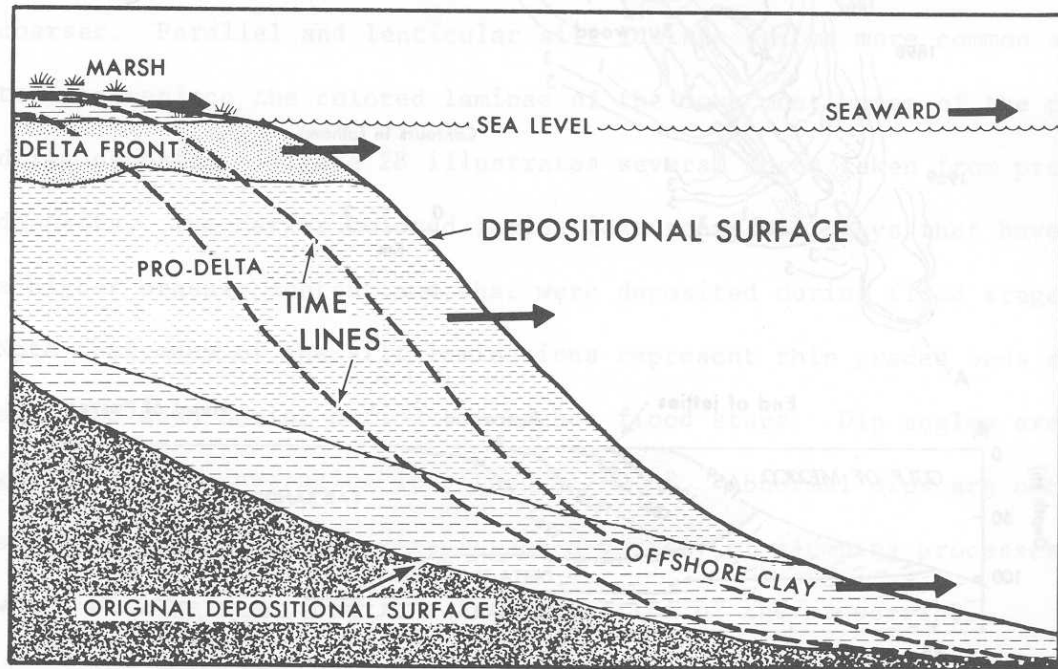


Figure 26. Time lines and lithofacies in a prograding distributary (modified from Scruton, 1960).

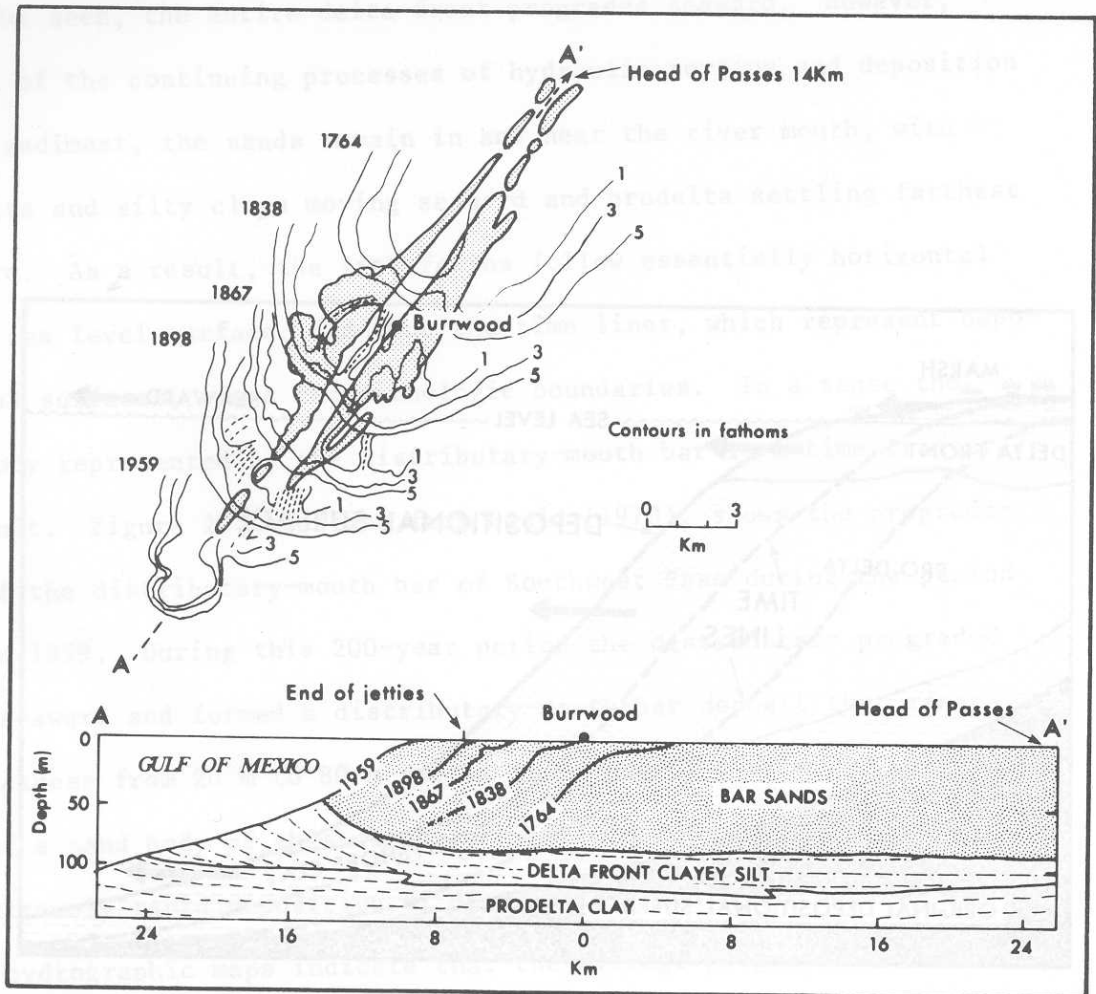


Figure 27. Seaward migration of distributary-mouth bar at Southwest Pass during the period 1764-1959 (modified from Gould, 1970).

rates of deposition associated with the prodelta normally preclude intense burrowing by marine organisms. However, burrowing layers will be present occasionally and will alternate with laminae that display little or no burrowing. Faunal species are normally high, especially foraminiferal tests, indicating an open marine environment; both number and species are high. The shallower water portions of the prodelta deposits tend to show laminae that are thicker and grain size that is normally coarser. Parallel and lenticular silt laminae become more common and tend to replace the colored laminae of the lowermost zones of the prodelta deposits. Figure 28 illustrates several cores taken from prodelta deposits. The darker colored laminations represent clays that have a higher organic content and that were deposited during flood stage. Note that many of the silt laminations represent thin graded beds and are laid down during periods of higher flood stage. Dip angles are generally low, averaging less than 0.2-0.3°. Abnormal dips are occasionally found, and these represent a variety of slumping processes, which will be described in a future section of the manuscript.

The thickness of the prodelta deposits varies considerably from delta to delta. In the Mississippi River delta these deposits can assume considerable thicknesses, ranging from 20 m to 100 m. They are extremely widespread, and it is possible to find essentially a continuous blanket of prodelta clays that has dimensions on the order of 200-250 m spread in front of the modern Mississippi Delta.

Distal-bar deposits. Upward or landward in the deltaic sequence is the distal bar (also referred to as the delta front or delta platform), which overlies the prodelta facies. This environment is the seaward-sloping margin of the advancing delta sequence. Increase in

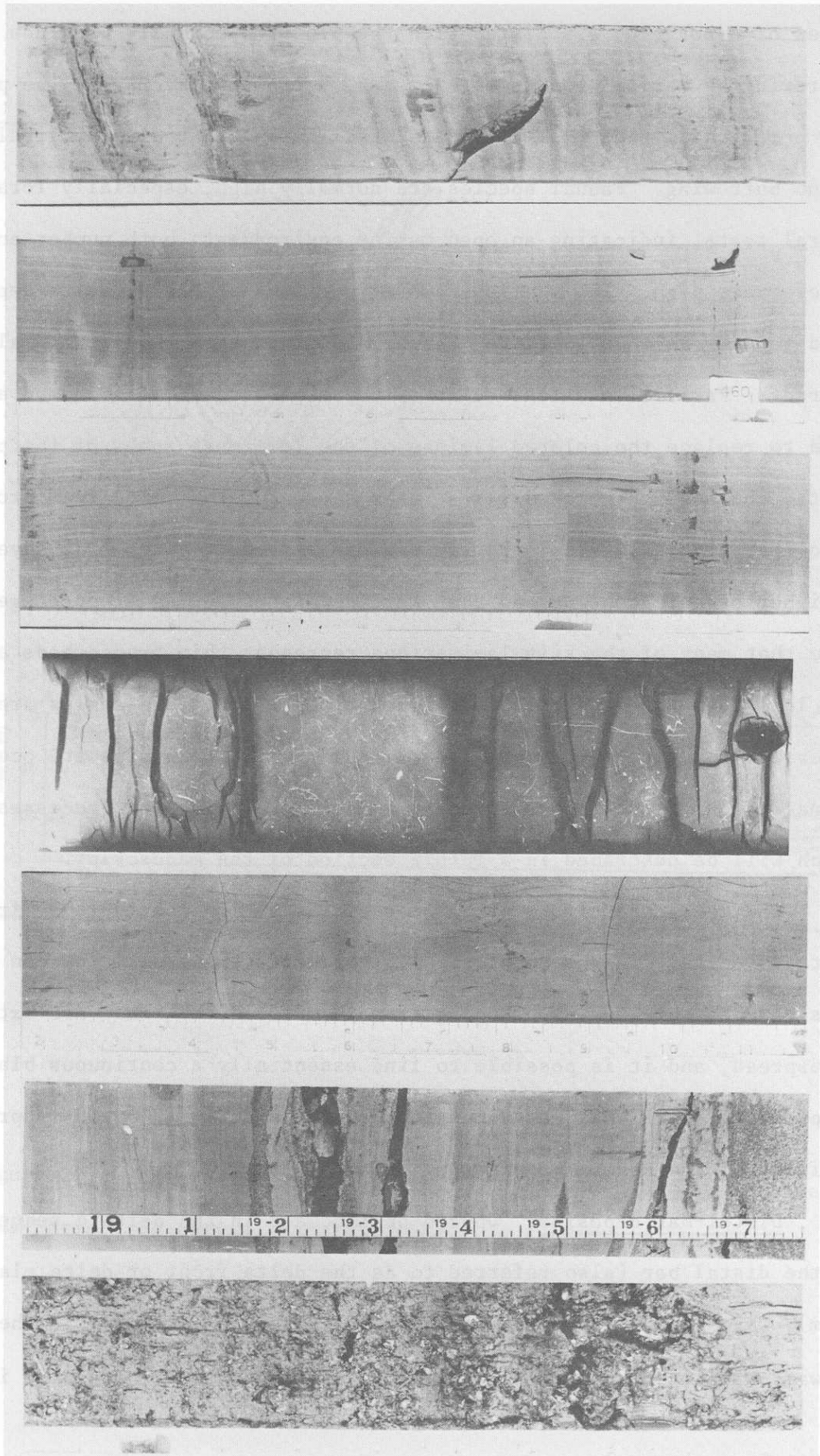


Figure 28. Cores from the prodelta deposits.

sedimentation rates and coarseness of the sediments distinguishes these deposits from prodelta clays. Dip angles are slightly higher; however, they rarely exceed  $0.5^{\circ}$ . Lithologically these deposits can be characterized as laminated silts, silty sands, and clays. The delta-front generally shows lower lateral continuity than the prodelta environment. In the more seaward portions of the distal bar, small burrows and shell remains are scattered throughout the deposits and often result in partial destruction of the parallel and lenticular laminations. Dilution of salinity by river water, along with the nutrient-laden currents derived from the river, makes this a highly favorable environment for burrowing organisms, especially soft-bodied worms, and often cores taken in the more seaward parts of the distal bar are characterized by high bioturbation. Because of the shallow-water nature of these deposits and proximity to the river mouths, currents associated with high floods on the river will normally feel bottom and produce a wide variety of sedimentary structures associated with current and wave processes. Sedimentary structures such as small-scale cross-laminae, current ripples, scour and fill, and erosional truncations attest to these physical processes. One of the more common features within these deposits is the abundance of graded bed sequences, in most instances grading from finer grained to coarser grained vertically upward. Figure 29 illustrates cores taken in the distal-bar environment. In many instances these deposits are coarse enough and clean enough to be classed as potential reservoir beds. In the Pleistocene deposits of offshore Texas and Louisiana, distal-bar deposits often contain large amounts of gas, and many fields have been developed within these distal ends of the delta sequence.

Distributary-mouth-bar deposits. The distributary-mouth bar is the area of shoaling associated with the seaward terminus of a distributary-

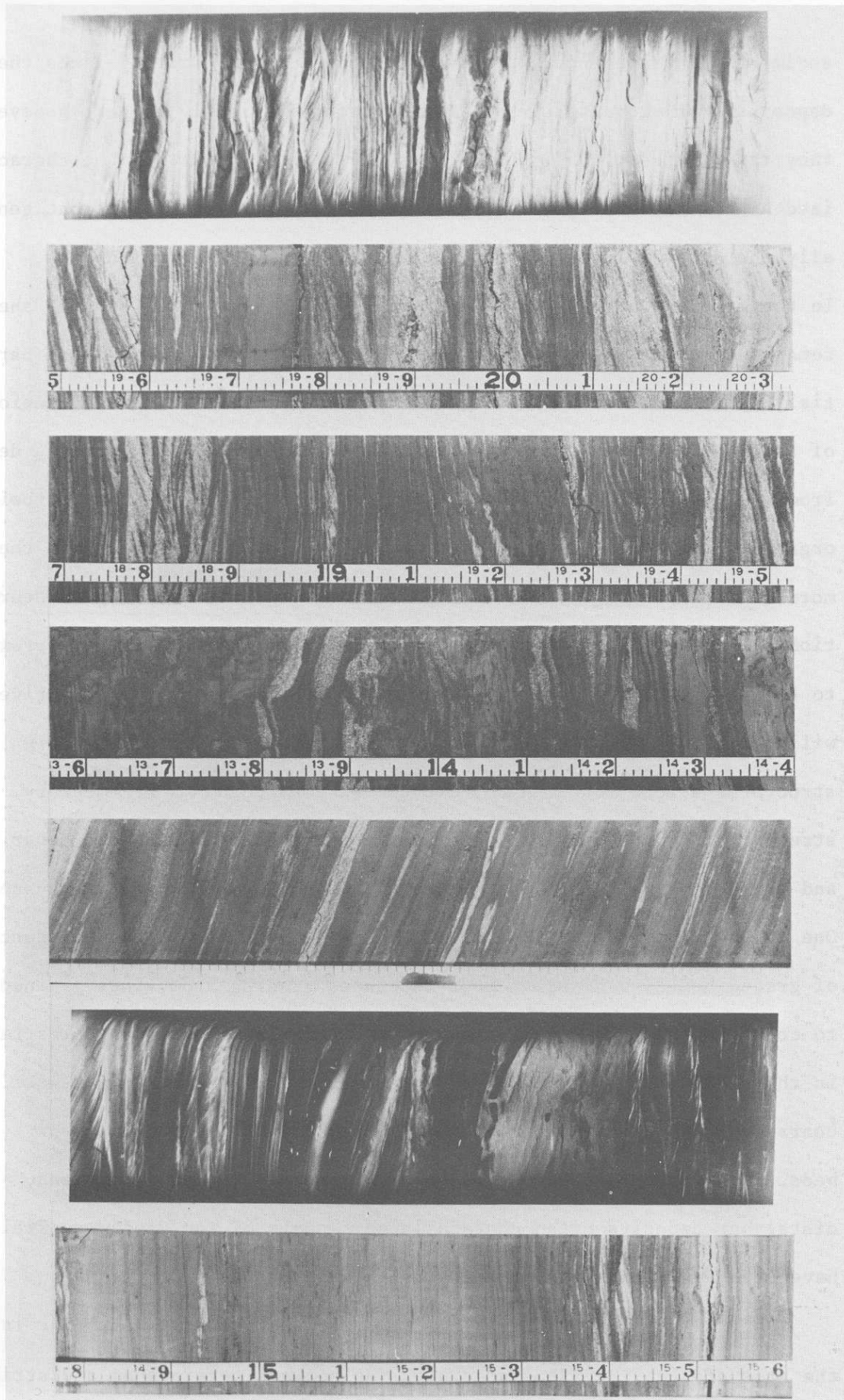


Figure 29. Cores from the distal-bar deposits.

mouth channel. Shoaling is a direct consequence of a decrease in velocity and a reduction in carrying power of a stream as it leaves the confines of its channel. Accumulation rates are higher than in any other environment associated with the delta sequence. In some places depositional rates of coarse sediments at the mouth of the Mississippi are as high as 4-5 m per year. The sediments are constantly subjected to reworking, not only by stream currents but also by waves generated in the open marine water beyond the channel mouth. The distributary-mouth bar commonly consists of clean, well-sorted sand and thus is an obvious potential reservoir for hydrocarbons. The most common sedimentary structures consist of a variety of small-scale cross-laminae and current ripple drift. In many cases mass-movement processes such as small localized slumps result in distorted laminations. Because of the rapid deposition, pore pressures are often high within the sand deposits, and a large number of pore fluid escape structures and localized compactional structures are found in these deposits. Near the top of the distributary-mouth bar large accumulations of river-transported organic debris are usually present. Water-saturated logs and other organic debris are transported down the rivers in times of floods and discharged into the nearshore zone, where wave action grinds the coarser wood particles into large concentrations of organic debris. These organic inclusions are often referred to as "coffee grounds." Within this environment mica content is generally extremely high, and the mica in many cases forms a significant number of individual laminations. The distributary-mouth bars vary considerably in thickness because of compaction and subsidence as the denser sands prograde over the high-water-content clays and silts of the underlying deposits. A normal stratigraphic section would generally show thicknesses on the order of 20 m. However,

localized compaction will increase this thickness to as much as 60-70 m. Widths of the deposits vary from distributary to distributary, depending on its sediment yield. However, in the Mississippi the width of the sandy distributary-mouth-bar deposits ranges from 3 to 6 km. In many instances the sand body will follow continuously parallel to the distributaries, and in those cases in which the distributaries consist of long, straight channels the distributary-mouth bar will be represented on an isopach map as an elongate sand body whose length is many times its width. In other instances, if the distributaries bifurcate and the river mouths remain close enough to one another, the sand body at each river mouth will merge and often form a distinct sand sheet that fronts the advancing delta lobe. This situation exists in the eastern portion of the modern Mississippi Delta, where the Pass a Loutre complex contains distributary mouths close enough to one another so that the entire distributary-mouth bar merges as a continuous sand sheet. In contrast, in the southern and western portions of the modern delta Southwest Pass and South Pass have prograded seaward as individual distributaries, and hence a long, linear sand body some 40 km long, 4.5 km wide, and averaging 25 m in thickness parallels each of these distributaries.

As the distributary continues to prograde seaward, the distributary-mouth bar will be capped by a variety of overbank splays and shallow interdistributary-bay deposits. These overbank splays are commonly referred to as natural levees. During annual floods on the river the river stage will normally top the distributary channel and numerous small overbank splays will result. Each splay will be maintained for a year or several years, until it builds up or grades the natural levee to flood level; then it will cease to be active. Thus, capping the distributary-mouth bar is commonly a series of small coarsening-upward

sequences representative of these splay deposits. These deposits are characterized by a wide variety of sedimentary structures, with climbing current ripples and small-scale cross-laminae being the most common. Burrowing by plant roots and other organisms also characterizes these sequences. Figure 30 shows several cores taken in distributary-mouth-bar deposits. Note the variety of the types of laminations present within these cores. All of the cores illustrated consist of 70-80% sand-sized particles, and although the sand is fine grained, in this case it is extremely clean and could serve as reservoir rock.

Figure 31 illustrates the sedimentary characteristics of the distributary-mouth-bar deposits. The upper left diagram shows a schematic view of the relationship between the prodelta clays, the distal bar, and the distributary-mouth bars of two distributaries that have prograded to the continental shelf in front of an advancing delta. The upper right diagram illustrates some of the vertical sequence characteristics of these deposits. Low in this section are the prodelta clays, which consist of fine-grained clay and silt deposits showing parallel organic and silt layers and distorted laminations alternated with burrowed zones. Dip angles within these deposits are low; however, occasionally high-angle dips of 12-15° can be found. These high-angle dips are associated with subaqueous slumping processes. Grading up vertically the rippled and lenticular laminated silts and silty sands represent the distal bar deposits. Sand content increases, and the deposits are characterized by a large number of finely graded coarse clastic layers. Vertically overlying the distal bar are the distributary-mouth-bar deposits, consisting almost entirely of clean, well-sorted sands. Dip angles once again are generally low, rarely exceeding 0.5°. Small-scale ripple

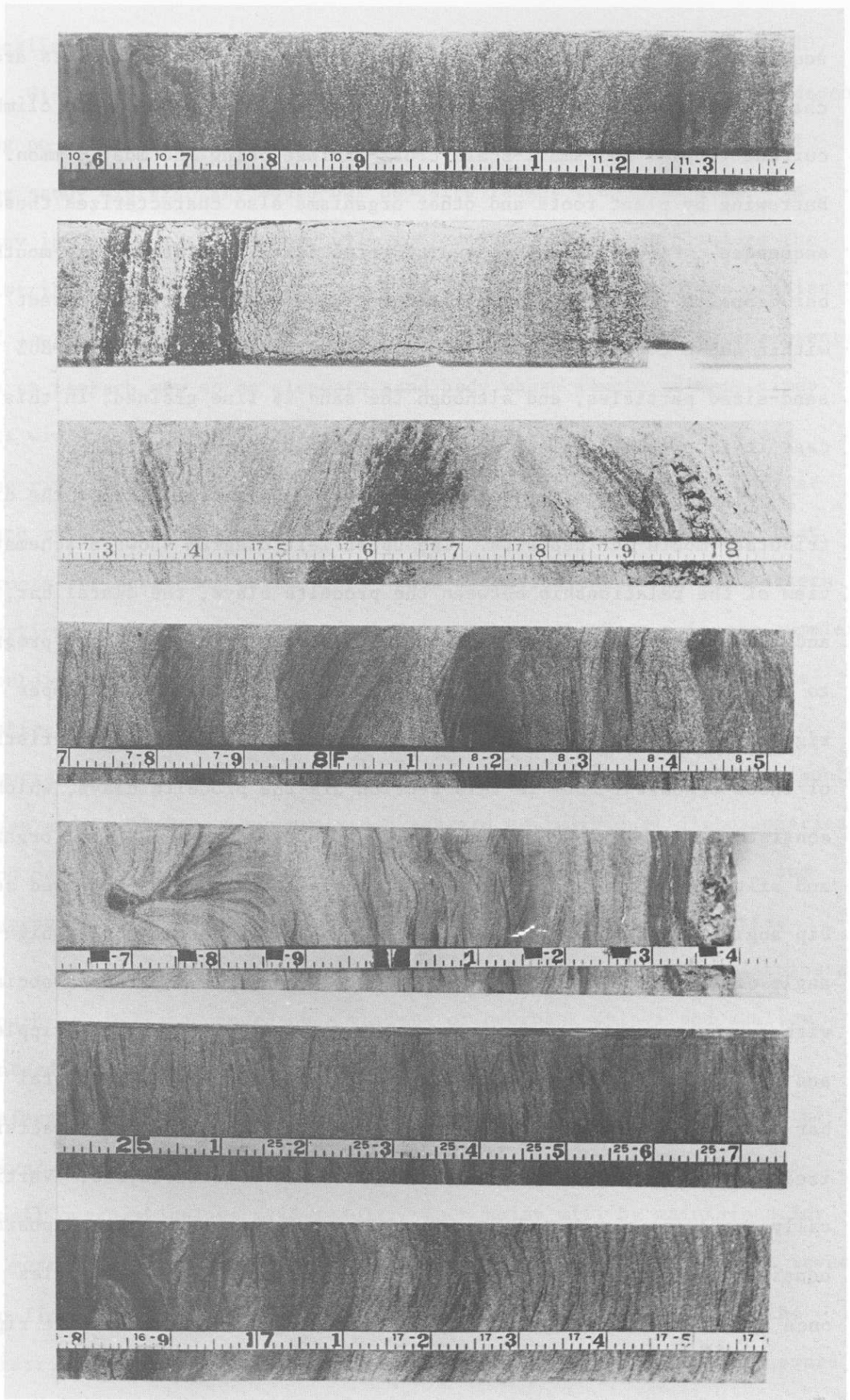


Figure 30. Cores from distributary-mouth-bar deposits.

# DISTRIBUTARY MOUTH BAR

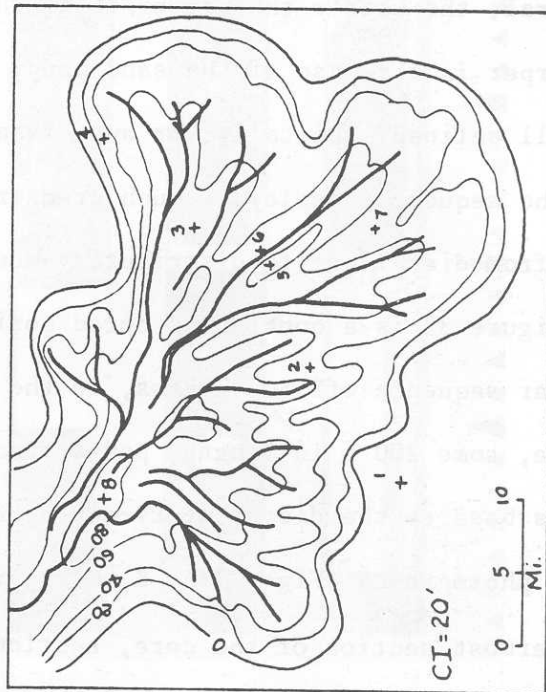
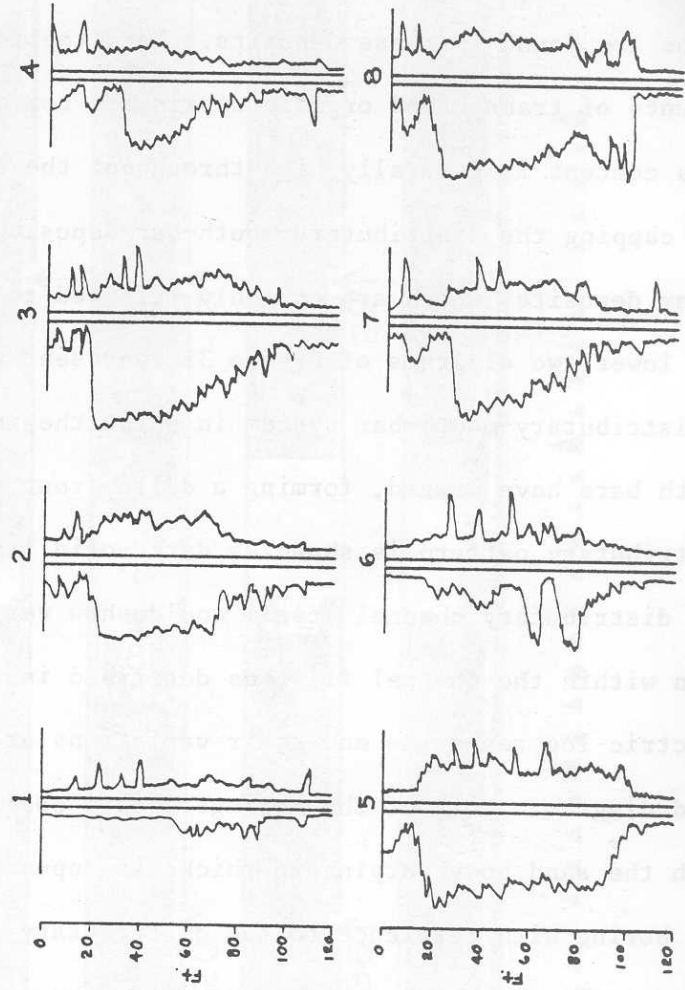
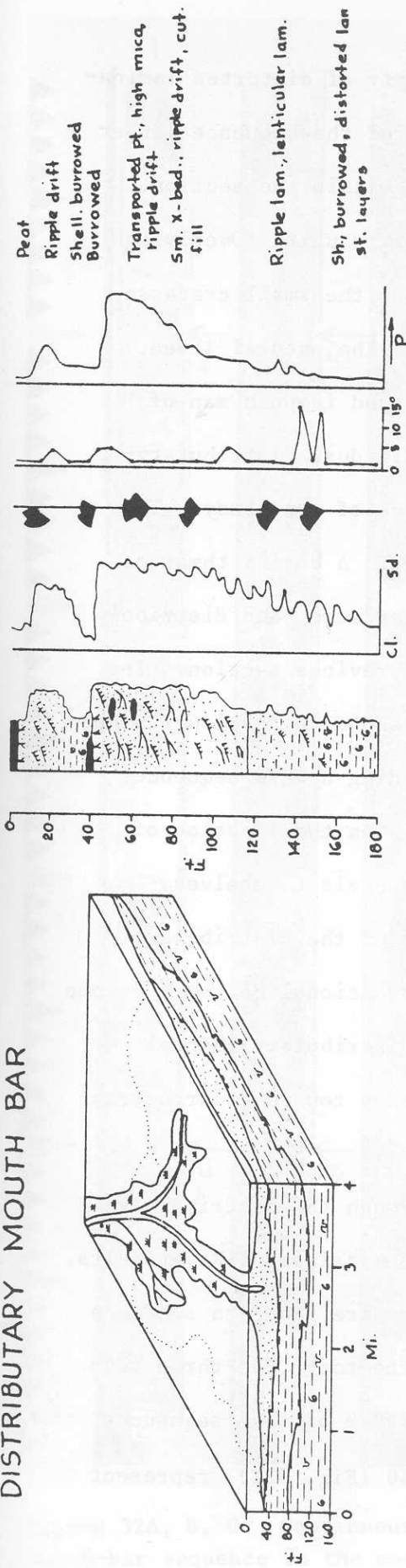


Figure 31. Diagram illustrating the sedimentary characteristics of the distributive-mouth-bar deposits.

laminations, low-angle cross-bedding, and a variety of distorted laminations are found in these deposits. Near the top of the sequence larger amounts of transported organic debris are common within the section. Mica content is generally high throughout the entire unit. Overlying and capping the distributary-mouth-bar deposit are the small crevasse splay deposits, which are commonly referred to as the natural levee. The lower two diagrams of Figure 31 represent a sand isopach map of a distributary-mouth-bar system in which the individual distributary-mouth bars have merged, forming a delta-front type of sand body. The distributary pattern is shown as dark solid lines. A boring through the distributary channel itself would show very erratic sand distribution within the channel fill, as described in a previous section. The electric log responses and their variations are shown in the lower right-hand diagram. Most of the borings show a coarsening-upward sequence, with the sand body varying in thickness depending on the location of the boring with reference to the distributary channels themselves. In general, the nearer the boring is to the axis of the distributary, the sharper is the base of the sand body, and gradational contacts become less well defined. Distally, or away from the distributary-channel axis, the sequence displays a much greater tendency toward a large transition from distal bar to distributary-mouth bar.

Figure 32 is a continuous cored boring through the distributary-mouth-bar sequence off South Pass, in the modern Mississippi River delta. The core, some 200 m in length, penetrated the entire prodelta sequence from its base to the distributary-mouth bar at the top. The three sets of core photographs (Figs. 32A, B, C) represent 42 m of this sequence. The lowermost section of the core, sections 35-40 (Fig. 32C), represent

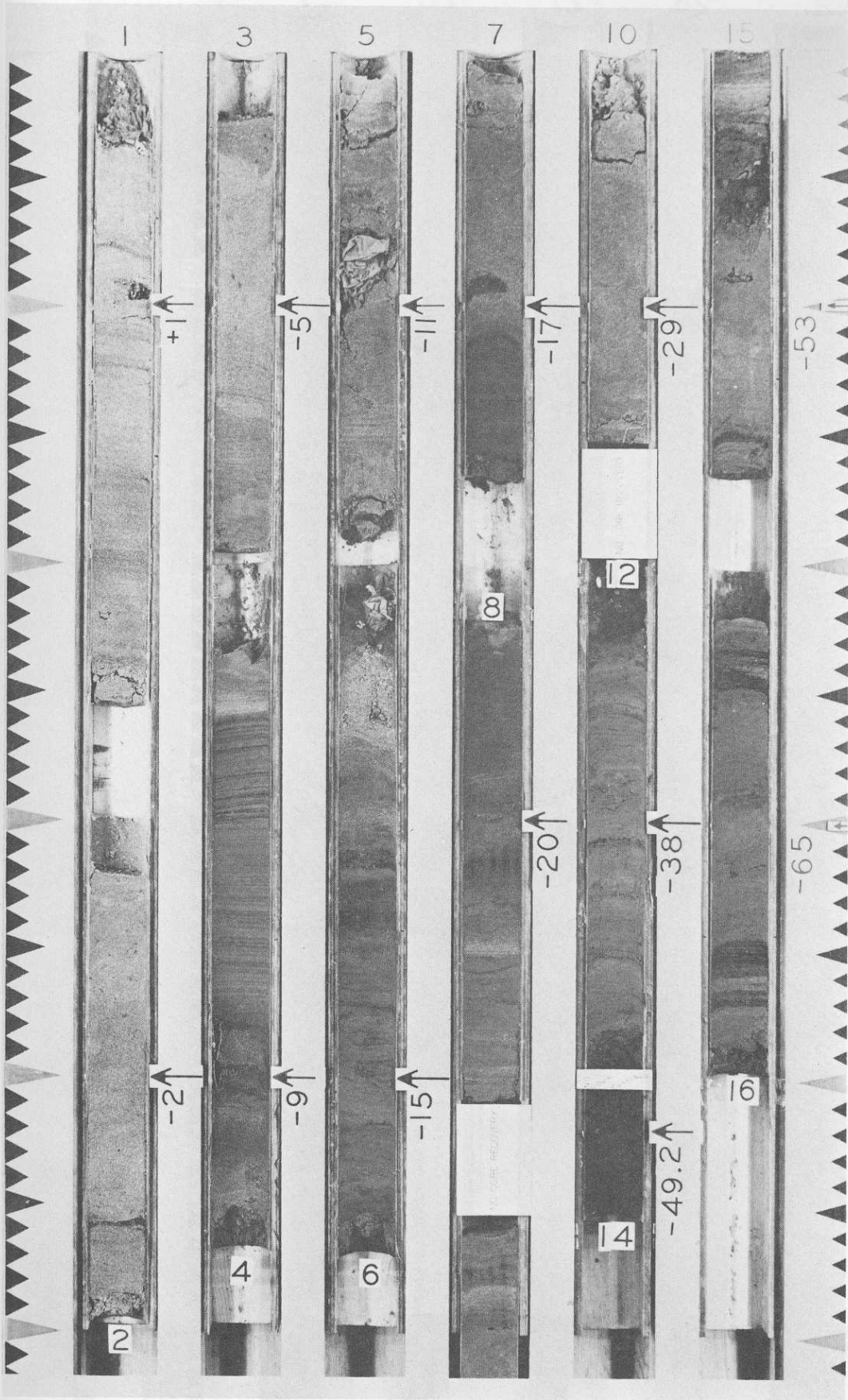


Figure A

Figure 32A, B, C. Continuous cored boring through the distributary-mouth-bar sequence in the modern Mississippi River delta.

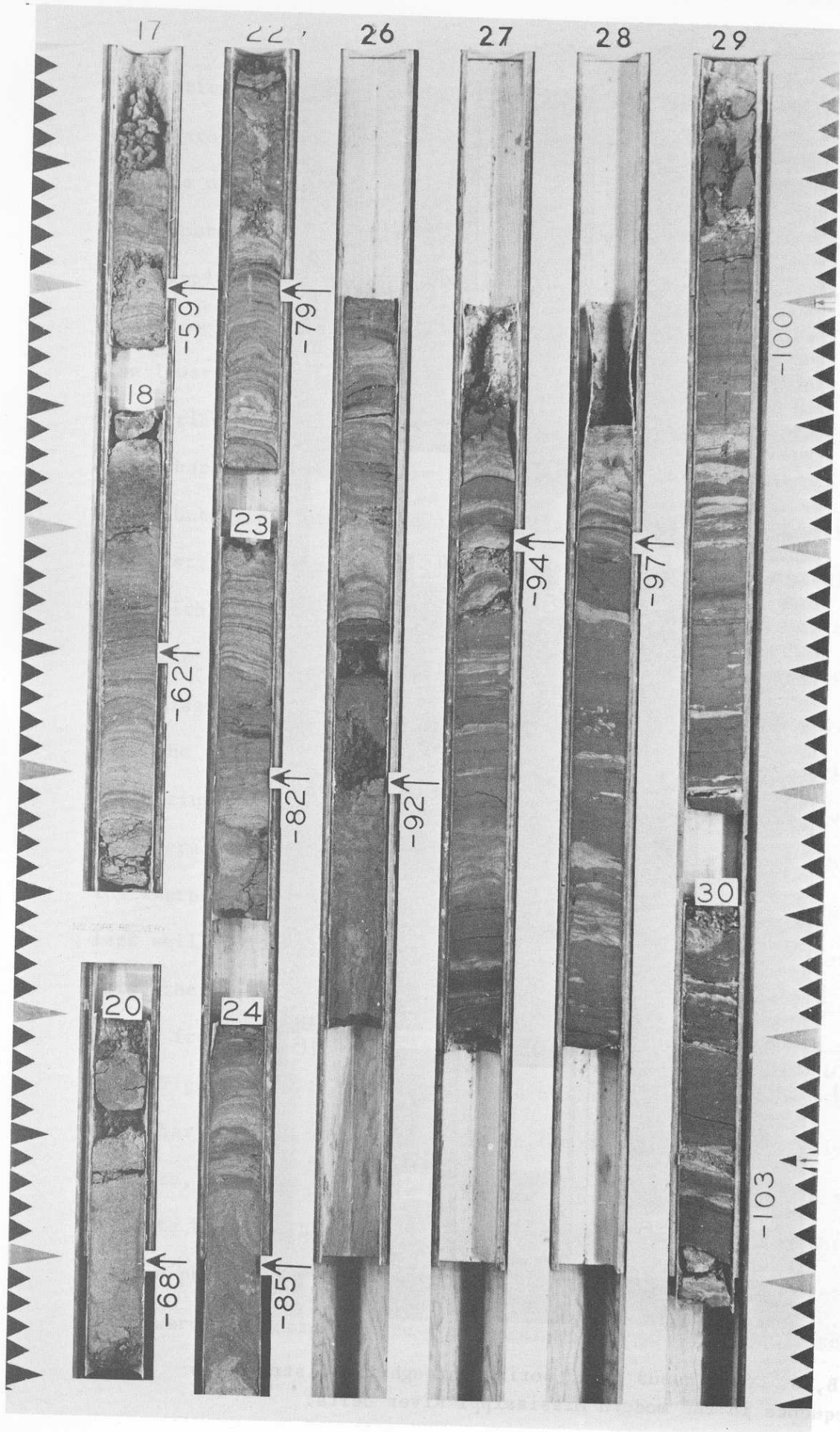


Figure B

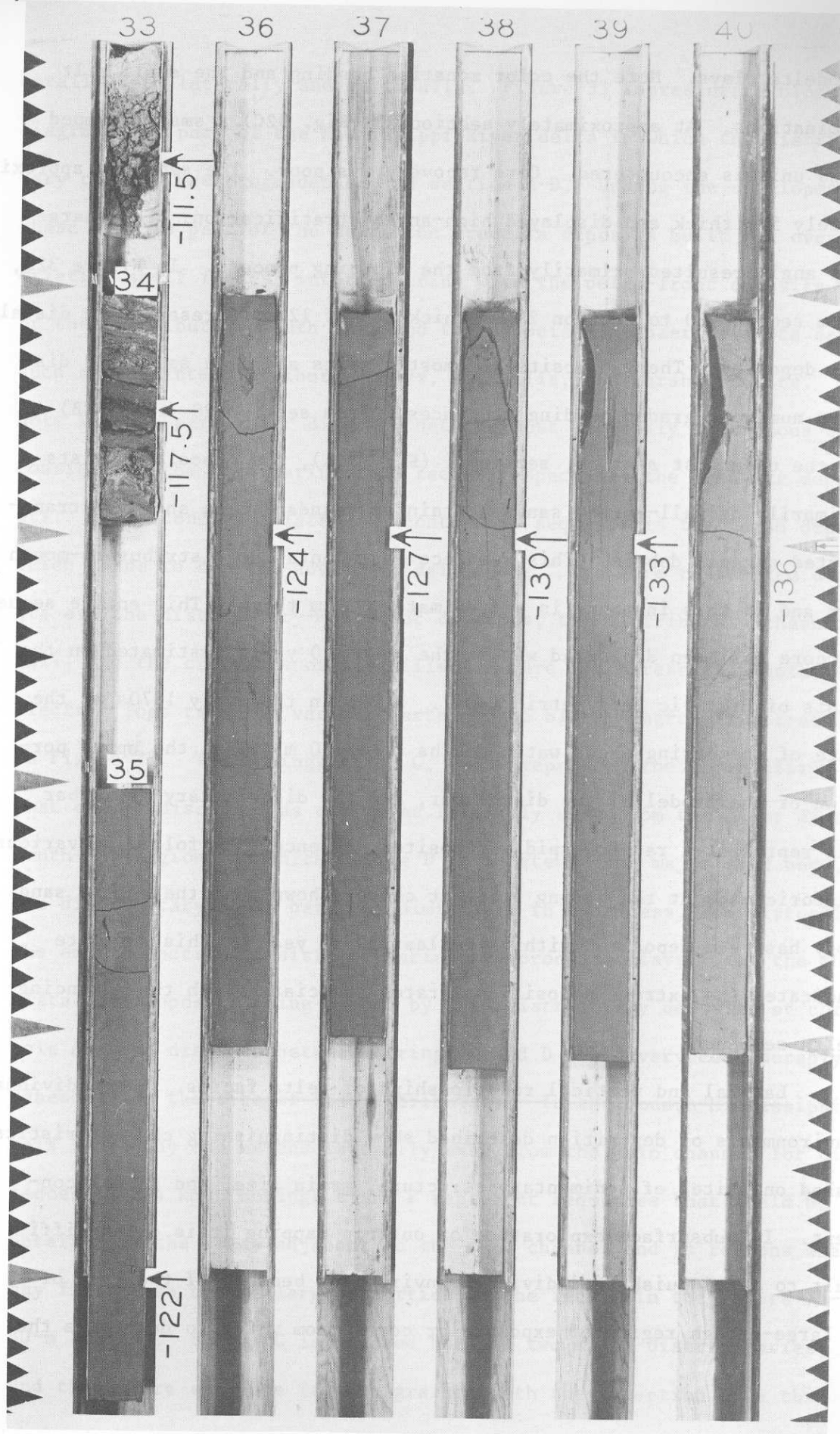


Figure C

prodelta clays. Note the color zonation banding and the small silt laminations. At approximately section 33 (Fig. 32C) a small slumped sand unit is encountered. Core recovery was poor. The sand was approximately 5 m thick and displayed high-angle stratification. This large dip angle resulted primarily from the slumping process. In Figure 32B, from section 30 to section 20, a thickness of 12 m represents the distal-bar deposits. These deposits are mostly silts and fine sands and display numerous graded bedding sequences. From section 20 (Fig. 32B) to the uppermost section, section 1 (Fig. 32A), the deposit consists primarily of well-sorted sands containing abundant mica and high transported organic debris. This sequence represents the distributary-mouth bar and in this instance is approximately 21 m thick. This entire sequence of core has been deposited within the last 120 years (estimated on the basis of historic bathymetric maps). A map in the early 1870s at the site of the boring shows water depths of 49-50 m. Thus the upper portion of the prodelta, the distal bar, and the distributary-mouth bar all represent a rather rapidly deposited sequence. By following various historic maps at the boring site, it can be shown that the entire sand body has been deposited within the last 30-35 years. This estimate indicates the extreme depositional rates associated with the advancing delta sequence.

Lateral and vertical relationships of delta facies. The individual environments of deposition described show distinguishing characteristics based on suites of sedimentary structure, grain size, and faunal content. In subsurface exploration or outcrop mapping it is often difficult to distinguish an individual environment because of the lack of a large-enough region of exposure or cores from which to determine the

details both laterally and vertically. Figure 33 represents a block diagram of a part of the Mississippi River delta in which the distributary channel has prograded beyond section A-B. During the developmental phase of this part of the delta the prodelta deposits built out over existing shelf facies, interfingering with the delta-front deposits or the distributary-mouth bars and the associated subaerial delta deposits such as the interdistributary bays, bay fills, and marsh deposits. Note in this particular diagram that the most laterally continuous deposit consists of the more marine-type facies, especially the prodelta deposits. The second most laterally continuous sequence is the marsh deposit, which tends to cap the advancing delta lobe. The more restricted deposits are the distributary-mouth-bar deposits, the distributary-channel fill, and the crevasses or bay fills. Figure 34 represents hypothetical electric logs taken on various parts of the block diagram illustrated in Figure 33. The borings A, B, C, and D represent the variability that can be discerned as one moves laterally away from the major distributary-mouth-bar region, on which boring D is located. The major sand body, the distributary-mouth bar, has diminished in thickness, and virtually the entire section consists of marine and prodelta clays, with the thin distal-bar deposits being capped by interdistributary deposits at core hole A. The distance between borings A and D could vary considerably, depending on the size of the distributary. In the modern Mississippi, this sand body can extend laterally away from the main channel for distances of 2-4 km. Borings E and F represent sequences that would be obtained in the areas adjacent to the main channel and in regions where bay fills make up the largest portion of the facies in the entire 75-80-m section. Boring G is located between two major distributaries, and the entire sequence is fine grained with the exception of a thin

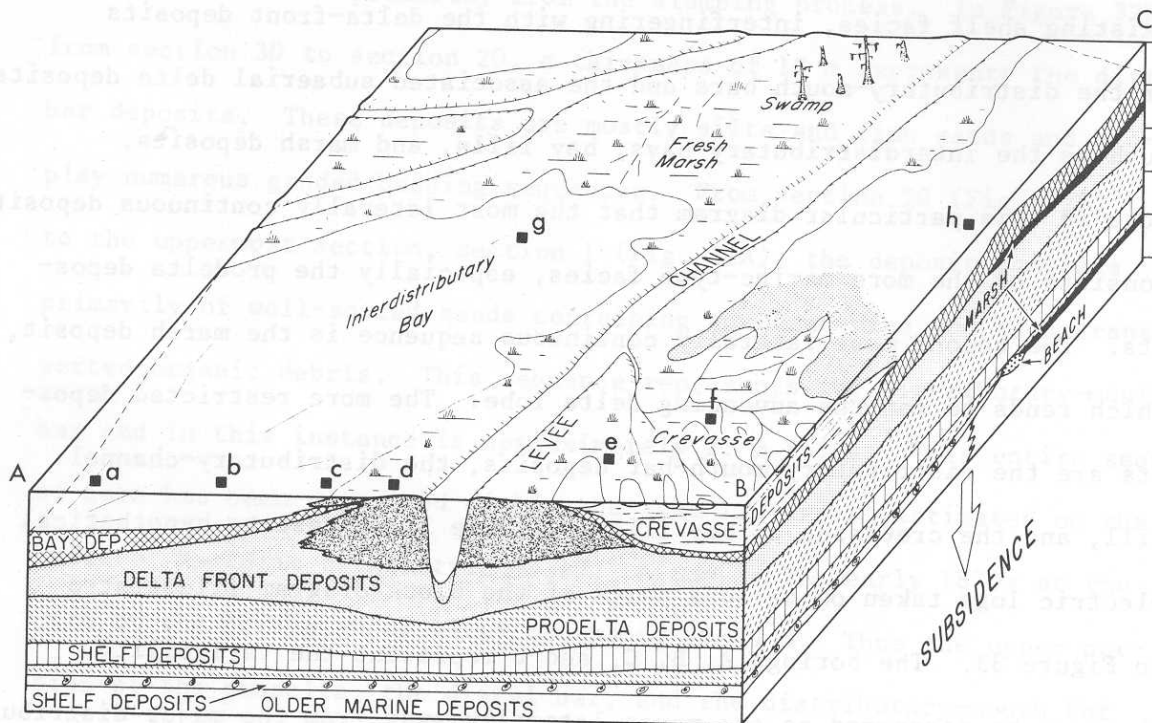


Figure 33. Block diagram showing vertical and lateral facies relationships of deltaic deposits. Typical electric log sequences (A-H) are shown in Figure 34.

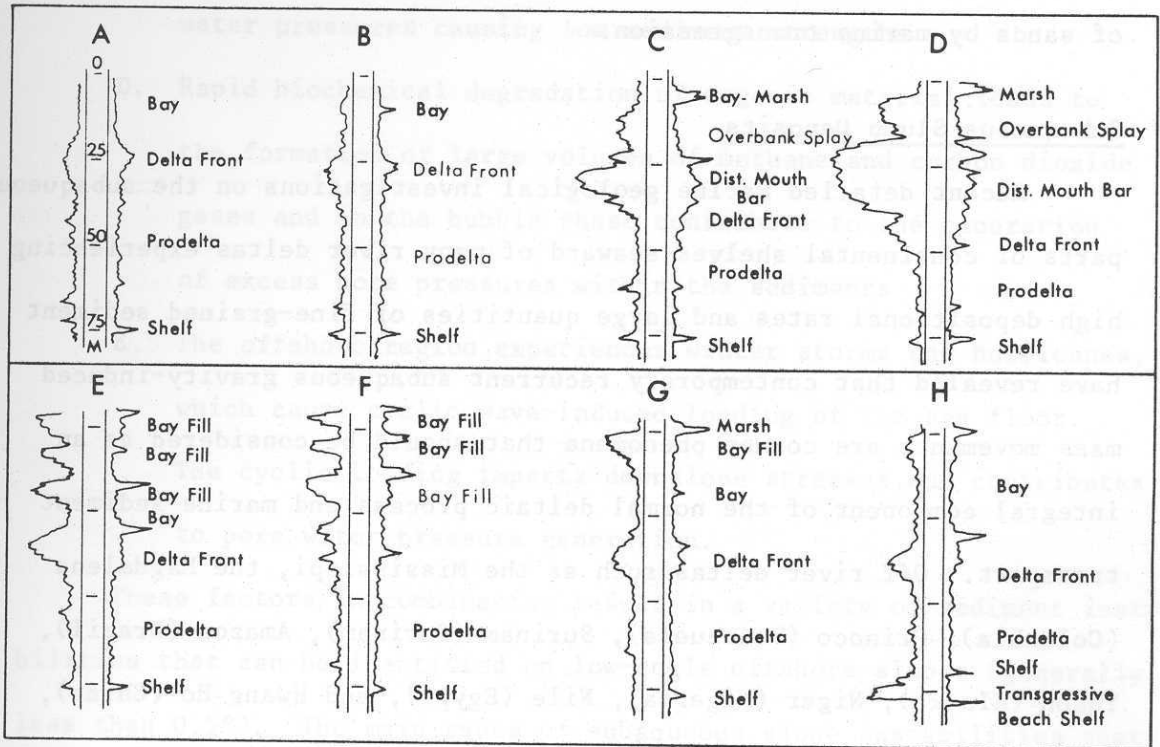


Figure 34. Schematic electrical log response in deltaic facies. Location of bore holes indicated in Figure 33.

clastic wedge representing the distal portions of the distal bar and the bay fill that is shown near the top of the section. At the position of boring H virtually no sands are present within the column, with the exception of a small transgressive beach deposit near the base, which represents reworking of an earlier deltaic deposit and concentrations of sands by marine transgression.

#### Subaqueous Slump Deposits

Recent detailed marine geological investigations on the subaqueous parts of continental shelves seaward of many river deltas experiencing high depositional rates and large quantities of fine-grained sediment have revealed that contemporary recurrent subaqueous gravity-induced mass movements are common phenomena that should be considered as an integral component of the normal deltaic process and marine sediment transport. Off river deltas such as the Mississippi, the Magdalena (Columbia), Orinoco (Venezuela), Surinam (Surinam), Amazon (Brazil), Yukon (Alaska), Niger (Nigeria), Nile (Egypt), and Hwang Ho (China), subaqueous slumping and downslope mass movement of sediments are common processes. The instabilities and mass movement of sediment in these regions generally display the following characteristics: (a) instability occurs on very low angle slopes (generally less than  $2^{\circ}$ ) and (b) large quantities of sediment are transported from shallow waters offshore along well-defined transport paths and in a variety of translational slumps. The major characteristics of deltas and their offshore slopes that influence the stability of bottom sediments are as follows:

- A. Rapid sedimentation results in widespread sedimentary loading of the upper delta-front slopes, especially near the mouths of the passes

- B. Coarse-grained sands and silts, which comprise the distributary-mouth bars, differentially load the underlying and adjacent delta-front fine-grained deposits
- C. Fine-grained delta deposits, because of their rapid deposition, are generally underconsolidated, with large excess pore water pressures causing low sediment strengths
- D. Rapid biochemical degradation of organic material leads to the formation of large volumes of methane and carbon dioxide gases and in the bubble phase contribute to the generation of excess pore pressures within the sediments
- E. The offshore region experiences winter storms and hurricanes, which cause cyclic wave-induced loading of the sea floor. The cyclic loading imparts downslope stresses and contributes to pore water pressure generation.

These factors in combination result in a variety of sediment instabilities that can be identified on low-angle offshore slopes (generally less than  $0.5^\circ$ ). The main types of subaqueous slope instabilities that can be recognized in the 5-100-m water depths are illustrated schematically in Figure 35, which shows their distribution around a single distributary and part of an interdistributary bay. Similar features and spatial organizations can be identified in each of the three main distributary and bay areas of the delta. In the immediate vicinity of the river mouths differential weighting by dense distributary-mouth-bar sands causes vertical diapiric uplift and the formation of mudlumps. In the adjacent shallow-water bays a variety of small-scale features such as collapse depressions and bottleneck slides occur. Seaward of the river mouth and on the peripheral edge of the distributary-mouth bar are found a wide variety of peripheral slumps. Immediately seaward

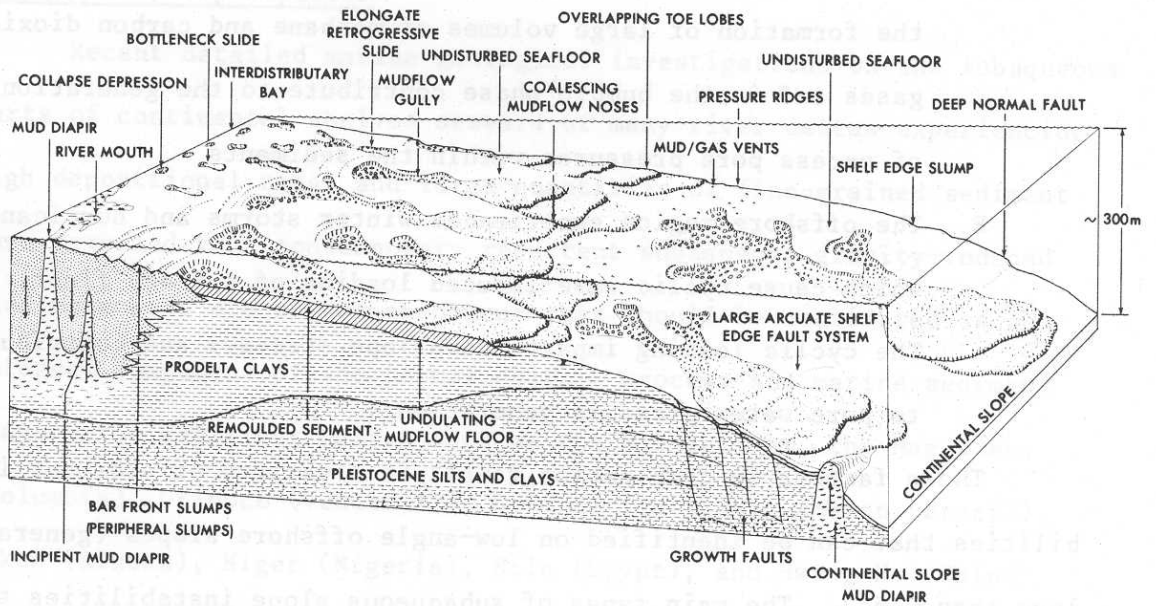


Figure 35. Schematic diagram illustrating the types and distributions of subaqueous sediment failures in the Mississippi River delta.

of the bar, commencing in water depths of 10 m or less, are a large number of mudflow gullies and their resulting mudflow depositional lobes. These mudflow gullies and lobes differentially weight the outer continental shelf clays and result again in other types of deformation, including a wide variety of shelf-edge arcuate slumping and contemporaneous faulting and diapirism that are found primarily near the shelf edge and upper continental slope. Each of the main types of feature will be described in detail, but it should be remembered that the categories are somewhat arbitrary, and intermediate and compound forms are also present.

Differential weighting and diapirism. Rapid deposition of localized dense distributary-mouth-bar sands over less dense plastic prodelta and marine clays results in a major sediment instability. This situation leads to instability of the underlying clays, and this stress is relieved by diapiric intrusion of the clays from beneath and into the overlying sand bodies. The intrusion of the older shelf and prodelta clays into and through the bar deposits results in vertical displacement of clays by as much as 200 m and causes corresponding subsidence of the bar sands, which accumulate to thicknesses of as much as 150 m. The major mappable features that result from this differential weighting are thin spines of diapiric intruded mud, which forms islands or mud-lumps at the mouths of the major distributaries. Many of the diapirs do not rise above sea level, simply appearing as submarine highs in the immediate offshore region. In a single distributary-mouth pass (South Pass) covering an area of only  $13 \text{ km}^2$ , some 105 individual diapiric spines were mapped during the period 1876-1973. These diapiric spines form rapidly, and vertical displacement of more than 100 m has

been documented during a period of only 20 years. Figure 36 diagrammatically illustrates the process of diapiric intrusion associated with differential weighting. Stage A depicts initial loading and compaction of the underlying prodelta and shelf deposits by progradation of the massive sands of the river-mouth bar. During stage B continued accumulation of delta-front and bar deposits accelerates lateral flowage of clays. The clays thin beneath the deltaic loading and thicken near its seaward periphery. During stage C the delta front continues to prograde seaward, and diapiric intrusion into overlying bar deposits is initiated. The load is transmitted to older and older clay units, and greater and greater amounts of vertical displacement continue. During stage D the differential loading of overlying bar sediments causes diapiric intrusion to assume a slightly asymmetrical form. Folding also affects the lower clay beds, and a submarine prominence exists on the seaward-sloping delta front of the bar deposits. In many instances high gas content is associated with diapiric intrusion of the clays, and small mud volcanoes and methane gas venting are common. In this type of mass wasting large volumes of older prodelta and marine clays are bowed up and intruded into the younger delta deposits. Wave reworking of the intruded marine clays results in incorporating deepwater marine microfauna into the shallow-water sands. Thus in some cases the shallow-water distributary-mouth-bar sands take on a marine faunal characteristic because of this process.

Collapse depressions. These depressions occur primarily in the shallow-water areas of interdistributary bays. They are associated with slopes of  $0.1-0.2^\circ$  and with sedimentation rates that are relatively small by comparison with those of more active areas of the delta. Figure 37 illustrates schematically the morphology of these features.

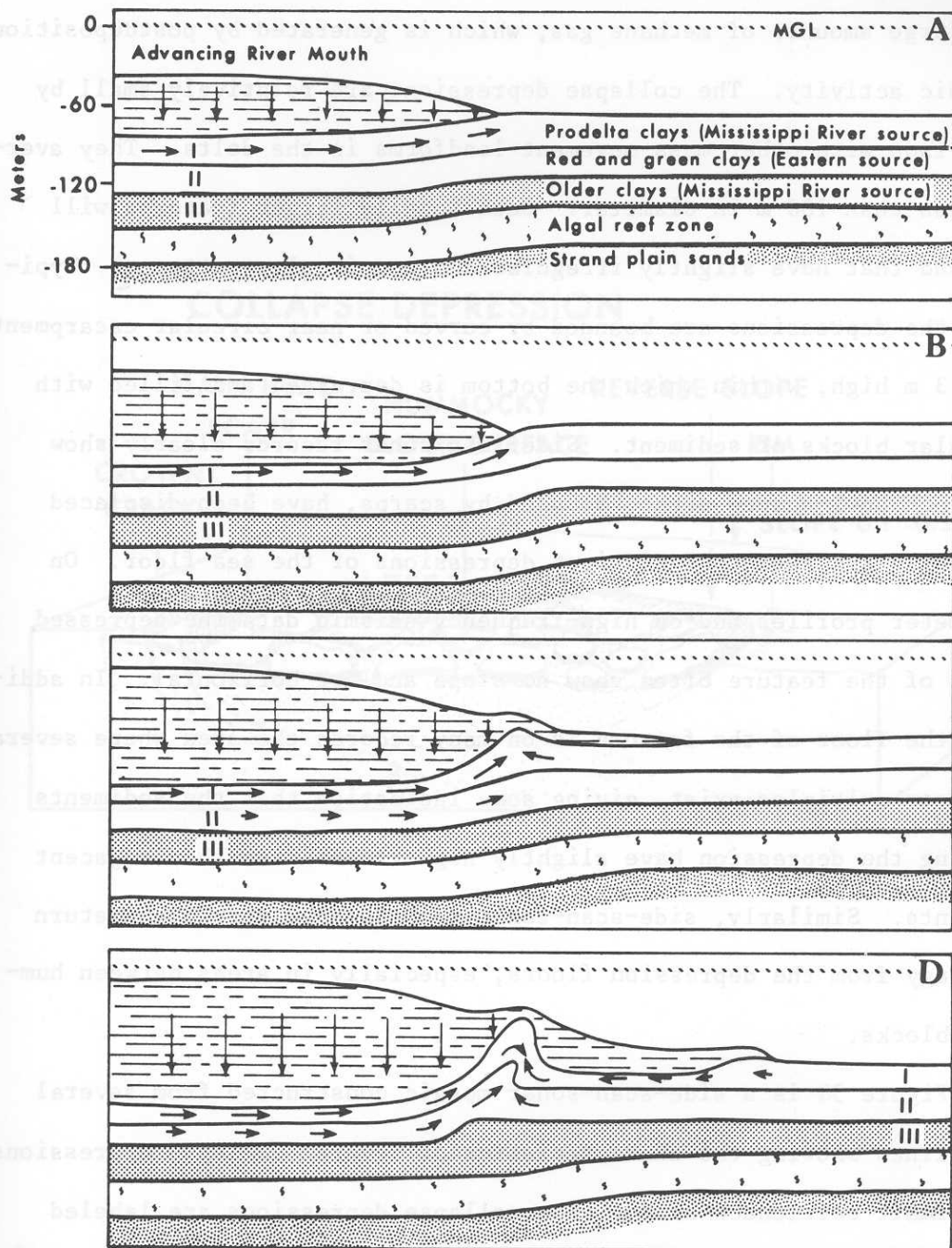


Figure 36. Diagram illustrating formation of mudlumps or diapirs (modified from Morgan et al., 1968).

The extremely soft bottom sediments consist of recently deposited clay-rich materials and organic debris. These sediments in particular contain large amounts of methane gas, which is generated by postdepositional biogenic activity. The collapse depressions are relatively small by comparison with other mass-movement landforms in the delta. They average less than 100 m in diameter. Occasionally larger features will be found that have slightly irregular and noncircular patterns. Typically the depressions are bounded by curved or near-circular escarpments up to 3 m high, within which the bottom is depressed and filled with irregular blocks of sediment. Side-scan-sonar records clearly show that such bowl-shaped areas, bounded by scarps, have been displaced vertically and represent distinct depressions of the sea floor. 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 than adjacent sediments. Similarly, side-scan-sonar records show very high return of energy from the depression floors, especially in areas between hummocky blocks.

Figure 38 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 24 m to 370 m and have depressed floors that range from less than 1 m to 3 m below the surrounding sea floor. Note the irregular and hummocky topography associated with these features. Note also the strong reflections of the acoustic

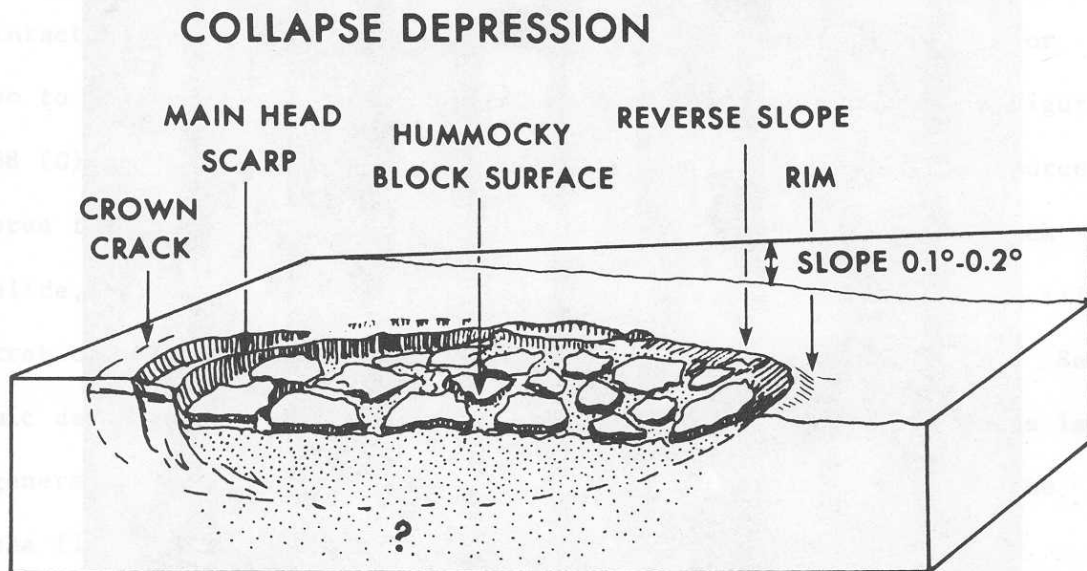


Figure 37. Schematic representation of the morphology of collapse depressions.



Figure 38. Side-scan sonar mosaic illustrating several collapse depressions and a bottleneck slide. The grids are 25 m apart and the mosaic covers an area of 1.3 km by 2.3 km. A, Collapse depressions; B, crown cracks; C, bottleneck slide; D, depositional lobe of bottleneck slide.

signal that are often seen in the features. On slightly steeper slopes within the interdistributary regions and on slopes that approach 0.2-0.4° 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 margin of the failure through which remolded debris is discharged over surrounding intact slopes. The bottleneck slides range in length from 150 m or so to well over 1.5 km. A typical bottleneck slide is shown in Figure 38 (C) and has a length of 1.1 km. Note the similarity of the source area for this feature and for collapse depressions. The bottleneck slide, however, has a large depositional lobe, labeled "D" in the illustration. This lobe occupies an area of approximately  $6 \times 10^4 \text{ m}^2$ . Seismic data across the depositional lobe indicates that the thickness is generally less than 2 m and the feature forms a raised mound on the sea floor.

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 3 to 7 m and have slopes of 1-4°. In many cases they give the bar front a stairstepped appearance in profile view. Tensional 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 and high-resolution seismic. Figure 39 shows a schematic diagram illustrating the major morphology of these features. Figure 40 shows a high-resolution seismic line run across several of these features. This type of morphology is indicative of rotational sliding over slightly curved shear planes that are concave upward, combined with subsequent translational movements in a downslope direction. Examination of high-resolution seismic data confirms that the multiple concave-upward shears tend to merge at depth into a single basal shear surface that is inclined parallel to the sediment surface. The average depth of movement of the shear plane is approximately 30-35 m. Cores of sediments from within the rotated blocks show laminations inclined in an upslope direction with dip angles as high as 30° by comparison to the almost horizontal attitude of the sediments nearby. Although the displacement begins as shallow rotational slumps, increasing movement downslope over the basal shear means that they become predominantly translatory in nature. This type of mass movement is responsible for moving large volumes of sediment downslope across the gentle continental shelf in front of the prograding delta. Since many of these features are confined primarily to the immediate vicinity of the distributary-mouth bars, in a large number of instances the slump blocks themselves consist of distributary-mouth-bar and distal-bar deposits that are sliding shallow-water sediment downslope to be encased in deeper water marine shales.

Mudflow gullies and depositional lobes. Extending radially seaward from each of the distributaries in water depths of 7-100 m are major elongate systems of sediment instabilities referred to as delta-front gullies or mudflow gullies. The features were first described from hydrographic maps by Shepard (1955), and an illustration of a topographic area of 1.3 km by 1.3 km. A, Collapse depression; B, crown cracks; C, bottleneck slide; D, depositional lobe of bottleneck slide.

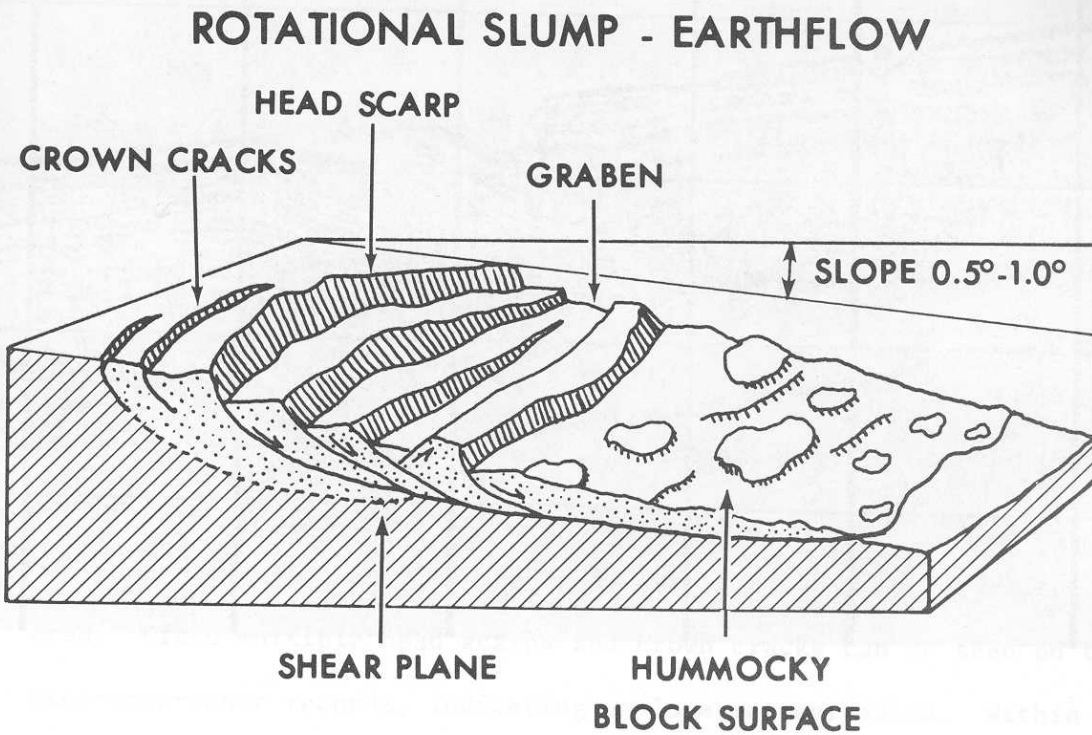


Figure 39. Schematic diagram illustrating the morphology of rotational peripheral slides.

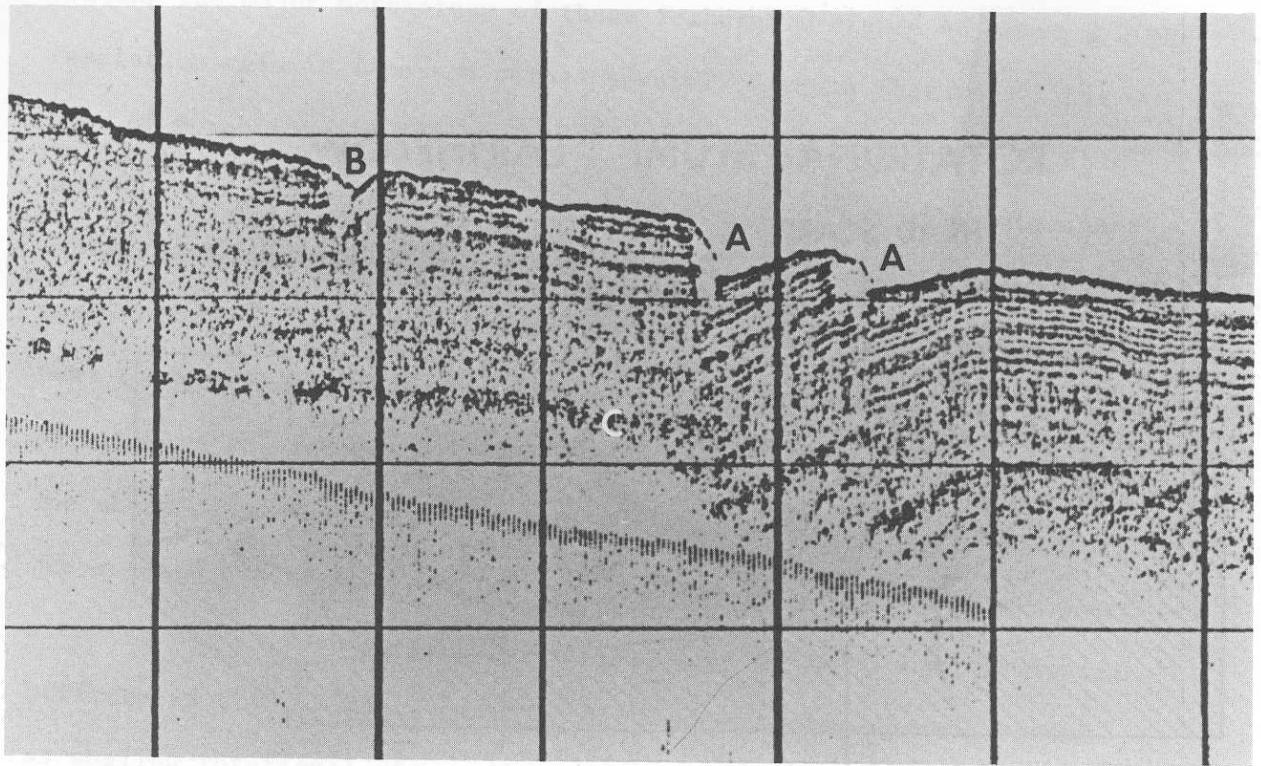


Figure 40. High-resolution seismic line run across several peripheral slides. Navigation fixes are 152 m apart and timing lines are 10 m apart. A, rotational slides; B, newly formed rotational slide upslope; C, offset in reflection horizon.

graphic configuration is given in Figure 41. Note on the hydrographic map the numerous topographic gullies that scar the delta platform. Side-scan-sonar records and high-resolution seismic data show that these valleys or gullies emerge from within an extremely disturbed area of slump 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 gully possesses a long, sinuous, narrow chute or channel that links a depressed hummocky source area on the upslope margin to composite overlapping depositional mudflow lobes on the seaward end. Figure 42 schematically illustrates the major morphologic characteristics of these features. The 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 arrangements can be discerned. Downslope from the bowl-shaped source area is an essentially elongate narrow chute. These chutes or gullies are bounded 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 3 m to as much as 20 m below the adjacent intact bottom. The slopes along the sides of the gullies range from less than  $1^{\circ}$  to as high as  $19^{\circ}$ . Most of the gullies extend downslope approximately at right angles to the depth contours and may be more than 7-10 km long.

In plan view, the features are rarely straight, and quite commonly

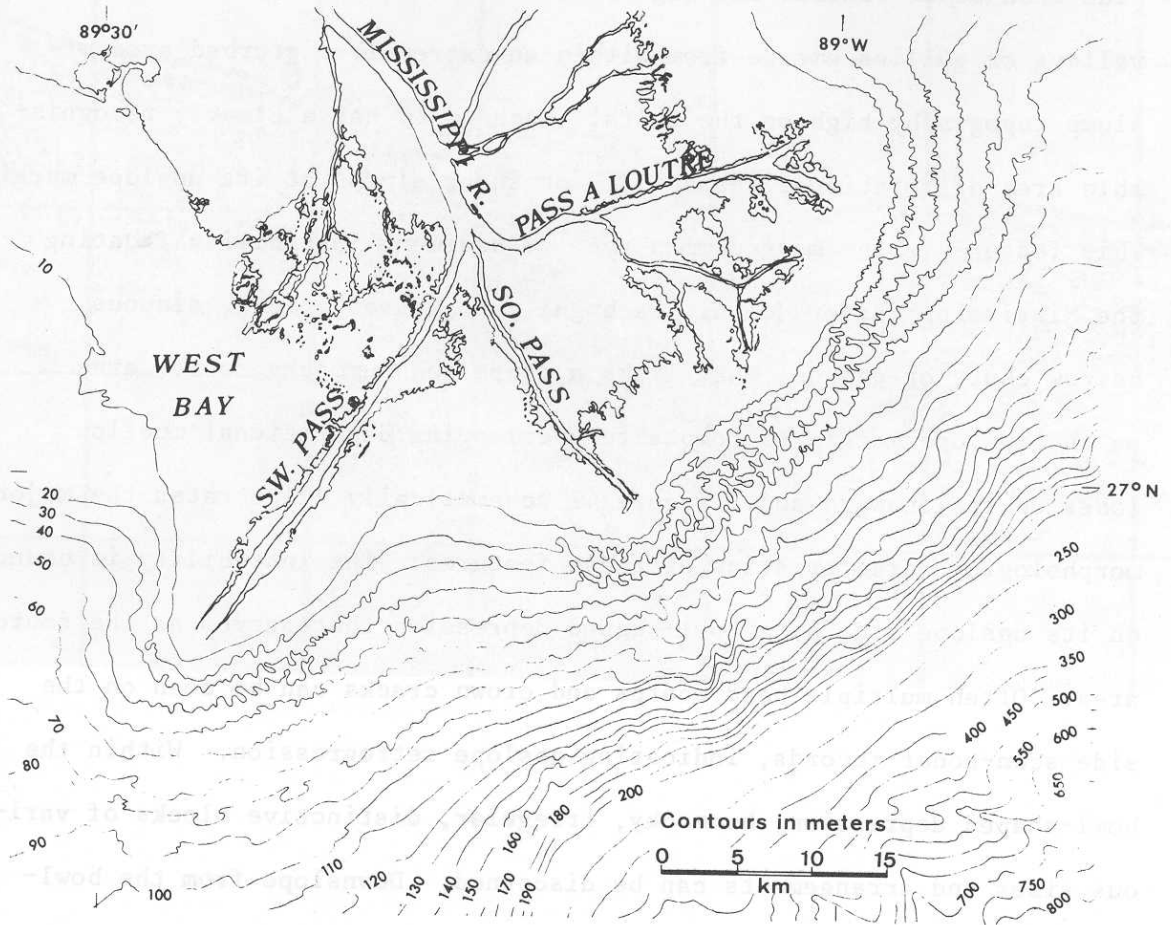


Figure 41. Hydrographic map of the delta front of the Mississippi River. Note the numerous gullies that scar the delta platform.

**ELONGATE SLIDE**

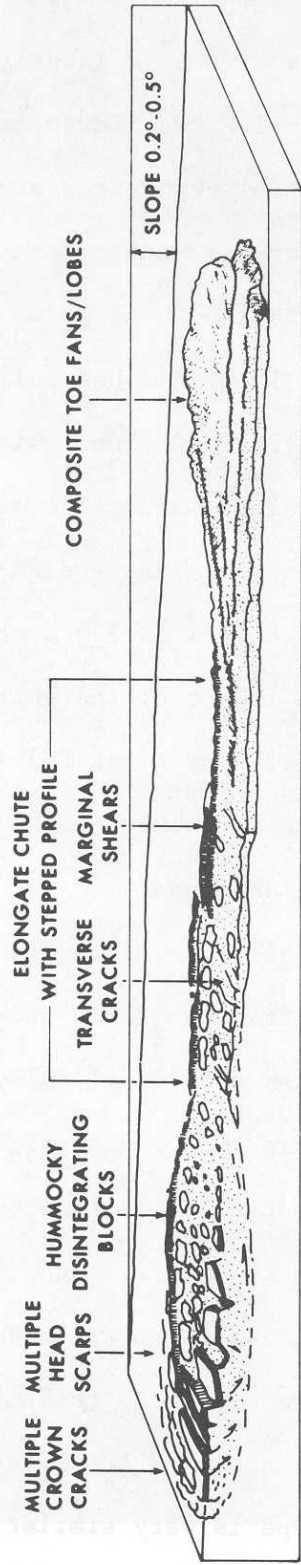


Figure 42. Schematic diagram illustrating the morphology of mudflow gullies and depositional mudflow lobes.

are markedly sinuous and have alternating narrow constrictions or chutes and wider bulbous sections. Figure 43 is a side-scan-sonar mosaic constructed from lines run across a zone of landslide gullies. The area covered by the mosaic is 1.2 x 1.8 km. Three major elongate gully systems are shown, beginning with blocky source areas (A) bounded by scarps. The source area geometry is very irregular; considerable differences exist in block size and orientation. One gully has retrogressed upslope and eaten into an adjacent well-established gully (B). The narrow gullies are relatively deeply incised (C), and evidence of side-wall instability is indicated by small slumps along the gully margin (D) and by the alternations of bulbous source areas and narrow chutes. The widths of the individual gullies range from 18-150 m at the narrow points to 370-550 m 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 2 km can be found.

The side walls of the mudflow gullies are subject to instability; this slumping can produce contrast in forms and is probably responsible for localized widening along an individual gully system. Figure 44 shows 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. The formation of elongate chutes of this type is very similar to the morphology associated with subaerial debris flows and some types of mudflows. The chutes or channels generally emanate from upslope slump zones and con-

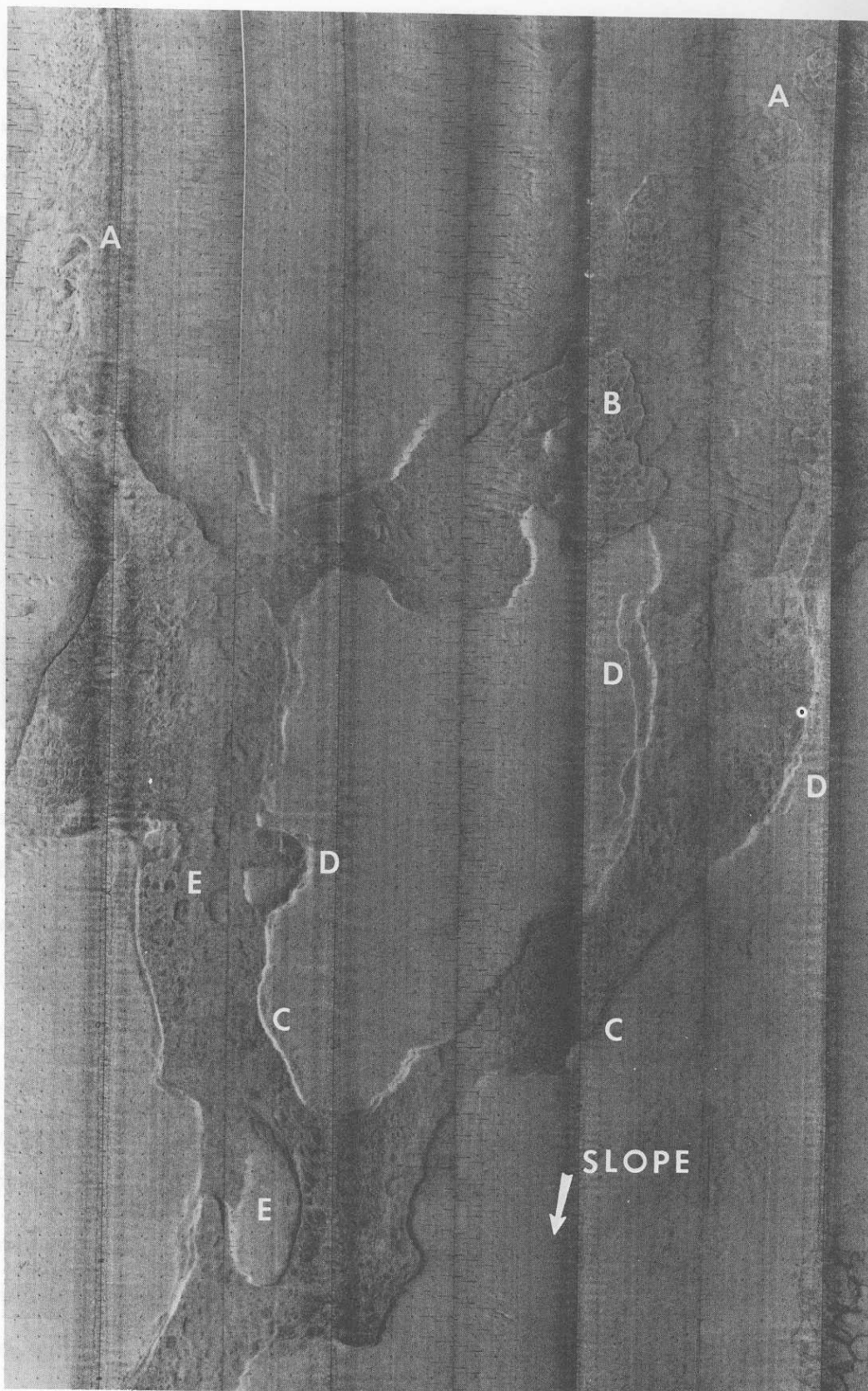


Figure 43. Side-scan-sonar mosaic showing several mudflow gullies. Grid is 25 x 24 m, and the mosaic is 1.2 x 1.8 km. Water depths are approximately 21 m at the top of the figure and 34-m at the lower end. A, source area; B, retrogressive gully; C, narrow incised gully; D, side-wall instability slides; E, large erratic blocks in fully floor.

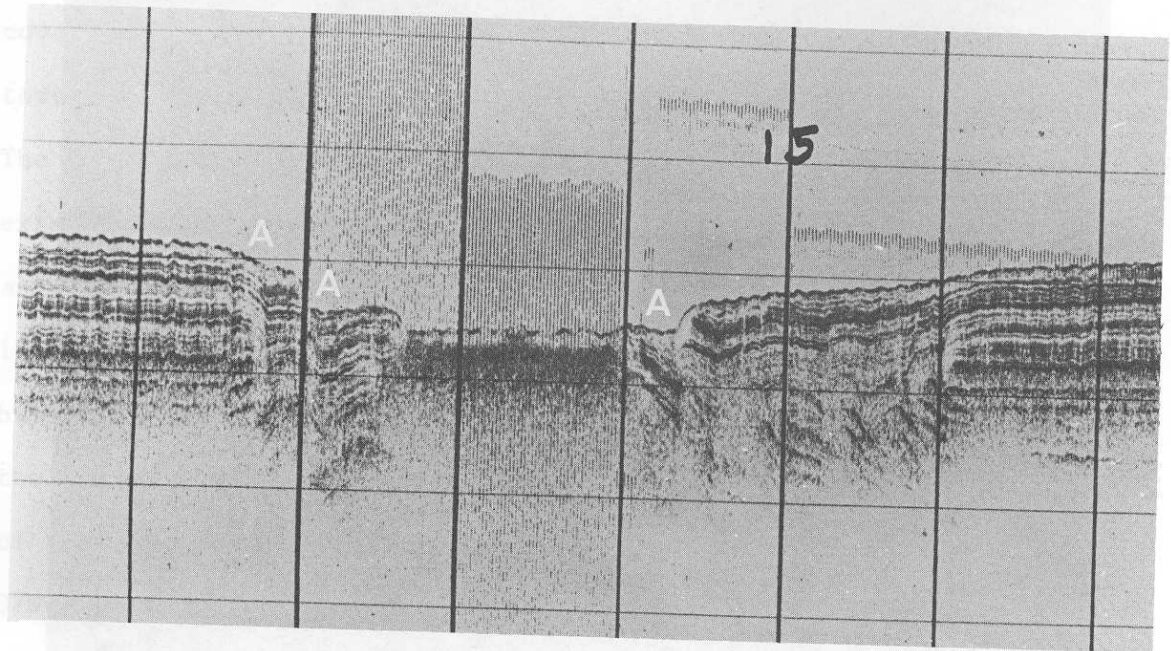


Figure 44. High-resolution seismic line run across a mudflow gully that shows numerous side-wall rotational slides (A). Navigation fixes are 152 m apart and timing lines are 10 m apart.

stitute transport conduits for disturbed and remolded sediments, together with displaced blocks of various sizes. The mechanism of transport is probably characterized as slurry flow, which can be a type of plug flow in which rigid plugs move over and within a zone of liquefied mud. The presence of partially disintegrated rafted blocks suggests laminar or plug flow rather than turbulent flow. Often cores taken within the gully floors indicate good preservation of finely laminated sands and silts, indicating transport as a series of blocks. The only evidence of transported debris downslope is displaced fauna within the debris and extremely high depositional dip angles within the deposits. The shear planes beneath the transport gullies are extremely thin, and extremely closely spaced corings are required to permit recognition of a shear plane.

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 42. Each lobe is composed of two morphological features: an almost flat or gently inclined surface (less than  $0.5^\circ$ ) and an abrupt distal scarp representing the downslope nose of the displaced debris. The seaward scarps range in height from only a few metres to more than 25 m and have slopes as great as  $7-10^\circ$ . 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 mudflow gullies that front the present delta, the displaced debris from adjacent gullies may coalesce, providing an almost continuous sinuous frontal scarp that extends peripheral to the modern bird-foot delta. Detailed mapping, however, shows that the depositional areas are com-

posed 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 contain many small mud volcanoes and gas vents produced by localized sedimentary loading.

Figure 45 is a side-scan-sonar mosaic (1.5 x 2.1 km) 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 discharge debris consists of extremely erratic large blocks, most of which are about 30 m or so in diameter. Larger blocks (D) are often incorporated in the depositional lobes, and may be 150-300 m in diameter. The average thickness of these individual lobes is 10-15 m; however, high variation exists from one part of the delta to another. Figure 46 is a high-resolution seismic line run across a depositional mudflow lobe. The vertical scale is in milliseconds (100 msec = 76 m), and the length of the line is approximately 10 km. Note that this mudflow has moved beyond the shelf and is presently located at approximately the shelf upper slope break, which occurs at approximately 200 m of water depth. This particular lobe is composed of multiple overlapping lobes; however, in this diagram the entire mass is fairly amorphous and is approximately 50 m thick.

Figure 47 illustrates the distributional aspect of these mudflow gullies, a few collapse depressions, and peripheral slumps off a part of the Mississippi River delta. The particular area is seaward of Southwest Pass, and it shows numerous mudflow gullies that crease the delta front, with their depositional mudflow lobes spread out across the shelf

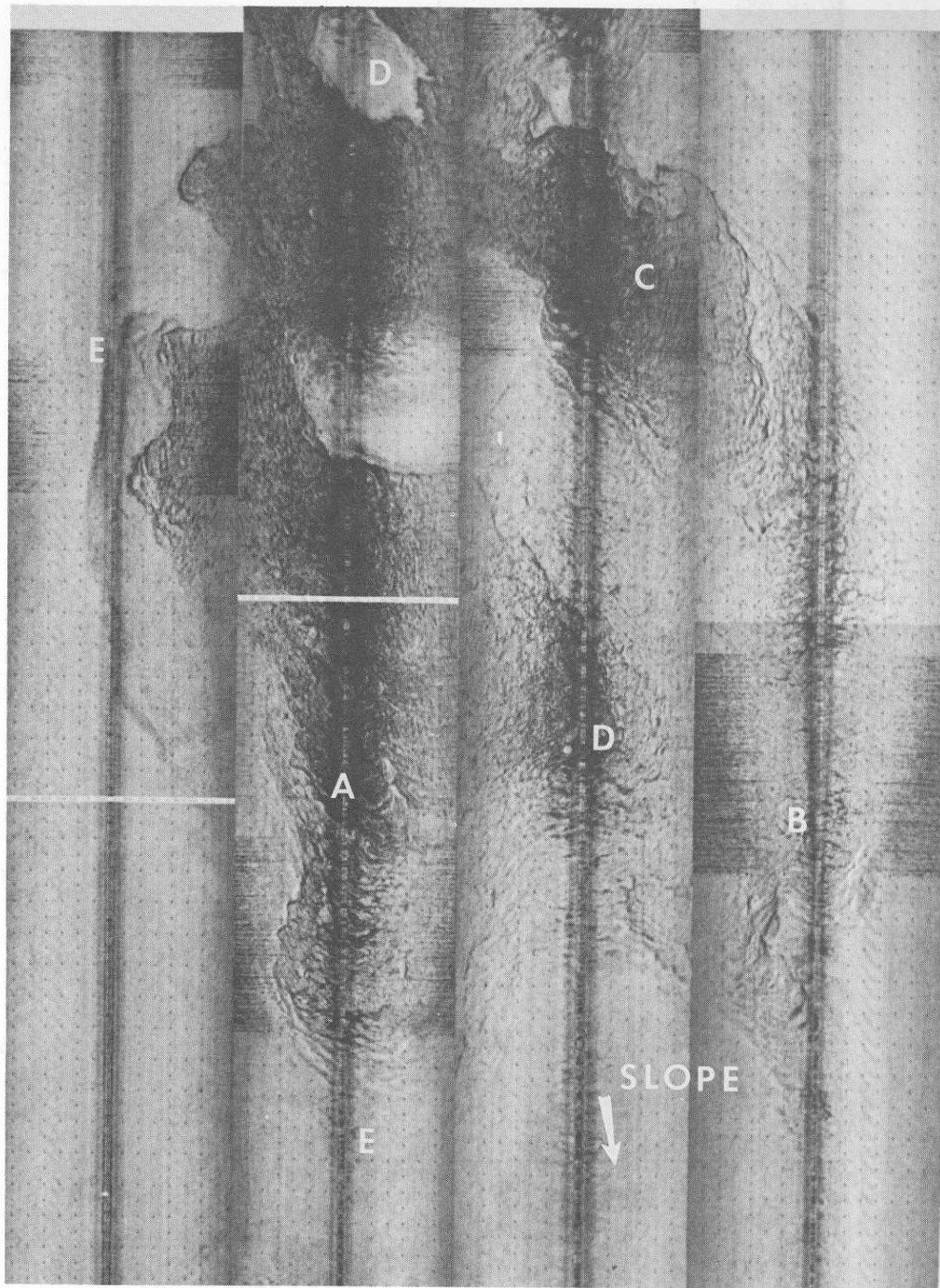


Figure 45. Side-scan sonar mosaic showing multiple overlapping mudflow depositional lobes. The mosaic covers an area 1.5 x 2.2 km of sea floor. The grid marks are 25 m apart. A, B, C, mudflow lobes; D, erratic blocks; E, pressure ridges.

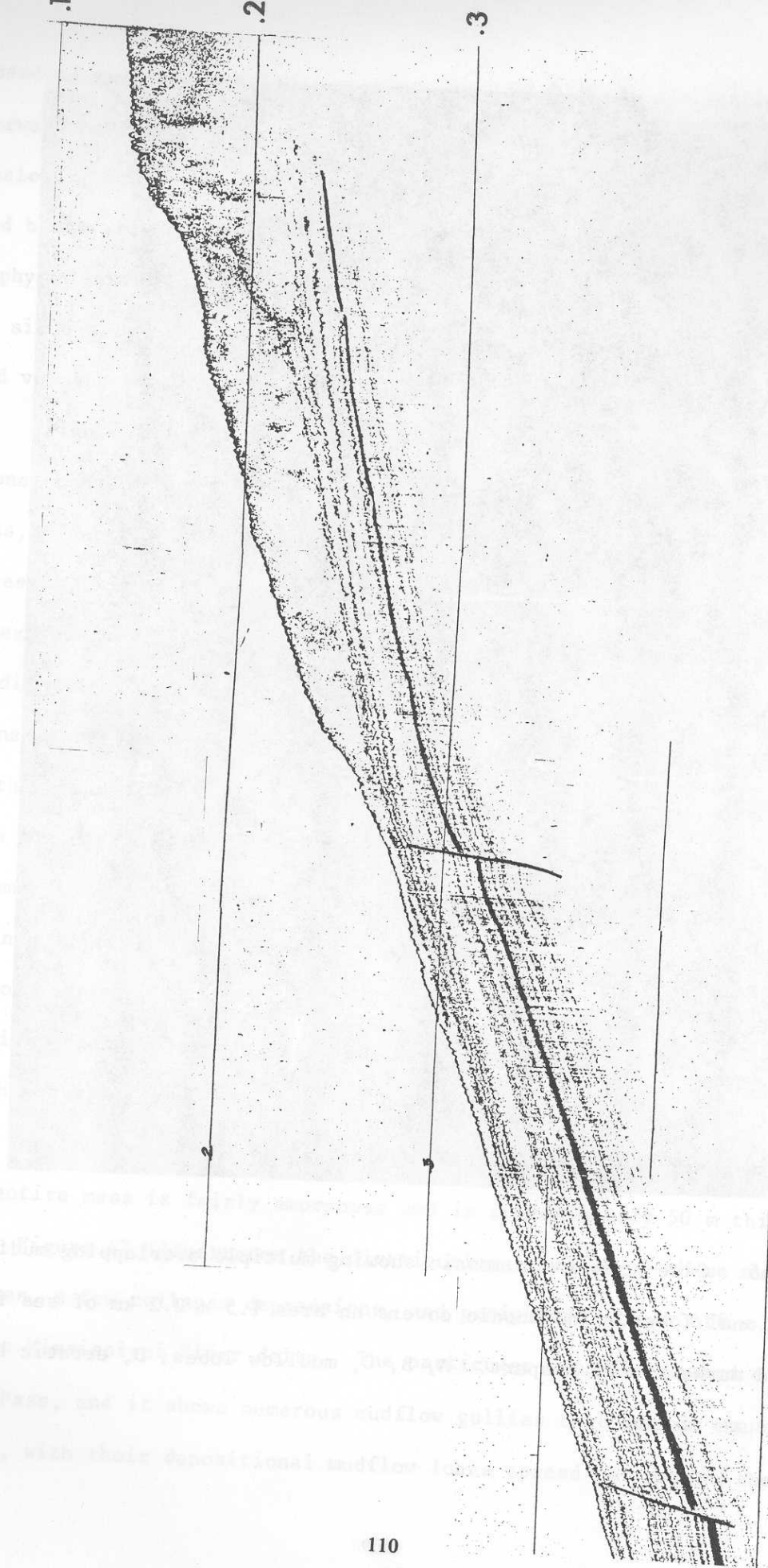


Figure 46. High-resolution seismic line run across a depositional mudflow lobe.

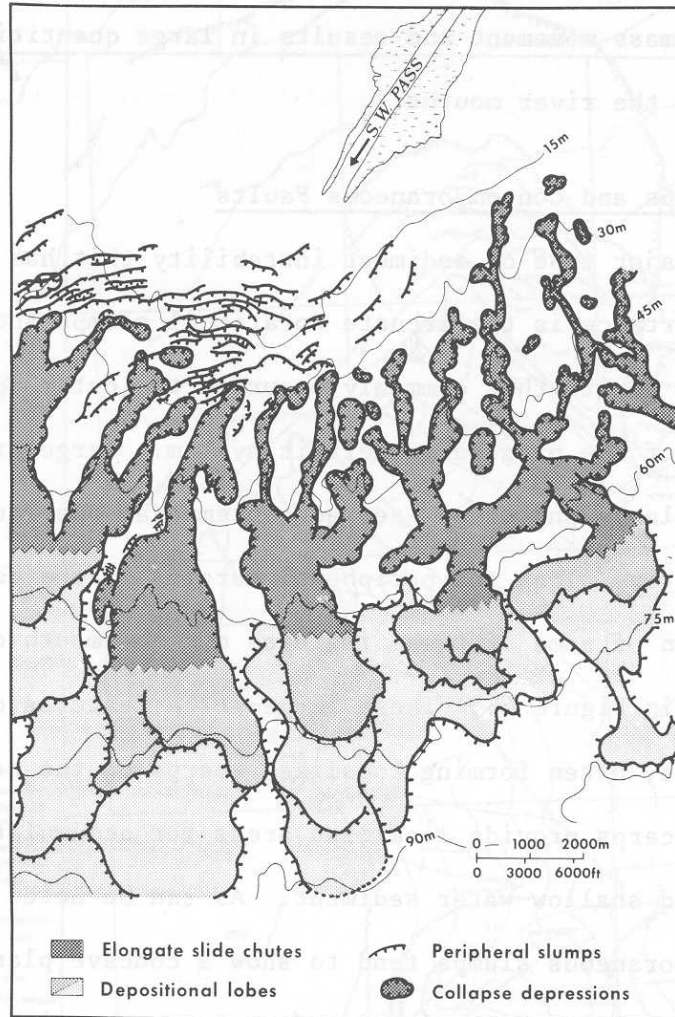


Figure 47. Map showing the distribution of mudflow gullies and mudflow lobes around a portion of the delta off Southwest Pass.

in front of the delta. Studies of the entire delta show that this is a major transport mechanism of moving shallow-water sediment across the shelf into deeper offshore water depths. Approximately 40% of the sediment that flows down the major distributaries of the Mississippi is involved in mass movement and results in large quantities of transport seaward of the river mouths.

#### Shelf-Edge Slumps and Contemporaneous Faults

Another major type of sediment instability that has significant geological importance is the arcuate rotational slumps and growth or contemporaneous faults that commonly occur on the outer continental shelf in front of the prograding deltaic system. Large arcuate families of shelf-edge slumps and deeper seated contemporaneous faults tend to be presently active along the peripheral margins of the delta fronts. The distribution of some of these features off the mouth of South Pass is illustrated in Figure 48. These large-scale features cut the modern sediment surface, often forming localized scarps on the sea floor, and these surface scarps provide localized areas for accumulation of down-slope mass-moved shallow-water sediment. As can be noted in Figure 48, the contemporaneous slumps tend to show a concave plan-view pattern. The shear planes are concave upward and tend to merge into bedding planes with depth. The shelf-edge slumps and slump faults tend to give a stairstepped appearance to the edge of the continental shelf and are highly reminiscent of the rotational peripheral slumps higher up on the continental shelf, near the mouths of the modern distributaries. However, these features are generally on a much larger scale and cut a column of sediment ranging from 50 to 250 m in thickness. Lateral continuities of individual slump scarps range from a few kilometres to

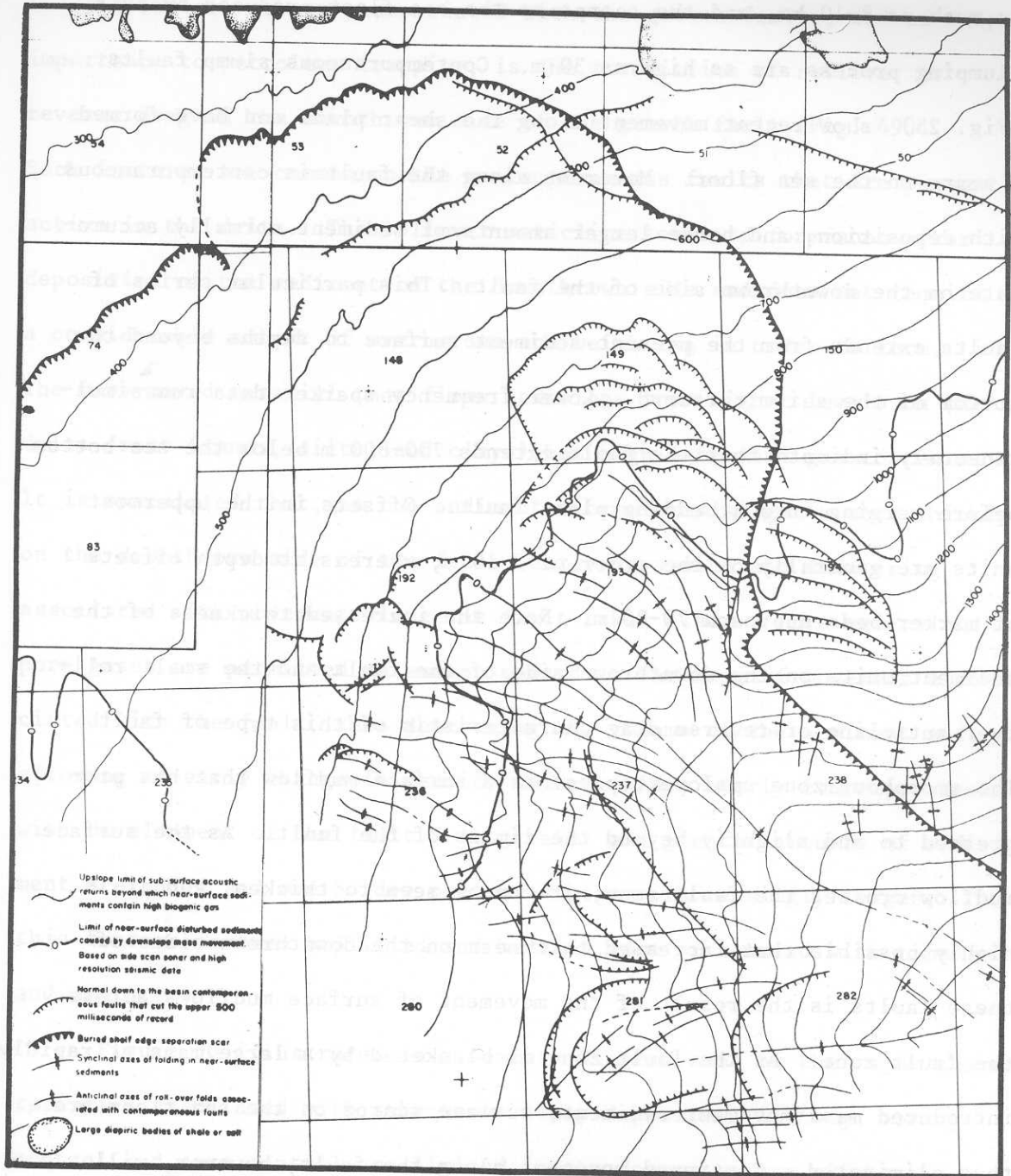


Figure 48. Map showing the distribution of contemporaneous faults off South Pass, Mississippi River delta. These faults occur approximately 23 km seaward of the river mouth and in water depths that approximate 250 to 300 m.

as much as 8-10 km, and the scarps on the sea floor produced by this slumping process are as high as 30 m. Contemporaneous slump faults (Fig. 25) show recent movement along the shear plane and have formed a scarp on the sea floor. Movement along the fault is contemporaneous with deposition, and hence larger amounts of sediment normally accumulate on the downthrown side of the fault. This particular series of faults extends from the present sediment surface to depths beyond the bottom of the seismic record. Lower frequency sparker data run simultaneously indicate that the fault extends 700-800 m below the sea bottom before merging into a bedding plane fault. Offsets in the uppermost units are generally on the order of 5-10 m, whereas at depth offsets of marker beds approach 70-80 m. Note the increased thickness of the sediment units on the downthrown side of the fault and the small roll-over anticline or reverse drag characteristic of this type of fault. The amorphous zone upslope represents a surface mudflow that has progressed to and slightly beyond the limits of the fault. As the surface mudflow crosses the fault zone, it can be seen to thicken, and it is highly possible that increased thickness on the downthrown sides of these faults is the result of the movement of surface mudflows across the fault zone. As the fault zone is blanketed by a large mass of rapidly introduced mass-movement sediment, surface scarps on the sea floor are thus eliminated. Continued movement along the fault, however, will cause a new scarp to form and, given enough time, another mudflow will then move across the feature, adding increased amounts of sediment to the downthrown side. This type of interaction between surface mudflow movements and contemporaneous faults quite possibly may play a large role in maintaining the continuing movement along the fault planes.

A feature commonly associated with the growth faults, and of extreme importance to petroleum trapping, is the association of rollover or reverse drag on the downthrown side of the growth fault (Fig. 49). Such features are common on the contemporaneous faults that are presently active in the delta. The rollover anticline tends to form soon after deposition of the sediment on the downthrown side and does not require a considerable amount of overburden and weighting in order to form. The mass-moved material that flows downslope from higher levels on the delta front (sands, silts, and clays) has high water and gas contents. It is speculated that, as the sediment accumulates slightly more thickly on the downthrown side of the fault, early degassing and dewatering associated with movement along the fault take place. Pore waters and pore gases are permitted to escape upward in the zone of movement associated with the fault, thus decreasing the volume of the sediment and allowing an early change in density to take place nearly contemporaneously with development of the fault. As greater and greater amounts of sediment are added and overburden pressures become increasingly larger, this feature is then amplified and becomes more pronounced with time and depth.

Figure 50 illustrates in a summary diagram some of the major characteristics associated with subaqueous slump deposits. Although boring control and core control are limited in the deeper waters offshore, enough foundation borings have penetrated some of the sequences to give a fairly good indication of the type of deposits that accumulate offshore on the downthrown sides of some of the slump fault features. In addition, numerous articles exist on the Gulf Coast Tertiary sequences that indicate the type of deposition associated with slump deposits.

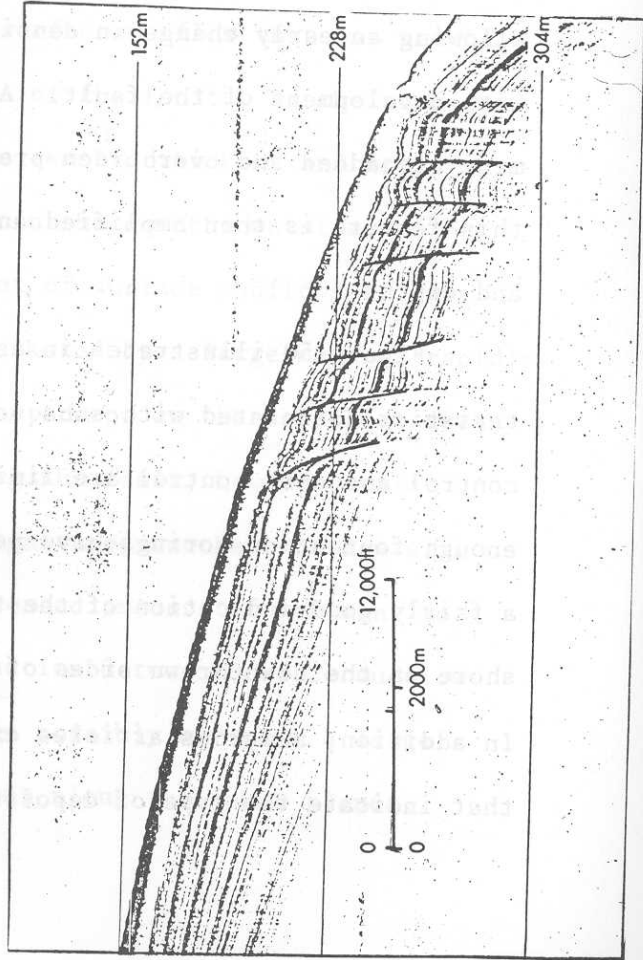
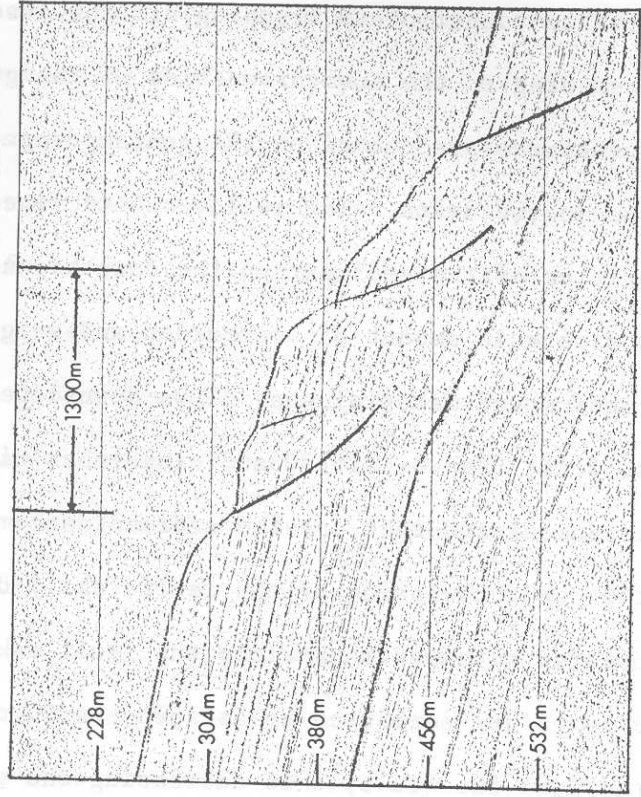
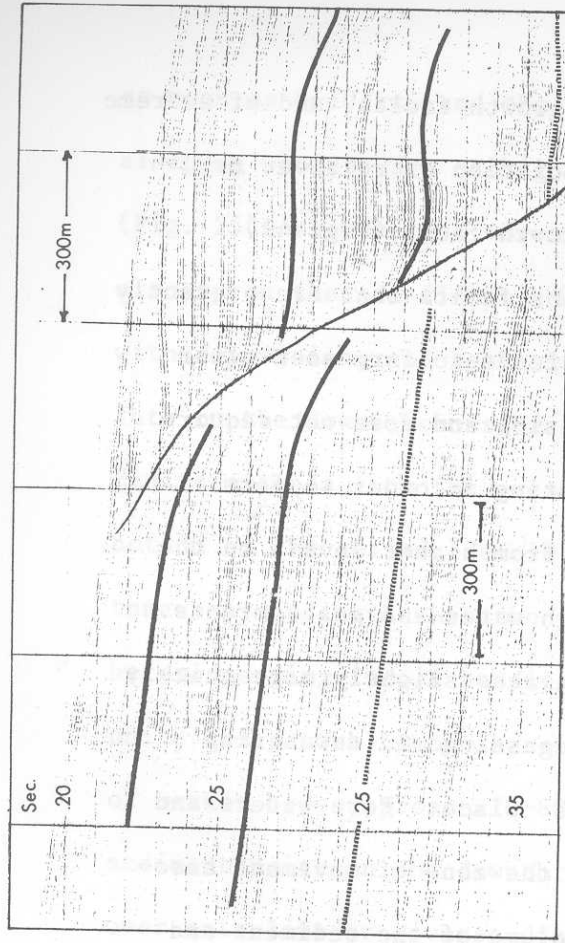
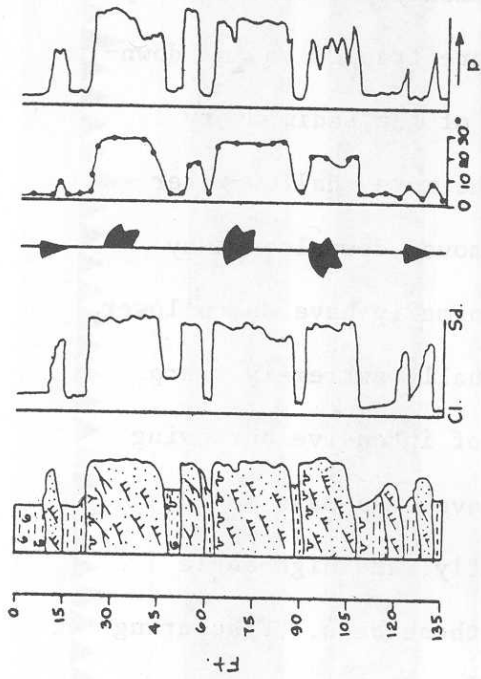
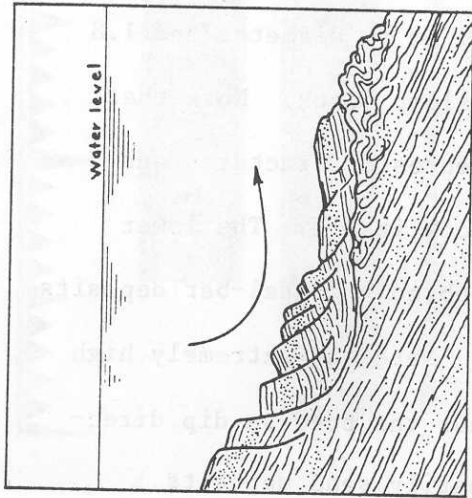


Figure 49. High-resolution seismic lines run across a variety of types of shelf-edge slumps and contemporaneous slump faults.

# SUBAQUEOUS SLUMPS



Sd., graded bedding  
 Sh., burrowed  
 Sd., ripple drift, x-lam., sharp base  
 Sd., sm. x-lam.  
 Cl. w/shell, burrowed  
 Sd., ripple drift, sharp base, burrowed top  
 Sd., ripple drift, sharp base, fractured, burrowing at top, st. stringata  
 cl.-st., burrowed, shell  
 Ripple drift, sharp base, graded bedding

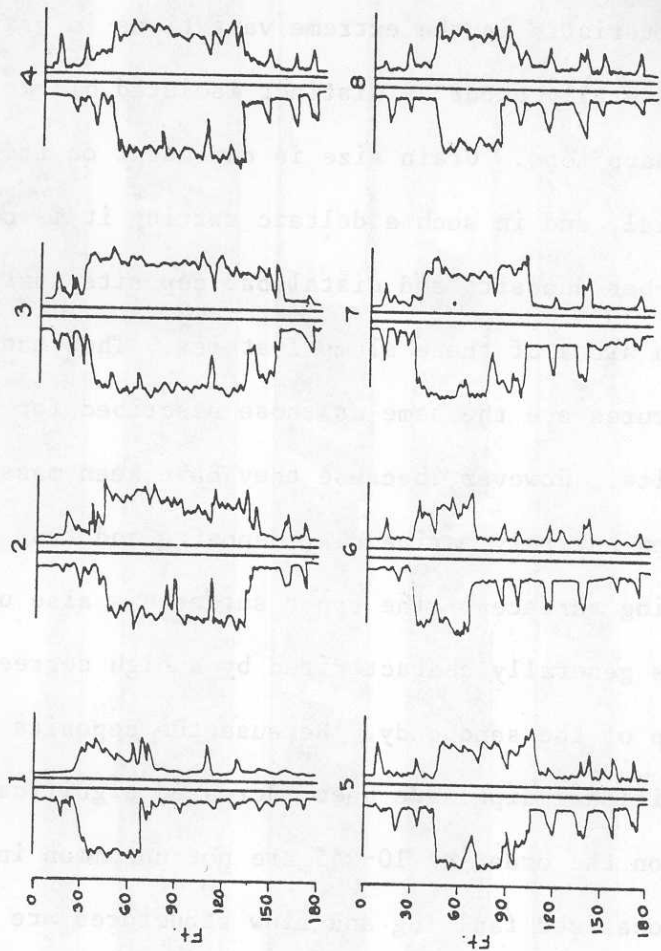
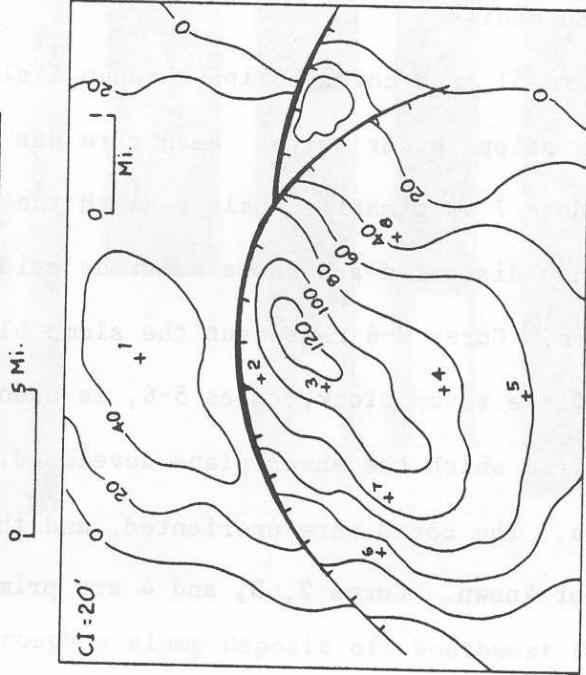


Figure 50. Diagram illustrating sedimentary characteristics of slump deposits offshore of the deltaic sequence.

The upper right-hand diagram illustrates a vertical sequence that commonly is associated with offshore slump deposits. The first striking characteristic is the extreme variations in grain size. The sandy deposits generally occur as distinct isolated blocks showing both sharp bases and sharp tops. Grain size is dependent on the source of the slump material, and in such a deltaic setting it is commonly the distributary-mouth-bar deposits and distal-bar deposits that are trapped on the down-thrown sides of these slump features. Thus many of the sedimentary structures are the same as those described for the more shallow-water deposits. However, because they have been mass moved downslope they rest on entirely marine clay deposits and thus normally have sharp lower bounding surfaces. The upper surface is also usually extremely sharp and is generally characterized by a high degree of intensive burrowing on top of the sand body. Because the deposits have been mass moved, depositional dips have been increased significantly, and high-angle dips on the order of 10-25° are not uncommon in these beds. Fracturing and localized faulting and flow structures are also abundant in most of the sand bodies.

Figure 51 is a cored boring through a slump block off Southwest Pass, Mississippi River delta. Each core was 9 cm in diameter and 1.8 m long. Core 7 is a marine shale beneath the slump block. Note that it is highly distorted and shows numerous evidences of fractures and disturbance. Cores 2-6 represent the slump block itself. The lower section of the slump block, cores 5-6, is undoubtedly distal-bar deposits, the zone from which the shear plane developed. Note the extremely high angle dips. The cores were unoriented, and thus the precise dip direction is not known. Cores 2, 3, and 4 are primarily sand deposits.

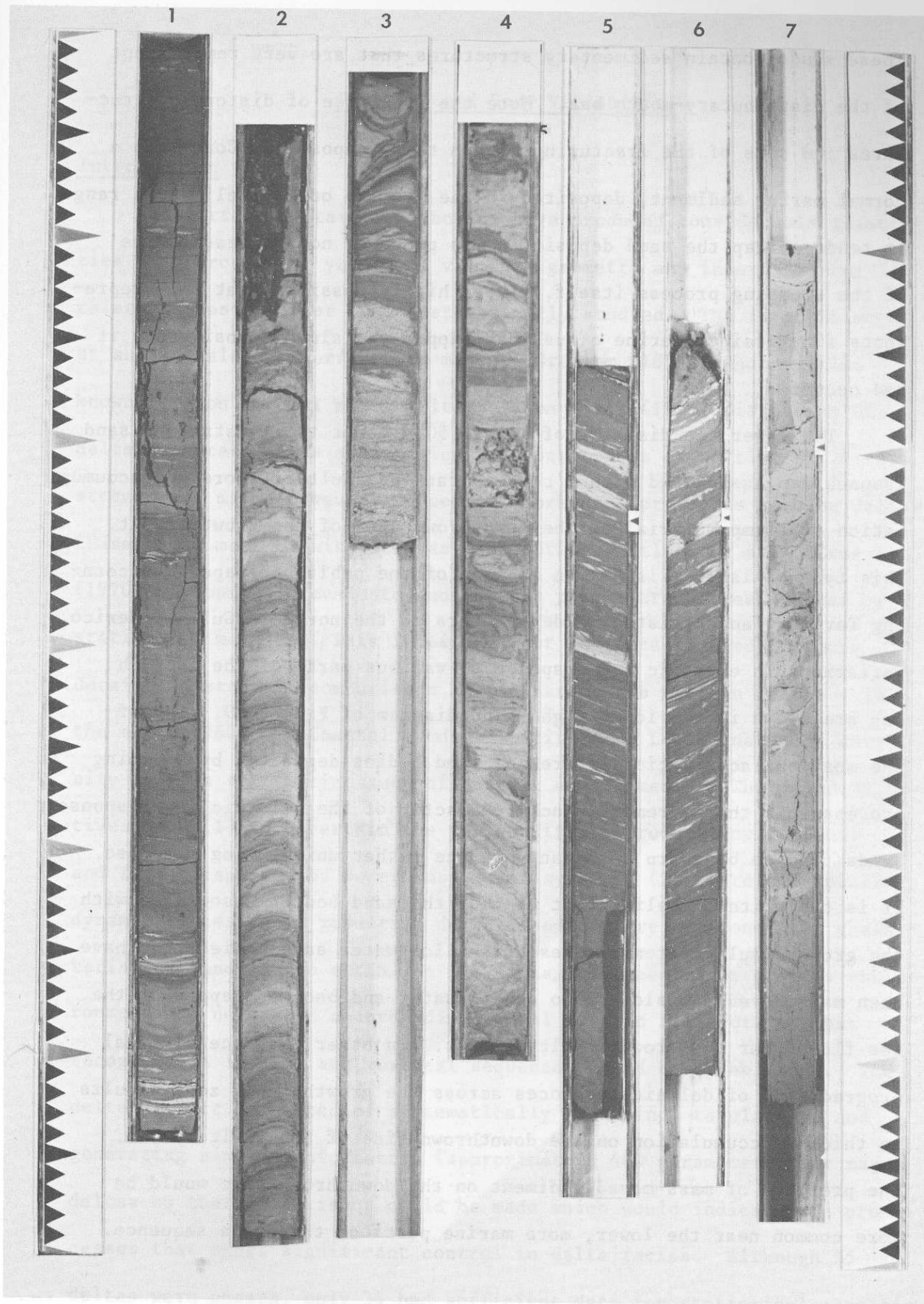


Figure 51. Cored boring through a slump deposit off Southwest Pass, Mississippi River delta.

These sands contain sedimentary structures that are very reminiscent of the distributary-mouth bar. Note the abundance of distorted structures and some of the fracturing within these deposits. Core 1 is a normal marine sediment, deposited in the mid- to outer-shelf depth range. It tends to cap the sand deposit and is probably not representative of the slumping process itself. It is highly possible that this represents fine-grained marine clays that capped the slump deposit once it had occurred.

The lower two diagrams of Figure 50 attempt to illustrate a sand isopach map associated with a contemporaneous fault offshore and accumulation of slump material on the downthrown side of the growth fault. This type of isopach is common in many of the published papers concerning Tertiary and Pleistocene depocenters in the northern Gulf of Mexico. Variations in electric log response to various parts of the isopach map are shown in the lower right-hand diagram of Figure 50. One of the most characteristic features of sand bodies deposited by slumping processes is the extremely blocky character of the electric log response. Sands tend to be sharp based and produce rather uniform log response. It is the writers' belief that many of the sand bodies associated with the growth fault systems represent shallow-water sand bodies that have been mass moved downslope into deeper water and become trapped on the sea floor near the growth fault systems. In other instances, normal progradation of deltaic sequences across the growth fault zone results in thicker accumulation on the downthrown side of the fault system. The presence of mass-moved sediment on the downthrown side would be more common near the lower, more marine parts of the delta sequence.

Deltaic Sand Body Variability

Introduction

Subsurface deltaic sand bodies have produced considerable quantities of hydrocarbon; yet their variable geometry and interfingering relationships have not been systematically studied. The first attempt at such a delta comparison was made by Credner (1878), who compiled known data on several major deltas. Samajlov's (1956) discussion of deltaic processes was accompanied by descriptions of 65 rivers. Little attempt was made, however, to compare forms and processes between deltas inasmuch as most of his work was descriptive. Silvester and LaCruz (1970) attempted to evaluate and compare parameters between deltas by statistical methods. This initial effort indicated a need for more detailed systematic comparisons of the parameters between deltas. In the early 1960s the Coastal Studies Institute of Louisiana State University began a systematic study of deltaic environments. The major objectives were (1) to ascertain the variability of process environments and forms displayed by modern-day river systems, (2) to relate specific dynamic processes to resulting deltaic sedimentary environmental characteristics; and (3) to establish the linkage between major process environments in deltas in a three-dimensional deltaic framework so that recognizable lateral and vertical sequences could be established. The delta project consisted of systematically acquiring, tabulating, and generating similar information (approximately 400 parameters) for major deltas so that comparisons could be made which would indicate the processes that exert significant control in delta facies. Although 55 deltas were chosen, only 34 had sufficient data for statistical comparison.

Figure 52. Flow chart showing approach to comparison study of deltas.

sons. The approach used in the study is illustrated in Figure 52. The first step was to define rigidly the components and parameters to be measured and tabulated. These definitions were based on experience, published literature, and numerous discussions with scientists in various fields. Reconnaissance trips to deltas in various parts of the world were conducted to ascertain the validity of the definitions and to modify them if necessary. The next step was to compile and evaluate existing data on each delta. Much of the raw data was derived from government and consulting engineering firms. During this stage the variables were selected and limits in accuracy were defined. Standardized techniques for measuring and reducing raw data were also developed. Optimum scales for maps and photographs were determined by the availability of maps for each delta. The data were then compiled and utilized for generating specific process and form information. As an example, a computer program was developed for determining quantitative wave power for delta areas. The resulting information and data were then structured, formatted, and stored for efficient handling and retrieval. At this point statistical techniques were used to compare and ascertain similarities and differences between the deltas. From the various types of statistical analyses, significant variables and their interrelationships and information deficiencies were identified. The final products were determination of the process-form variability of deltas and the identification of delta models.

#### Vertical Sequences and Delta Examples

Six deltas have been chosen to illustrate the relationships between the process setting and the resulting sedimentary sequence. The following deltas are described:

# COASTAL INFORMATION PROGRAM

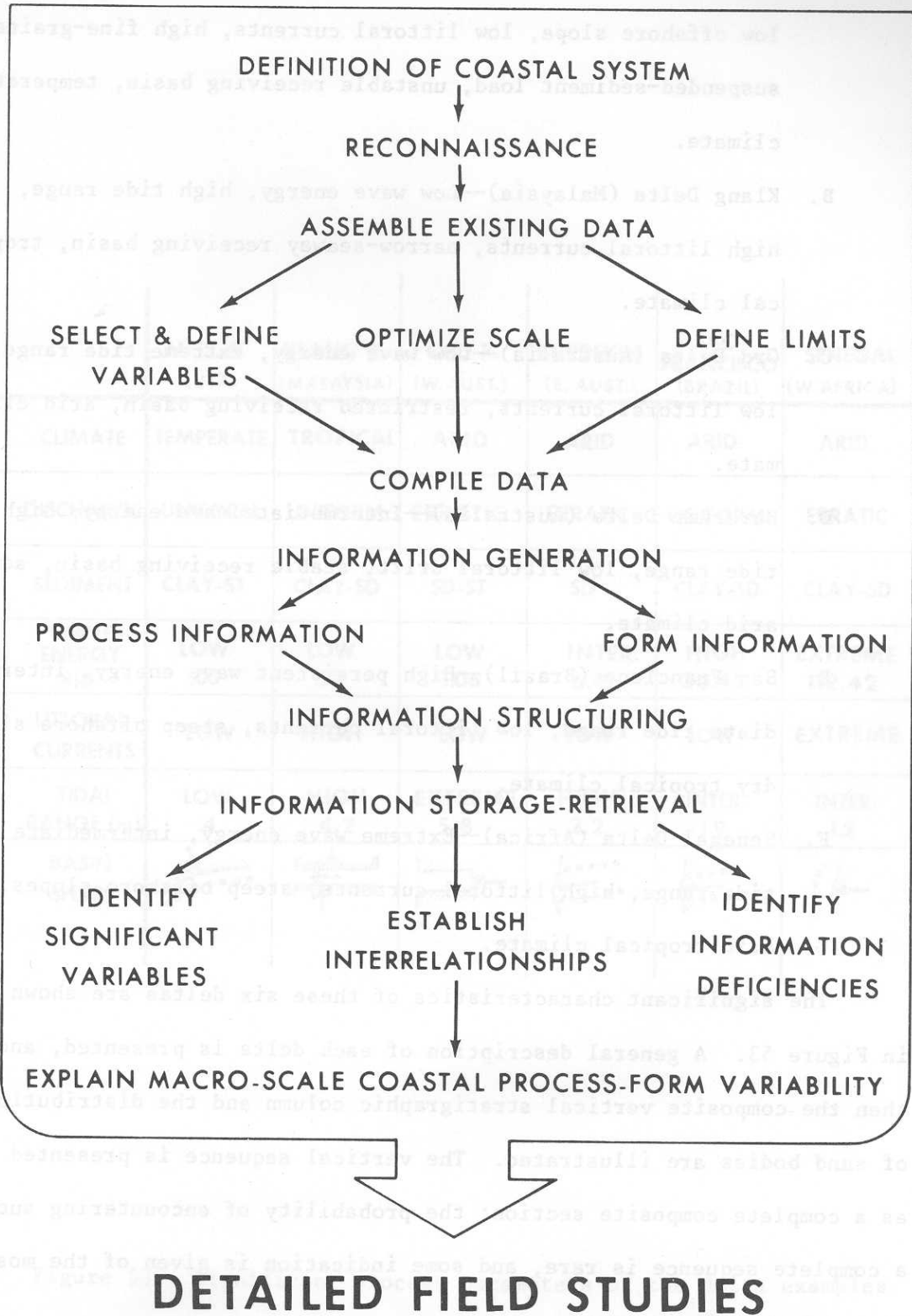


Figure 52. Flow chart showing approach to comparison study of deltas.

- A. Mississippi Delta (U.S.A.)--Low wave energy, low tide range, low offshore slope, low littoral currents, high fine-grained suspended-sediment load, unstable receiving basin, temperate climate.
- B. Klang Delta (Malaysia)--Low wave energy, high tide range, high littoral currents, narrow-seaway receiving basin, tropical climate.
- C. Ord Delta (Australia)--Low wave energy, extreme tide range, low littoral currents, restricted receiving basin, arid climate.
- D. Burdekin Delta (Australia)--Intermediate wave energy, high tide range, low littoral drift, stable receiving basin, semi-arid climate.
- E. Sao Francisco (Brazil)--High persistent wave energy, intermediate tide range, low littoral currents, steep offshore slope, dry tropical climate.
- F. Senegal Delta (Africa)--Extreme wave energy, intermediate tide range, high littoral currents, steep offshore slopes, arid tropical climate.

The significant characteristics of these six deltas are shown in Figure 53. A general description of each delta is presented, and then the composite vertical stratigraphic column and the distribution of sand bodies are illustrated. The vertical sequence is presented as a complete composite section; the probability of encountering such a complete sequence is rare, and some indication is given of the most common types of sequence.

Mississippi River delta. The Mississippi, the largest river system in North America, drains an area of 3,344,560 km<sup>2</sup>. The sediment

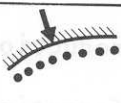
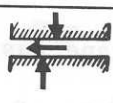
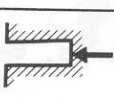
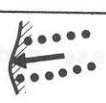
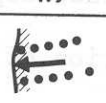
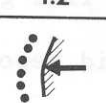
	MISS. R. (USA)	KLANG R. (MALAYSIA)	ORD R. (W. AUST.)	BURDEKIN (E. AUST.)	SAO FRANCISCO (BRAZIL)	SENEGAL (W. AFRICA)
CLIMATE	TEMPERATE	TROPICAL	ARID	ARID	ARID	ARID
DISCHARGE	UNIFORM	UNIFORM	ERRATIC	ERRATIC	UNIFORM	ERRATIC
SEDIMENT	CLAY-ST	CLAY-SD	SD-ST	SD	CLAY-SD	CLAY-SD
WAVE ENERGY x10 <sup>7</sup>	LOW .03	LOW .22	LOW 1.06	INTER. 6.41	HIGH 30.42	EXTREME 112.42
LITTORAL CURRENTS	LOW	HIGH	LOW	LOW	LOW	EXTREME
TIDAL RANGE (m)	LOW .4	HIGH 4.2	EXTREME 5.8	HIGH 2.2	INTER. 1.9	INTER. 1.2
BASIN SHAPE						

Figure 53. Significant process parameters of the delta examples.

discharge is extreme, and the sediments consist predominantly of clays, silts, and fine sands. The delta plain has a total area of 28,568 km<sup>2</sup>, of which 23,900 km<sup>2</sup> is subaerial. Marshes and open bays form the bulk of the subaerial deposits. The warm, humid climate favors in situ accumulation of high organic clays in marshy areas, and the interdistributary bays are characterized by highly burrowed silts and clays. Shoreline wave power is extremely low, averaging only  $0.03 \times 10^7$  ergs/sec. Thus riverine processes dominate; the river mouths protrude in long, fingerlike configurations, and the coastline is extremely irregular. Crevasses and bay fills are common along the distributaries and vary considerably in size. The smaller ones emanate from low depressions in the distributary bank and splay out as small lenses of sand. The larger crevasses break or scour across the channel levee and form bay fills that have areal extents on the order of 160 km<sup>2</sup>. These subdeltas are virtually the only sands that occur within the subaerial delta deposits.

The Mississippi River carries a high suspended-sediment load, and fine-grained deposits are spread long distances from the river mouth. Rapid deposition of these sediments, methane gas production, and excess pore water pressure result in a wide variety of deformational and subaqueous slump processes. As a result of differential compaction and formation of thick distributary sands, diapiric clay intrusions are present; seaward mass wasting, slumping, and abundant faulting across the shelf are characteristic of the subaqueous delta processes. Long, fingerlike protrusions of distributary channels are formed, and the abandoned channels are filled with silty and organic clays.

Figure 54 shows the major types of resulting sand bodies that are formed in such a setting. In the subaerial delta, the only major sands are represented by the overbank crevasse splays and bay fills.

# MISSISSIPPI DELTA

## COMPOSITE STRATIGRAPHIC COLUMN

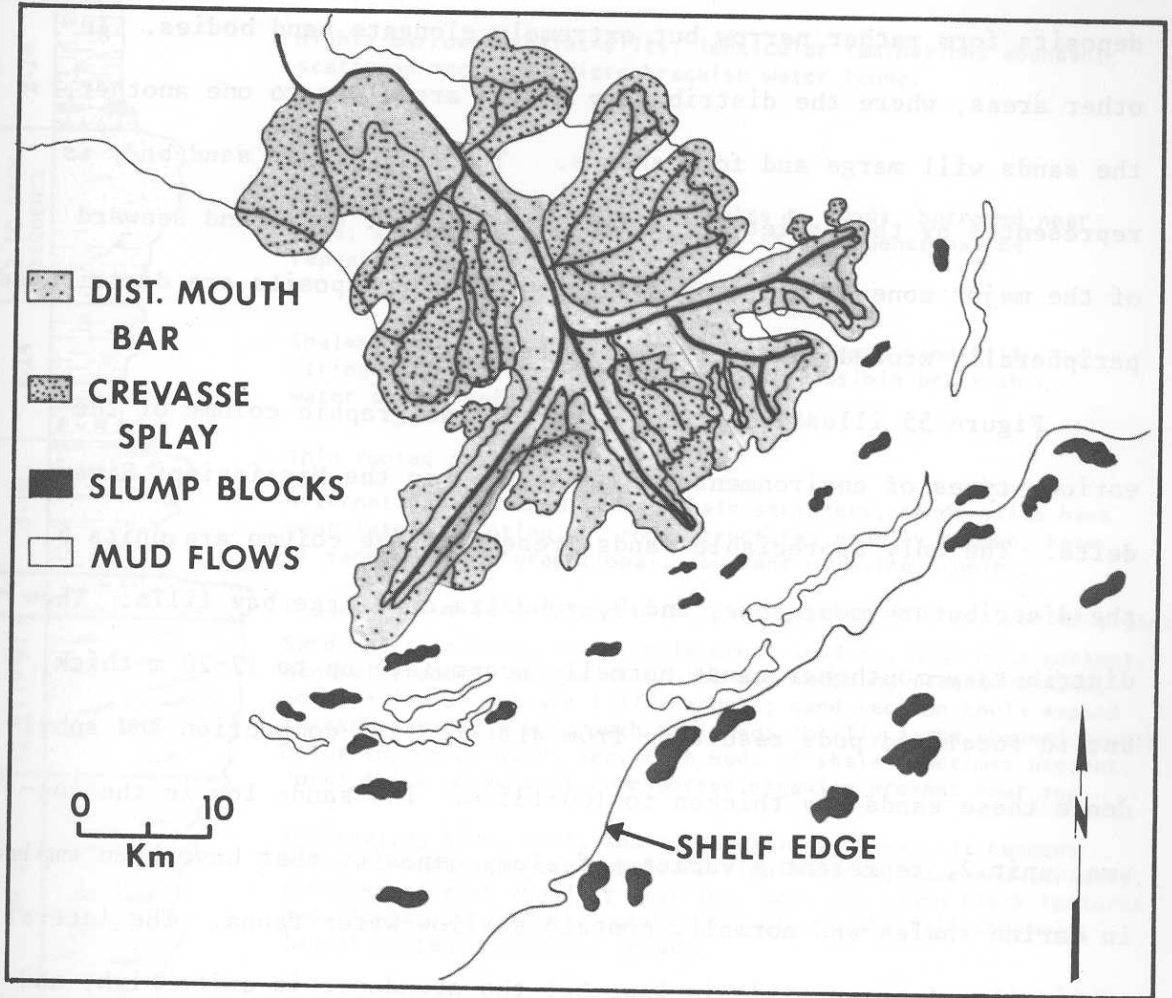


Figure 54. Sand-body distribution in the Mississippi Delta model.

These vary considerably in size, as can be seen in the diagram. In the subaqueous delta the main sandy deposit is represented by the distributary-mouth-bar and distal-bar deposits. In some instances these deposits form rather narrow but extremely elongate sand bodies. In other areas, where the distributary mouths are close to one another, the sands will merge and form sheets. The third major sand body is represented by the variety of slump deposits that are found seaward of the major zone of delta progradation. These deposits are distributed peripherally around the entire delta front.

Figure 55 illustrates a composite stratigraphic column of the various types of environments of deposition in the Mississippi River delta. The only appreciable sands present in the column are units 5, the distributary-mouth bar, and 9, subdelta and large bay fills. The distributary-mouth-bar sands normally accumulate up to 12-20 m thick, but in localized pods resulting from differential compaction and subsidence these sands may thicken to 100-135 m. The sands low in the column, unit 2, represent a variety of slump deposits that have been emplaced in marine shales and normally contain shallow-water fauna. The lateral continuity of these sands is low, but the abundance is quite high, and a single boring may encounter several sands within the shale deposits. Units 1-5 primarily represent subaqueous delta deposits and show a typical coarsening-upward sequence, and units 6-10 consist of subaerial deposits (marsh, bay fills, and interdistributary-bay deposits), which are normally deposited at or slightly below high-tide level. Capping the entire delta sequence are high organic clays and peats that persist and continue growing after abandonment of the delta lobe.

Klang River delta. The Klang River system originates in the central highlands of Malaysia and drains into the Straits of Malacca.

# MISSISSIPPI DELTA

## COMPOSITE STRATIGRAPHIC COLUMN

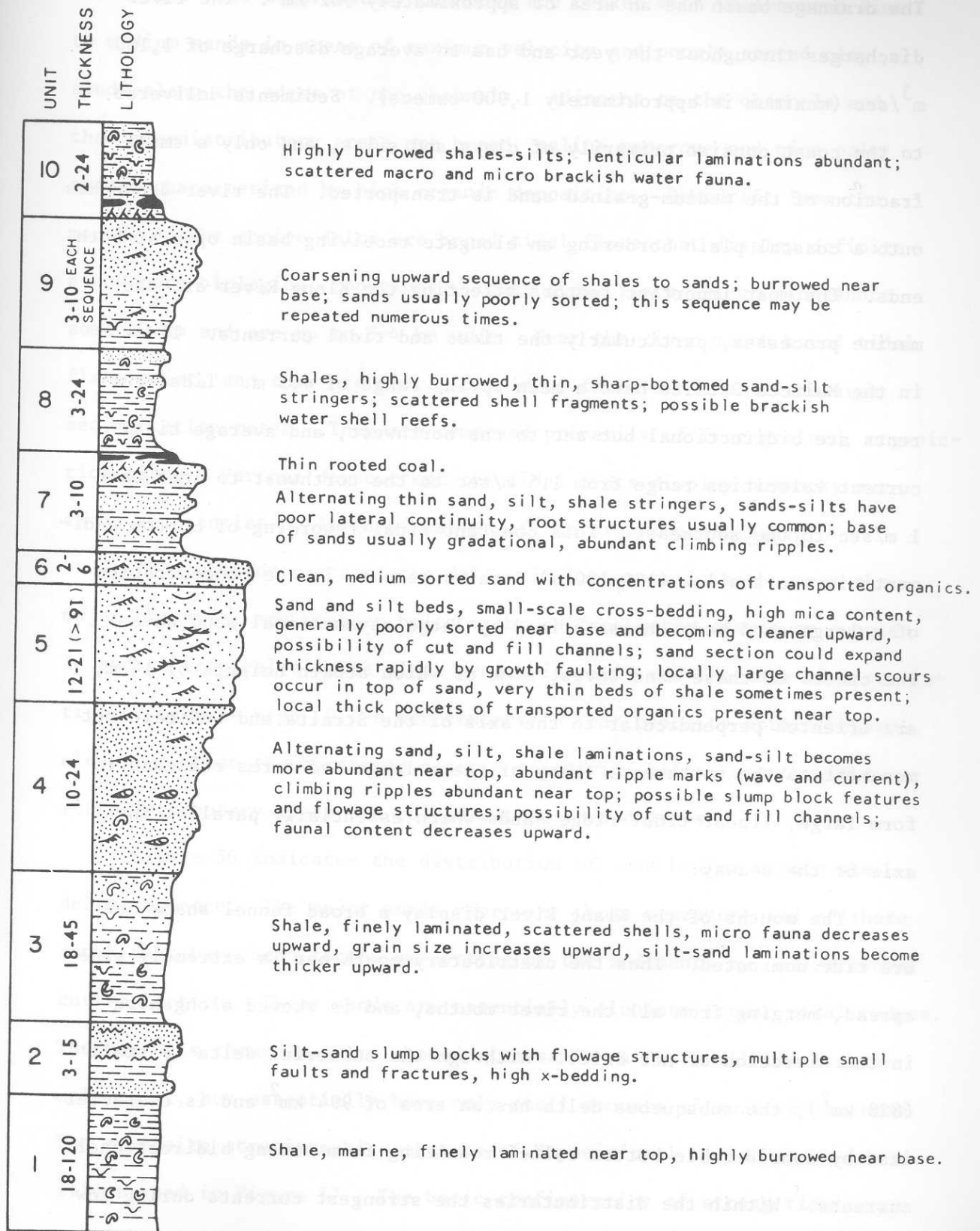


Figure 55. Composite stratigraphic sequence of depositional environments in the Mississippi River delta.

The drainage basin has an area of approximately 902 km<sup>2</sup>. The river discharges throughout the year and has an average discharge of 1,100 m<sup>3</sup>/sec (maximum is approximately 1,900 cumecs). Sediments delivered to the coast consist primarily of clays and silts, and only a small fraction of the medium-grained sand is transported. The river debouches onto a coastal plain bordering an elongate receiving basin open at both ends. The most important factors affecting the Klang River are the marine processes, particularly the tides and tidal currents. Tides in the Malacca Straits have a mean spring range of 4.3 m. Tidal currents are bidirectional but set to the northwest, and average tidal current velocities range from 1.5 m/sec to the northwest to less than 1 m/sec to the southeast. This constant tidal reworking of bottom sediments in the shallow (120-180 m) Straits results in the concentration of a large sand body characterized by large asymmetrical sand waves. The crests of these sand waves, some of which attain heights of 14 m, are oriented perpendicular to the axis of the Straits and indicate net movement to the northwest. Many of these large bed forms coalesce to form large, linear tidal-ridge sands which essentially parallel the axis of the seaway.

The mouths of the Klang River display a broad funnel shape and are tide dominated. Thus the distributary-mouth bar is extremely widespread, merging from all the river mouths, and is skewed alongshore in the direction of net drift. Although the subaerial delta is small (823 km<sup>2</sup>), the subaqueous delta has an area of 994 km<sup>2</sup> and is characterized by considerable bottom relief resulting from strong bidirectional currents. Within the distributaries the strongest currents during low river stage are directed upstream, attaining velocities in excess of

1.5 m/sec. The distributary channels are choked with well-sorted fine to medium sands in areas of maximum velocity and poorly sorted clay sands along the edges of the channels. Adjacent to the channels and the interdistributary areas are broad, saline mangrove and nipa palm swamps characterized by high organic deposition. Downdrift from the mouths of the active delta are broad tidal flats that display definite alongshore biological zonations. These tidal flats extend alongshore some 20 km and are up to 3-4 km wide. Near the river mouth broad tidal flats exist, and they are nearly devoid of fauna because of the high sedimentation rates. They are composed primarily of fine-grained, organic-rich clays. Farther downcurrent the tidal flats display hummocky surfaces and consist of large biomasses of the brachiopod Lingula.

The interior parts of the delta, in the areas lying between the major channels, are meander belts or broad freshwater swamps or jungles. In such a tropical climate plant growth is rapid and the rate of accumulation of peat is high (0.1 m per century). Peat deposits attain higher elevations than the bordering clastic meandering belts, and thus the interdistributary areas are raised rather than depressed.

Figure 56 indicates the distribution of sand bodies within the delta sequence. The major sands represent those nearshore and offshore sands that have been formed by sorting of the sediments by bidirectional current action. These sands are essentially elongate linear tidal ridges. The channels themselves are choked with sand. A few small tidal channels exist, but essentially have only small amounts of sand within them. The composite stratigraphic sequence of depositional environments is illustrated in Figure 57. The basic configuration of strong tidal currents sorting sediments within the Malacca Straits results in a well-

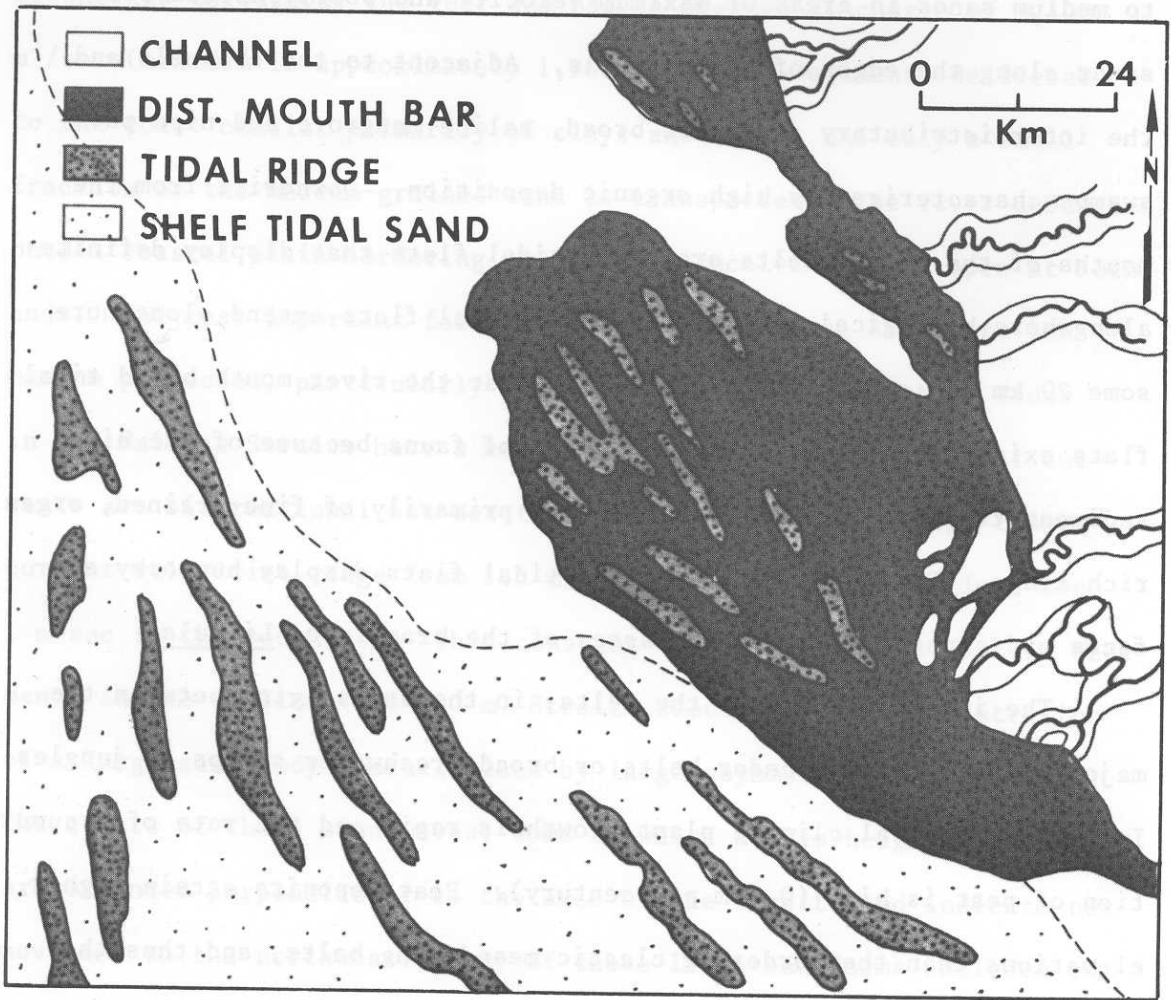


Figure 56. Sand-body distribution in the Klang River delta model.

# KLANG DELTA

## COMPOSITE STRATIGRAPHIC COLUMN

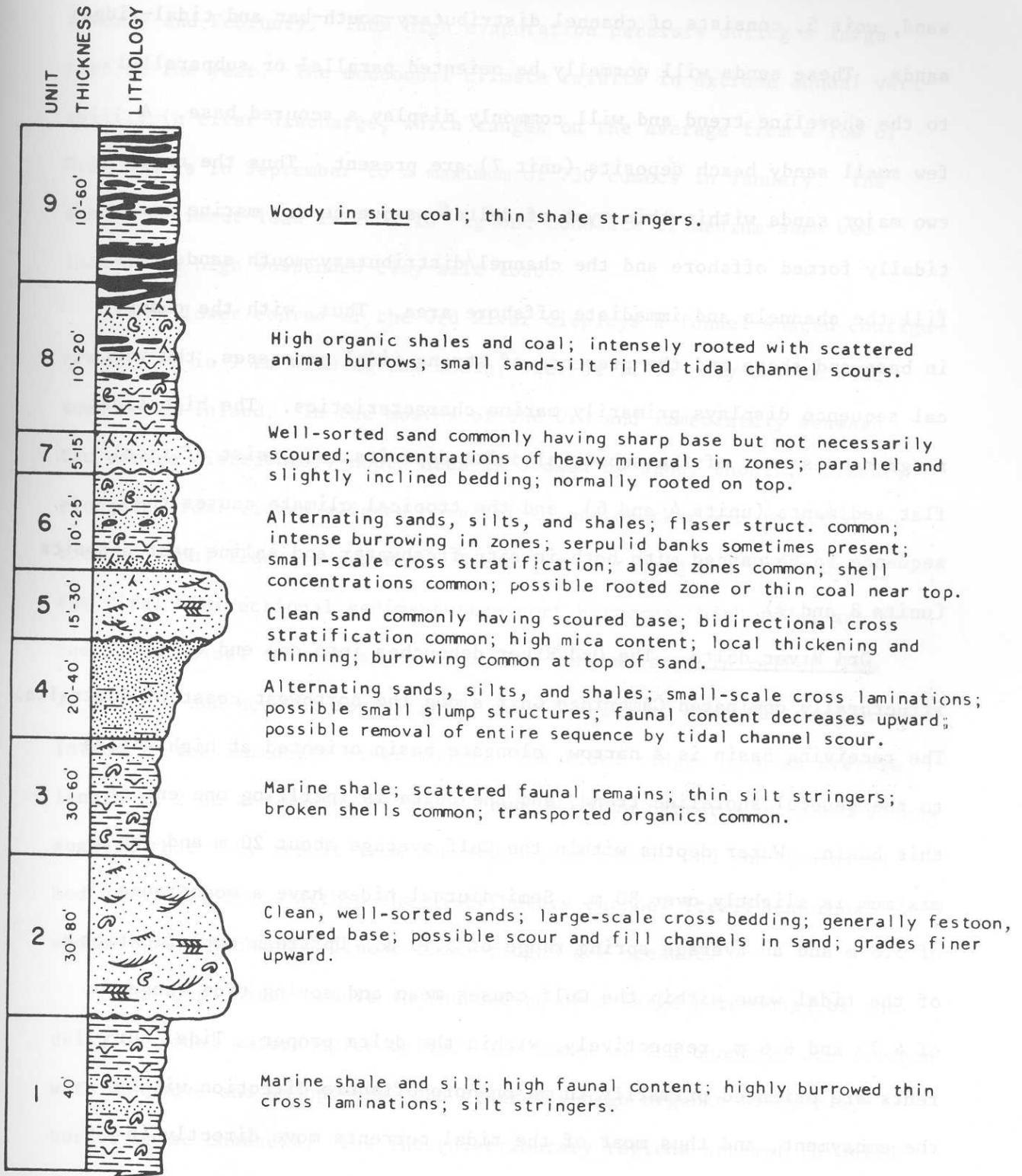


Figure 57. Composite stratigraphic sequence of depositional environments in the Klang River delta.

developed tidal marine sand low in the section (unit 2). The upper sand, unit 5, consists of channel distributary-mouth-bar and tidal-ridge sands. These sands will normally be oriented parallel or subparallel to the shoreline trend and will commonly display a scoured base. A few small sandy beach deposits (unit 7) are present. Thus the only two major sands within this type of deltaic sequence are marine sands tidally formed offshore and the channel/distributary-mouth sands that fill the channels and immediate offshore area. Thus, with the change in base and shape and the presence of strong tidal processes, the vertical sequence displays primarily marine characteristics. The high tidal range causes most of the subaerial delta deposits to consist of tidal flat sediments (units 4 and 6), and the tropical climate causes the sequence to be capped with both in situ freshwater and saline peat deposits (units 8 and 9).

Ord River delta. The Ord River debouches into one end of the structurally dominated Cambridge Gulf along the northwest coast of Australia. The receiving basin is a narrow, elongate basin oriented at high angles to the general shoreline trend, and the delta is infilling one end of this basin. Water depths within the Gulf average about 20 m and the maximum is slightly over 80 m. Semi-diurnal tides have a mean range of 3.8 m and an average spring range of 5.15 m. Upstream amplification of the tidal wave within the Gulf causes mean and spring tide ranges of 4.75 and 6.6 m, respectively, within the delta proper. Tidal currents are oriented primarily in an onshore-offshore direction within the embayment, and thus most of the tidal currents move directly in and out of the river mouth.

The Ord River rises from a tropical drainage basin 78,000 km<sup>2</sup> in area and experiences a hot, dry tropical monsoon climate. Within

the delta there is a water balance deficit during every month except January and February. Thus high evaporation persists during a large part of the year. The monsoonal climate results in extreme annual variability in river discharge, which ranges on the average from a low of 0.07 cumecs in September to a maximum of 730 cumecs in January. The annual sediment load is  $22 \times 10^9$  kg and consists of medium-sand bed load and a high suspended-clay-silt load.

The lower course of the Ord River displays a funnel-shaped configuration; it is 9 km wide at the mouth, whereas it is only 0.9 km wide some 60 km inland. In the mouths of the Ord and immediately seaward the entire distributary-mouth area is choked by sandy shoals. Linear, elongate tidal ridges aligned parallel to one another and to the direction of tidal flow are present. These linear ridges are related to the tidal bidirectional sediment-transport patterns, high tidal amplitudes, and tidal current asymmetry. The ridges range in relief from 10 to 22 m and account for slightly over  $5 \times 10^6$  m<sup>3</sup> of total sand accumulation in the immediate river mouth. The tidal ridges have an average length of 2 km and widths of 300 m, and bed-form patterns on these ridges suggest that they result from convergence of flood- and ebb-dominated bedload transport. Within the distributary channel itself numerous shoals and mid-channel linear tidal ridges are present.

The high tides result in inundation of a large percentage of the delta by tidal waters twice daily. The banks of the channels are fringed with mangrove and halophytes, and generally high organic silty clays border these channels. The interdistributary regions attempt to build to the level of highest tides, and supratidal deposits accumulate. Much of the interdistributary area contains barren mudcracked algal

flats. The high evaporation results in intercalations or thin stringers of evaporites with silty clay sediments. The interior parts of these basins often accumulate considerable quantities of evaporites. Some of the salt accumulations have dimensions of 14 x 20 km and thicknesses up to 7 m. Branching off the main distributaries of the river are large, sinuous tidal channels that transport large quantities of sandy material. These channels meander actively across the delta plain and form sandy channel deposits that range in thickness from 3 to 12 m.

Figure 58 shows the major sand-body distributions in the Ord River delta model. The major sand body consists of a large number of linear tidal ridges that form well out in front of the distributary, within the distributary mouth, and within the distributary channels themselves. The only other sand that is present in the entire system results from the migratory nature of the large meandering tidal channels. As they meander across the subaerial delta they leave behind a large number of tidal point bars. The composite stratigraphic sequence shown in Figure 59 displays the one prominent sand unit that consists primarily of tidal-ridge (distributary-mouth bar) deposits that continue from beyond the river mouth and to the distributary channels themselves. These units offshore generally have high lateral continuity, whereas within the channel their continuity is rather restricted. Sand unit 3 in Figure 59 represents this particular environment. Near the seaward edge of the sand body large-scale bidirectional cross-bedding is common. This sand body grades landward into sandy channel-fill deposits that display sharp scoured bases and primarily landward-oriented cross bedding directions. The lower units (1 and 2) are shallow marine deposits that grade rather abruptly into the tidal-ridge deposits. The sand body (unit 5) is composed of tidal-channel sediments and consists pri-

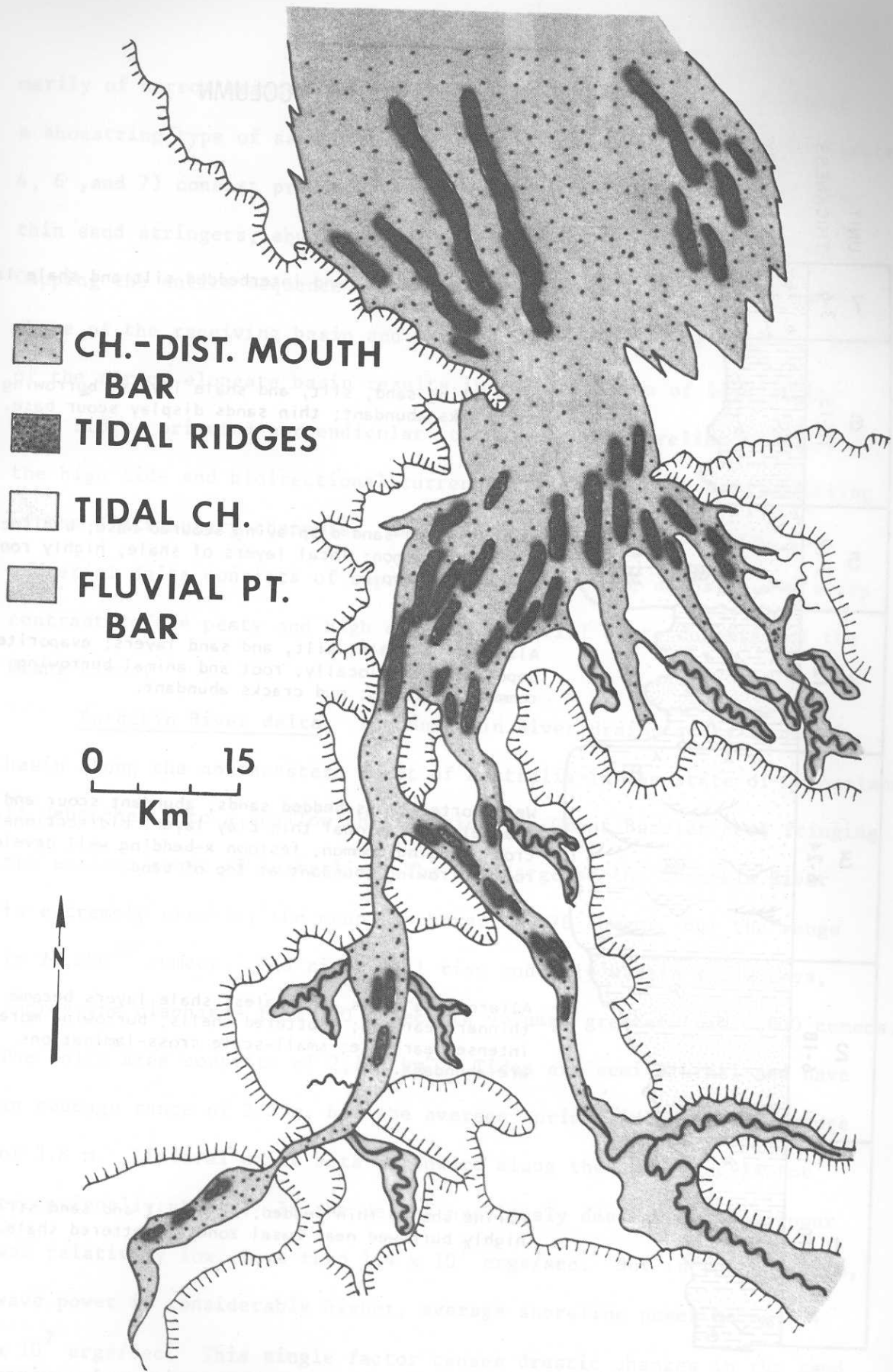


Figure 58. Sand-body distribution in the Ord River delta model.

# ORD DELTA

## COMPOSITE STRATIGRAPHIC COLUMN

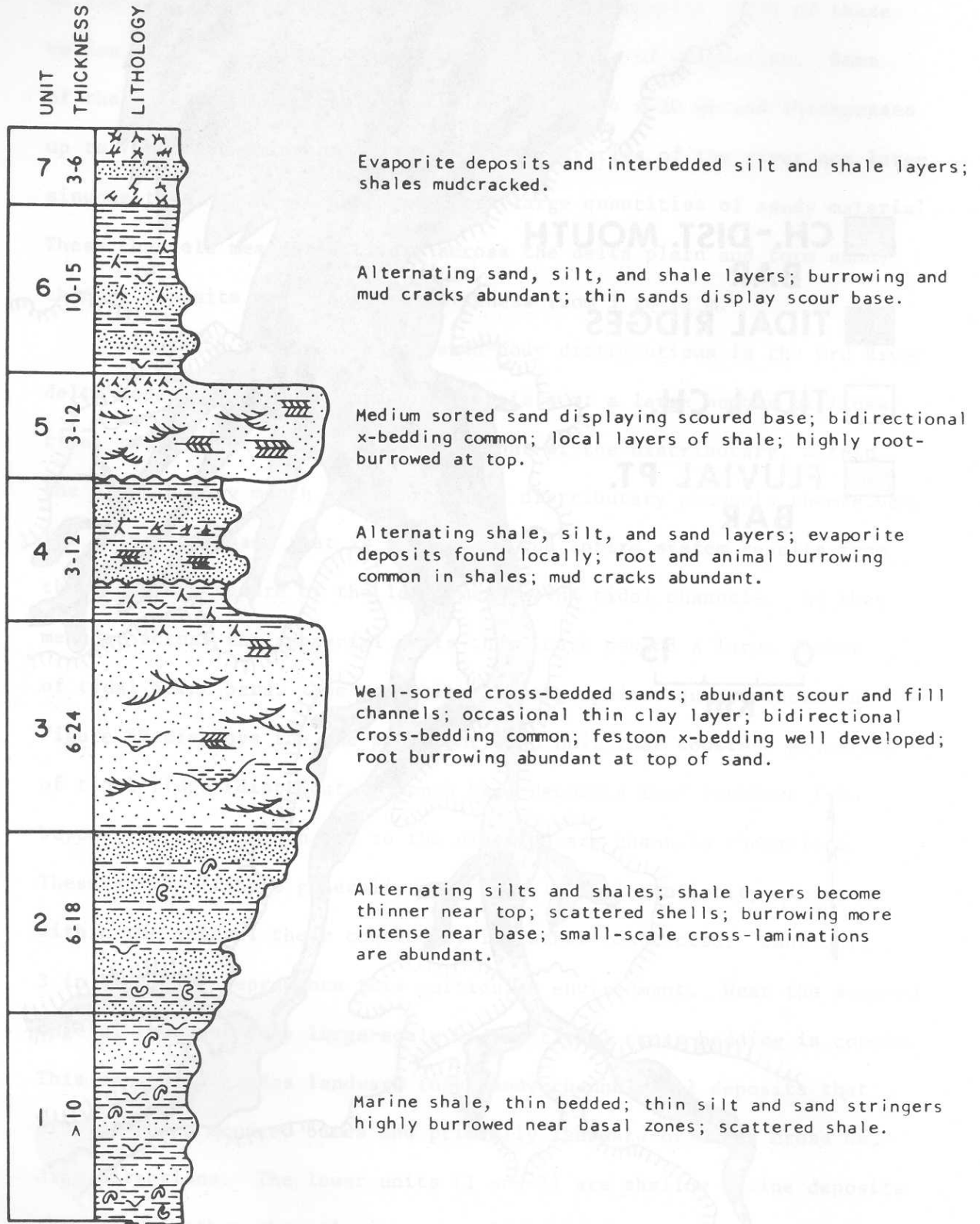


Figure 59. Composite stratigraphic sequence of depositional environments in the Ord River delta.

marily of narrow meander-belt deposits. These deposits would display a shoestring type of sand-body geometry. Subaerial delta deposits (units 4, 6, and 7) consist predominantly of tidal-plain sediments with local thin sand stringers, abundant burrowing, and desiccation structures. Capping the entire sequence are the evaporite deposits. The closed shape of the receiving basin and the feeding of the river into one end of the narrow elongate basin results in the formation of long, linear sand ridges oriented perpendicular to the general shoreline trend, and the high tide and bidirectional currents cause extensive sand infilling of the distributary channels. As a result of the arid climate, the subaerial delta consists of supratidal and evaporite deposits, in sharp contrast to the peaty and high organic subaerial delta deposits of the Klang River.

Burdekin River delta. The Burdekin River drains a dry tropical basin along the northeastern coast of Australia in the state of Queensland. It debouches into a shallow shelf behind the Great Barrier Reef fringing the eastern coast of Australia. The discharge of the Burdekin River is extremely erratic; the mean discharge is 476 cumecs, but the range is  $24,286^{10}$  cumecs. The river will rise suddenly within a few days, increasing discharge from 100 cumecs to volumes greater than 4,000 cumecs. The delta area consists of  $2,112 \text{ km}^2$ . Tides are semi-diurnal and have an average range of 2.2 m, but the average spring tides attain a range of 3.8 m. Littoral drift sets northward along the coast but is not exceptionally strong. In the deltas previously described, wave power was relatively low, less than  $1.4 \times 10^7$  ergs/sec. But in the Burdekin, wave power is considerably higher, average shoreline power being  $6.4 \times 10^7$  ergs/sec. This single factor causes drastic changes in the sand

ORD DELTA

body geometry, orientation, and mineral composition.

The river transports considerable quantities of coarse-grained materials, cobbles being abundant in the alluvial valley only a few kilometres upstream from the delta apex. Coarse sand is abundant at the river mouth, but the river does not transport a high suspended silt and clay load except during river floods.

The active delta of the Burdekin comprises some 430 km<sup>2</sup> and consists of numerous bifurcated distributaries. The channels are characterized by numerous linear tidal shoals and are choked by coarse sediment. The mouths of the river are bell shaped, and within the channel mouth and the immediate offshore sandy shoals and large bed forms are common. Thus the distributary-mouth bar merges landward with sandy channel-fill deposits.

The other major depositional environment and sand-body accumulations consist of beach-dune-ridges and adjacent sandy offshore tidal flats. These features result from the reworking and concentration of riverborne sediments by wave action. This is the first delta described that displays appreciable quantities of marine wave-worked sands. Whereas the channel sands are oriented at high angles to the shoreline trend, the beach sands are oriented parallel to the shoreline. In addition, the channel sands normally have a high feldspar content, whereas the beach deposits approach nearly 95% quartz. This cleaning of the delta-introduced sediment is primarily the result of the high wave energy. This particular delta receives more wave energy in 2 days than the Mississippi does in an entire hydrologic year. This high wave energy is responsible for reworking and cleaning the sediments and concentrating the more resistant quartz grains.

The high tide range, combined with high wave energy, results in the formation of broad sandy tidal flats. Twice daily the shoreline transgresses and regresses an average of 3.5 km and the high wave energy reworks the sediment into broad, well-sorted, high-quartzose, sandy tidal-flat deposits. These sands are extremely widespread and form a sheetlike deposit that has an average areal extent of 250 km<sup>2</sup>. These sandy deposits grade landward into tidal-plain deposits that consist of mangrove swamps, barren algal flats, and localized salt pans, where evaporites are accumulated.

The change in environmental setting, particularly the increase in wave energy, results in a different distribution and types of sand bodies. Figure 60 shows the major sand body distributions in the Burdekin River delta model. Note that the three primary types of sands are represented by the sand-filled channels which merge with the tidal distributary-mouth-bar sandy shoals: broad tidal flats, which because of high wave energy, represent clean, quartzose, blanket-type sands; and finally the reworked beach-ridge deposits and their associated coastal dunes. Figure 61 shows the composite stratigraphic sequence of depositional environments. The lower sand body (unit 3) comprises the distributary-mouth bar (primarily linear tidal ridges) and channel-fill deposits. These sands are oriented at high angles to the shoreline trend, show a high percentage of feldspar, and are not primarily wave reworked. The upper sand unit (Fig. 61) consists of clean, well-sorted, high quartzose sands that form as a result of wave and wind action and is oriented parallel to the shoreline trend. This unit grades seaward into sandy tidal-flat deposits that display high lateral continuity (unit 4). The dune deposits are an integral part of the beach ridges and commonly attain heights of several metres. Some of the larger dunes can be seen

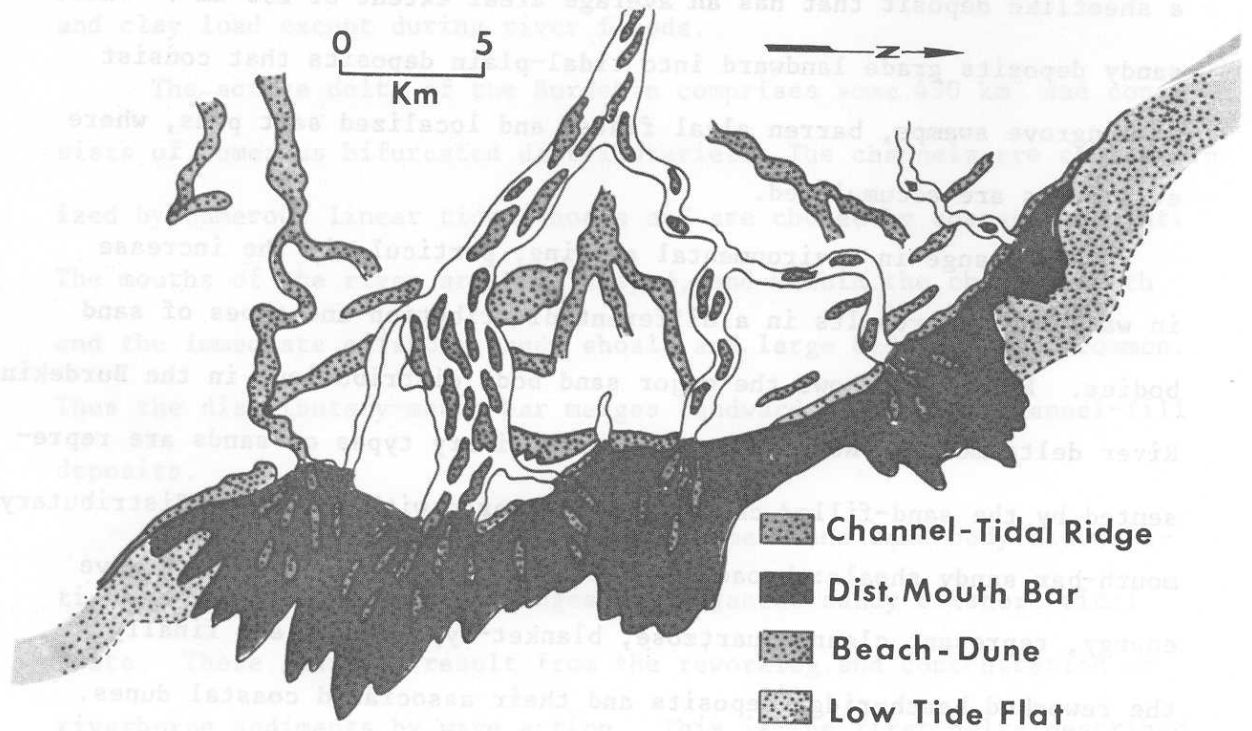


Figure 60. Sand-body distribution in the Burdekin River delta model.

# BURDEKIN DELTA

## COMPOSITE STRATIGRAPHIC COLUMN

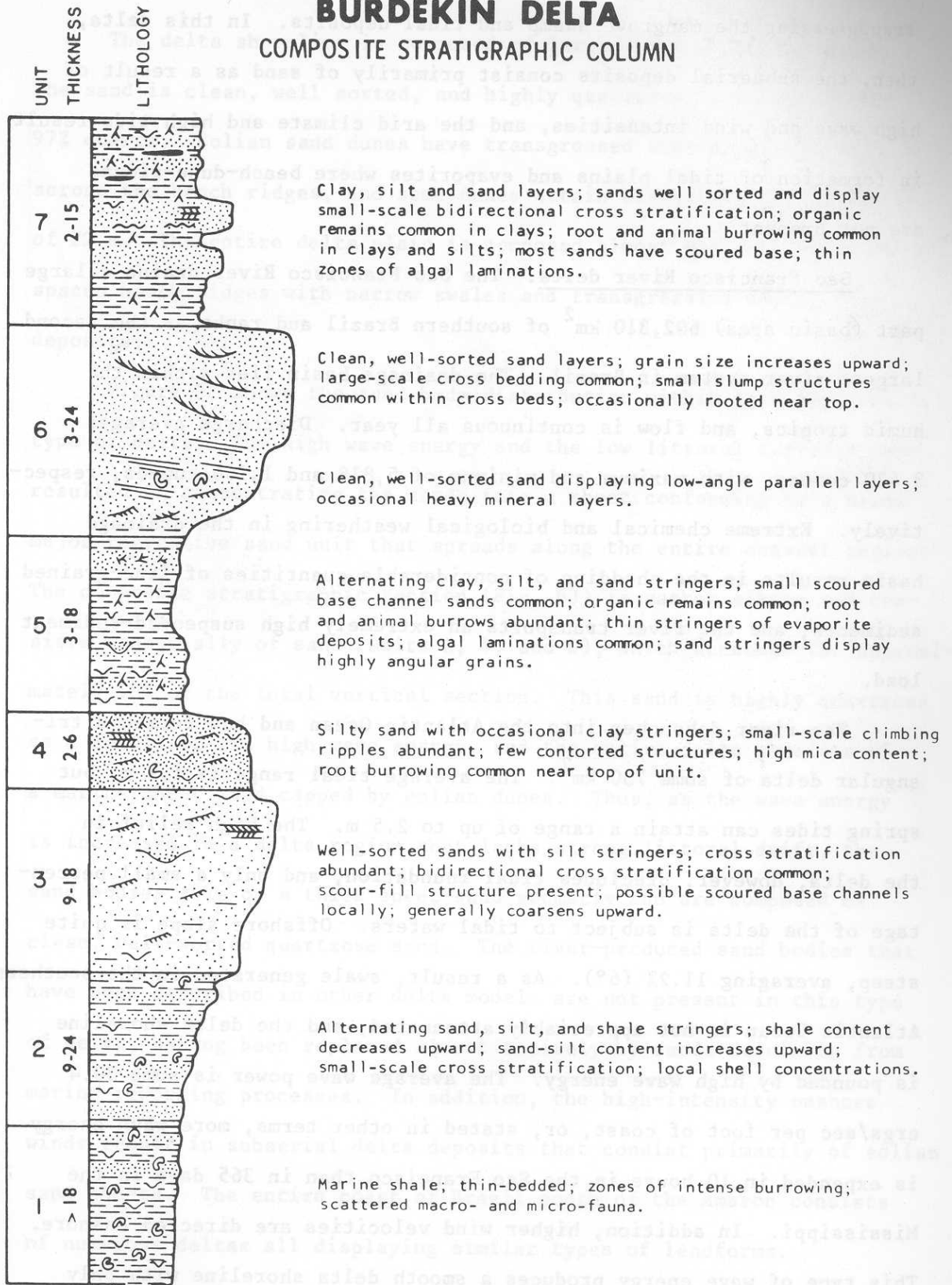


Figure 61. Composite stratigraphic sequence of depositional environments in the Burdekin River delta.

transgressing the mangrove swamp and tidal deposits. In this delta, then, the subaerial deposits consist primarily of sand as a result of high wave and wind intensities, and the arid climate and high tide result in formation of tidal plains and evaporites where beach-dune-ridges are not present.

Sao Francisco River delta. The Sao Francisco River drains a large part (basin area)  $602,310 \text{ km}^2$  of southern Brazil and ranks as the second largest river system in Brazil. The drainage basin lies within the humid tropics, and flow is continuous all year. Discharge averages 3,420 cumecs, with maximum and minimum of 5,818 and 1,166 cumecs, respectively. Extreme chemical and biological weathering in the drainage basin results in the shedding of considerable quantities of fine-grained sediments, and the river transports an extremely high suspended-sediment load.

The river debouches into the Atlantic Ocean and has formed a triangular delta of some  $730 \text{ km}^2$ . The average tidal range is 1.9 m, but spring tides can attain a range of up to 2.5 m. The high relief in the delta, however, precludes tidal inundation, and only a small percentage of the delta is subject to tidal waters. Offshore slope is quite steep, averaging 11.2% ( $6^\circ$ ). As a result, swale generated in the southern Atlantic Ocean is not appreciably attenuated, and the delta shoreline is pounded by high wave energy. The average wave power is some 30.4 ergs/sec per foot of coast, or, stated in other terms, more wave energy is expended in 10 hours in the Sao Francisco than in 365 days in the Mississippi. In addition, higher wind velocities are directed onshore. This type of wave energy produces a smooth delta shoreline with only a minor protrusion at the river mouth.

SÃO FRANCISCO DELTA

The delta shoreline is composed of large, broad, sandy beaches. The sand is clean, well sorted, and highly quartzose, approaching 95-97% quartz. Eolian sand dunes have transgressed several kilometres across the beach ridges, and some dunes attain elevations in excess of 22 m. The entire delta plain is composed almost entirely of closely spaced beach ridges with narrow swales and transgressive eolian dune deposits.

Figure 62 shows the sand body distribution within this particular type of delta. The high wave energy and the low littoral currents have resulted in concentrating the sands into a sheet conforming to a broad major regressive sand unit that spreads along the entire coastal region. The composite stratigraphic section (Fig. 63) is rather simple and consists essentially of sand (units 3, 4, and 6), which accounts for approximately 50% of the total vertical section. This sand is highly quartzose as a result of the high wave energy, and the entire delta consists of a marine sheet sand capped by eolian dunes. Thus, as the wave energy is increased in a delta region that lacks strong littoral drift, the sand bodies take on a thick sheet-sand geometry and are composed of clean, well-sorted quartzose sand. The river-produced sand bodies that have been described in other delta models are not present in this type of delta, having been replaced almost entirely by sands resulting from marine reworking processes. In addition, the high-intensity onshore winds result in subaerial delta deposits that consist primarily of eolian sand sheets. The entire coast of Brazil south of the Amazon consists of numerous deltas all displaying similar types of landforms.

Senegal River delta. The Senegal River, some 1,800 km long, drains a large basin on the western coast of Africa and debouches into the

Figure 63. Composite stratigraphic sequence of depositional environments in the São Francisco River Delta.

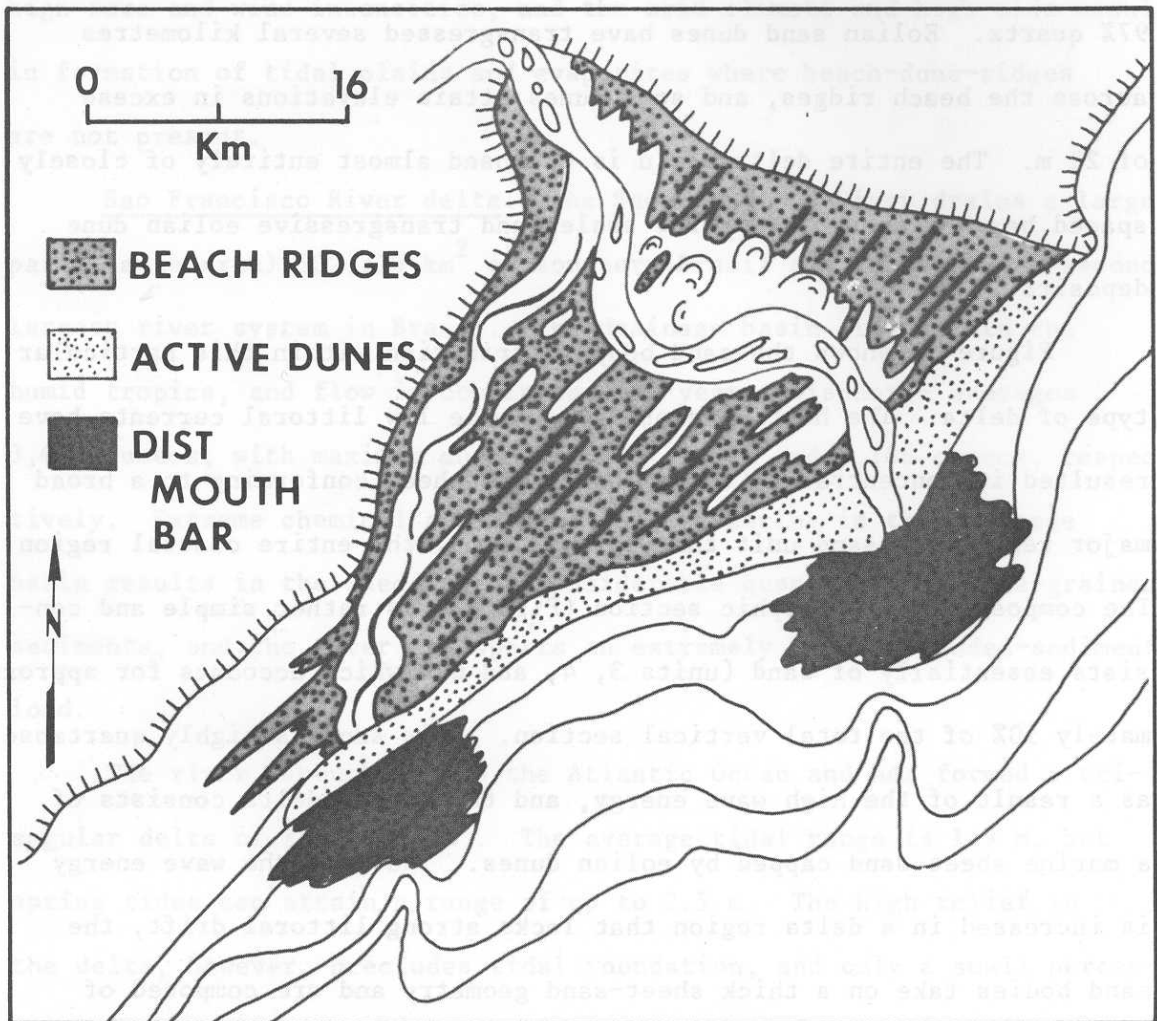


Figure 62. Sand-body distribution in the Sao Francisco Delta model.

# SÃO FRANCISCO DELTA

## COMPOSITE STRATIGRAPHIC COLUMN

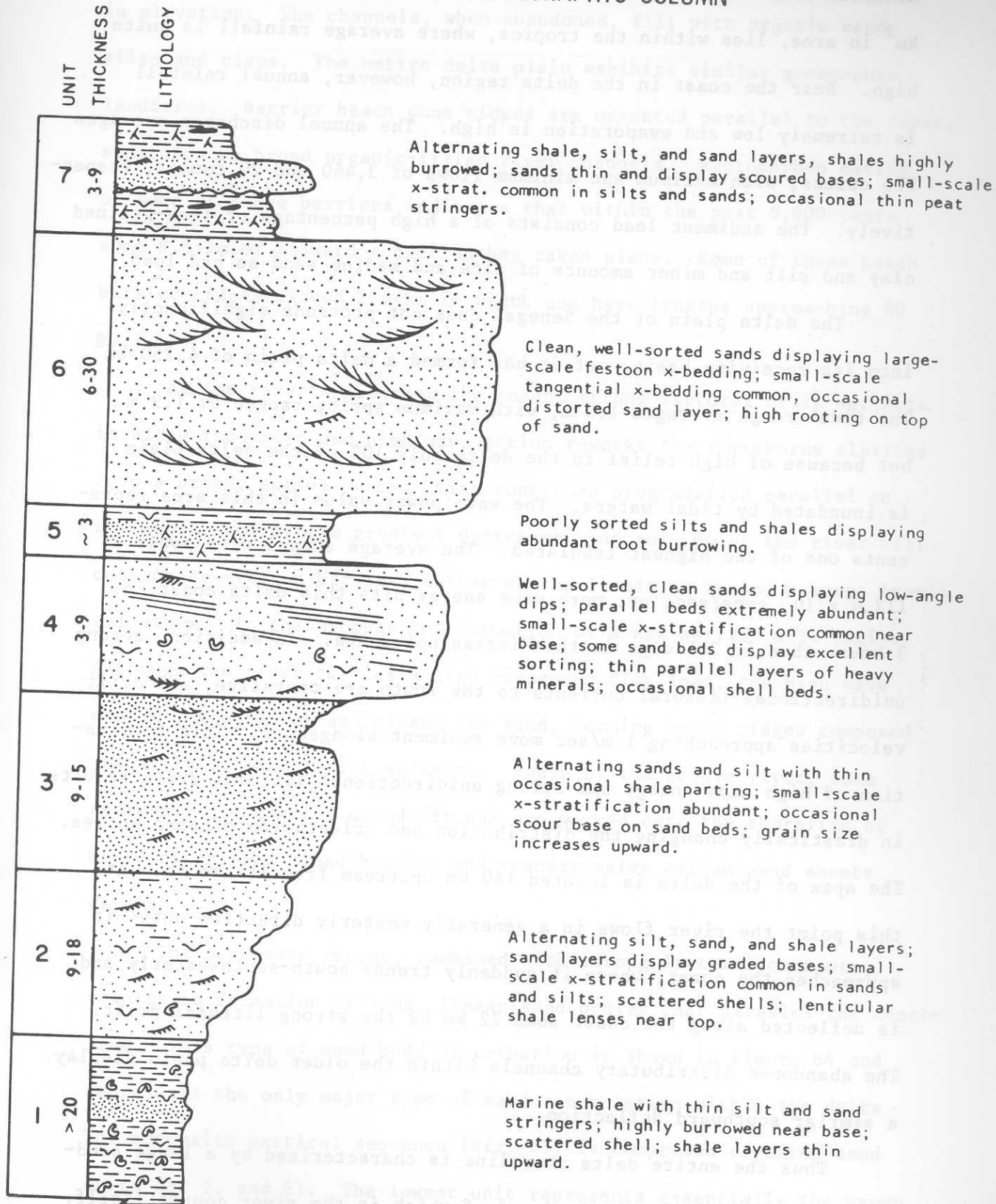


Figure 63. Composite stratigraphic sequence of depositional environments in the Sao Francisco River Delta.

Atlantic Ocean at the port of St. Louis, Senegal. The basin, 196,460 km<sup>2</sup> in area, lies within the tropics, where average rainfall is quite high. Near the coast in the delta region, however, annual rainfall is extremely low and evaporation is high. The annual discharge averages 770 cumecs, with maximum and minimum flows of 3,460 and 20 cumecs, respectively. The sediment load consists of a high percentage of fine-grained clay and silt and minor amounts of fine and medium sand as bed load.

The delta plain of the Senegal does not protrude significantly into its receiving basin, yet it has formed a delta plain of 4,250 km<sup>2</sup>. The tidal range averages 1.3 m, with maximum spring ranges of 1.9 m, but because of high relief in the delta only 10% of the delta plain is inundated by tidal waters. The wave power value in this area represents one of the highest tabulated. The average annual wave power is  $112.4 \times 10^7$  ergs/sec, or, more wave energy hits this delta coast in 3 hours than in 365 days in the Mississippi delta. In addition, strong unidirectional littoral currents to the south are operative, and drift velocities approaching 1 m/sec move sediment alongshore. This combination of high wave energy and strong unidirectional littoral drift results in drastically changing the distribution and orientation of sand bodies. The apex of the delta is located 160 km upstream from its mouth. At this point the river flows in a generally westerly direction until it approaches the coast, where it suddenly trends south-southwesterly and is deflected along the coast some 22 km by the strong littoral drift. The abandoned distributary channels within the older delta plain display a similar southward deflection.

Thus the entire delta shoreline is characterized by a large sand-beach barrier immediately landward of which is the river course itself.

SENEGAL DELTA

Capping the shoreline beach are large eolian dunes, some exceeding 16 m in elevation. The channels, when abandoned, fill with organic sandy silts and clays. The entire delta plain exhibits similar geomorphic landforms. Barrier beach dune ridges are oriented parallel to the coast, separated by broad organic-filled river channels. Radiocarbon dating of some of these barriers indicates that within the past 5,000 years some 8.5 km of seaward accretion has taken place. Some of these beach barrier ridges exceed 2.5 km in width and have lengths approaching 80 km.

As the river approaches the coast, strong littoral drift deflects it along the coast and high wave action reworks the riverborne clastics into a broad, active beach. With continued progradation parallel to the coast, the stream gradient decreases. At some point the river will cut across its own barrier, either during floods or during a large tropical storm. In the process the formation of a new barrier will begin. Although the river carries a high suspended clay load, the high wave energy concentrates and cleans the sand, forming beach ridges composed primarily of quartz-rich sediment. South of the active river, some sediments are carried downdrift and are worked onto the shoreline by wave action, and broad beaches and transgressive eolian sand sheets develop.

The high wave energy, combined with strong littoral currents, results in formation of long, linear sand bodies that parallel the coastline. This type of sand body distribution is shown in Figure 64 and represents the only major type of sand accumulation within the delta. The composite vertical sequence (Fig. 65) is comprised of three sand units (3, 5, and 6). The lowest unit represents essentially the wave-

Figure 65. Composite stratigraphic sequence of depositional environments in the Senegal River delta.

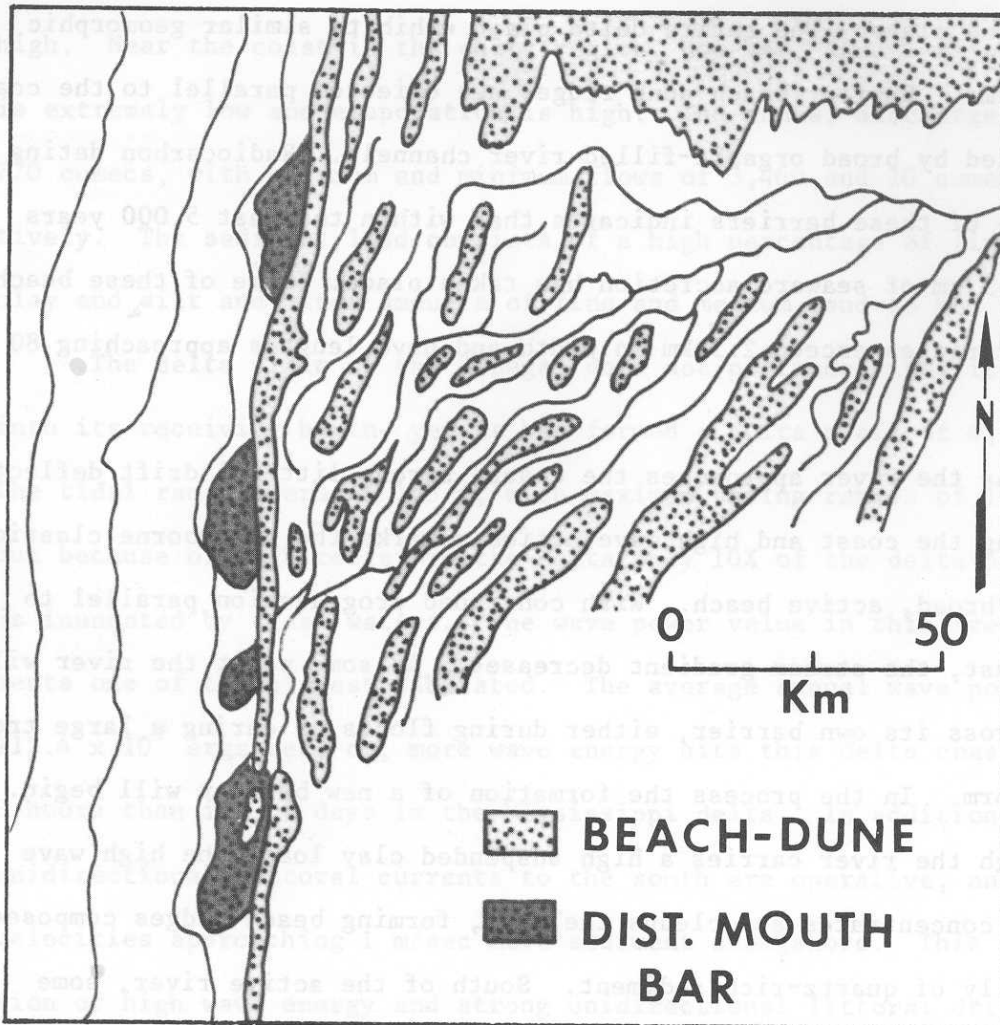


Figure 64. Sand-body distribution in the Senegal River delta model.

# SENEGAL DELTA

## COMPOSITE STRATIGRAPHIC COLUMN

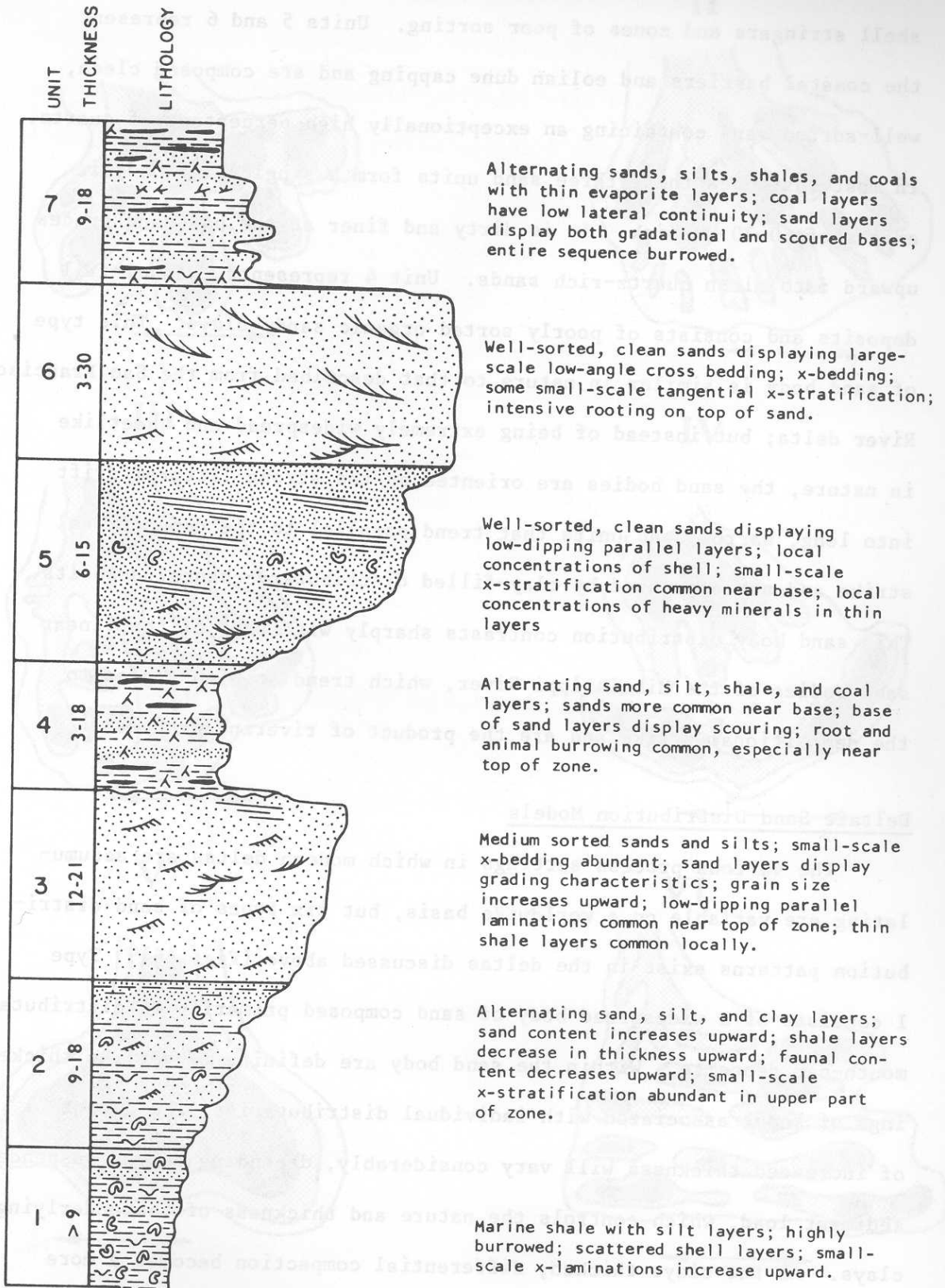


Figure 65. Composite stratigraphic sequence of depositional environments in the Senegal River delta.

reworked distributary-mouth-bar sands, which occasionally display thin shell stringers and zones of poor sorting. Units 5 and 6 represent the coastal barriers and eolian dune capping and are composed clean, well-sorted sand containing an exceptionally high percentage of quartz. In most instances these three sand units form a single sand body in excess of 60-70 m thick. It is dirty and finer at the base and grades upward into clean quartz-rich sands. Unit 4 represents channel-fill deposits and consists of poorly sorted organic sandy clays. This type of sand body is similar in nature to that described from the Sao Francisco River delta; but instead of being extremely widespread and sheetlike in nature, the sand bodies are oriented by the strong littoral drift into long, narrow sand units that trend parallel to the depositional strike and are separated by clay-filled distributary-channel deposits. This sand body distribution contrasts sharply with that of the linear sand bodies of the Mississippi River, which trend at high angles to the depositional strike and are the product of riverine processes.

#### Deltaic Sand Distribution Models

The various process settings in which modern deltas are accumulating are variable on a worldwide basis, but six types of sand distribution patterns exist in the deltas discussed above (Fig. 66). Type I consists of a widespread body of sand composed primarily of distributary-mouth-bar deposits. Within the sand body are definite fingerlike thickenings of sands associated with individual distributaries. The amount of increased thickness will vary considerably, depending on the suspended-sediment load, which controls the nature and thickness of the underlying clays. As the clays thicken, differential compaction becomes a more important process, and sands can expand their thickness considerably,

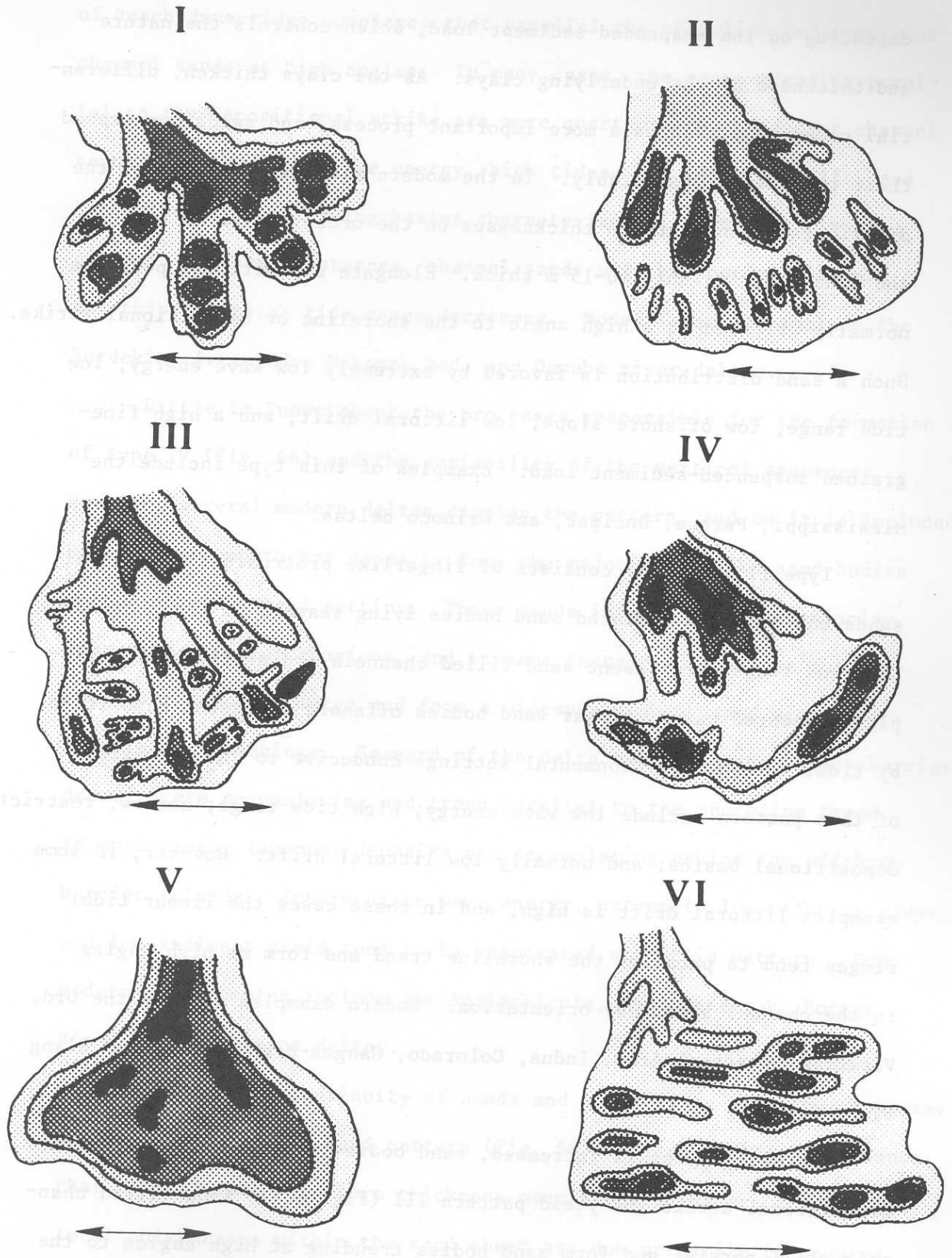


Figure 66. Net sand distribution patterns in modern deltas.

depending on the suspended-sediment load, which controls the nature and thickness of the underlying clays. As the clays thicken, differential compaction becomes a more important process, and sands can expand their thickness considerably. In the modern Mississippi, some of the distributary sands attain thicknesses on the order of 120 m, whereas the sand sheet is only 10-15 m thick. Elongate depositional pods are normally oriented at a high angle to the shoreline or depositional strike. Such a sand distribution is favored by extremely low wave energy, low tide range, low offshore slope, low littoral drift, and a high fine-grained suspended-sediment load. Examples of this type include the Mississippi, Parana, Dneiper, and Orinoco deltas.

Type II (Fig. 66) consists of fingerlike protrusions of channel sands and numerous isolated sand bodies lying seaward of the shoreline. The sand fingers represent sand-filled channels and nearly always display a scoured base. Linear sand bodies offshore represent deposition by tidal action. Environmental settings conducive to the formation of this pattern include low wave energy; high tide range; narrow, restricted depositional basins; and normally low littoral drift. However, in some examples littoral drift is high, and in these cases the linear tidal ridges tend to parallel the shoreline trend and form at high angles to the channel sand body orientation. Modern examples include the Ord, Victoria, Shatt-al-Arab, Indus, Colorado, Ganges-Brahmaputra, and Klang river deltas.

As wave energy is increased, sand bodies begin to align with the depositional strike and yield pattern III (Fig. 66). Sand-filled channels still persist and form sand bodies trending at high angles to the shoreline, but increased wave energy is responsible for the formation

of beach-dune-ridge complexes that parallel the shoreline and intersect channel sands at high angles. In many cases, the sands trending parallel to the depositional strike are more quartzose than adjacent channel sands. Intermediate wave energy, high tides, low littoral drift, and shallow, stable receiving basins characterize this sand distribution pattern. In some instances, channel sands will be poorly developed, and this occurs as tide range decreases. Modern examples include the Burdekin, Irrawaddy, Mekong, Red, and Danube river deltas.

Little is known about the processes responsible for the formation of type IV (Fig. 66) and the variability of the vertical sequences. However, several modern deltas display the pattern, and so it is included. Distributary-mouth-bar deposits form the major fingerlike sand bodies in the more landward setting. These sands in some instances display long fingerlike protrusions, and in some instances the distributary-mouth-bar deposits merge and form a widespread sheet sand with only localized thickenings. Seaward of the delta sedimentation, beach-barrier deposits are accumulating and trend parallel to the shoreline trend. In most cases, lagoonal deposits are accumulating behind the offshore barrier islands. Intermediate wave energy, extremely low offshore slope, and low sediment yield tend to be associated with this pattern. Some modern-day examples include the Apalachicola, Sagavanirktok, Horton, Rio Soto, and Brazos deltas.

High lateral continuity of sands and a sheetlike geometry characterize the fifth type of sand pattern (Fig. 66). Clean, well-sorted sands that display rather uniform thickness over large areas are common, and local thicknesses within the sand sheet are due primarily to scoured channels, which may or may not be sand filled (in most instances the

sand-filled channels are extremely shaley). High, persistent wave energy, low littoral drift, and steep offshore slope characterize the environmental setting. The Sao Francisco, Grijalva, Godavari, and Tana river deltas are modern examples.

These patterns will likely be slightly modified as more subsurface data are obtained, but the ones presented in Figure 66 do exist among modern deltas. The variability within each type, however, is not known. Thus different combinations of processes determine a process setting in which particular types of delta sand bodies form. The above discussion deals with the planar distribution of the sand bodies, but each type is additionally characterized by specific vertical accumulation sequences described earlier.

Table 1

## Wave Power and Delta Morphologies

## A. Wave Power

River	Wave Power (erg/sec)		Discharge Rate $\times 10^3$ ( $m^3/sec$ )	Discharge Effectiveness Index	Attenu- ation Ratio
	Deepwater	Nearshore			
Mississippi	$1.06 \times 10^8$	$1.34 \times 10^4$	17.69	1.00	7913.3
Danube	$2.30 \times 10^7$	$1.40 \times 10^4$	6.29	$2.14 \times 10^{-1}$	2585.0
Ebro	$7.28 \times 10^7$	$5.09 \times 10^4$	0.55	$4.87 \times 10^{-2}$	1299.5
Niger	$6.76 \times 10^7$	$6.59 \times 10^5$	10.90	$8.03 \times 10^{-4}$	102.8
Nile	$1.36 \times 10^8$	$3.21 \times 10^6$	1.47	$5.86 \times 10^{-4}$	42.5
Sao Francisco	$3.71 \times 10^8$	$9.97 \times 10^6$	3.12	$2.37 \times 10^{-4}$	37.2
Senegal	$1.56 \times 10^8$	$3.77 \times 10^7$	0.77	$4.75 \times 10^{-5}$	4.2

## B. Delta Morphologies

	Coastline and River Mouth Configuration	Delta Shoreline Landforms	Delta Plain Landforms
Mississippi	Highly indented coastline, multiple extended digitate distributaries--"bird-foot"	Indented marsh coastline, sand beaches scarce and poorly developed	Marsh, open and closed bays
Danube	Slightly indented with protruding river mouths	Marsh coastline with sand beaches adjacent to river mouths	Marsh, lakes, and abandon beach ridges
Ebro	Smooth shoreline with single protruding river channel	Low sand beaches and extensive spits with some eolian dunes	Salt marsh with a few beach ridges
Niger	Smooth, arcuate shoreline, multiple river mouths slightly	Sand beaches nearly continuous along shoreline	Marsh, mangrove swamp, and beach ridges
Nile	Gently arcuate, smooth shoreline with two slightly protruding distributary mouths	Broad, high sand beaches and barrier formation with eolian dunes, beach ridges at distributary mouths	Flood plain with abandoned channels and a few beach ridges, hypersaline flats and barrier lagoons near present shoreline
Sao Francisco	Straight, sandy shoreline with single slightly constricted river	High, broad sand beaches with large eolian dunes	Stranded beach ridges and dunes
Senegal	Straight coastline with extensive barrier deflecting river mouth	High, broad sand beaches with large eolian dunes	Large linear beach ridges and swales, eolian dunes