Plate 1. The Mississippi River delta covers an area of ~30,000 km² and its coastal wetlands comprise 41% of those in the United States. Over geologic time major relocations of the Mississippi's course have resulted in five Holocene delta complexes and a sixth one is in an early stage of development as a product of the latest Atchafalaya River diversion.

Journal of Coastal Research	14	3	698–716	Royal Palm Beach, Florida	Summer 1998

Mississippi River Delta: an Overview

James M. Coleman, Harry H. Roberts, and Gregory W. Stone

Coastal Studies Institute
Louisiana State University
Baton Rouge, LA 70803, U.S.A.

ABSTRACT

COLEMAN, J.M.; ROBERTS, H.H., and STONE, G.W., 1998. Mississippi River Delta: an Overview. *Journal of Coastal Research,* 14(3), 698–716. Royal Palm Beach (Florida), ISSN 0749-0208.

Over the last century, the river-dominated Mississippi delta has received increasing attention from geoscientists, biologists, engineers, and environmental planners because of the importance of the river and its deltaic environments to the economic well-being of the state of Louisiana and the nation. Population growth, subsurface resource extraction, and increased land-water use have placed demands on the delta's natural geologic, biologic, and chemical systems, therefore modifying the time and spatial scales of natural processes within the delta and its lower alluvial valley. As a result, the combined effects of natural and human-induced processes, such as subsidence, eustatic sea level rise, salt water intrusion, and wetland loss, have produced a dynamically changing landscape and socioeconomic framework for this complex delta.

Under natural conditions, the fundamental changes that result in land-building and land loss in the Holocene Mississippi River delta plain are rooted in the systematic diversion of water and sediment associated with major shifts in the river's course—the process of delta switching. Research over the last half century has shown that major relocations of the Mississippi's course have resulted in five Holocene delta complexes and a sixth one in an early stage of development as a product of the latest Atchafalaya River diversion. Collectively, these Holocene deltas have produced a delta plain that covers an area of $\sim$30,000 km^2 and accounts for 41% of the coastal wetlands in the United States. After a river diversion takes place, the resulting delta evolves through a systematic and semipredictable set of stages generally characterized by: (a) rapid progradation with increasing-to-stable discharge, (b) relative stability during initial stages of waning discharge, (c) abandonment by the river in favor of a higher gradient course to the receiving basin, and (d) marine reworking of a sediment-starved delta as it undergoes progressive submergence by the combined processes of subsidence. Delta switching has taken place every 1000 to 2000 years during Holocene times, and resulting deltas have an average thickness of approximately 35 m. Within a single delta there are subdeltas, bayfills, and crevasse-splays that have higher frequency delta cycles ranging from several hundred years to a few decades. These depositional features are usually less than 10 m thick, and some have produced marshland areas of over 300 km^2. The net result of these delta-building events is a low-lying landscape with components that are changing (building and deteriorating) at different rates. Geologically, these depositional cycles produce a thick accumulation of coarsening, upward deltaic deposits that have various thicknesses in response to development on a variety of temporal and spatial scales.

In this river-dominated delta system, distributaries can prograde seaward at rates of over 100 m/year. The cumulative effect of the Holocene depository has been to depress the underlying Pleistocene surface. In a local setting, e.g., the modern Balize Lobe, differential loading causes the vertical displacement of underlying clay-rich facies (shale diapirs-mudlumps). The delta front of this lobe, which has prograded into deep water of the outer continental shelf, is characterized by rapid deposition of silt- and clay-rich sediments and slope instability, which results in seaward displacement of sediments by a variety of mass-movement processes.

Superimposed on the natural processes and forms of the Mississippi deltaic plain and its associated estuarine environments, are human impacts, most of which have been imposed in this century. The most significant impacts have resulted from a decrease in sediment input to the river from its tributaries and the alteration of the river's natural sediment dispersal processes through the construction of levees. Measures are now being taken to reinstate some of the delta's natural processes, thereby mitigating landloss so that decline in animal and plant productivity can be mitigated.

ADDITIONAL INDEX WORDS: *Mississippi River delta, delta cycle, progradation, subsidence, shoreline change.*

INTRODUCTION

Since Late Cretaceous times the central portion of North America has drained to the south into the Gulf of Mexico (BUFFLER, 1981). The ancestral Mississippi and other rivers around the northern Gulf of Mexico rim are responsible for delivering large volumes of sediment derived largely from erosion of the Rocky Mountains at the western margin of the drainage basin and the Appalachian Mountains to the east. Flooding of the northern Gulf of Mexico with sediments from these sources caused progradation of the shelf edge several hundred kilometers basinward to its present position. Much of the time delta-building occurred at or near the shelf edge because of frequent lowered sea levels (WINKER, 1991). Regardless of sea level position, however, the Mississippi River and its ancestors have been the suppliers of huge volumes of sediment to the northern Gulf, resulting in fluvio-deltaic deposition from the shoreline to the shelf edge. The southward

98150 received and accepted in revision 25 May 1998.

progradation of the continental margin has been directly linked to these delta-building processes.

Following the last glacial maximum (~18,000 BP), sea level rose rapidly until the early Holocene (7000 to 8000 BP) when the rate of rise decreased dramatically. At this time the delta-building area, now south Louisiana, was characterized by frequent shifting of the locus of deposition, rapid subsidence, local regressions and transgressions, the buildup of a sediment column characterized by highly cyclic depositional units, and wide-spread transport of fine-grained sediments downdrift of the active deltas. In contrast, during periods of lowered sea level during the Pleistocene and older intervals of geologic time when the ancestral Mississippi Rivers drained the central continent, deep fluvial entrenchment and migration of deltaic deposition toward the shelf edge was common (FISK, 1944; SUTER and BERRYHILL, 1985; SYDOW and ROBERTS, 1994). During the Holocene highstand, delta-building occurred over the wide alluvial valley which was cut deeply into underlying deposits during Pleistocene periods of lowered sea level. This relationship created thick accumulations of compaction-prone valley-fill muds and peats that formed zones of abnormally high subsidence. In the modern Mississippi River delta plain, thick sections of rapidly deposited and young deltaic sediments fill and overlie the river's wide alluvial valley. These areas of the delta plain experience the highest rates of subsidence and land loss (ROBERTS, *et al.*, 1994) and are currently being evaluated for large-scale remediation measures to help offset these trends.

During modern historical times, the river has received considerable attention for practical reasons associated with commerce and engineering. The Mississippi River is primarily a meandering type of river with regular flood and non-flood discharge cycles, as well as a fine-grained sediment load. The average maximum and minimum discharges are 57,900 and 2,830 m^3/sec, and the annual sediment discharge is estimated at 6.21×10^{11} kg (COLEMAN, 1988). The annual sediment discharge of the Mississippi is an order of magnitude greater than all other Gulf Coast rivers combined (WINKER, 1991). In the lower part of the Mississippi River course where it nears the Gulf of Mexico, most of the sediment is carried as a suspended load that consists of 65% clay and about 35% silt and fine sand. In the alluvial valley the bedload contains coarse sand and gravel. Below the city of New Orleans, however, the bedload consists of 90% fine sand. Thus, deltaic sand bodies, such as distributary mouth bars, channel sands, and bay-fills are all relatively fine-grained (fine sand and coarse silt).

Stratigraphically, the deposits of the Holocene delta plain reflect the autocyclic shifting of the locus of deposition from one part of the delta plain to another (KOLB and VAN LOPIK, 1958). Clearly, the sediment column records upward coarsening cycles of various dimensions, which reflect rapid pulses of deltaic deposition that operate on different scales, both in time and space (ROBERTS *et al.*, 1994). Each coarsening upward cycle is generally separated from the next by organic-rich deposits and surfaces of erosion associated with abandonment of the delta by a distributary network capable of delivering sediment.

The purpose of this paper is to provide a summary of the depositional framework for the Mississippi River and its Holocene deltas (Figure 1), with emphasis on the cyclic nature of the constructional delta-building processes and their transgressive, destructional counterparts. A clear understanding of the fundamental processes that drive delta formation, as well as abandonment and destruction, are necessary for charting the future course for human compatibility and utilization of this valuable natural resource. Management problems and proposed mitigative approaches are discussed also.

FUNDAMENTAL PROCESSES AND DEPOSITIONAL COMPONENTS

Deltas are extremely dynamic depositional settings that can undergo significant changes in short periods of time and have high lateral and vertical variability in sediment properties over short distances. CREDNER (1878), in a study of some of the world's largest deltas, commented on the rapid changes in deltaic landscape through time that can be attributed to the delivery of sediments in large volumes. LYELL (1847) and RIDDELL (1846) made special references, for example, to the rapid changes in geomorphology and sites of sedimentation at the mouths of Mississippi River distributaries. These early studies along with those of TROWBRIDGE (1930), RUSSELL (1936, 1939, 1940), and others relied primarily on geomorphology, vegetation patterns (Figure 2), and surface sediment properties to interpret processes of deposition and sedimentation patterns. However, with the publication of scientific results of studies of the Mississippi River alluvial valley and deltaic plain as interpreted from hundreds of soil borings (FISK, 1944, 1947, 1952), the three-dimensional characteristics of the Mississippi's fluvial and deltaic deposits were realized. The work of Fisk and his colleagues provided the first major step toward our current understanding of the stratigraphic-sedimentological architecture of the alluvial valley and Holocene delta plain. These landmark studies, funded by the U.S. Army Corps of Engineers, had implications far beyond the confines of the Mississippi River delta. This new three-dimensional approach to studying sediment bodies initiated an era of process sedimentology in the geosciences where this method of study is utilized.

Application of geomorphic data from the alluvial valley and delta plain to the new shallow subsurface data sets generated by Fisk and his colleagues provided the first clear connection between previous courses of the Mississippi River, still visible in the surface geomorphology of the alluvial valley-deltaic plain and their down-dip deltas. This linkage between the conduits that supplied sediments for the delta-building process and the numerous deltas that developed provided the first clear understanding of the fundamental process that built Louisiana's complex coastal plain, the process of delta switching (Figure 1).

Delta Switching

Although RUSSELL (1936, 1939, 1940) and FISK (1938) identified and described characteristics of previous Mississippi river courses and other early workers discussed delta-building (TROWBRIDGE, 1930; RUSSELL and RUSSELL, 1939), FISK (1944) made the first comprehensive attempt to connect

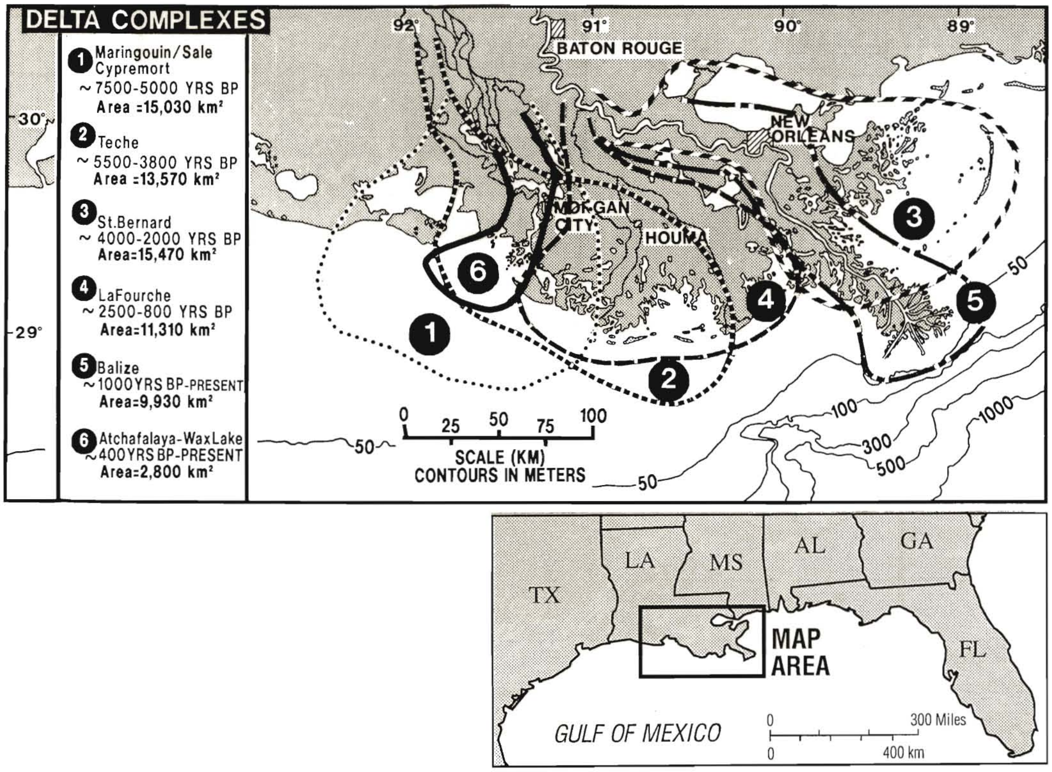

Figure 1. Location map of the Mississippi River delta and coastal plain built from previous Holocene deltas (modified from Roberts, 1997).

old Mississippi River courses and their tributaries throughout the alluvial valley to their deltaic depositional counterparts. The first map showing the shifting depositional sites for the Mississippi River during Holocene times appeared in the Fisk (1944) alluvial valley report. Figure 3 depicts a later map (Fisk, 1952a), which shows this first interpretation of post-Teche Mississippi river courses and their deltas. This figure implies that the Lafourche delta is older than the St. Bernard. Eventually, archaeological data were used to establish a relative chronology for these deltas (McIntire, 1954), which placed the St. Bernard delta between the Teche and Lafourche deltas as it remains today as confirmed by radiometric dating (Fisk and McFarlan, 1955; Frazier, 1967; and Tornqvist *et al.,* 1996). Later, Kolb and Van Lopik (1958) popularized the delta-switching concept with a more complete illustration of Holocene river courses and their resulting deltas. The fundamental relationships between sediment delivery systems, deltas, and relative ages of major del-

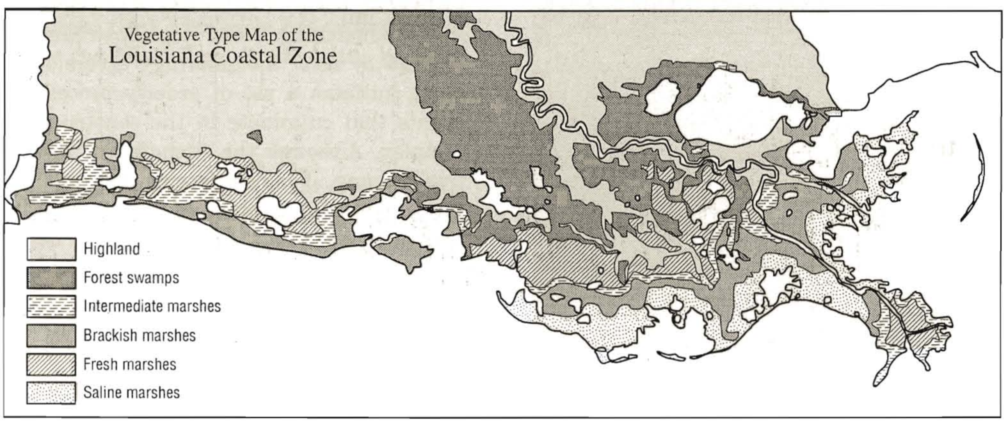

Figure 2. Vegetation patterns of the Louisiana coastal plain (adapted from Chabreck, 1988).

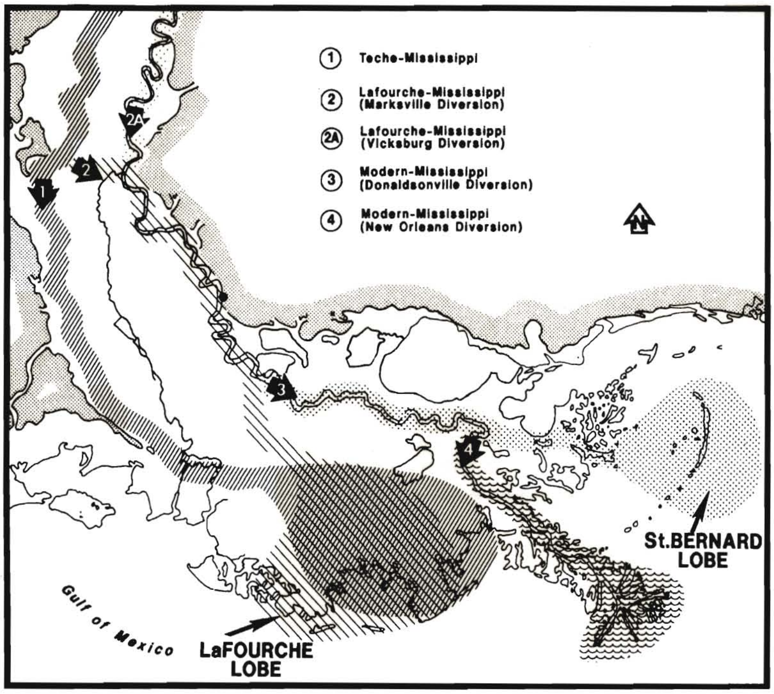

Figure 3. Mississippi River courses as initially interpreted by Fisk (1952a). Note that diversion 3, which built the St. Bernard delta is interpreted as being younger than diversion 2, which led to construction of the Lafourche delta. He later corrected this chronology based on archoreological data (McIntire, 1954).

ta-building events provide a powerful conceptual basis for understanding the gross geomorphic complexity of Louisiana's coastline and delta plain, as well as changes that can be expected as deltas deteriorate after being abandoned by their sediment source, the Mississippi River.

Over historic time, only one diversion of the Mississippi River to a more favorable course has occurred. FISK (1952) indicates that this capture of Mississippi water and sediment

Figure 4. Satellite image (SPOT HRV Ch 3, 1987) of the Atchafalaya (east) and Wax-Lake (west) bayhead deltas building along the central coast of Louisiana as a product of Atchafalaya River diversion (inset map) of Mississippi River water and sediment.

by the Atchafalaya River was already underway by the 1500s when the first explorers of the Mississippi River noted that the Atchafalaya was a distributary. It is thought that major river diversions occur because of a loss of gradient and flow efficiency as a river course lengthens through progradation during delta-building. During this evolutionary stage of delta-building, the distribution of discharge becomes more complicated by the development of numerous deltaic distributaries. For example, the Atchafalaya River course that flows through the Atchafalaya Basin to the central Louisiana coast is over 300 km shorter to the Gulf of Mexico than the Mississippi course, as measured from the diversion point (ROBERTS *et al.*, 1980). Regardless of the circumstances that cause a delta-switching event (e.g. upstream crevasse or stream capture by river meandering), diversion of water and sediment initiates a set of orderly processes and depositional events that culminate in the construction of a major delta complex. Although the Atchafalaya River diversion is relatively young, it is now forcing delta-building in Atchafalaya Bay and starting a phase of rapid progradation of the central Louisiana coastline (Figure 4). This deposition is an early part of a predictable set of events that begins with stream capture and delta-building and ends with abandonment and delta deterioration, the delta cycle.

The Delta Cycle in the Mississippi River System

Once a delta switching event is initiated, the delta cycle begins. Figure 5 schematically illustrates the various stages

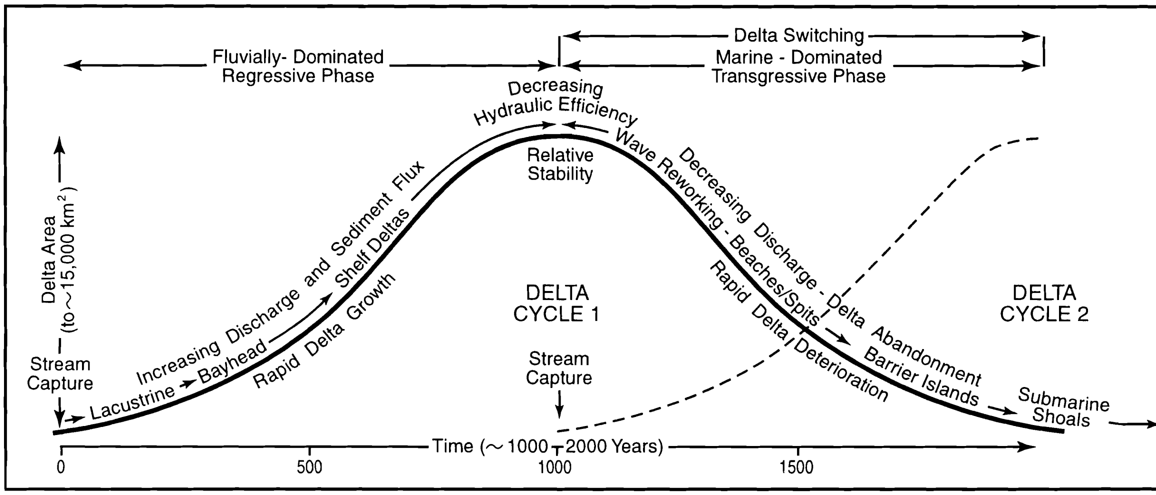

Figure 5. A graphic representation of the systematic changes associated with delta growth and abandonment: the delta cycle (modified from Roberts, 1997).

that accompany the building of a delta and its deterioration once the source of sediment and water have been diverted by another episode of delta-switching. Early workers, especially RUSSELL (1940) and FISK (1944), not only discussed the existence of multiple river courses but also described the dendritic nature of offset and overlapping delta lobes. In addition, LBLANC (1973) indicates that RUSSELL and RUSSELL (1939) recognized the importance of marine reworking by shoreline processes to create sand bodies, beaches and barrier islands, along the perimeters of parts of old delta coastlines undergoing local transgressions. In later publications (FISK, 1955; FISK and MCFARLAN, 1955; and KOLB and VAN LOPIK, 1958) it was clearly established that deltas of the Louisiana coastal plain had specific stages in their evolution. These stages are part of the "delta cycle" that incorporates: (a) initiation and rapid progradation of a delta, (b) systematic loss of flow efficiency and sediment dispersal, (c) abandonment of the delta by diversion of flow to a more favorable course, and (d) marine reworking of the delta perimeter during a local transgression driven primarily by the combined effects of subsidence (local sea level rise). This cycle has recently been described in detail for the Mississippi River deltas by ROBERTS (1997).

Constructional Phase

The regressive or constructional part of the cycle is currently underway because of diversion of Mississippi River water and sediment down the Atchafalaya River course to the central Louisiana coast. FISK (1952a) indicates that the Atchafalaya River began capturing Mississippi flow at least four centuries ago, but only in this century has the volume of diverted flow increased significantly. However, the building of a control structure in 1963 has limited discharge down the Atchafalaya course to 30% of the Mississippi River discharge plus the added flow of the Red River (ROBERTS *et al.*, 1980). The result has been the sediment filling of an interdistributary basin, the Atchafalaya basin trapped between the old Teche levees on the west and the modern river and Lafourche levees on the east. This basin has filled primarily with fine-grained swamp deposits and sand-rich lacustrine deltas (COLEMAN, 1966; TYE and COLEMAN, 1989). Since the basin filled to near capacity in the 1950s, sediments have been arriving at the coast in sufficient volumes to initiate delta-building in Atchafalaya Bay. Today, over 150 km^2 of new land has developed in Atchafalaya Bay as a product of delta-building associated with diversion of Mississippi River discharge down the Atchafalaya course (MAJERSKY-FITZGERALD, 1998). This new land occurs in two bay-head deltas, one at the mouth of the natural Lower Atchafalaya River Outlet and one opposite the man-made Wax Lake Outlet (Figure 4). Table 1 gives important statistics concerning the growth of these deltas, discharge allocation, and accomodation space. The next stage of development is for these deltas to prograde past the confines of Atchafalaya Bay and to begin construct-

Table 1. *Criteria that collectively show the maximum areal extent of the Atchafalaya and Wax lake deltas. Compiled and modified from MAJERSKY (1998).*

Delta	Discharge % of the Mississippi	Years of Progradation	Maximum km^2	Growth km^2 Per Year	Growth Hectares/Year	Accommodation Space (m)
Atchafalaya Delta	21.0%	21	102.00	4.85	485.0	2.5
Wax Lake Delta	9.0%	21	63.00	3.00	299.9	2.5

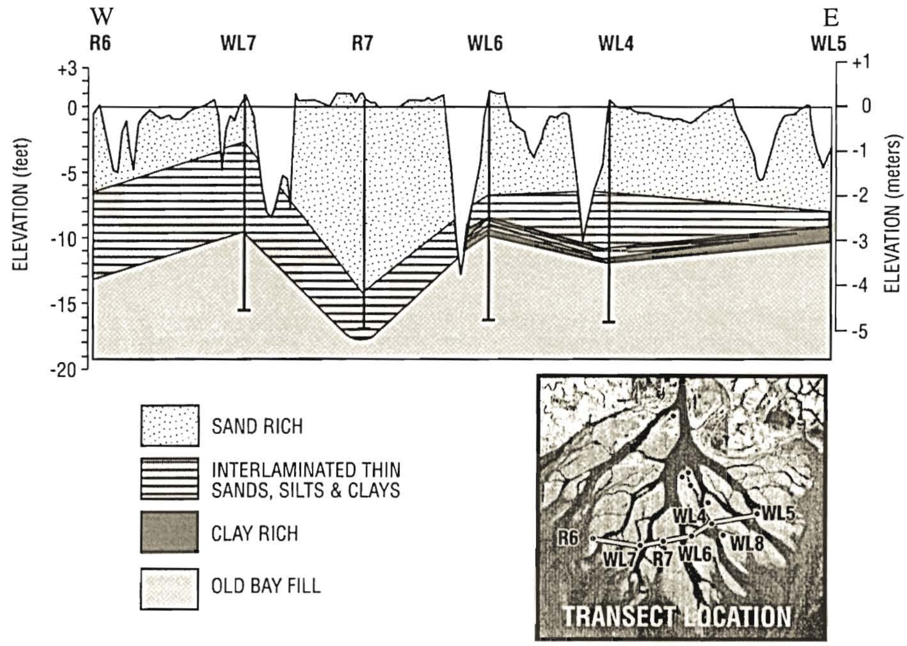

Figure 6. A strike-oriented cross section of the Wax Lake bayhead delta showing the distribution of fused distributary mouth bar sands and subaqueous levee deposits making a continuous sand trend similar to a delta front sheet sand described by Fisk (1955) (adapted from Roberts *et al.*, 1997).

ing a combined and larger delta on the inner continental shelf. This progression of delta-building (lacustrine-to-bay-head-to-shelf deltas) has been suggested to be the normal regressive stages of delta evolution for the Mississippi River system (ROBERTS, 1997). There are, however, variations on this theme and one of the most important variations deals with accommodation space in the shelf delta phase.

After Fisk published his landmark study of the alluvial valley, he and his colleagues (FISK *et al.*, 1954; FISK and MCFARLAN, 1955; and FISK, 1955) explored the geometry of sediment bodies and the facies architecture of deltas comprising the Louisiana coastal plain. One delta type developed in the shallow water of the inner shelf and another in the deeper water of the middle and outer shelf.

The inner shelf deltas, for example the deltas constructed during Lafourche and St. Bernard times, built into limited accommodation space of the shallow continental shelf. These deltas were relatively thin (10–30 m thick) but covered large areas. The Lafourche delta complex is estimated to have covered over 11×10^3 km^2, while delta-building during the St. Bernard times developed a delta complex that occupied an area estimated at over 15×10^3 km^2 (ROBERTS, 1997). The fundamental sand bodies and facies relationships in these thin inner shelf deltas were defined by numerous borings taken by FISK (1955) and his colleagues. Thin inner shelf deltas, such as crevassed-splays and bayhead deltas later studied by COLEMAN and GAGLIANO (1964) and VAN HEERDEN and ROBERTS (1988), tend to have many distributaries that cause sedimentary facies to merge laterally from one distributary to the next. For example, FISK (1955) recognized that deltas, particularly lobes of the Lafourche delta, were quite different from those of their deeper water counterpart in the modern Balize delta. Sands deposited at the mouths of closely spaced and branched distributaries of the Lafourche delta merged to form a semi-continous sand sheet Fisk referred to as delta-front sheet sands. These sands were found to vary in thickness in a strike orientation between approximately 6 to 20 m and accounted for the most important sand body in this delta type. Recent research on the bayhead deltas building opposite the Lower Atchafalaya River Outlet and the Wax Lake Outlet in Atchafalaya Bay illustrate this same sand body geometry. As shown in Figure 6, sand from fused distributary mouth bars and subaqueous levees of the Wax Lake delta combined to produce a continuous sand trend similar to the Lafourche delta front sheet sands defined by FISK (1955).

In both bayhead deltas and larger inner shelf deltas, such as the Lafourche and St. Bernard, the sand trends are broken only by distributary channels that frequently erode far below the deltaic sediments they deposited. Therefore, sands deposited as part of the channel-fill are commonly found to be stratigraphically below their wide-spread distributary mouth bar counterparts.

The only Holocene delta that has built into accommodation space characterized by middle-to-outer continental shelf water depths has been the modern "birdfoot" or Balize delta (Figure 1). FISK (1955, 1961) and FISK and MCFARLAN (1955) investigated the differences between the sedimentary facies architecture in this modern, thick delta that has prograded to near the shelf edge and its inner shelf counterparts. The Balize delta is approximately 200 m thick and has a broad and thick (50–100 m) base of clay-rich prodelta deposits that

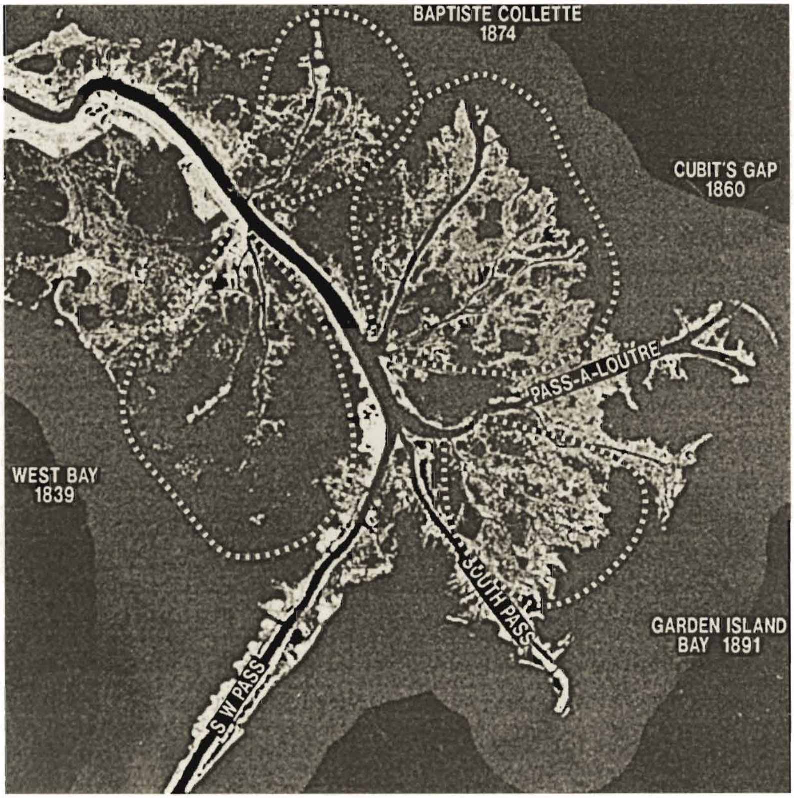

Figure 7. Landsat TM 1993 image (composite of Bands 7, 5, 3) showing the modern Balize delta and the marshlands and distributaries associated with subdelta development. The dates refer to years the subdeltas were initiated (adapted from Roberts, 1997).

are compaction-prone and deformation-prone. The coarser facies of the delta have prograded over these deposits, resulting in sand body geometries and deformational features, *e.g.* mud diapirs (MORGAN, 1961), that are not commonly associated with inner shelf deltas that do not have a thick, compaction-prone base of prodelta clays. The prograded distributary mouth bar deposits of the modern Balize delta occur in thick, linear trends that tend to be separate from one distributary to another. FISK (1961) referred to these lineated and dip-oriented sand bodies as bar-finger sands. Borings by MORGAN (1961) and his co-workers confirmed that bar-finger sands thicken locally (to > 100 m) and displace underlying fine-grained and plastic prodelta deposits into shale diapirs (mudlumps) that commonly become subaerial as small muddy islands in front of the prograding distributaries.

Superimposed on this framework of filling middle-to-outer shelf accommodation space with thick prodelta deposits and rapidly prograding distributary mouth bar sands are thin deltaic wedges of sediment that fill the shallow interdistributary areas and bays of the prograding delta platform and create the marshlands that give the delta its form in map view (Figure 7). High-standing *Phragmites communis* (Figure 8) and shorter *Spartina patens* are the two marsh plants that are most common to this low relief deltaic landscape. WELDER (1959) and COLEMAN and GAGLIANO (1964) were the first to describe these thin deltaic deposits in detail, which are referred to in the scientific literature as bay-fill subdeltas, crevasse-splays, and overbank-splays. Although the work of Frazier (1967) confirmed that these depositional features are integral components of earlier thin inner shelf deltas, the detailed data concerning processes of formation for these deltas that form in shallow water adjacent to the river and its distributaries comes from the modern birdfoot or Balize delta. While the major delta complexes developed, were abandoned, and deteriorated on time scales of approximately 1000 to 2000 years, these smaller deltas have delta-cycles that range from a couple of centuries to a few decades (ROBERTS, 1997). However, depositionally, they mimic developmental processes and resulting depositional forms of thin inner shelf and bayhead deltas.

In the modern Balize delta there are four major subdeltas (Baptiste Collette, Cubit's Gap, Garden Island Bay, and West Bay) on which most of the marshlands of this delta have developed (Figure 7). Table 2 gives the maximum areal extent to which these systems evolved at the peak of their delta cycles, the percent of Mississippi River discharge diverted to each subdelta, and the growth rates based on studies of historical maps and more recent aerial photography. During the early growth stage, these depositional features receive primarily suspended load sediments through small breaks in the channel banks and levees. As the breach in the levee widens and deepens, coarser sediments are added to the delta-build-

Figure 8. A low oblique aerial photograph of a part of the Cubit's Gap subdelta (see Figure 7) showing the high-standing (3–4 m high) *Phragmites communis* that covers the subdeltas over much of the Balize delta.

ing processes. WELDER (1959) described the historical development of Cubit's Gap and the processes involved in sediment delivery and deposition adjacent to the Mississippi River. Later, COLEMAN and GAGLIANO (1964) explained the cyclic nature of subdelta development and deterioration, culminating in a geological model for subdeltas and crevasses-splays. Extensive coring of the West Bay subdeltas (Figure 9) indicates that, during the tenure of the larger Balize delta, three separate subdeltas have occupied this shallow accomodation space west of the river. That is, three complete cycles of subdelta growth and deterioration are represented at this site.

Because each of the four subdeltas shown in Figure 7 has progressed through the rapid growth phases of their delta cycles and are now systematically deteriorating, the Balize delta is steadily losing land even though it is a sediment-rich system. To help offset high rates of landloss here, as well as other places in the delta plain near the Mississippi River, both controlled and uncontrolled diversions of river water are being implemented in order to build new land, mitigate excessive land loss, and provide freshwater and nutrients to flanking river environments. Since the 1930s the Louisiana coastal plain has lost an estimated 3,950 km^2 of wetlands (BRITSCH and DUNBAR, 1993) and currently the State of Louisiana and the federal government are spending in excess of $40 million per year to mitigate land loss and associated problems. Figure 10 illustrates man-made breaches in the levees of the South Pass and Pass-a-Loutre distributaries in the modern Mississippi River delta where natural delta-building processes are building new marshlands in East Bay between the South Pass and Southwest Pass distributaries.

Instability of the Delta Front

Considering the fact that the modern Balize delta of the Mississippi River has been steered into deep water by the presence of the St. Bernard delta to the east and Lafourche delta to the west and built a thick sediment column (~200 m), it is not surprising that different types of sediment deformation, operating on different temporal and spatial scales, developed. Following the classical onshore investigations of the Mississippi River alluvial valley and coastal plain by RUSSELL (1936, 1940); FISK, (1944, 1952, 1955); FISK *et al.* (1954) a study was funded by the American Petroleum Institute (API Project 51) to investigate the offshore Mississippi

Table 2. *Criteria that collectively indicate the maximum areal extent of four subdeltas of the modern Balize delta. Compiled and modified from* VAN HEERDEN (personal communication), *WELLS et al. (1983), and MAJERSKY (1998).*

Delta	Discharge % of the Mississippi	Years of Progradation for Calculations	Maximum km^2	Growth km^2 Per Year	Growth Hectares/Year	Accommodation Space (m)
Baptiste Collette	2.6%	72	57.2	0.79	30.5	2–6
Cubits Gap	13.2%	83	193.1	2.33	54.1	2–10
Garden Island Bay	4.0%	31	124.0	4.00	100.1	2–8
West Bay	4.4%	93	300.05	3.23	73.4	4–10

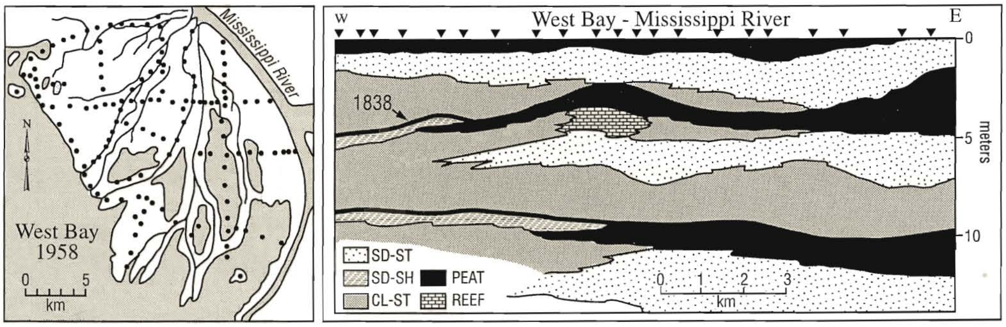

Figure 9. Results of an extensive coring program on the West Bay subdelta, indicating the existence of three subdeltas at this site.

delta area and the continental shelf of the northwest Gulf of Mexico (SHEPARD *et al.,* 1960). Prior to this more comprehensive investigation, SHEPARD (1955) noted the extreme complexity of the delta front area of the modern Balize delta (Figure 11). Through systematically contouring the delta front using several bathymetric data sets provided primarily by the U.S. Coast and Geodetic Survey, Shepard defined families of shallow gully-like valleys that radiated downslope away from each of the major Mississippi River distributaries. In other settings, an earlier study by DALY (1936) had attributed similar features to erosion by turbidity currents, a mechanism triggered by submarine landslides that SHEPARD (1955) suggested may have caused the complex bathymetry on the Mississippi delta front.

In the late 1960s the petroleum industry moved offshore with fixed production platforms to water depths of 100 m or more. With the loss of two of these platforms in Main Pass Lease Block 20 on the Mississippi delta front, as a product of sediment stability problems during hurricane Camille in 1969, the need to know more about mass movement processes and seafloor stability became essential (BEA, 1971). Techniques, such as side-scan sonar, improved bathymetric pro-

Figure 10. High altitude photograph of part of the Balize delta showing the positions of man-made crevasses along the South Pass and Pass-a-Loutre distributaries, taken in 1991.

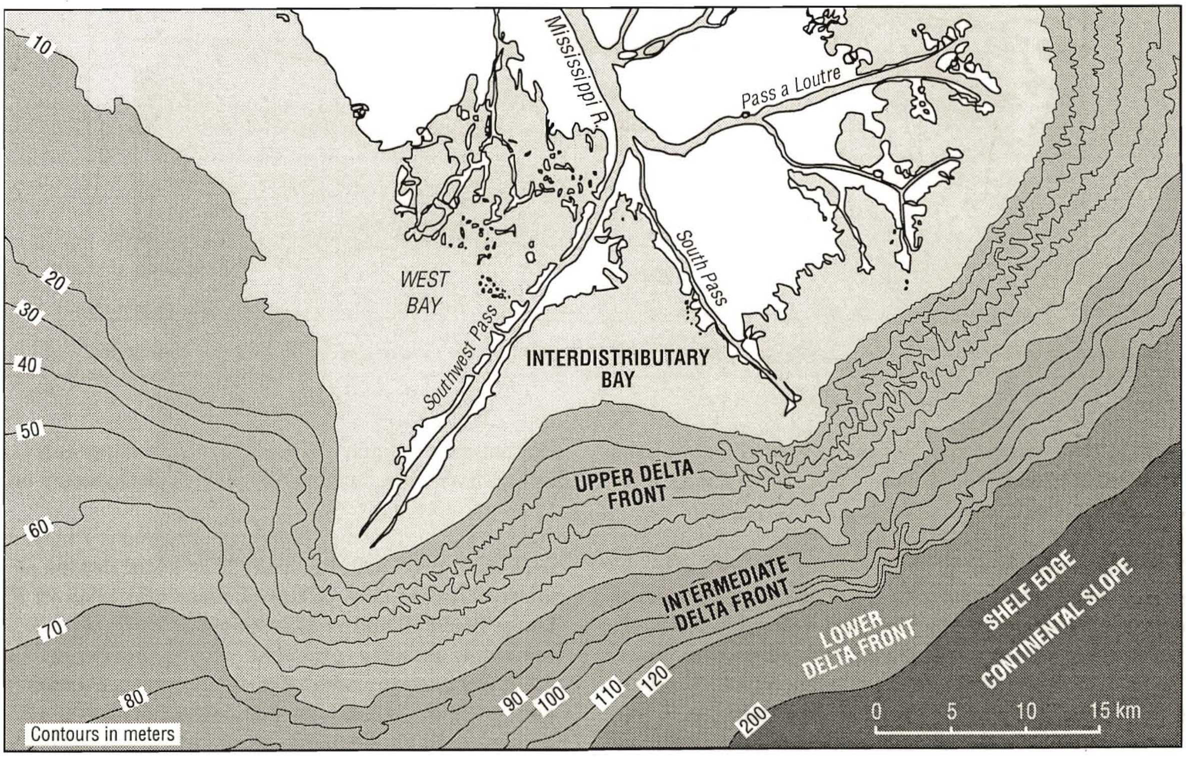

Figure 11. Bathymetry of the delta front of the modern Balize delta of the Mississippi River. The crenulated isobaths represent gullies of the upper and middle delta front that function as sediment transport pathways to the outer shelf and upper continental slope.

filing, and high resolution seismic, were applied by industry and academic institutions in the 1970s to determine the character of the seafloor fronting the delta in an attempt to understand the processes and response features associated with sediment instability on offshore slopes of generally less than 0.5°. In addition, *in-situ* testing of sediment properties and soil mechanics models were developed to determine the primary processes that governed sediment instability and led to the complex features that SHEPARD (1955) originally described.

Comprehensive geophysical surveys and *in-situ* studies during the 1970s and early 1980s revealed that the high depositional rates of fine-grained sediment on the upper delta front set the stage for contemporary and gravity-driven recurrent subaqueous mass movements (COLEMAN *et al.*, 1974; COLEMAN and GARRISON, 1977; PRIOR and COLEMAN 1978a, b; COLEMAN and PRIOR, 1980; ROBERTS *et al.*, 1980; and others). In the Mississippi case, sediment instability occurs on very low angle slopes and is the primary mode of transporting sediment from the shallow delta front to deeper water settings of the shelf and upper continental slope. Three major factors set the conditions for sediment instability on the delta front: (a) rapid sedimentation, (b) gas formation, and (c) cyclic loading of the seafloor by storm waves. Rapid sedimentation of clay-rich sediments from each major distributary results in sediment accumulation rates too high and too continuous to allow normal consolidation processes to take place. The result is a sediment mass that is underconsolidated, with large excess pore water pressures, causing low sediment strength. Because the sediments of the Mississippi River contain high contents of particulate organics, microbial breakdown of this material upon burial results in gas production, primarily methane (WHELAN *et al.*, 1975). This gas occurs both in bubble phase and as being dissolved in the pore waters. During storms, cyclic loading of these gas-prone bottom sediments causes dissolved gas to shift to gas in bubble phase, reducing sediment strength and thereby causing slope failures and downslope transport of sediment. Figure 12 schematically illustrates the main types of slope instabilities on the Mississippi River delta front (water depths from about 5–200 m). In the shallow or proximal part of this diagram, distributary mouth bar sands load thick underlying prodelta clays that result in mud diapirs or mudlumps (MORGAN, 1961). Seaward of the distributaries and beyond the fields of mud diapirs, families of arcuate slumps and peripheral slumps occur at the shallow ends of elongate retrogressive slides (mudflow gullies and depositional lobes) that extend downslope near the shelf edge or beyond (Figure 13).

Destructional Phase

The continued evolution of a delta through distributary development results in the initial phases of delta abandonment and deterioration. As the distributaries continue to grow, the

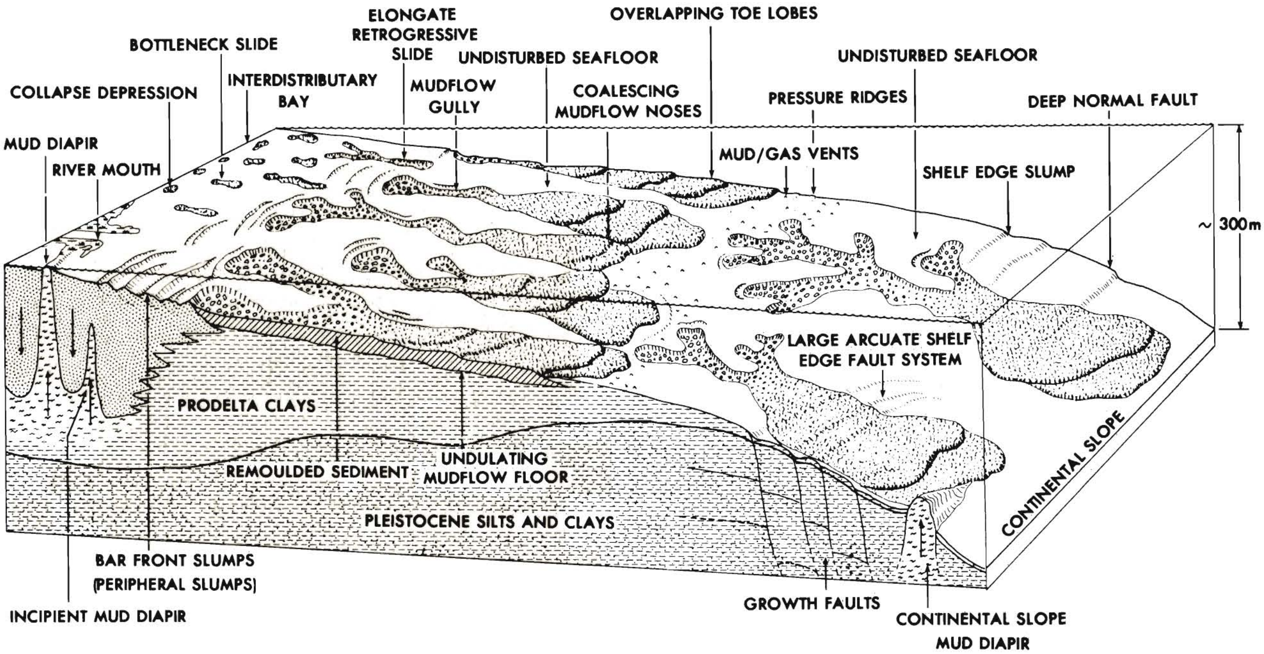

Figure 12. A schematic representation of sediment instability features common to the delta front and distributary mouths of the modern Balize delta of the Mississippi River (Coleman *et al.,* 1980).

overall hydrodynamic efficiency of the system begins to decrease, and, when coupled with a decrease in stream bed gradient because of progradation of the system, results in stream capture upriver (ROBERTS, 1997). The delta now experiences a shift from progradation to a new evolutionary stage dominated by marine processes and subsidence. The concept of delta evolution through constructional and destructional phases has been well documented in the early literature (RUSSELL, 1936; FISK, 1955) and more recently, emphasis has been placed on the renants of delta lobe abandonment, namely transgressive sand body evolution (KAHN, 1980; PENLAND, 1985 and ISACKS, 1989). The Mississippi River deltaic plain presently exhibits the signatures of the various stages of delta deterioration and associated transgressive deposits (PENLAND and BOYD, 1981; PENLAND *et al.,* 1985).

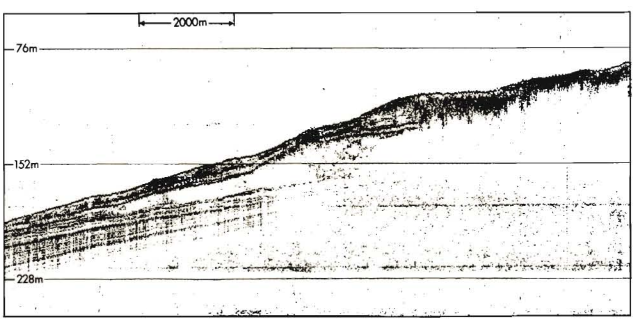

Figure 13. A high resolution seismic profile across the shelf edge south of the South Pass distributary showing the thick accumulation of mudflow deposits at the shelf edge-upper slope boundary. Note the thickness of these deposits (~50 m) and the acoustically opaque deposits (secondary mudflows) that are impacting the continental slope.

In a marine dominated, transgressive phase of delta evolution, post-deposition dewatering and compaction are among the two most critical components of subsidence that drive land loss and marine transgression. It has been shown (ROBERTS *et al.,* 1994), that sections of the deltaic plain overlying thick Holocene sediments of the entrenched alluvial valley experience higher rates of subsidence than those located beyond the valley. As an example, the Lafourche delta likely has a considerably shorter marine-dominated transgressive phase than that of the St. Bernard complex because the former is located within the confines of the alluvial valley, and the latter is located over a shallow Pleistocene base (ROBERTS, 1997). These relationships a significant influence on the shorter term (historic) evolution and morphological maintenance of the barrier systems as discussed in more detail below.

Barrier Island Evolution and Geomorphology

The erosional remnants of the Lafourche and St. Bernard deltas are delineated by the Isles Dernieres, Timbaliers, Caminada-Moreau headland, and Chandeleur Islands. The Caminada-Moreau headland plays a critical role as a source of sediment allowing for the evolution and morphological maintenance of barriers to the east and west. The mainland beach is rapidly retreating at rates of approximately 33 m/yr (MCBRIDE and BYRNES, 1997) and the back-beach marsh surface is being episodically covered by a thin veneer of overwash deposits comprised of beach and nearshore sands, particularly during winter storms and hurricanes (STONE *et al.*, 1993; 1995 and 1997). Infusions of large volumes of sediment to the littoral zone have resulted in rapid downdrift progradation of the barriers, and, when coupled with high rates of subsidence, and therefore relative sea-level rise, aggradation of barrier sediments is minimal. Thus, the low-profile nature of the barriers has resulted in their high susceptibility to overwash and breaching resulting in the evolution of tidal passes. The degree to which many of the smaller passes have been bypassed has not yet been quantified; however, some net communication likely exists between the respective barriers, particularly west of the Caminada-Moreau headland. Nevertheless, these barriers are rapidly disintegrating in space and transforming into a series of isolated shoals, thereby indicating a significant deficiency in the volume of available, littoral sediments.

Unlike the barriers downdrift of the Caminada-Moreau headland, the Chandeleur Islands on the flank of the St. Bernard deltaic complex are classic, overwash dominated, transgressive features. The Gulf-facing shoreline is relocating landward (west) at an approximate rate of 6.5 m/yr whereas the sound shoreline is moving in the same direction at a rate of approximately 3 m/yr (MCBRIDE and BYRNES, 1997). A noted asymmetry is evident in shoreline change rates where erosion rates in excess of 18 m/yr occur along the southern flank of the barrier. Recent evidence indicates this may be a function of a well-developed and mature bi-cellular longshore sediment transport system, where net transport is preferentially to the north (ELLIS and STONE, in prep.). This is an interesting variant to the evolution and morphological maintenance of barriers in south-central Louisiana, where bayside erosion rates in excess of 2 m/yr are common (MCBRIDE and BYRNES, 1997). There is evidence indicating that the marsh and Chandeleur Island barrier mass co-existed for a short time during the initiation of the transgressive phase of the delta cycle. However, marsh deteoriortion and, hence, marsh shoreline migration, exceed the landward transgression of the barrier mass, resulting in the latter progressively lagging farther behind with time. The mere orientation of the Chandeleur Islands (north-south) when compared with the barriers in south-central Louisiana (oriented generally east-west) ensures that the latter back bay barrier shorelines are more susceptible to wave erosion during post-frontal northerly winds. Thus, the preservation potential for overwash deposits accompanying severe storms or hurricanes is higher on the Chandeleurs, allowing for landward migration. In addition, the markedly higher subsidence rates being experienced in the Lafourche area are a critical, but not always recognized, factor.

The ultimate phase of destruction is the complete transition of a sub-aerial barrier mass to a subaqueous shoal, with the adjacent marsh shoreline having transgressed farther inland. This transgression results in transforming formerly protected, low energy bay environments to open, shallow marine embayments. An example of this transformation is clearly apparent in south-central Louisiana, off the Isles Dernieres barrier chain. Ship Shoal is the drowned remnant of a former barrier system. Over 50 km in length, and between 4 to 6 m thick, the shoal appears to be migrating landward at rates of between 7 and 15 m/yr (CUOMO, 1982), as a function of storm wave processes (STONE and XU, 1996; STONE *et al.* 1997). The shoal's primary sediment source appears to have been the Maringouin delta lobe (PENLAND *et al.* 1988), above which Ship Shoal is presently located.

The Importance of Storms

Historically, the morphology of Louisiana's deltaic plain has been significantly impacted by hurricanes (MORGAN *et al.*, 1958; NUMMENDAL, 1982; PENLAND *et al.*, 1988; RITCHIE and PENLAND, 1988; MCBRIDE *et al.*, 1992; STONE *et al.*, 1993; 1995; 1997). For a comprehensive review the reader is referred to STONE and FINKL (1995) and STONE *et al.* (1997). The low profile nature of the coast allows repetitious breaching and overwashing of the foredune system during storms. When coupled with high rates of relative sea-level rise, these are the primary reasons for high rates of historic shoreline retreat and barrier island disintegration. The importance of hurricanes on the morpho-sedimentary dynamics of marshes and barrier islands in south-central Louisiana was clearly evident during the recent landfall (1992) of Hurricane Andrew. On entering the Gulf of Mexico, Hurricane Andrew re-intensified to Category 4 status with sustained winds in excess of 60 m s^{-1}. Hindcast estimates indicate that the significant wave height approached 14 m, and may have exceeded 20 m, on portions of the Louisiana shelf (GRYMES and STONE, 1995; STONE *et al.*, 1995). Wave attenuation was calculated to have occurred in water depths of up to 200 m. The low gradient inner shelf slope adjacent to Isles Dernieres played a critical role in dissipating wave energy, with calculated rates of 5 jl m^{-3} occurring in depths of 25 to 30 m. Maximum near-bottom orbital velocities reached 20 cm s^{-1} in depths of around 150 m, and increased to 200 cm s^{-1} in 30 m of water. Depth-limited breaker wave heights ranged from 0.5 m off Point au/Fer Island to > 3 m along the Caminada-Moreau headland.

Severe overwash and breaching were apparent along over 100 km of the south-central Louisiana barrier island coastline as Hurricane Andrew passed within 50 km of the Isles Dernieres (Figure 14). Along one of these islands, Trinity Island, beach surveys conducted by personnel of the United States Geological Survey since 1986, showed upper foreshore retreat of approximately 25 m and sediment loss of 92 m^3 m^{-1}. Comparison of post-Andrew surveys with those conducted between 1986 and 1991 demonstrate the force of the Hurricane where, between 1986 and 1991, the berm crest retreated 90 m, and approximately 81 m^3 m^{-1} of sediment were eroded. Virtually all of the sand was stripped from the Isles Dernieres during Andrew, leaving an exposed mud platform (Figure 14).

As Hurricane Andrew moved across the Louisiana coast, super-elevated water levels and winds significantly impacted the marshes (Figure 15). Because Louisiana's marshes are experiencing rapid erosion, several study sites undergoing long-term monitoring have been established in the past. Many of these sites were reoccupied by researchers after Hurricane Andrew made landfall, providing unique pre-and post-storm data sets (see STONE and FINKL, 1995). Evidence in-

Figure 14. Barrier island response to storm generated waves caused by Hurricane Andrew (1992) along the Isles Dernieres, Louisiana. Note morphological condition of the barrier pre-Andrew (top left) and complete removal of coarser-grained material that exposes the mud core (top right) during and after landfall. Similiarly, sand masses comprising the barriers and fronting the back barrier marshes (bottom left) were completely removed, leaving marshes prone to wave erosion (bottom right).

dicates two contrasting effects of the storm surge on Louisiana's marshes with coarse-grained sediment being deposited on the marsh surface during water level set-up and fine-grained sediment being distributed across the marsh surface during relaxation of the water surface after the storm moved inland. Sediment deposition and marsh surface change was measured up to 130 km from the storm track, and data indicate an increase of short-term sediment deposition after Hurricane Andrew up to 1 to 3 orders of magnitude greater than pre-storm rates. These findings confirm the importance of storms in supplying significant amounts of sediment to deltaic coastal marshes (CAHOON *et al.,* 1995). Although hurricanes and trcpical storms play a largely destructive role on the barrier islands and beaches along the Louisiana coast, there is considerable evidence indicating that productivity in coastal ecosystems may be increased by hurricane impacts (CONNOR *et al.,* 1989).

LARGE-SCALE MANAGEMENT OF THE DELTAIC SYSTEM

Louisiana leads the nation, and likely the world, in area lost to coastal erosion and wetlands deterioration. Louisiana's barrier islands have decreased in area on average by more than 40%, and some barriers, namely the Isles Dernieres, have lost 75% of their area within historic time (MCBRIDE and BYRNES, 1997; STONE *et al.,* 1997). Predictions based on past erosion rates suggest that some barriers are likely to completely erode away and be transformed into submarine sand bodies within the next several decades unless large-scale restoration projects are undertaken. Numerical wave modeling indicates that significant wave heights could increase 1 m in the bays because of projected barrier island loss (STONE *et al.,* in prep.). The eventual loss of these protective coastal barriers would likely contribute to further land loss and deterioration of the coastal wetlands and back-barrier

Figure 15. Deformation of an extensive flotant mat in the upper deltaic plain of the central Louisiana coastal plain caused by wind forcing and water level set-up associated with Hurricane Andrew (1992). (Photo by S. Penland).

estuaries and lagoons (STONE and MCBRIDE, 1998). Louisiana contains 25% of the vegetated wetlands and 41% of the nation's coastal and estuarine wetlands in the 48 conterminous states. These coastal wetland environments, which include associated bays and estuaries, support a harvest of renewable natural resources with an estimated annual value in excess of $1 billion. Unfortunately, Louisiana is experiencing rapid wetlands loss: 80% of the nation's total loss of wetlands has occurred in this state. According to measurements by the US Army Corps of Engineers and the US Fish and Wildlife Service, since 1956 more than 2500 km^2 of coastal wetlands in Louisiana have been eroded or converted to open-water habitats. If these rates continue, an estimated 4,000 km^2 of wetlands will be lost in the next 50 years, severely impacting the state's economy and directly increasing flooding threats to New Orleans and surrounding urban areas (STONE *et al.*, 1997).

As summarized in this paper, the physical processes caus-

Figure 16. Floating marsh in the upper deltaic plain fragmented by the effects of Hurricane Andrew (1992). (Photo by S. Penland).

ing or contributing to barrier island erosion and loss of wetlands are complex and varied, and many remain poorly understood. There continues to be considerable debate in scientific and engineering communities regarding which of the many contributing processes, both natural and human-induced, are the most significant. There is further controversy over some of the proposed measures to alleviate or mitigate coastal land loss. Much of the discussion focuses on the reliability of predicted results of a given management, restoration, or erosion mitigation technique. With a better understanding of the processes and geologic conditions that cause barrier island erosion and wetland loss, such predictions are certain to become more accurate, and a clearer consensus of how to best reduce and mitigate land loss is likely to appear.

Since 1986, the Coastal and Marine Geology Program within the USGS, in cooperation with other federal agencies, Louisiana State University and other universities, has undertaken four major comprehensive coastal geologic studies in the Mississippi River deltaic plain and the Chenier plain of Louisiana. The primary objectives of these studies are to scientifically assess the rapid coastal erosion, wetlands loss, and environmental change taking place and to better understand and quantify the natural and anthropogenic processes responsible.

Studies such as the USGS efforts described above have been useful in understanding the processes that lead to coastal land loss in Louisiana. Other efforts that have informed the decision-making process include work by generations of Louisiana State University researchers such as H.N. Fisk, R.J. Russell, H.V. Howe, and J.P. Morgan, who produced seminal work on deltaic form and processes. Current efforts at Louisiana State University, Louisiana Universities Marine Consortium, other universities, federal, state and local planning, and resource protection agencies, and the private sector continue to shed new light on forms and process of coastal land loss and on possible solutions. Much is known about problems and potential solutions. Yet a continuing problem for Louisiana is harnessing the will and the means to implement effective solutions.

Significant progress was made in 1990 when a federal law entitled the Coastal Wetlands Planning, Protection and Restoration Act was passed by Congress. The Act is commonly referred to as the Breaux-Johnston Act or CWPPRA. The Act provides federal money to states for coastal restoration activities. In Louisiana, a maximum of $40 million per year may be spent on a cost-share basis of 75% federal: 25% state or local monies. Five federal agencies and the Governor of Louisiana form a Task Force to administer the CWPPRA program within the state. The participating agencies are the U.S. Army Corps of Engineers, the Environmental Protection Agency, the Department of Interior, the Natural Resources Conservation Service, and the National Marine Fisheries Service. Though presently used primarily in Louisiana, the CWPPRA program can be applied to other coastal states. As required by the CWPPRA program, Louisiana completed its plan, entitled the Louisiana Coastal Wetlands Restoration Plan, in November 1993. The plan sets out an initial philosophy in its Executive Summary. First, by phasing in an adequate investment now, it is technically feasible to significantly slow or reverse coastal wetland loss and thereby protect, sustain, and enhance the most valuable environmental and economic assets of the region . Secondly, the no-action alternative condemns the nation to a far more expensive course of uncoordinated and increasingly futile emergency efforts to protect existing investments in the economic infrastructure without hope of achieving sustainability. The bulk of the plan consists of appendices describing specific projects that can combat loss of coastal wetlands in each of nine geographically defined basins. Each year, the CWPPRA Task Force prepares a list of priority projects from the plan that is submitted to Congress for funding under the Act.

To undertake the restoration of the degraded coastal wetlands system in Louisiana requires several strategies. Accordingly, projects of several general types are included in the Louisiana Coastal Wetlands Restoration Plan: small-scale restorations, river diversions, and barrier island restoration. Five priority project lists have been submitted to Congress and projects of all three types have been included. Completed CWPPRA projects have been primarily small-scale restorations and small river diversions, such as siphons. At present, three projects are being completed that will involve pumping nearly 20 million m^3 of sediment from adjacent borrow sites to restore several tens of kilometers of barrier islands along the Isles Dernieres.

Two feasibility studies are nearing completion that should begin to provide the answers to some of the questions that have delayed implementation of large-scale projects. One CWPPRA feasibility study is the Mississippi River Comprehensive Diversion Study for which the U.S. Army Corps of Engineers is the lead agency. The other CWPPRA feasibility study is the Barrier Island Restoration Feasibility Study, which is being completed under contract with the Louisiana Department of Natural Resources as lead agency. The latter study has used state-of-the-art approaches to coastal processes and engineering. These studies should outline long-term, large-scale approaches to using the Mississippi River to restore coastal wetlands and possibly using offshore sand sources and other means to restore rapidly eroding barrier islands and shorelines, respectively. A significant amount of information has been collected by the USGS and the U.S. Minerals Management Service on the potential use of shelf sands offshore Louisiana for nourishment purposes. Additional studies on potential environmental effects of sand removal has been carried out at Louisiana State University with support from MMS (STONE and XU, 1996).

Costs associated with future large-scale barrier restoration efforts will likely aproach the billion dollar level. However, the value provided by the barrier islands is considered to be great. The resource base to be protected consists of beach, dune, mangrove, and marsh habitat, which provide nursery grounds and refuge to fish and wildlife. The islands provide protection to oil and gas pipelines and infrastructures, and provide storm wave and storm surge attenuation for marshes and communities, including New Orleans. The barrier islands are part of the natural system that is an economic engine for much of Louisiana and that provides significant benefits to the nation.

SUMMARY

The Mississippi River has built a broad and complex coastal plain through the fundamental process of changing its location for delta-building every 1000 to 2000 years. Each delta-building episode is characterized by the development of a hierarchy of deltas that have different temporal and spatial scales. Regardless of size, each delta evolves through a cycle of events that begins with sedimentation and rapid growth (constructional or regressive phase), followed by systematic abandonment of the delta by its channel network (sediment delivery system) and delta deterioration (destructional or transgressive phase). The coastal plain of Louisiana and inner continental shelf display deltas in all phases of this delta cycle, from the Atchafalaya-Wax Lake bayhead deltas that represent the products of the latest delta switching event to deltas that are in the final stages of reworking and submergence. Human intervention in the Mississippi River's natural sediment and water dispersal processes have accelerated the destructional or transgressive phase of the delta cycle by reducing the sediments available for offsetting the effects of subsidence and providing mineral matter nutrients for maintaining high organic productivity. Beginning in the 19th century, dams and other sediment control structures on tributaries to the Mississippi have reduced the sediment available to the Mississippi River, while artificial levees have essentially eliminated crevassing and the river's overbank sediment dispersal processes. Mitigating procedures are now underway to reinstate sediment and water to river-flanking environments by creating artificial crevasses and controlled diversions.

When the rapid developmental phase of delta building is initiated, as exemplified by the latest Atchafalaya diversion of Mississippi River water and sediment, delta evolution is characterized by three delta types: (a) lacustrine deltas, (b) bayhead deltas, and (c) shelf deltas. Two types of shelf phase deltas can be recognized from the Mississippi River's Holocene deltaic deposits. Counting the latest Atchafalaya delta-building event, five of the six commonly recognized Holocene delta complexes are thin inner shelf deltas, which have numerous distributaries, merged distributary mouth bar sands, and channels that erode below the delta deposits. In contrast, the modern birdfoot or Balize delta has prograded into deep water near the shelf edge. This delta has a thick base of clay-rich prodelta deposits, widely spaced distributaries, isolated and elongate distributary mouth bar sands, and sediment deformation in the form of mud diapirs and a variety of mass movement features on the low sloping delta front.

The Louisiana coast is experiencing probably the highest rates of erosion in the United States. Without a concerted, large-scale restoration effort, it is likely that the marsh loss problem will worsen in that the sheltered bays could convert to open marine embayments as early as the first quarter of next centry. Two important studies are nearing completion that will likely shed new light on future approaches to large-scale conservation of the deltaic plain, mainland and barrier coasts.

ACKNOWLEDGMENTS

This paper is a review of research conducted by the many workers cited in the text. However, special acknowledgment goes to U.S. Geological Survey support for a multi-year program entitled "Critical Physical Processes of Wetland Loss," Contract No. 14–08–0001–23411. This program produced the most up-to-date information on the processes of subsidence that are largely responsible for driving the changes a delta undergoes after abandonment by the fluvial system that built it. The U.S. Army Corps of Engineers, New Orleans District, is acknowledged for support of both work in the Atchafalaya-Wax Lake delta system and a "Study of Sedimentation and Subsidence in the South-Central Coast Plain of Louisiana," Contract No. DACW29–84–C–0081. The United States Geological Survey is credited for supporting the acquisition of both side-scan sonar and high resolution seismic data from the front of the modern Mississippi River delta. We appreciate the cartographic assistance of Celia Harrod, Mary Lee Eggard, Clifford Duplechin and Kerry Lyle.

LITERATURE CITED

Bea, R.G., 1971. How sea floor slides affect offshore structures. *Oil and Gas Journal,* 69(48), 88–92.

Britsch, L.D. and Dunbar, J.B., 1993. Land loss rates: Louisiana coastal plain. *Journal of Coastal Research,* 9, 324–338.

Buffler, R.T., 1981. Seismic stratigraphy and geologic history of the Gulf of Mexico basin. *Gulf Coast Association of Geological Societies Short Course,* 172p.

Cahoon, D.R.; Reed, D.J.; Day, J.W.; Steyer, G.D.; Boumas, R.M.; Lynch, J.C.; McNally, D., and Latif, N., 1995. The influence of Hurricane Andrew on sediment distribution in Louisiana Coastal marshes. *Journal of Coastal Research,* SI 21, 280–294.

Chabreck, R.H., 1988. *Coastal Marshes, Ecology and Wildlife Management*: University of Minnesota Press, 138p.

Coleman, J.M., 1966. Ecological changes in a massive freshwater clay sequence. *Transactions Gulf Coast Association of Geological Societies,* 16, 159–174.

Coleman, J.M., 1988. Dynamic changes and processes in the Mississippi River delta. *Geological Society of America Bulletin,* 100, 999–1015.

Coleman, J.M. and Garrison, L.E., 1977. Geological aspects of marine slope instability, northwestern Gulf of Mexico. *Marine Geotechnology,* 2, 9–44.

Coleman, J.M. and Prior, D.B., 1980. Deltaic sand bodies: Continuing Education Course Note Series #15. Tulsa, Oklahoma: *American Association of Petroleum Geologists,* 171p.

Coleman, J.M.; Prior D. B., and Garrison, L.E., 1980. Subaqueous sediment instabilities in the offshore Mississippi River delta. *Bureau of Land Management Open File Report 80–01,* New Orleans, La.

Coleman, J.M.; Prior, D.B., and Lindsay, J.F., 1983. Delta influences on shelf edge stability processes. *In* D.J. Stanley and G.T. Moore, (eds.), The shelf break critical interface on continental margins. *Society Economic Paleontologists Special Publication* 33, 121–137.

Coleman, J.M. and Gagliano, S.M., 1964. Cyclic sedimentation in the Mississippi River delta plain. *Transactions Gulf Coast Association of Geological Societies,* 14, 67–80.

Connor, W.H.; Day, J.W.; Baumann, R.H., and Randall, J.M., 1989. Influence of hurricanes on coastal ecosystems along the northern Gulf of Mexico. *Wetlands Ecology and Management,* 1(1), 45–56.

Cuomo, R.F., 1982. The geologic and morphologic evolution of Ship Shoal, Northern Gulf of Mexico. Masters Thesis, Department of Geology, Louisiana State University, Baton Rouge, LA, 249p.

Ellis, J. and Stone, G.W., (in prep.). Net longshore sediment transport and granulometric characteristics along Chandeleur Island, Louisiana, U.S.A.

FISK, H.N., 1938. Geology of Grant and LaSalle Parishes. Louisiana Department of Conservation, Geological Bulletin 10, pp. 1–246.

FISK, H.N., 1944. Geological investigation of the alluvial valley of the Lower Mississippi River. U.S. Army Corps of Engineers, Mississippi River Commission, Vicksburg, Ms., 78 p.

FISK, H.N., 1947. Fine-grained alluvial deposits and their effects on Mississippi River activity. U.S. Army Corps of Engineers, Mississippi River Commission, Vicksburg, Ms., 82p.

FISK, H.N., 1952a. Geologic investigation of the Atchafalaya Basin and the problem of Mississippi River diversion. U.S. Army Corps of Engineers, Mississippi River Commission, Vicksburg, Ms., 145p.

FISK, H.N., 1952b. Mississippi River valley geology relation to river regime. *Transactions American Association of Civil Engineers,* 117, 667–689.

FISK, H.N., 1955. Sand facies of recent Mississippi delta deposits. *Proceedings 4th World Petroleum Congress (Rome, Italy)*, Section 1–3, 377–398.

FISK, H.N. and MCFARLAN, E., JR., 1955. Late Quaternary deltaic deposits of the Mississippi River. *Geological Society of America Special Paper,* 62, 279–302.

FISK, H.N., 1961. Bar-finger sands of the Mississippi delta. *In*: PETERSON, J.A. and OSMOND, J.C. (eds.), *Geometry of sandstone bodies*. OK.: American Association of Petroleum Geologists, *Tulsa,* 22–52.

FRAZIER, D.E., 1967. Recent deltaic deposits of the Mississippi River, their development and chronology. *Transactions Gulf Coast Association of Geological Societies,* 17, 287–315.

GAGLIANO, S.M., 1989. Controlled diversions in the Mississippi River deltaic plain. *In*: KUSLES, J.A. and DALY, S., (eds.), *Proceedings of International Symposium* (Wetlands and River Corridor Management, July 5–9, Charleston, South Carolina), Association of Westland Managers, pp. 257–268.

ISACKS, T.S., 1989. Geologic evolution and sedimentary facies of the Timbalier Island, Louisiana. MS Thesis, Department of Geology, Louisiana State University, 191p.

KAHN, J.H., 1980. The role of hurricanes in the long-term degradation of a barrier island chain. MS Thesis, Department of Marine Sciences, Louisiana State University, 120p.

KAHN, J.H. and ROBERTS, H.H., 1982. Variations in storm response along a microtidal transgressive barrier island arc. *Sedimentary Geology,* 33, 129–146.

KOLB, C.R. and VAN LOPIK, J.R., 1958. Geology of the Mississippi deltaic plain-southeastern Louisiana. *U.S. Army Corps of Engineers, Waterways Experiment Station, Technical Report* 2, 482p.

LEBLANC, R.J., 1973. Significant studies of modern and ancient deltaic sediments. *In*: M.L. BROUSSARD, (ed.), *Deltas*. Houston, Texas: Houston Geological Society, pp. 13–85.

LYELL, C., 1847. On the Mississippi delta. *American Journal of Science,* 2 (3), 118–119.

MAJERSKY-FITZGERALD, S., 1998. The development and sand body geometry of the Wax Lake Outlet Delta, Atchafalaya Bay, Louisiana. Ms Thesis, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, Louisiana, 130p.

MCBRIDE, R.A.; PENLAND, S.; JAFFE, B.; WILLIAMS, S.J.; SALLENGER, A.H., JR., and WESTPHAL, K.A., 1991. Shoreline changes of the Isles Dernieres barrier island arc, Louisiana, from 1853 to 1989. U.S. Geological Survey Misc. Investigation Map Series, Map 1–2186 (1 sheet @ 42 × 58"), scale 1:75,000.

MCBRIDE, R.A. and BYRNES, M., 1997. Regional variations in shore response along barrier island systems of the Mississippi River delta plain: Historical change and future prediction. *Journal Coastal Research,* 13(3), 628–655.

MORGAN, J.P., 1961. Mudlumps at the mouths of the Mississippi River. *In*: *Genesis and Paleontology of the Mississippi River Mudlumps*. Louisiana Department of Conservation Bulletin, 35, 1–116.

MORGAN, J.P.; NICHOLS, L.G., and WRIGHT, M., 1958. Morphological Effects of Hurricane Audrey on the Louisiana Coast. Coastal Studies Institute Technical Paper 58–3, Louisiana State University, Baton Rouge, LA, 53p.

MCINTIRE, W.G., 1954. *Correlation of Prehistoric Settlements and Delta Development*. Coastal Studies Institute Technical Report 5, Louisiana State University, 65p.

NUMMEDAL, D., 1982. Hurricane landfalls along the N.W. Gulf coast. *In*: NUMMEDAL, D., (ed.), *Sedimentary Processes and Environments along the Louisiana-Texas Coast*. Field trip Guidebook for the 1982 Annual Meeting of the Geological Society of America (New Orleans, LA, October, 1982), pp. 63–78.

PENLAND, S. and BOYD, R., 1981. Shoreline changes on the Louisiana barrier coast. *IEEE Oceans,* 81, 209–219.

PENLAND, S.; BOYD, R.; NUMMEDAL, D., and ROBERTS, H.H., 1981. Deltaic barrier development on the Louisiana coast. *Transactions Gulf Coast Association of Geological Societies,* 31, 471–476.

PENLAND, S.P.; SUTER, J.R., and BOYD, R., 1985. Barrier island areas along abandoned Mississippi River deltas. *Marine Geology,* 63, 197–233.

PENLAND, S.P.; BOYD, R., and SUTER, J.R., 1988. The transgressive depositional systems of the Mississippi River delta plain: A model for barrier shoreline and shelf sand development. *J. Sedimentary Petrology,* 58(6), 932–949.

PRIOR, D.B. and COLEMAN, J.M., 1978a. Disintegrating retrogressive landslides on very-low-angle subaqueous, Mississippi delta. *Marine Geotechnology,* 3, 37–60.

PRIOR, D.B. and COLEMAN, J.M., 1978b. Submarine landslides on the Mississippi River delta-front slope. *Geoscience and Man,* School of Geoscience, Louisiana State University, Baton Rouge, 19, 41–53.

RITCHIE, W. and PENLAND, S., 1988. Rapid dune changes associated with overwash processes on the deltaic coast of south Louisiana. *Marine Geology,* 81, 97–122.

RIDDELL, J.L., 1846. Deposits of the Mississippi and changes in its mouth. *DeBow's Review,* 2, 433–448.

ROBERTS, H.H., 1997. Dynamic changes of the Holocene mississippi River delta plain: The delta cycle. *Journal of Coastal Research,* 13(3), 605–627.

ROBERTS, H.H.; BAILEY, A., and KUECHER, G.J., 1994. Subsidence in the Mississippi River delta: Important influences of valley filling by cyclic deposition, primary consolidation phenomena, and early diagenesis. *Transactions Gulf Coast Association of Geological Societies,* 44, 619–629.

ROBERTS, H.H.; SUHAYDA, J.N., and COLEMAN, J.M., 1980. Sediment deformation and transport on low-angle slopes: Mississippi River delta. *In*: COATES, D.R. and VITEK, J.D., (eds.), *Thresholds in Geomorphology*. London: Allen and Unwin, pp. 131–167.

ROBERTS, H.H.; ADAMS, R.D., and CUNNINGHAM, R.H.W., 1980. Evolution of sand-dominant subaerial phase, Atchafalaya Delta, Louisiana. *American Association of Petroleum Geologists Bulletin,* 64, 264–279.

RUSSELL, R.J., 1936. Physiography of lower Mississippi River delta: Lower Mississippi River Delta. *Geological Bulletin 8,* Louisiana Geological Survey, 199 p.

RUSSELL, R.J., 1939. Louisiana stream patterns. *American Association of Petroleum Geologists Bulletin,* 23, 1199–1227.

RUSSELL, R.J., 1940. Quaternary history of Louisiana. *Geological Society of America Bulletin,* 51, 1199–1234.

RUSSELL, R.J. and RUSSELL, R.D., 1939. Mississippi River delta sedimentation. *In*: TRASK, P.D. (ed.), *Recent Marine Sediments,* American Association of Petroleum Geologists, Tulsa, Ok., pp. 153–177.

SHEPARD, F.P., 1955. Delta front valleys bordering the Mississippi distributaries. *Geological Society of America Bulletin,* 66: 1489–1498.

SHEPARD, F.P.; PHLEGER, F.B., and VAN ANDEL, TJ.H., 1960. Recent sediments northwest Gulf of Mexico. *American Association Petroleum Geologists,* 394p.

STONE, G.W.; GRYMES, J.M.; ROBBINS, K.; UNDERWOOD, S.G.; STEYER, G., and MULLER, R.A., 1993. A chronological overview of climatological and hydrological aspects associated with Hurricane Andrew and its morphological effects along the Louisiana Coast, U.S.A. *Shore and Beach,* 61(2), 2–13.

STONE, G.W. and FINKL, C.W., (eds.), 1995. Impacts of Hurricane Andrew on the coastal zones of Florida and Louisiana: 22–26 August, 1992. *Journal of Coastal Research,* SI 21, 364p.

STONE, G.W. and XU, J.P., 1996. Wave climate modeling and evaluation relative to sand minimg on Ship Shoal, offshore Louisiana, for coastal and barrier island restoration. *OCS study 96–0059,* U.S. Department of the Interior, Minerals Management Service, 265p.

STONE, G.W.; GRYMES, J.W.; DINGLER, J.R., and PEPPER, D.A., 1997. Overview and significance of hurricanes on the Louisiana coast, U.S.A. *Journal of Coastal Research,* 13(3), 656–669.

STONE, G.W. and MCBRIDE, R., 1998. Louisiana barrier islands and their importance in wetland protection: Forecasting shoreline change and subsequent response of wave climate. *Journal of Coastal Research,* 14, 3.

STONE, G.W.; ZHANG, X.P., and WANG, P. (in prep.). The relationship between barrier islands and wave climatology in Louisiana's bays.

SUTER, J.R. and H.L. BERRYHILL, JR., 1985. Late Quaternary shelf margin deltas, northwest Gulf of Mexico. *American Association of Petroleum Geologist Bulletin,* 69, 77–91.

SYDOW, J. and ROBERTS, H.H., 1994. Stratigraphic framework of a Late Pleistocene shelf-edge delta, northeast Gulf of Mexico. *American Association of Petroleum Geologists Bulletin,* 78, 1276–1312.

TORNQVIST, T.E.; KIDDLER, T.R.; AUTIN, W.J.; VAN DER BORG, K.; DEJONG, A.F.M.; KLERKS, C.J.W.; SNIJDERS, E.M.A; STORMS, J.E.A.; VANDAM, R.L., and WIEMANN, M.C., 1996. A revised chronology for Mississippi River subdeltas. *Science,* 273, 1693–1696.

TYE, R.S. and COLEMAN, J.M., 1989. Evolution of Atchafalaya lacustrine deltas, south-central Louisiana. *Sedimentary Geology,* 65, 95–112.

VAN HEERDEN, I.L. and ROBERTS, H.H., 1988. Facies development of Atchafalaya delta, Louisiana: A modern bayhead delta. *American Association of Petroleum Geologists*, 72, 439–453.

WELDER, F.A., 1959. *Processes of Deltaic Sedimentation in the Lower Mississippi River.* Coastal Studies Institute Technical Report 12, Louisiana State University, pp. 1–90.

WELLS, J.T.; CHINBURG, S.J., and COLEMAN, J.M., 1983. *Development of Atchafalaya River Deltas: Generic Analysis.* Contract DACW 39–80-C-0082, Report to U.S. Army Corps of Engineers, Waterways Experiment Station: Vicksburg, MS, 98p.

WHELAN, THOMAS, III; COLEMAN, J.M.; SUHAYDA, J.N., and GARRISON, L.E., 1975. The geochemistry of Recent Mississippi River delta sediments: Gas concentration and sediment instability: *7th Offshore Technology Conference* (Houston, Texas), pp. 71–84.

WINKER, C.D., 1991. Summary of Quaternary framework, northern Gulf of Mexico. *Gulf Coast Section Society of Economic Paleontologists and Mineralogists 12th Annual Research Conference Proceedings,* pp. 280–284.