Journal of Coastal Research	13	3	605–627	Fort Lauderdale, Florida	Summer 1997

Dynamic Changes of the Holocene Mississippi River Delta Plain: The Delta Cycle

Harry H. Roberts

Coastal Studies Institute
Center for Coastal Energy and Environmental Resources
Louisiana State University
Baton Rouge, LA 70803, U.S.A.

ABSTRACT

ROBERTS, H.H., 1997. Dynamic Changes of the Holocene Mississippi River Delta Plain: The Delta Cycle. *Journal of Coastal Research,* 13(3), 605–627. Fort Lauderdale (Florida), ISSN 0749-0208.

Previous geologic research on Holocene Mississippi River deltaic deposits has verified that the present delta plain and associated nearshore barrier islands and submarine shoals are either direct or indirect products of cyclic delta-building events that have operated on a variety of temporal and spatial scales. A major depositional element of the modern delta plain is the delta complex, of which there are six: (1) Maringouin, (2) Teche, (3) St. Bernard, (4) Lafourche, (5) Balize, and (6) Atchafalaya. Major delta-building events have occurred at a frequency of one every 1–2 kyr. Deposits associated with the six major delta complexes are fundamental constructional units of the delta plain, which collectively covers an area of $\sim$ 30,000 km^2. Sedimentary deposits associated with these delta-building events range in thickness from about 10 to 100 m. Their construction is modulated by stream capture, which develops a new delta complex by way of a new river course. Delta complexes may be comprised of one or more delta lobes. As a product of this delta switching, the depositional architecture of the delta plain consists of laterally offset and stacked delta lobes. Within delta lobes are subdeltas and even smaller crevasse-splays. These smaller scale deltas sedimentologically and geomorphically mimic their larger delta lobe counterparts, but they are considerably thinner, cover less area, and have a shorter period of development and abandonment. Subdeltas are usually $<$ 10 m thick and may fill shallow bays that cover over 300 km^2. They build and deteriorate on time-scales of 150–200 years. Crevasse-splays or overbank splays are $<$ 5 m thick, cover only a few square kilometers, and are abandoned after several decades of active growth.

Each delta evolves through a rapid regressional phase as water and sediment are captured from an antecedent river course. If highstand conditions persist long enough, deltas may prograde to the outer shelf to form wedges of deltaic sediment much thicker than their inner shelf counterparts. The delta-building process starts with the filling of interior lakes (lacustrine deltas), which is followed by bayhead delta-building at the coast, and finally by progradation across the marine shelf (shelf delta). Delta complexes and delta lobes, as well as their smaller counterparts, experience three phases of growth and abandonment: (1) rapid growth with increasing-to-stable discharge, (2) relative stability during initial stages of waning discharge, when sediment input balances the collective effects of subsidence, and (3) abandonment, followed by rapid subsidence-driven subaerial delta deterioration. In the rapid growth stage, formerly eroding-subsiding coastal environments experience delta plain accretion and coastal progradation from renewed sediment input. On the abandonment side of the cycle, marine processes overwhelm fluvial processes and rework the delta perimeter. Forced by the combined processes of subsidence, the delta surface undergoes progressive submergence. Transgressive sand bodies created by wave reworking of the delta evolve from headland beaches and spits, to barrier islands, and finally to submarine shoals as the abandonment phase is completed.

ADDITIONAL INDEX WORDS: *Delta cycle, progradation, subsidence, shoreline change.*

INTRODUCTION

Rationale

This paper constitutes a review of the depositional framework of Holocene Mississippi River deltaic deposits with a focus on the cyclic nature of the delta-building process. The delta cycle concept is extended beyond detail provided by previous workers with the intent of establishing a simple conceptual format for understanding an extremely complex network of depositional environments. Understanding the delta cycle is fundamentally important to both geoscientists, who want to know the geometries of sediment bodies and their stratigraphic relationships and environmental planners and engineers, who need to understand natural changes that deltaic surfaces and coastlines are likely to undergo. An appreciation of the fundamental processes and products associated with the delta cycle provides a framework for predicting behavior of a delta within the Mississippi River Holocene deposits in both its fluvially dominated regressive phase and its marine-dominated transgressive phase.

Setting

Holocene deposits of the Mississippi River are products of a drainage basin that covers 3,344,560 km^2, about 70% of the contiguous states of the continental United States and parts of two provinces of Canada (COLEMAN, 1988). Although drainage from the mid-continent has been prograding the northern rim of the Gulf of Mexico since the early Cretaceous (BUFFLER, 1981), it is only during the Holocene that specific

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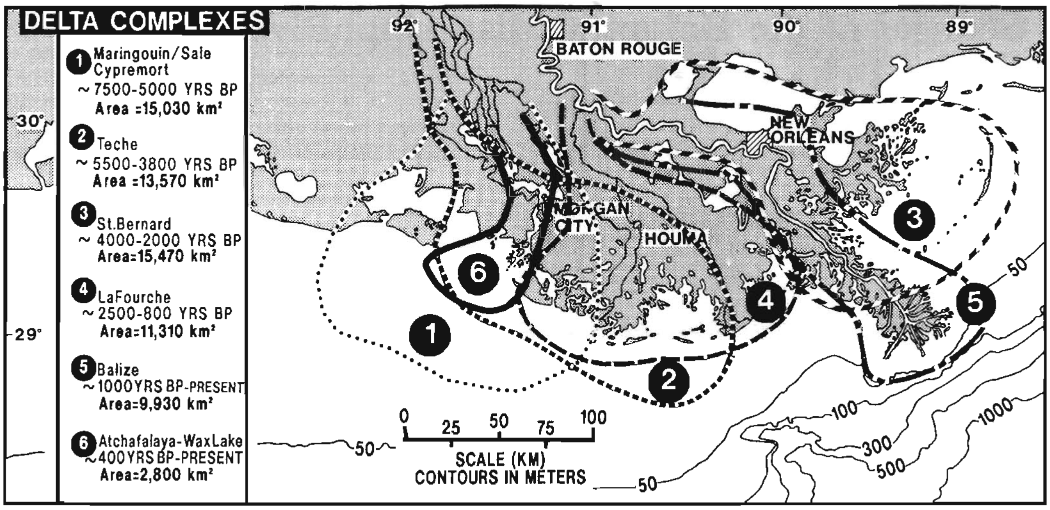


Figure 1. The Mississippi River deltaic plain, illustrating the locations of major delta complexes, including their approximate ages and sizes.

river courses and associated delta plain depositional responses can be linked with reasonable confidence. Because of the meandering nature of all exposed Mississippi River courses and the similarity of their meander belt characteristics, most researchers have concluded that long-term average river discharge has not changed significantly during the Holocene and that the river has been subject to a regular flood-nonflood annual discharge cycle. Presently, the Mississippi River discharges an average of over 15,360 m^3/sec of freshwater into the Gulf of Mexico, with maximum discharges reaching nearly 60,000 m^3/sec. Annual sediment discharge of the Mississippi River is estimated at about 6.21×10^{11} kg; bedload consists of 90% fine sand and suspended load is characterized by 65% clay and 35% silt in the lower river (COLEMAN, 1988). To the west (Figure 1), its relatively new distributary, the Atchafalaya River, captures ~ 30% of the Mississippi River flow at Old River, north of Baton Rouge. Combined with water contributed by the Red River, an average annual discharge of about 6500 m^3/sec is typical of the Atchafalaya River (MOSSA, 1990). In comparison, the Atchafalaya River annually discharges an average of about 2.2×10^8 kg of sediment into Atchafalaya Bay and onto the adjacent shelf (ROBERTS *et al.,* 1980b).

Compared to many other major river deltas, the Mississippi and Atchafalaya Rivers are building their deltas into a quiescent receiving basin, the Gulf of Mexico, which is characterized by low annual wave, tidal, and current energy (WRIGHT and COLEMAN, 1973). Resulting deltas from these rivers are perhaps the best examples of the river-dominated delta type (GALLOWAY, 1975; WRIGHT and COLEMAN, 1972; COLEMAN and WRIGHT, 1975).

Historical Background

Detailed geologic research on Holocene Mississippi River delta deposits started with the studies of TROWBRIDGE (1930), RUSSELL and HOWE (1935), RUSSELL (1936, 1939, and 1940), FISK (1938), and RUSSELL and RUSSELL (1939). These early investigations described the dendritic shapes of delta lobes, identified many abandoned river courses and their depositional components, and made the fundamental observations that led to understanding that delta plain configuration is a product of multiple offset and overlapping deltas. Later, results by FISK (1944, 1947, 1952, 1955), FISK *et al.* (1954), FISK and MCFARLAN (1955), and KOLB and VAN LOPIK (1958) clearly established that these researchers understood that each major delta-building episode was characterized by a rapid regressive phase that deposited a broad delta, followed by eventual fluvial abandonment and transgressive reworking of the deltaic deposits. Understanding this cycle of events started with identification of abandoned Mississippi River courses in the alluvial valley and their linkage downdip to the deltas they built. RUSSELL (1940) was the first to publish on this relationship. Early work by FISK (1938) in the alluvial valley (GRANT and LASALLE parishes, Louisiana) identified ancient courses of the Mississippi and, along with similar observations by TROWBRIDGE (1930) and RUSSELL (1936), helped set the stage for Russell's later and more comprehensive observations. This body of work led to the well known and widely accepted concept of "delta switching," the fundamental depositional style that has shaped coastal environments of the Mississippi River delta plain throughout Holocene times (Figure 1).

THE DELTA CYCLE

Delta plain construction by a series of major delta-building events was firmly established as a new and important concept by the mid-1950s, and a rough chronology was worked out by archeological relationships (MCINTIRE, 1954). Work on these relationships culminated in the late 1950s with the study by KOLB and VAN LOPIK (1958), who constructed a now widely used diagram of delta complexes and their respective ages. Later, MCFARLAN (1961) and FRAZIER (1967) added a temporal framework to delta building provided by radiocarbon dating. Through numerous borings and radiocarbon dates, FRAZIER (1967) subdivided the delta plain into sixteen separate delta lobes. Fourteen of these deltas were associated with the Teche, St. Bernard, and Lafourche delta-building episodes, two deltas were assigned to the most recent delta-building event which has culminated in the active Balize or "birdfoot" delta. Smaller within-delta depositional cycles were not clearly identified in Frazier's work or in the research of earlier workers, even though WELDER (1959) provided the first details on these depositional systems. COLEMAN and GAGLIANO (1964) were the first to stress the orderly repetition of subdelta and crevasse—splay deposition within a major delta. Their observations clearly defined the cyclic depositional style of delta lobes and their smaller scale subdelta components (Figure 1).

Since delta terminology is defined in different ways by different authors, this paper will attempt to establish the most accurate hierarchy of terms used consistently by authors who did the fundamental research on Holocene delta geomorphology and chronology. Commonly cited previous studies (KOLB and VAN LOPIK, 1966; FRAZIER, 1967) indicated that the Holocene delta plain is built from six delta complexes: (1) Maringouin, (2) Teche, (3) St. Bernard, (4) Lafourche, (5) Balize, and (6) Atchafalaya. These events typically had a duration of 1000–2000 years, produced marshlands that covered up to ~ 15,000 km^2, and developed sedimentary sequences up to ~ 30 m thick on the inner shelf.

Within a delta complex there may be several major distributaries that produce individual delta lobes. FRAZIER (1967) identified sixteen delta lobes within the six delta complexes identified above. Within a delta lobe, subdeltas and smaller crevasse-splays or overbank splays develop from secondary channels that become established from breaks in the natural levees of major distributaries. WELDER (1959) and COLEMAN and GAGLIANO (1964) illustrated that subdeltas fill shallow bays flanking major deltaic distributaries with thin sedimentary sequences, typically less than 10 m thick, and may have a subaerial expression of over 300 km^2 at periods of maximum development. Evolution of a subdelta from initiation of a sediment dispersal network to abandonment, subsidence, and open water conditions takes ~ 150–200 years. Much smaller crevasse—splays or overbank splays have deposition—abandonment cycles of a few decades, duration and produce wedges of sediment only a few meters thick. Therefore, the hierarchy of major depositional features comprising the Holocene deltaic deposits of the Mississippi River are: (1) delta plain (1st order), (2) delta complex (2nd order), (3) delta lobe (3rd order), (4) subdelta (4th order), and crevasse-splay or overbank splay (5th order). This series of "deltas within deltas" results from cyclic deposition that occurs on different temporal and spatial scales. The orderly progression of events that accompanies both the rapid regressive phase and the slower transgressive phase of these delta-building events can be explained by the "delta cycle."

Figure 2 schematically explains the delta cycle in terms of the dynamic and progressive stages in the development of a major delta lobe, from stream capture and establishment of a well-defined channel network to abandonment, subsidence, and transgressive reworking to form beaches, spits, barrier islands, and finally submarine shoals. In the following sections of this paper, each phase of delta development and abandonment will be discussed by using examples from the Holocene Mississippi River delta plain in various stages of the delta cycle.

Delta Initiation and Rapid Growth: Fluvially Dominated Regressive Phase

Initiation of a major delta starts with the availability of modest volumes of sediment associated with the first stages of the stream capture process. As Figure 2 illustrates, delta building starts by filling of inland lakes. Lacustrine deltas soon are replaced by delta building at the coast and finally on the marine shelf. Figure 3 illustrates these three stages in the evolution of a delta lobe using the lacustrine deltas of Atchafalaya Basin, the bayhead deltas in Atchafalaya Bay, and the shelf stage Balize delta as the latest Holocene examples.

Stream Capture and Lacustrine Delta Development

Within the present Holocene delta plain, only the Atchafalaya River is capturing significant water and sediment from the Mississippi River. Stream capture by the Atchafalaya started at least by the 1500s (FISK, 1952). This event initiated the first stages of building a new delta. Until the 1900s, diversion of Mississippi River water and sediment down the Atchafalaya course was sporadic, but was aided periodically by dredging and by clearing of log-jams (FISK, 1952). As stream capture became more efficient through the early-to-middle 1900s, discharge steadily increased until it was stabilized in 1963 with a control structure that regulates flow down the Atchafalaya to 30% of the Mississippi flow (plus an added contribution from the Red River). However, sedimentation at the coast was not noticeable until the early 1950s (MORGAN *et al.,* 1953). Although the Atchafalaya course to the Gulf of Mexico is 307 km shorter than its Mississippi River counterpart (ROBERTS *et al.,* 1980b), several centuries were required after stream capture started, to fill Atchafalaya Basin with sediments so that significant quantities of sediment could by-pass the basin and be deposited at the coast. By the late 1940s-early 1950s the intricate network of swamps and lakes of the basin had filled with fluvial sediments so that significant quantities of suspended sediments were transported through the basin to Atchafalaya Bay. Bay-bottom accretion and coastal progradation started in local areas. The basin-filling process that preceded deposition at the coast was accomplished largely through lacustrine delta filling of the numerous shallow lakes that existed throughout the basin's history (TYE and COLEMAN, 1989a, b). Lacustrine deltas are presently filling the few remaining lakes in the southern part of the basin (Figure 4). TYE and COLEMAN (1989a) suggest that lacustrine delta-building is a very rapid process. Most of the lacustrine deltas that now fill the many lakes of the basin and comprise a significant part of the Atchafalaya Basin sedimentary fill probably developed in a few centuries.

The stratigraphic record documents numerous stacked and

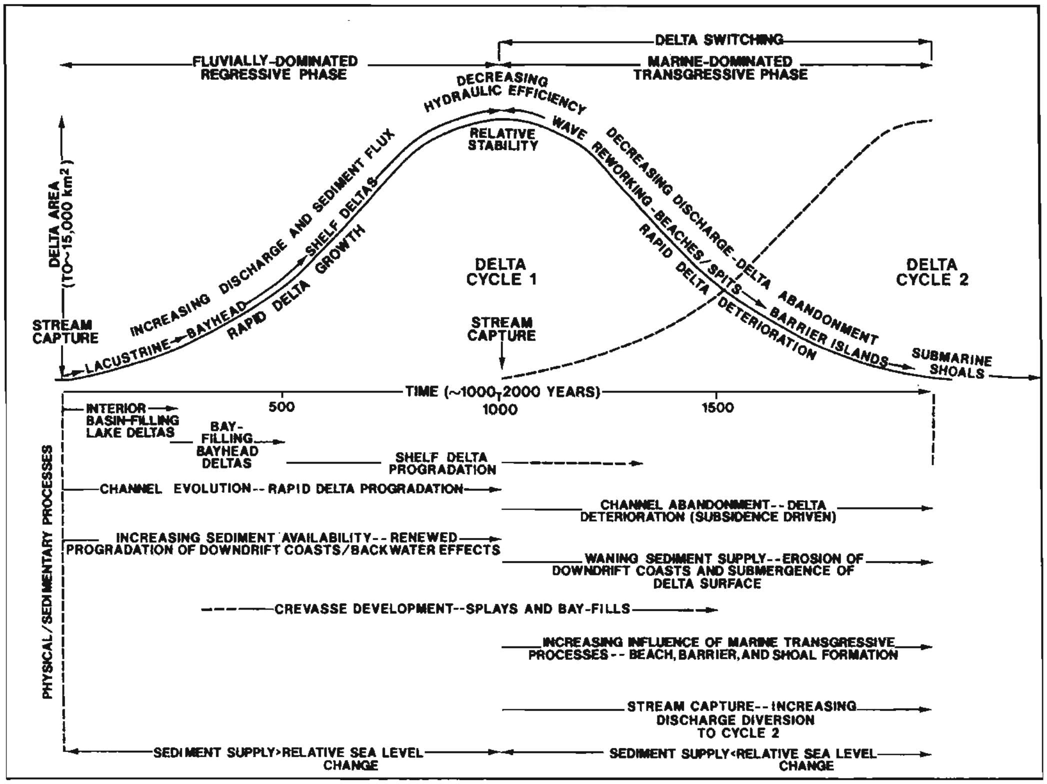


Figure 2. A graphic representation of the delta cycle stressing processes and responses in both the river-dominated regressive and marine-dominated transgressive phases of development.

laterally offset lacustrine deltas 1–5 m thick that resulted from subsidence-driven depositional cycles incorporating lacustrine, lacustrine delta, and swamp deposits. Because of strong underflows developed by sediment-laden river water entering a freshwater lake, sand-rich deposits in these deltas tend to be organized into elongate lobes that sometimes scour into underlying lacustrine deposits (Figure 5). These sands are categorized as distributary mouth bar and subaqueous levee deposits by TYE and COLEMAN (1989b). Although there is considerable sedimentologic variation in lacustrine deltas, a coarsening-upward sequence over laminated and bioturbated lacustrine clays, silty-clays, and silts is typical. These deltas in the Atchafalaya Basin have a parallel-laminated prodelta mud base which is followed by rippled to cross-laminated delta front silty sand and very fine-grained to medium-grained distributary mouth bar sands (TYE and COLEMAN, 1989a). Once a lacustrine delta is deposited, subsidence encourages backswamp development on top of the delta and across the former margins of the shallow lake that was filled. Therefore, these lacustrine/lacustrine delta sedimentary couplets are frequently constrained below and above by highly organic, throughly burrowed, and fine-grained swamp deposits.

The present filling of the last lakes in the southern part of the Atchafalaya Basin represents the final chapter in the lacustrine delta phase of major delta lobe development (Figure 4). The presence of two small but well-developed deltas at the coast, Atchafalaya and Wax Lake deltas in Atchafalaya Bay (Figure 6), indicates that the bayhead delta stage of the developmental cycle is underway and that the final shelf delta stage will be initiated in the very near future.

Bayhead Delta Stage-Atchafalaya/Wax Lake Deltas

Deposition of Atchafalaya River sediments in Atchafalaya Bay marked the beginning of bayhead delta building. This event drew little attention from the scientific community until MORGAN *et al.* (1953) recorded new mudflat accretion along the eastern chenier plain coast and Shlemon (1972; 1975) published results of U.S. Corps of Engineers bathymetric surveys showing dramatic shoaling around both the Lower Atchafalaya River Outlet and the Wax Lake Outlet (an artificial channel dredged in 1942). Later ROBERTS *et al.* (1980b) followed these initial observations with an appraisal of the Atchafalaya delta's early stages of subaerial growth, which started after the enormous flood of 1973. Peak discharges for the Atchafalaya River averaged about 11.5 × 10^3 m^3/sec prior to the 1973 flood, which peaked at over 20 × 10^3 m^3/sec. This flood scoured and resuspended sands stored in the lower Atchafalaya River channel, as interpreted from significant channel deepening (ROBERTS *et al.,* 1980). As a consequence, coarse sediment was transported to Atchafalaya

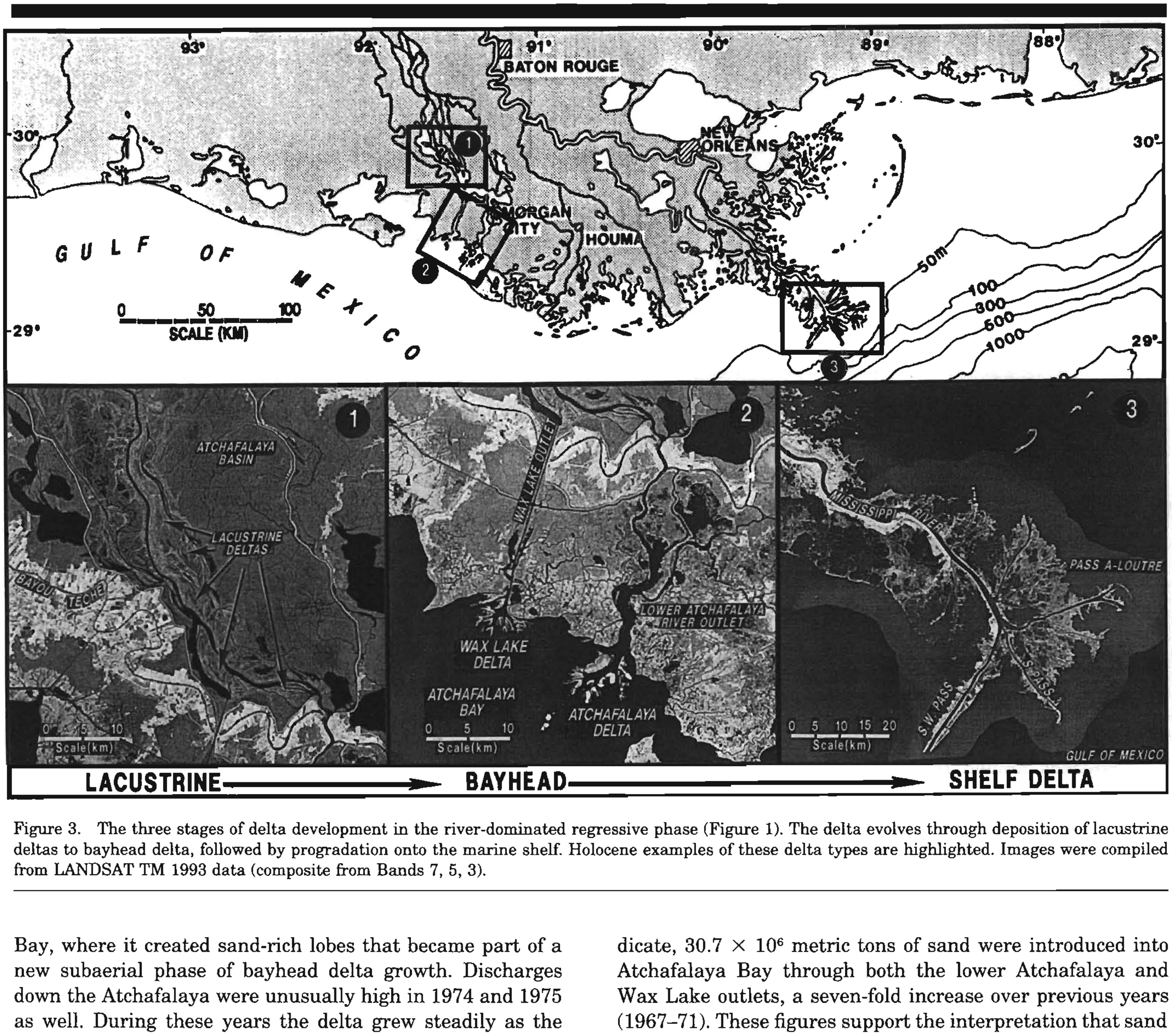


Figure 3. The three stages of delta development in the river-dominated regressive phase (Figure 1). The delta evolves through deposition of lacustrine deltas to bayhead delta, followed by progradation onto the marine shelf. Holocene examples of these delta types are highlighted. Images were compiled from LANDSAT TM 1993 data (composite from Bands 7, 5, 3).

Bay, where it created sand-rich lobes that became part of a new subaerial phase of bayhead delta growth. Discharges down the Atchafalaya were unusually high in 1974 and 1975 as well. During these years the delta grew steadily as the sediment load changed from a dominance of clay and silt in the early 1950s to an increasing abundance of sand through the early 1970s (ROBERTS *et al.,* 1980). Prior to the high-water years of the early 1970s, periodic sampling of the lower Atchafalaya River indicated an average annual suspended sediment load of 42.6×10^6 metric tons (1965–1971) (USACOE, 1974). During the three high-water years of the early 1970s, the average annual suspended sediment load more than doubled, the lower Atchafalaya River carrying 88.9×10^6 metric tons (USACOE, 1975). It is interesting to note that the coarsest particles (fine- to medium-sized sand) being carried by the lower Atchafalaya River can be easily transported as suspended load at flood velocities (200–600 cm/sec). Sand-sized sediment introduced into the Atchafalaya River during 1973–75 near the diversion point was 34×10^6 metric tons (ROBERTS *et al.,* 1980b), which represents a two-fold increase over previous years (1967–71). During the same period, U.S. Corps of Engineers data (ROBERTS *et al.,* 1980b) indicate, 30.7×10^6 metric tons of sand were introduced into Atchafalaya Bay through both the lower Atchafalaya and Wax Lake outlets, a seven-fold increase over previous years (1967–71). These figures support the interpretation that sand deposits in the lower reaches of the Atchafalaya River system were scoured and transported to the bay (ROBERTS and VAN HEERDEN, 1992). The net result of three high water years in the early 1970s, which forced a substantial increase in sand transport to Atchafalaya Bay, was to start the subaerial growth of two small deltas at the Atchafalaya River and Wax Lake outlets, both of which are expressions of the bayhead delta stage in the early evolution of a new delta lobe (Figure 6).

Figure 7 illustrates the steady increase of subaerial land that evolved for each delta from 1973 to 1990. The Atchafalaya delta curve is more variable than the one for the Wax Lake delta, partially because of the deep navigation channel through the Atchafalaya delta that is periodically dredged and maintained as an efficient conduit for sediment transport to the Gulf of Mexico. Times of distinct growth are in response to high flood years, when sediment is transported out of the navigation channel and spread through the natural

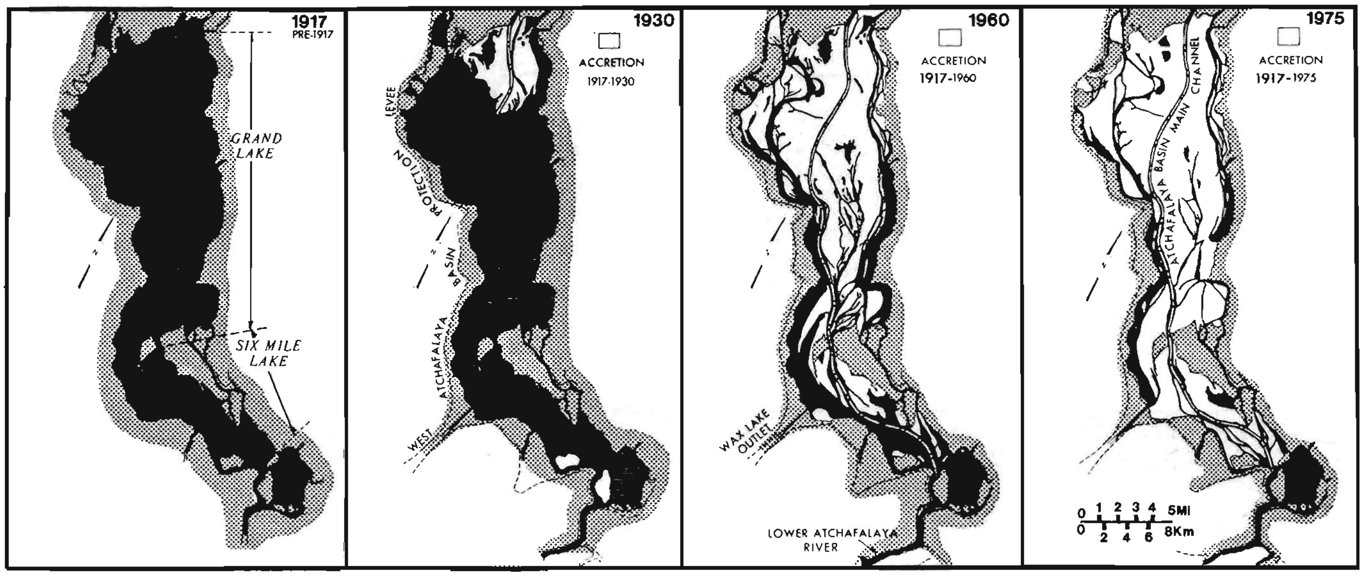


Figure 4. A record of filling of Grand Lake-Six Mile Lake in the southern Atchafalaya Basin with sand-rich lacustrine deltas (modified from Roberts *et al.*, 1980).

delta distributary network. During low water years, local dewatering and compaction, as well as sediment redistribution associated with winter cold front-generated waves, causes reductions in lobe elevations and apparent land loss (VAN HEERDEN and ROBERTS, 1980).

Marshlands around the perimeter of Atchafalaya Bay, which were deteriorating prior to the 1950s, are now actively accreting because of the availability of abundant suspended sediments. Turbid water is transported to the marshlands during high water level events associated with floods and water level set up caused by frontal passages during the winter months. Fronts are accompanied by strong winds, which cause wave-resuspension of sediment in coastal bays. Water level setup against the bay shoreline before the front passes forces turbid water into surrounding marshlands. The fact that the cold front season overlaps the period of maximum suspended sediment transport by the Atchafalaya River maximizes the availability of fluvial sediment to marshlands surrounding Atchafalaya Bay (MOSSA and ROBERTS, 1990). This back-water effect has enhanced substrate accretion and revitalized plant productivity in this area since the late 1960s and early 1970s.

Figure 8 illustrates a developmental history of the Wax Lake bayhead delta, which has been less modified by man's activities than its counterpart opposite the Lower Atchafalaya River Outlet. Progradation of this delta lagged behind the Atchafalaya delta because Wax Lake had to be filled with lacustrine delta deposits before significant quantities of sand and silt could be transported to Atchafalaya Bay.

Since the Atchafalaya delta appeared first and had the fastest initial growth (Figure 7), most detailed geomorphic and sedimentologic research has been concentrated on this feature (ROBERTS *et al.*, 1980b; VAN HEERDEN and ROBERTS, 1980; VAN HEERDEN, 1983; VAN HEERDEN *et al.*, 1983). More than two decades of study indicate that increases in delta area are largely related to fusion of sand-rich lobes by channel filling and upstream lobe growth. Figure 9 illustrates the results of this process (1976–1991) from the eastern part of the Atchafalaya delta, which displays minimal modifications by man's activities. Coring confirms that sand-rich deposits are added to the upstream ends of subaerial lobes as they fuse to become larger features. These lobes are composed primarily of distributary mouth bar and subaqueous levee deposits that became subaerial through overbank sedimentation and levee accretion. Present deposits of the Atchafalaya bayhead delta are thin (~3–4 m) because of limited accommodation space, have a limited (~1 m thick) prodelta facies, and consist mostly of silt/sand-rich distal bar, distributary mouth bar, and subaqueous levee deposits. Figure 10 is a cross section through the eastern part of the Atchafalaya delta constructed from vibracores. It illustrates the thin vertical sedimentary sequence and facies architecture of this bayhead delta.

The Atchafalaya River diversion of Mississippi River water and sediment has not only initiated a new delta through the progradational continuum of freshwater lacustrine deltas (Atchafalaya Basin fill) and bayhead deltas (Atchafalaya-Wax Lake deltas), but Atchafalaya River sediments are impacting downdrift coasts. Studies by WELLS and ROBERTS (1980), KEMP (1986), ROBERTS *et al.* (1989), and HUH *et al.* (1991) have documented renewed progradation of the eastern chenier plain where coastal retreat of 3–8 m/yr (MORGAN and LARIMORE, 1957) was characteristic prior to the significant input of Atchafalaya River suspended sediments to coastal Louisiana in the early 1950s. As more fine-grained sediments are transported westward, coasts that have been retreating throughout historical times are stabilizing or starting to prograde. Prograding coasts are fronted by a blanket of fluid

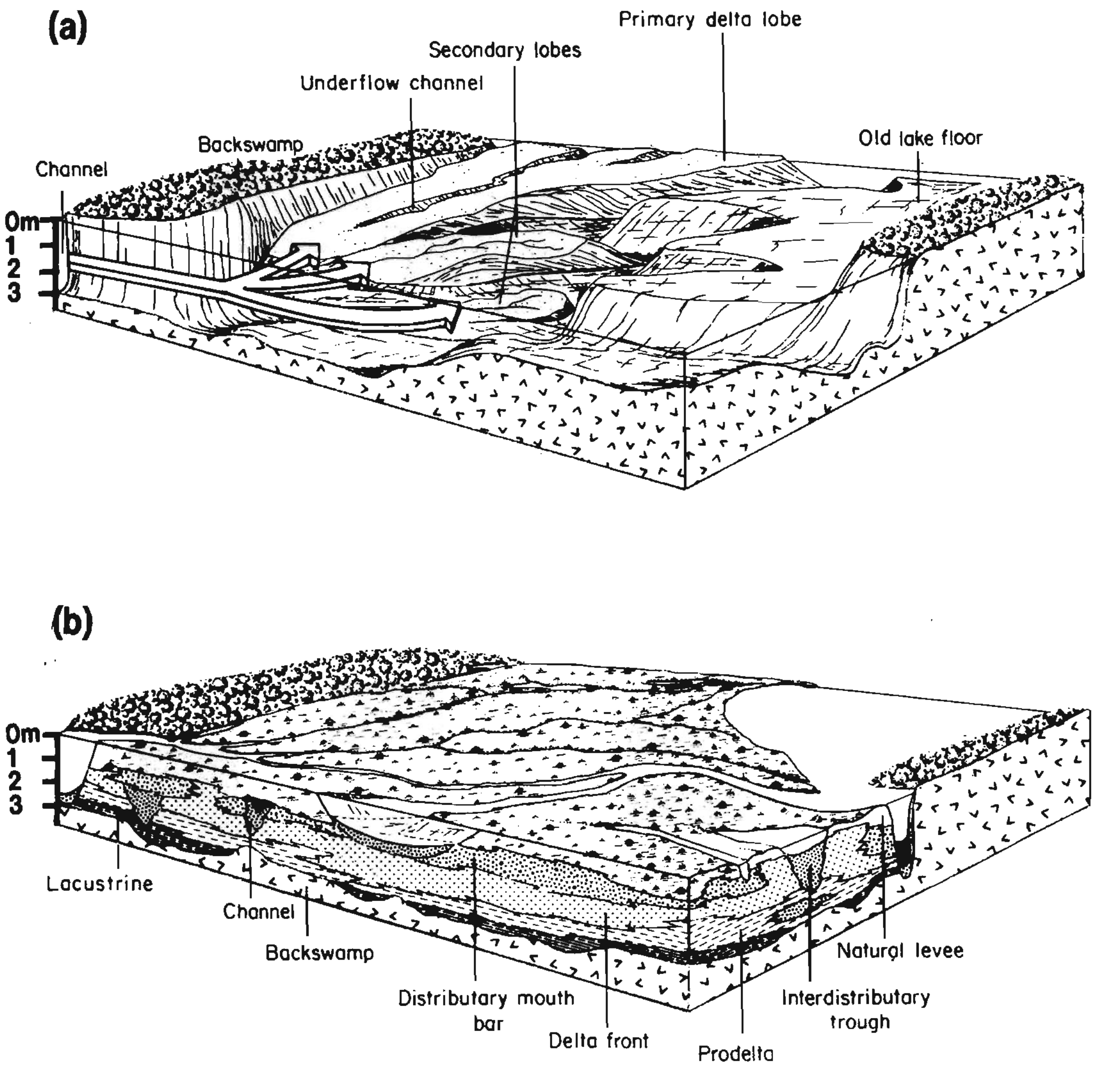


Figure 5. Schematic representation of lacustrine delta evolution illustrating (a) morphology of elongate lobes characteristic of these delta types and (b) sedimentary architecture of a fully developed delta (modified from Tye and Coleman, 1989).

mud that is transported shoreward, largely in response to processes associated with frontal passages during the fall and winter months, as documented by the studies cited above. This episode of renewed sediment supply to western Louisiana coasts is revitalizing the eastern chenier plain and causing coastal progradation of over 50 m/yr in very local areas since the mid-to-late 1980s (Figure 11). Although the zone of coastal progradation is lengthening and moving westward, recent studies of southwestern Louisiana coast shoreline dynamics by BYRNES *et al.* (1995) and MCBRIDE and BYRNES (1995) show that the coast is still dominated by alternating sectors of retreat (to 11 m/yr) and advance (to 20 m/yr). With continued input of Atchafalaya River suspended sediments to the coastal drift system, which has a net motion to the west, these areas of dynamic shoreline retreat are expected eventually to stabilize and then go into a progradational phase. As Figure 2 indicates, this response is to be expected throughout the fluvially dominated regressive phase of delta lobe development.

Shelf Stage Delta-Building

The Balize or birdfoot delta is the only modern example of an active shelf-stage delta (Figures 3 and 12). It began prograding over 1000 years ago (MCFARLAN, 1961; SAUCIER, 1963; T. TORNQVIST, *personal communication*) and assumed a southeasterly course between the relatively high topography established by the earlier St. Bernard lobe to the east and Lafourche delta to the southwest (Figure 1). These boundary conditions defined a narrow fairway that helped steer the delta into its present deep-water position near the shelf edge. Increasing accommodation space as the delta emerged onto the middle shelf caused delta progradation to slow and the sedimentary sequence of deltaic deposits to thicken significantly (from ~ 30 m to > 100 m).

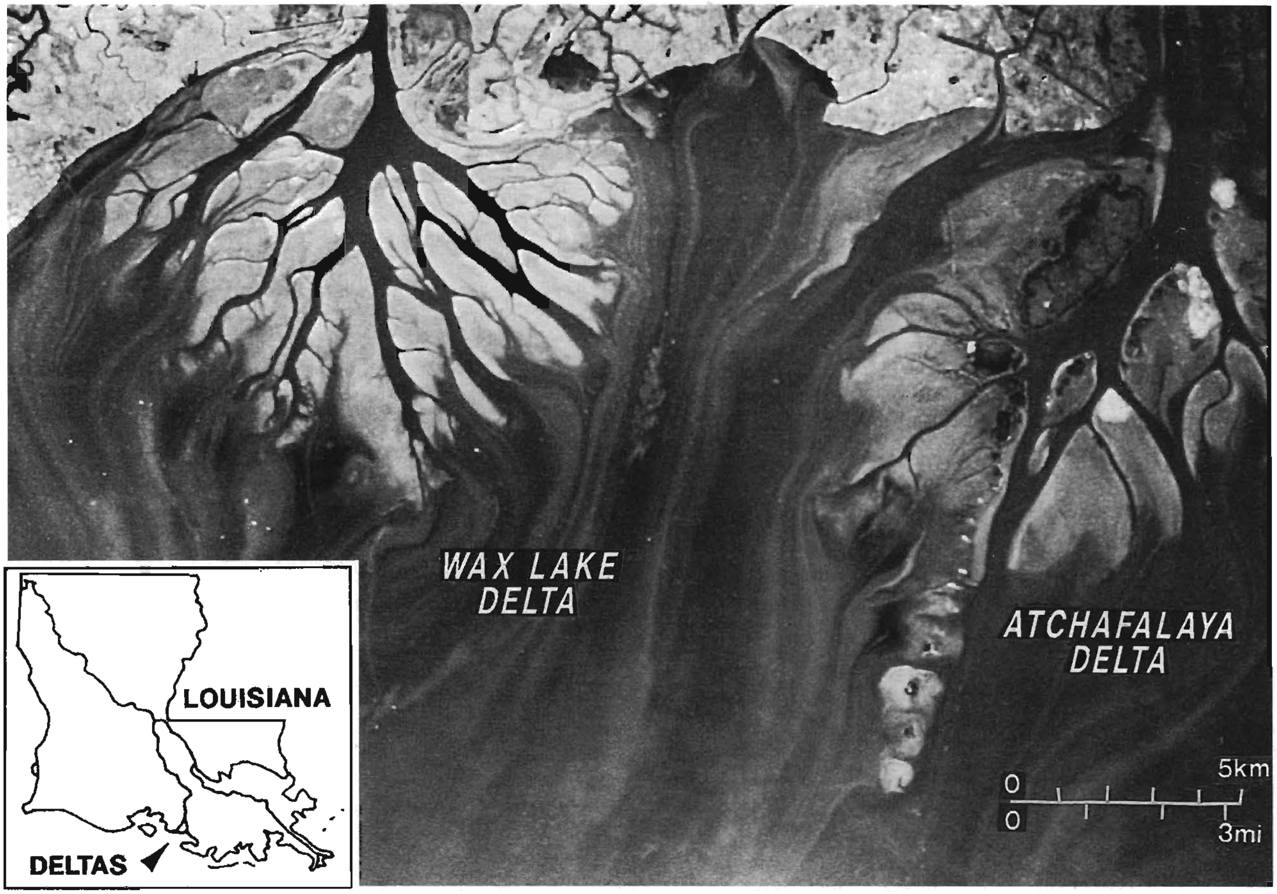


Figure 6. High altitude photograph of the Wax Lake and Atchafalaya bayhead deltas (December 1990). This photograph was taken following a cold front passage. Note the bay water streaming offshore in response to winds from the north.

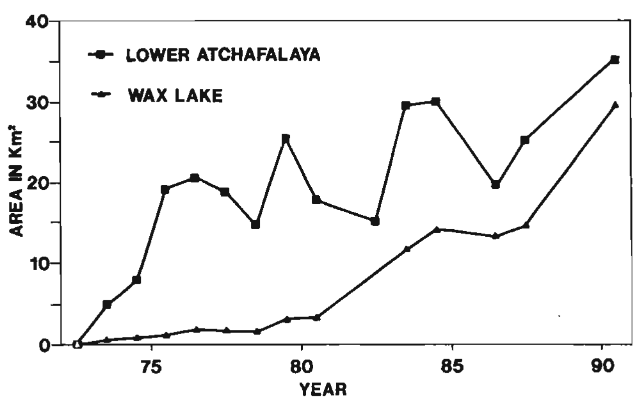


Figure 7. Atchafalaya and Wax Lake bayhead deltas subaerial delta growth curves expressed as area above mean low tide, 1972–1990 (Roberts and van Heerden, 1992).

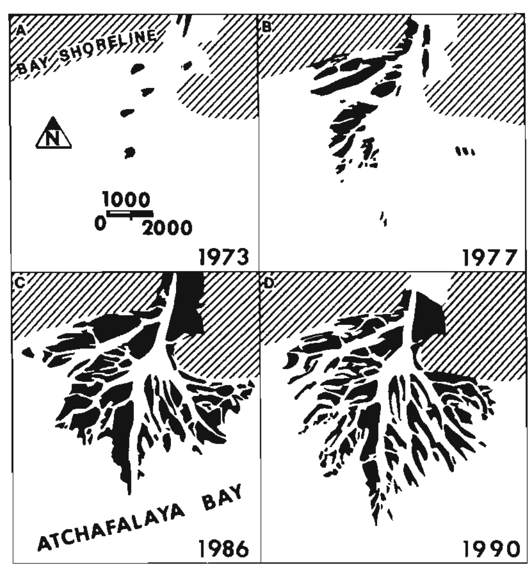


Figure 8. History of subaerial growth of the Wax Lake bayhead delta (Roberts and van Heerden, 1992).

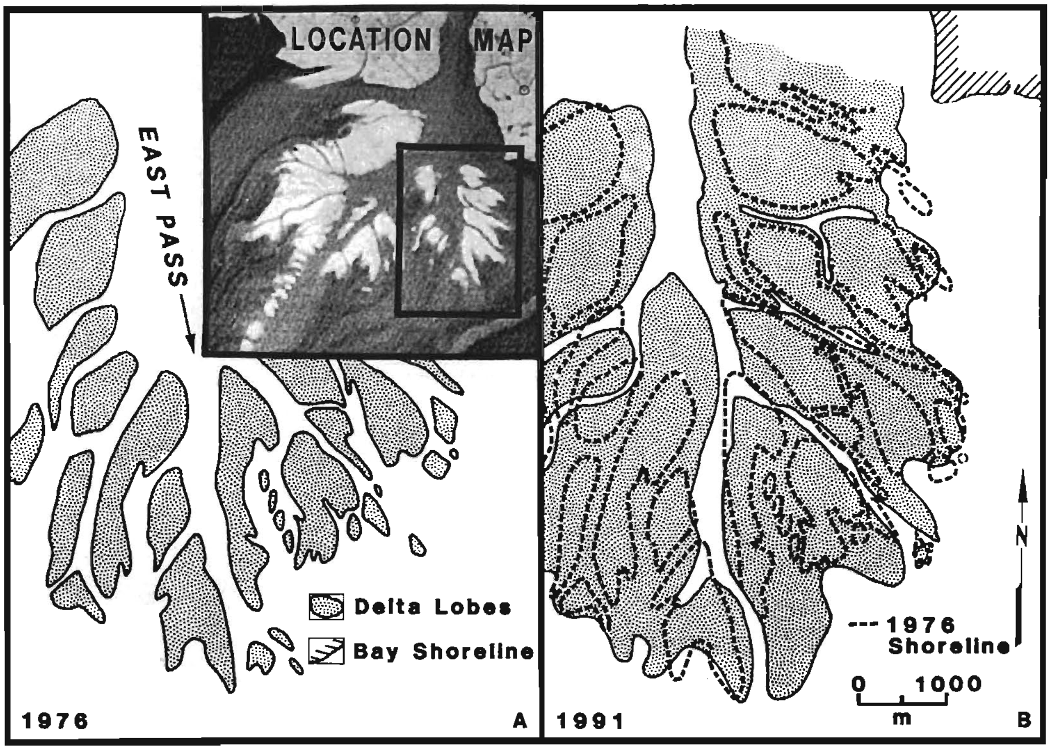


Figure 9. Comparison of sedimentary lobes in the eastern Atchafalaya delta (1976–1991) illustrating the process of lobe fusion and upstream accretion of sand-rich deposits.

Rates of deposition and general deltaic progradation have probably slowed in the Balize delta over the last century. Since 1850, KESEL (1988) estimates, a ~ 50% decrease in suspended load sediments transported by the lower Mississippi River has occurred. Changes in discharge have resulted primarily from land use practices and dam construction on tributaries. In addition, steady capture of flow by the Atchafalaya River, now controlled at 30% of Mississippi River discharge, has also diminished sediment availability to the Balize delta. Nevertheless, major distributaries of the delta are still actively prograding into the Gulf of Mexico, creating elongate distributary mouth bar sands (Figure 13), or bar finger sands (FISK, 1961), that thicken locally and produce vertically displaced prodelta deposits or mudlumps (MORGAN, 1961).

In contrast to the thick Balize lobe that has prograded to near the shelf edge, thinner inner shelf deltas, such as the Lafourche and St. Bernard, cover larger areas (11,310 km^2 vs 15,470 km^2; Figure 1) and have more numerous distributaries with facies that merge laterally. These deltas undoubtedly prograded at rates in excess of the 12–13 km/century rate typical of Southwest Pass progradation in the Balize delta, as determined from data presented by FISK (1961).

FISK (1955) recognized that the distributary mouth bar sands of the thin inner shelf deltas were different from those of the thicker and deeper water Balize lobe. He described the fused distributary mouth bar sands from the numerous closely spaced bifurcated distributaries typical of these deltas as "delta-front sheet sands" (Figure 14). These sands, typically 6–20 m thick, are the major sand-rich facies of inner shelf deltas such as the Lafourche. Both the modern shelf-stage Balize delta and earlier inner shelf counterparts display a typical coarsening-upward sequence associated with the progradation of distributary mouth bar sands over a fine-grained prodelta platform. Unlike the thicker Balize delta, channels of thin inner shelf deltas frequently cut completely through their distributary mouth bar deposits.

WELDER (1959) and COLEMAN and GAGLIANO (1964) documented the thin depositional units that cyclically prograde levees and fill interdistributary bays and other shallow accommodation spaces that occur stratigraphically above the thicker coarsening-upward delta sequence described above. During the early growth stage, these depositional features receive primarily suspended load sediments through small breaks in the channel banks and levees. Later, as the break widens and deepens, coarser sediments are introduced to the shallow bays flanking the river channel. WELDER (1959) initially described the process by which overbank sedimentation forms substantial areas of marshland in the Balize delta. COLEMAN and GAGLIANO (1964) later explained the cycle of deposition and deterioration associated with subdeltas or bayfills. These features have been responsible for most of the marshlands associated with the Balize delta. Figure 12 illustrates the cyclic depositional features of the modern birdfoot delta and the dates they were initiated. Because a variety of terms are used in the scientific literature to describe these

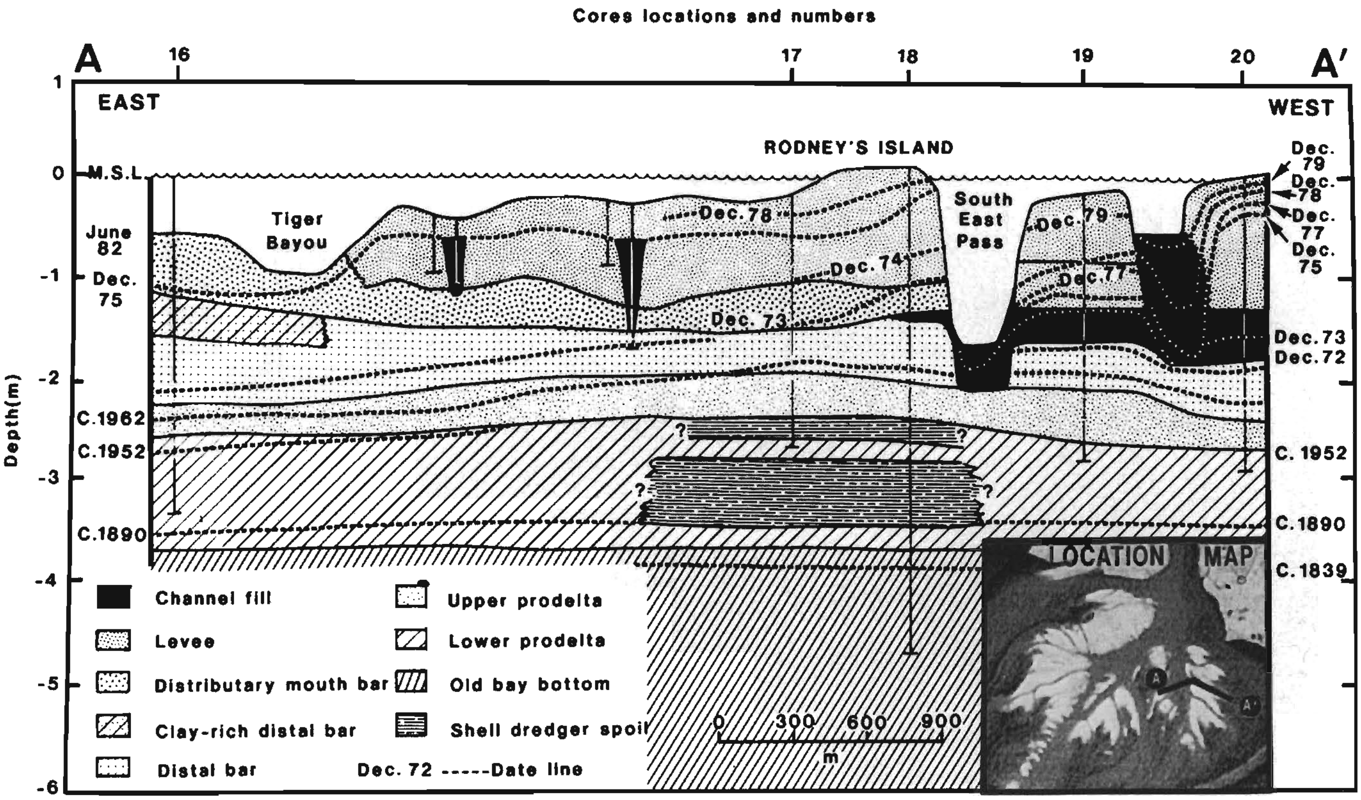


Figure 10. Stratigraphic cross section from the eastern sector of the Atchafalaya delta as prepared from a vibracore transect. Coring sites are designated on the cross section (modified from van Heerden, 1983). Chronostratigraphic surfaces determined by historical bathymetry of Atchafalaya Bay and surveyed profiles across the delta.

depositional forms, it is appropriate to define terms used in this discussion. Crevasse-splays/overbank-splays are small-scale depositional forms that develop from flood waters flowing out of the channel bank, overtopping and scouring the natural levee, and building a fan-shaped extension of the levee surface flanking the channel. In the initial stages, one of these features may appear as illustrated in Figure 15a. If the natural levee is narrow and separates the channel from a well-defined open water area (*e.g.*, interdistributary bay), a splay will develop that mimics larger deltas. Figure 15b shows one of these forms developing in the subsided proximal part of a much larger subdelta. The overbank splay in Figure 15b scoured through Bryant Bayou in the Cubit's Gap bay-fill in 1975. Within two decades, it has filled the accommodation space provided by the open water area between Bryant Bayou and Rafael Pass. This class of depositional feature is rarely active for more than 2–3 decades, usually has a thickness of 2–3 m, and covers an area of less than 15 km². Similar but larger depositional features fill the bays between major distributary channels. These features develop from a crevasse or breach in the natural levee adjacent to a large bay flanking the channel. Under these conditions successive river floods will scour a channel deep enough to allow a major depositional feature to develop. As COLEMAN and GAGLIANO (1964) point out, these subdeltas have a cycle of deposition and deterioration that mimics the larger delta lobe cycle schematically explained in Figure 2. However, subdeltas operate on a deposition-abandonment cycle that lasts about 150–200 years, develop sedimentary sequences from 5 to 20 m thick (usually ~ 10m), and cover areas of up to 300 km² (WELLS *et al.*, 1983).

Using the Cubit's Gap subdelta as an example, Figure 16 illustrates the historical development of this feature. It started in 1862 from a small man-made cut in the Mississippi River bank adjacent to Bay Rondo (WELDER, 1959). A major flood in 1868 widened (to ~ 200 m) and deepened the break, allowing the introduction of significant sediment into the bay which was approximately 10 m deep. By the late 1800s a delta characterized by bifurcating channels and intervening sand-rich lobes was rapidly prograding into the bay (Figure 16). In 1884, roughly 20 years after the initial levee break, the Cubit's Gap subdelta looked remarkably similar to today's Wax Lake bayhead delta prograding into Atchafalaya Bay (Figure 5), which presently has a history of about 20 years of subaerial growth (1976–1996). Rapid progradation in the Cubit's Gap subdelta continued into the mid-1940s. At that point, the channel network steadily began to lose efficiency, and delivery of sediment to the system was not sufficient to offset processes of subsidence driven primarily by compaction and dewatering (KUECHER, 1994). Marshland

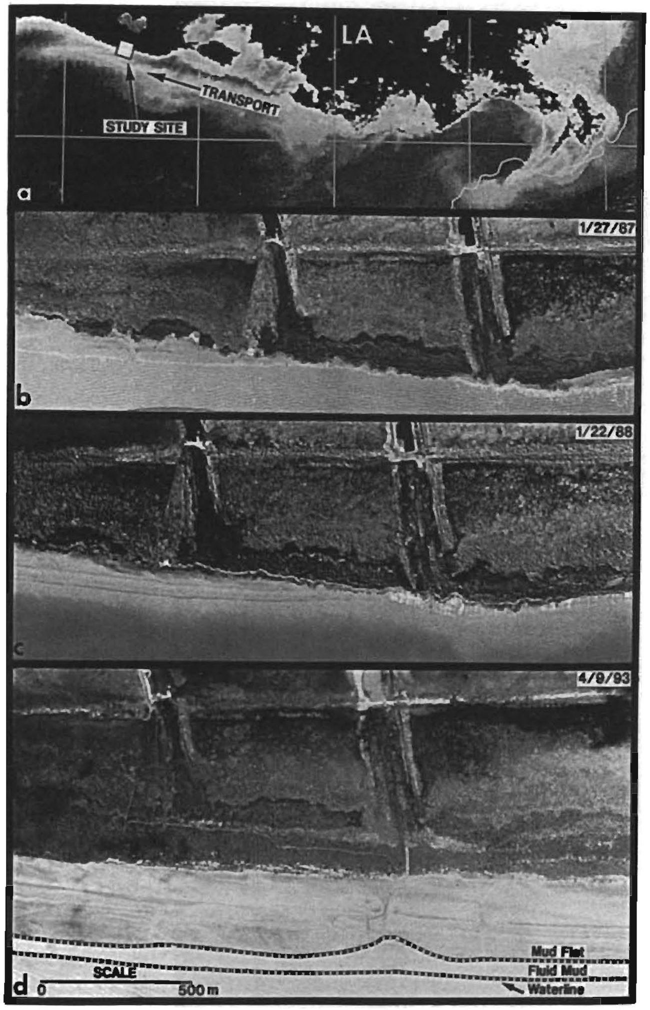


Figure 11. A series of photographs of the eastern chenier plain coast illustrating rapid progradation between 1987 and 1993. In this sector of the coast, average progradation rates were about 50 m/yr during this period. Fine-grained sediments supplied by the Atchafalaya River are responsible for these dynamic coastal changes.

started disappearing from the oldest proximal part of the system, causing rapid enlargement of open water areas between the narrow levees of major subdelta distributaries (Figure 16). By the late 1980s approximately 75% of the original marshland area of the Cubit's Gap subdelta had disappeared. As a consequence of subsidence and interdistributary bay development within the proximal part of Cubit's Gap subdelta, a new generation of overbank splays started filling this newly developed accommodation space (Figure 14). As discussed previously, the life cycle of these smaller depositional forms is measured in decades, and they are only a couple of meters thick. Despite this new generation of sedimentary features within the Cubit's Gap subdelta, progressive inefficiency of the sediment delivery network and on-going subsidence finally prevail to cause marshland disappearance and redevelopment of an open bay environment, which may eventually attract another subdelta.

Delta Front Instability

With rates of delta front progradation that approximate 125 m/yr (FISK, 1961) and sediment accumulation rates as high as 1 m/yr near distributary mouths (COLEMAN *et al.*, 1991), it is not surprising that processes of sediment instability are important modifiers of the sedimentary record in this dynamic setting. Although MORGAN (1961) clearly showed that dense distributary mouth bar sands differentially load thick deposits of underlying prodelta clay to produce mud diapirs (mudlumps), it was not until the 1970s and early 1980s that delta front instabilities were fully recognized and assessed. SHEPARD (1955) was the first to recognize that gullies radiate down-slope from each distributary. After his initial observations, availability of high resolution seismic and especially side-scan sonar data provided the data base for recognizing the regional importance of instability processes in transporting sediment from shallow to deep parts of the shelf. Figure 17 illustrates the distribution of sediment instability features of the low-sloping (< 1° and usually < 0.5°) delta front of the prograding Balize delta lobe. Rapid deposition of sediments from major distributaries is the primary condition that leads to sediment instability. Loading of the upper delta front with under consolidated and gas-prone fine-grained sediments is the primary condition that causes slope failure and down-slope sediment transport (ROBERTS *et al.*, 1980). The major instability features are retrogressive submarine slides (Figure 18). As discussed in PRIOR and COLEMAN (1978), the source area for sediment is characterized by slumps and blocky bottom topography that smooths seaward toward distal depositional lobes. Figure 18 illustrates the major components of these important delta front sediment transport and deposition systems. Complex lobes of sediment from these retrogressive slide systems reach thicknesses of up to ~ 60 m on the distal shelf to upper slope. Comparisons with historical bathymetry seaward of the Balize delta suggest that these thick mudflow deposits accumulate over time periods measured in decades (COLEMAN *et al.*, 1980) and without question represent products of the most important sediment transport-deposition process associated with the advancing deep-water shelf phase delta. Because of the direct association of thick, rapidly deposited, and under consolidated prodelta deposits with sediment instability, thin and widespread delta lobes of the inner shelf would not be expected to exhibit the retrogressive mudslides associated with the Balize delta.

Delta Abandonment and Deterioration: Marine-Dominated Transgressive Phase

As a delta lobe evolves, its distributaries continue to branch, reducing efficiency of the channel network to transport water and sediment through the system. This progressive hydraulic inefficiency, plus a reduction in gradient as a result of continued progradation, promotes eventual stream capture upriver. When stream capture occurs, as with the

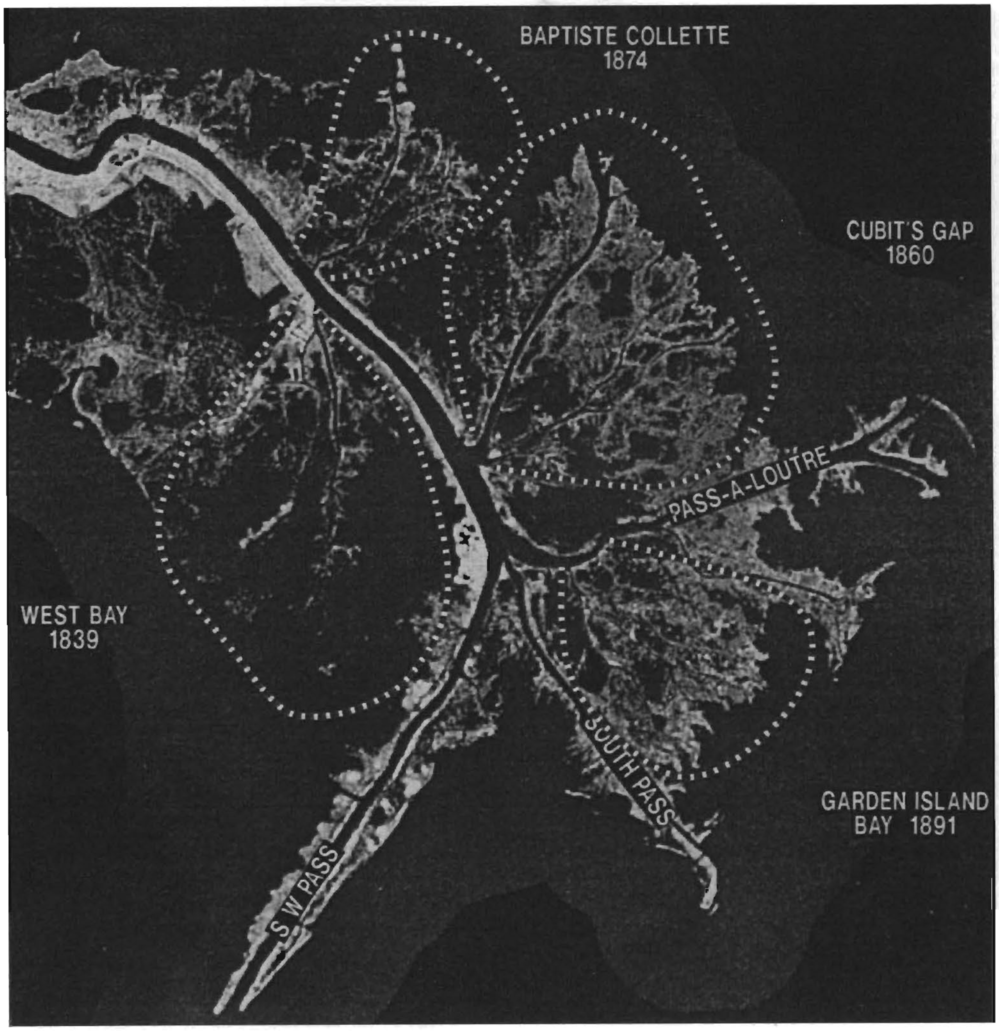


Figure 12. Landsat TM 1993 image (composite of Bands 7,5,3) of the Balize delta showing its major distributaries and subdeltas. Dates refer to times subdeltas were initiated.

Atchafalaya River now taking sediment and water from the Mississippi, the delta eventually shifts from active accretion and progradation to an evolutionary stage dominated by subsidence-driven processes and marine reworking (Figure 2). This progressive abandonment of a delta lobe by the river that built it is followed by predictable changes in the delta lobe surface and configuration of its perimeter. Although early workers clearly understood that deltas and subdeltas evolved through constructive and destructive phases (RUSSELL, 1936; FISK, 1955; SCRUTON, 1960; COLEMAN and GAGLIANO, 1964), it was not until the early 1980s that researchers focused on the transgressive sand bodies that develop from delta lobe abandonment (KHAN, 1980; NEESE, 1984; PENLAND *et al.*, 1985; ISACKS, 1989; and others). PENLAND and BOYD (1981) and later Penland et al. (1985) graphically organized the changes a delta undergoes from its active progradational stage to complete submergence, with emphasis on the evolution of transgressive components (beaches, spits, barrier islands, and submarine shoals). If one observes the configurations of deltas that presently comprise the Holocene deltaic plain (Figure 19), it is possible to identify delta deterioration and associated transgressive deposits in various stages of development. Although Figure 2, the schematic representation of the delta cycle, illustrates that the regressive and transgressive phases are of equal duration, they may in fact be quite different. Thin inner shelf deltas containing limited prodelta clay deposits would be expected to have a prolonged marine-dominated transgressive phase as compared to the Balize delta, with its thick compaction-prone prodelta deposits. However, in order to present a simple version of the delta cycle concept, a symmetrical growth and deterioration curve is used to illustrate the delta cycle in Figure 2. Figure 19 uses components of the Holocene delta complex to illustrate the progressive changes a delta undergoes as the collective processes of subsidence and marine transgression become dominant with time.

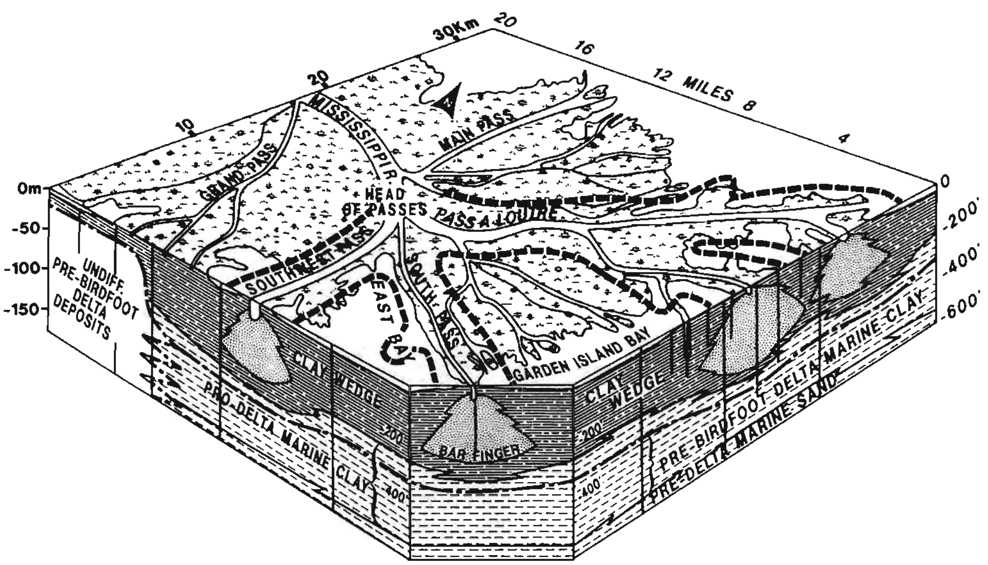


Figure 13. Block diagram of elongate distributary mouth bar sands, or bar-finger sands (Fisk, 1961), illustrating the elongate sand trends that develop in river-dominated deltas prograding into deep water (modified from Fisk *et al.,* 1954).

Important Effects of Subsidence

As early as the 1930s and 1940s investigators, especially R.J. Russell, postulated that the massive sediment load of the Mississippi River caused an isostatic response resulting in uplifted inland terraces and down-warped deltaic deposits at the coast and offshore. From coastal plain and offshore borings FISK and MCFARLAN (1955) and FISK (1955) deduced that down-warping of the pre-Quaternary surface accommodates a seaward-thickening wedge of younger deltaic deposits. On a more localized scale, FISK (1961) demonstrated that distributary mouth bar sediments of the Balize delta differentially loaded underlying plastic prodelta clays to cause abnormal thickening of bar deposits and displacement of clays. Seismic data and drilling in the northern Gulf of Mexico Basin have confirmed that this depositional province has repeatedly accommodated 1000s of meters of shallow-water deltaic sediments arranged in discrete depocenters (WOODBURY *et al.,* 1973). On these scales, regional to local, subsidence under load has been shown to be an important component of relative sea level change. In addition, recent work by KUECHER (1994) has demonstrated that early consolidation-settlement of highly organic and clay-rich facies associated with a newly deposited delta is a primary component in the combined processes of subsidence. Therefore, in the marine-dominated transgressive phase of delta evolution (Figure 19), postdepositional dewatering and compaction are generally the most important components of relative sea level change (subsidence) that drives land loss and the marine transgres-

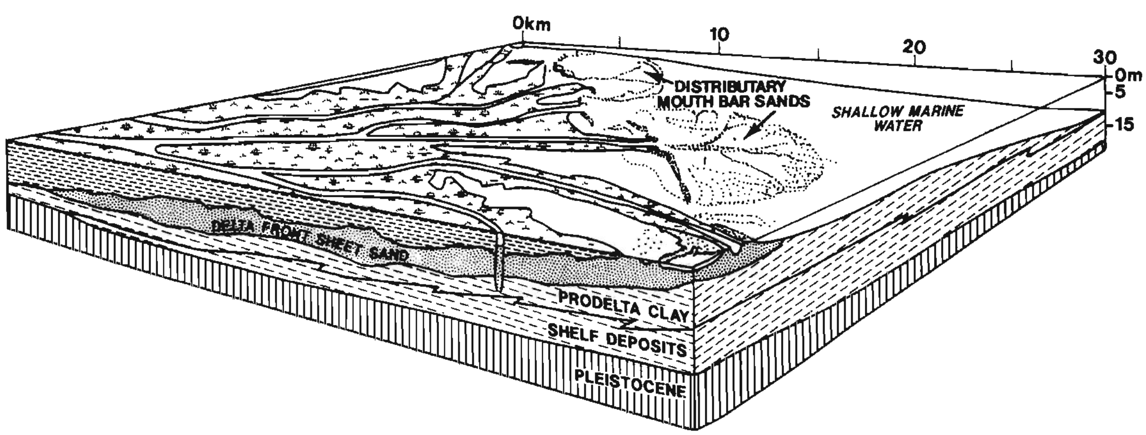


Figure 14. Block diagram depicting a delta front sheet sand associated with the numerous and closely spaced distributaries of a thin inner shelf delta, such as the Lafourche delta (modified from Fisk *et al.,* 1954).

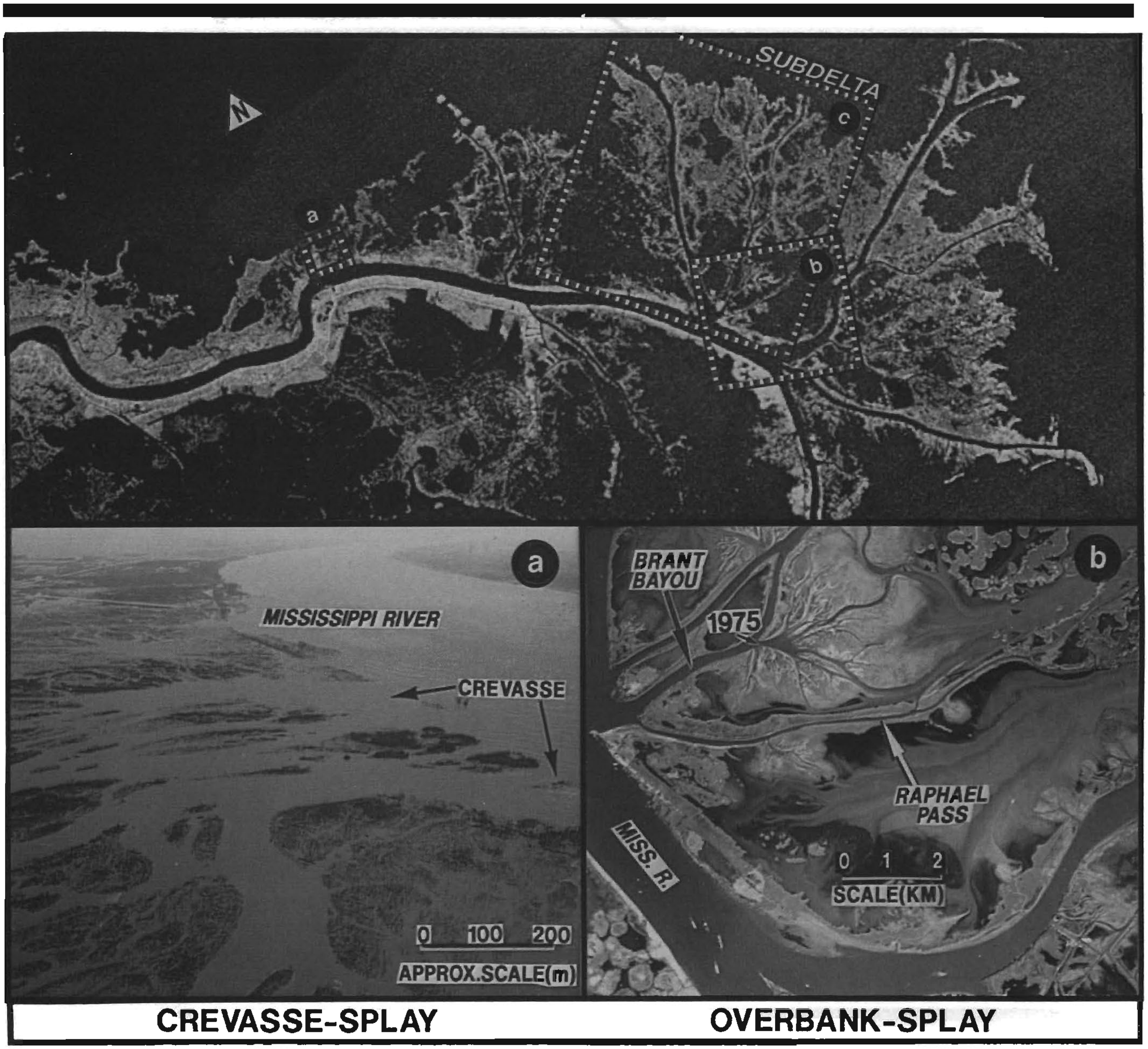


Figure 15. Crevasse-splays and the Cubits Gap subdelta of the Balize delta. (1) A crevasse-splay that is in the early stages of development. Note the break in the natural levee and numerous small channels that are splaying sediment that is extending the natural levee bayward (photograph taken in 1993, looking south). (2) This small splay broke through the levee of Bryant Bayou in the Cubits Gap subdelta in 1975 (photograph taken in November 1993). (3) The Cubit's Gap subdelta. Figure 16 is a developmental history of the Cubits Gap subdelta.

sion in the Mississippi River deltaic plain (KUECHER, 1994). Subsidence under load, at the scale of a delta lobe, larger scale basinal down-warping, and eustatic sea level rise are also factors that drive the marine transgressive phase of delta evolution.

Because sediment compaction-settlement phenomena are of primary importance in subsidence of a delta, the thickness of Holocene deposits over oxidized and less compactable late Pleistocene deposits is an important condition that affects regional subsidence of the delta plain. It has been demonstrated (ROBERTS, 1985; ROBERTS *et al.,* 1994) that areas of the delta plain overlying thick Holocene deposits of the entrenched alluvial valley subside at higher rates than delta plain areas outside the valley (Figure 20). This relationship probably affects the relative lengths of time needed for completion of the regressive and transgressive phases of any delta cycle. For example, delta lobes that have been built within the confines of the entrenched alluvial valley (*e.g.,* Lafourche delta) may have shorter marine-dominated transgressive phases because of accelerated subsidence rates as compared

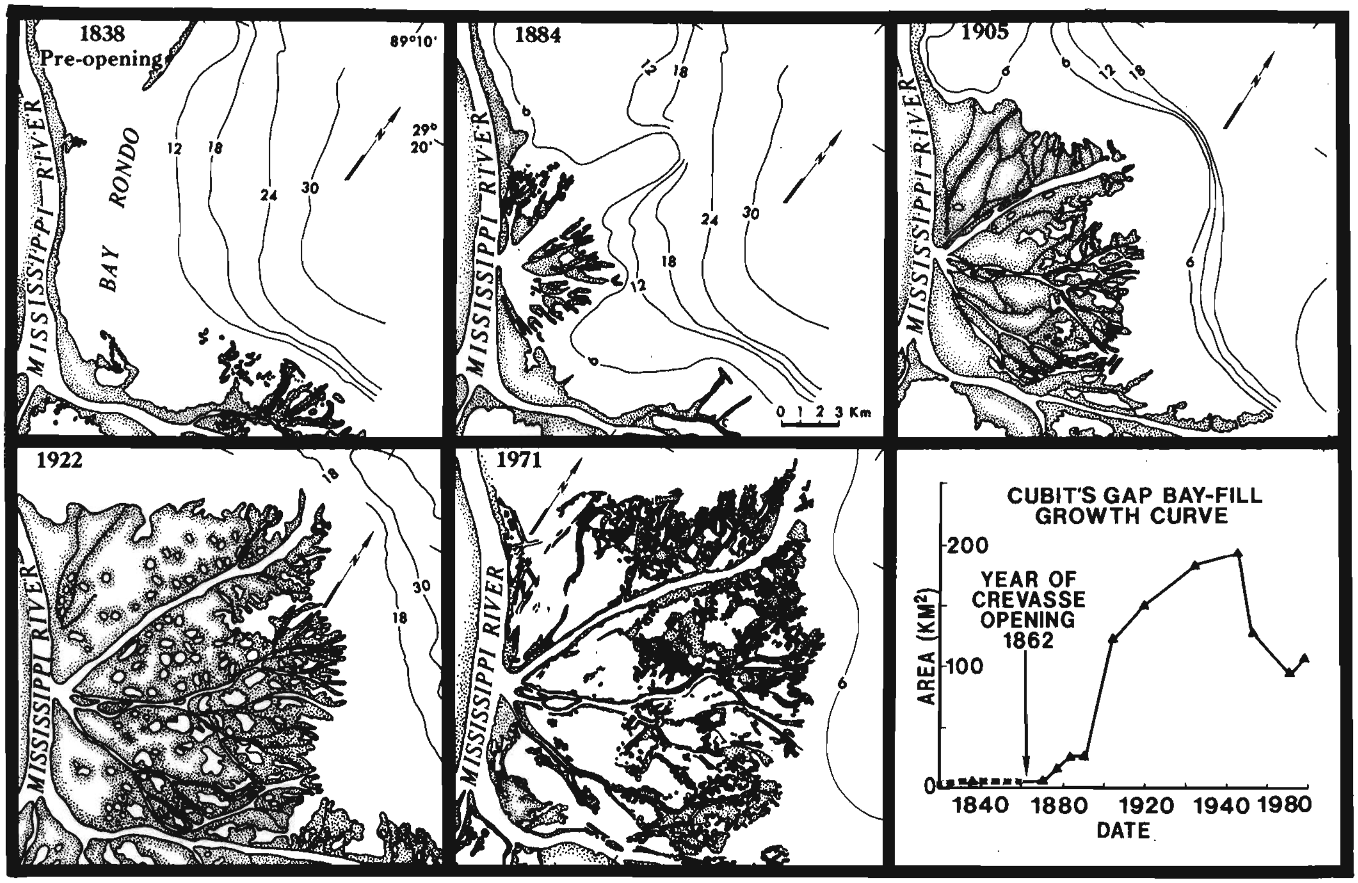


Figure 16. History of the Cubits Gap subdelta (modified from Wells *et al.,* 1983).

to lobes developed over a shallow Pleistocene base (*e.g.,* St. Bernard delta). Indications are that because of its thick base of compaction-prone prodelta clay the modern Balize delta would disappear very quickly if the Atchafalaya River stream capture were allowed to divert most of the Mississippi River water and sediment, as it surely would have done by now without man's intervention.

Sediment Reworking During the Regressive Phase

During the period of rapid distributary advancement and overall delta front progradation, local reworking in an active delta lobe does occur. COLEMAN and GAGLIANO (1964) discussed local transgressions associated with the cyclic filling of bays flanking the river and between major distributaries. Products of the abandonment, subsidence, and marine transgression of these subdeltas are thin beaches and oyster reefs. As the channel network of subdeltas like Cubit's Gap lose efficiency, subsidence causes interior open water areas to expand and waves to rework channel mouths into small beaches (usually < 1.5 m thick) that transgress across the subsiding subdelta surface. The highest topography on this progressively submerging landscape is associated with natural levees of the channel network. As these features submerge, oyster reefs commonly form on their crests as brackish-to-marine conditions progressively intrude upon the relic freshwater deposits.

On the larger scale, a small amount of sediment reworking takes place at the mouths of major distributaries. The beach at South Pass (Figure 21) is a good example of this limited sand body that represents a wave reworked top of the underlying distributary mouth bar. This particular sand body is about 2 km long, 2–3 m thick, and contains abundant detrital organic material. At the delta lobe scale, these sands are overshadowed in thickness and areal extent by the underlying distributary mouth bar sediments on which they rest.

Deltaic Headland Retreat—Beach, Spit, and Barrier Development

Figure 19 depicts a delta lobe in the first stages of subsidence and reworking by marine processes, primarily waves. In this illustration, transgression is taking place on the Lafourche delta lobe by erosion of the Caminada-Moreau headland. Sands derived from this process are transported laterally to build flanking barrier islands and recurved spits. Regressive deposits associated with Bayou Lafourche and its distributaries are the main sources of coarse sediment for beach, spit, and barrier development (GERDES, 1982). The beach along the Caminada-Moreau deltaic headland is thin

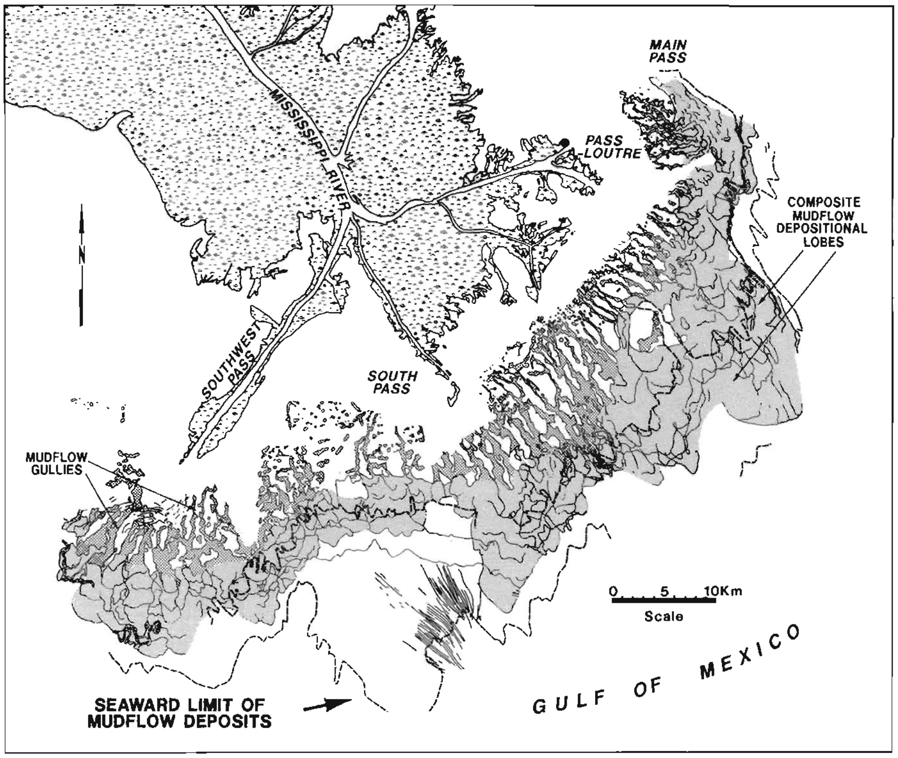


Figure 17. Distribution of mud flow gulley systems and their associated down-slope deposits (modified from Coleman *et al.* 1980).

with small washover fans that have been deposited on the back-beach marsh surface. McBride *et al.* (1992) document from historical map studies that coastal retreat in this area was > 3 km between the years 1887 and 1988, a rate of ~ 33 m/yr. With a sediment supply area retreating at this rate, coupled with subsidence-related enlargement of bays, barriers quickly detach and migrate landward. They also migrate downdrift by longshore drift and spit formation. During the lateral migration process, deep tidal passes are filled with relatively coarse sediment as marshlands retreat, and the

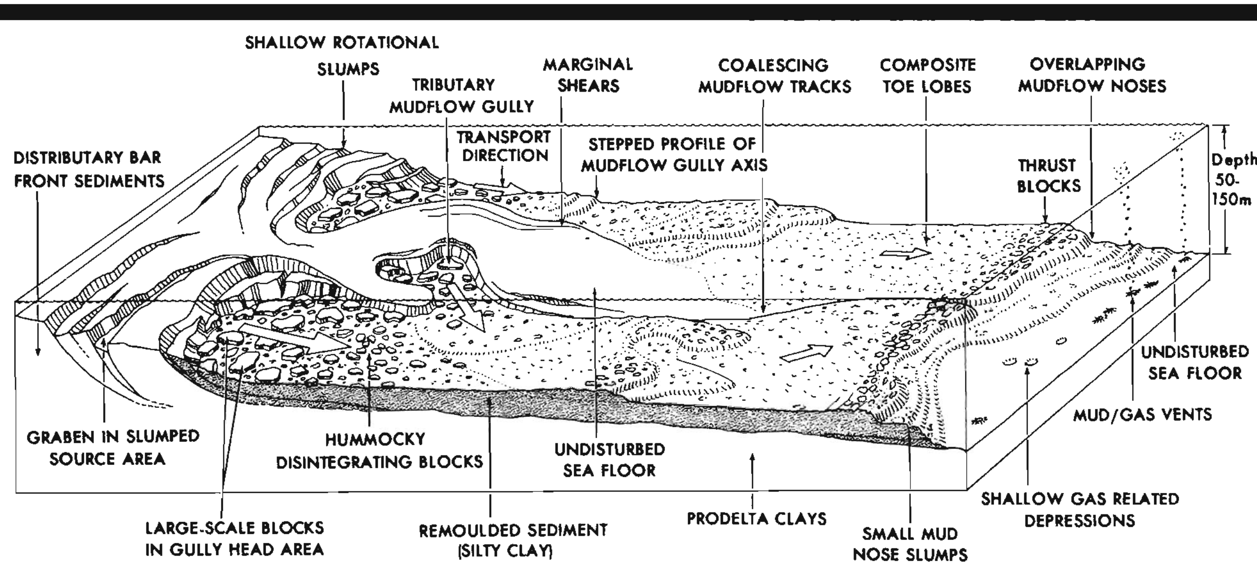


Figure 18. Block diagram showing the salient components of a retrogressive mudslide system typical of the Mississippi River delta front. The system has been greatly shortened for illustration purposes (Roberts *et al.,* 1980). Length to width ratios of these mudslide systems are 20–30:1.

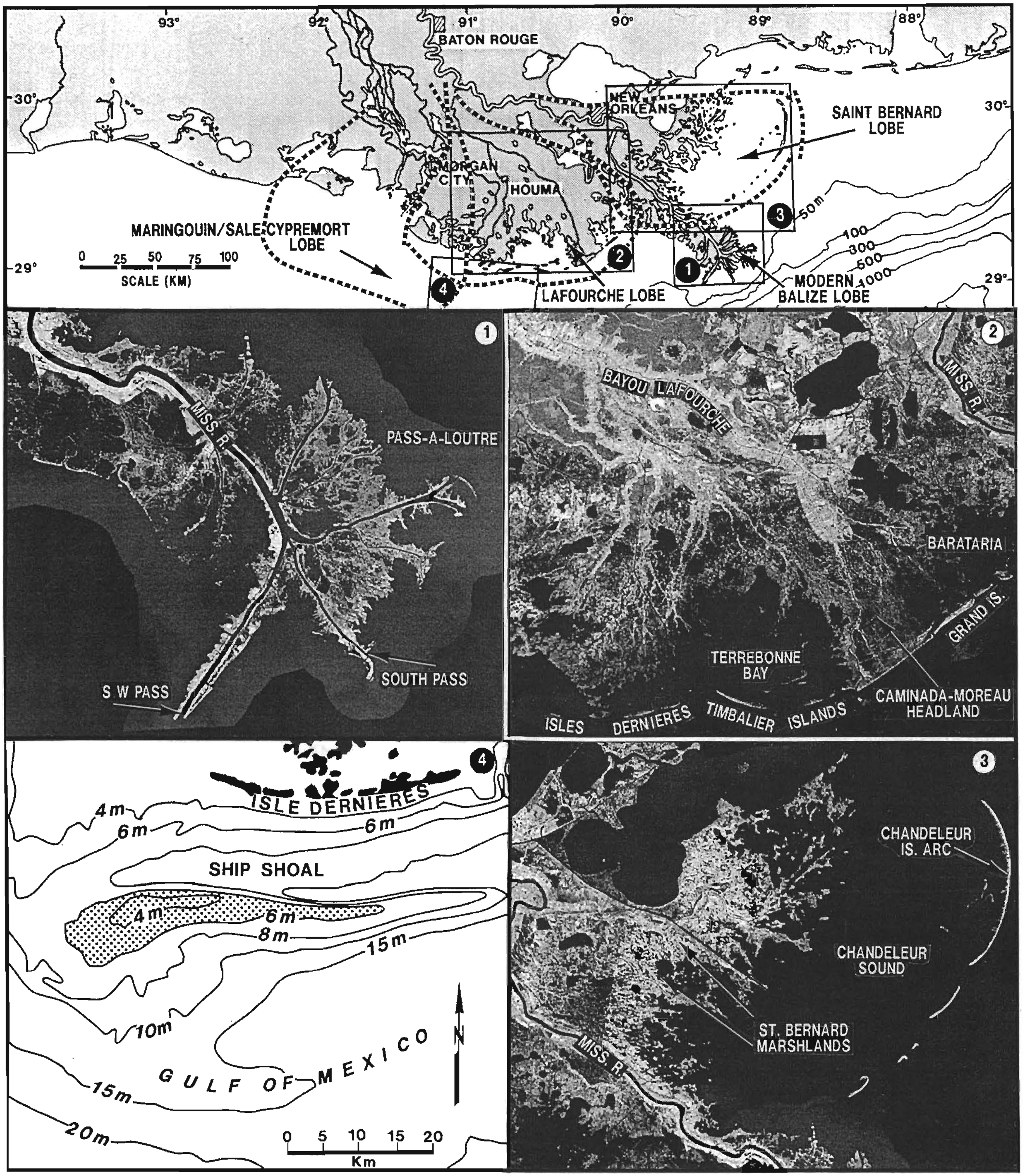
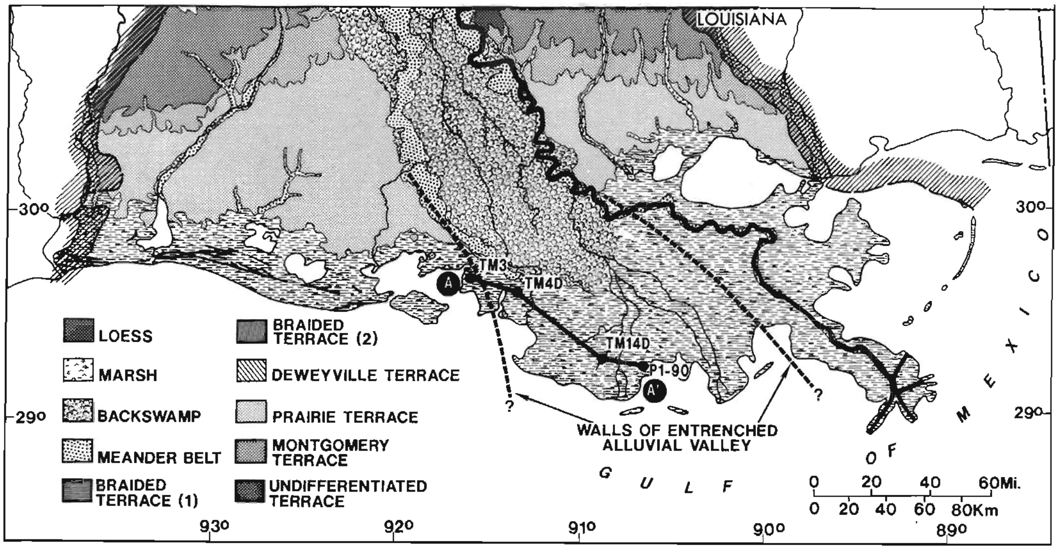


Figure 19. LANDSAT TM 1993 images (composite of Bands 7, 5, 3) from sectors of the Mississippi River deltaic plain showing delta complexes in various stages of abandonment, subsidence, and transgressive reworking. (1) The modern Balize delta which is still prograding. Only localized areas experience marine inundation and reworking. (2) The Lafourche delta is in the early marine-dominated transgressive phase. Part of the Lafourche delta is still providing sediment to flanking spits and barriers by processes of marine reworking. (3) The Chandeleur barrier island arc and remaining marshlands of



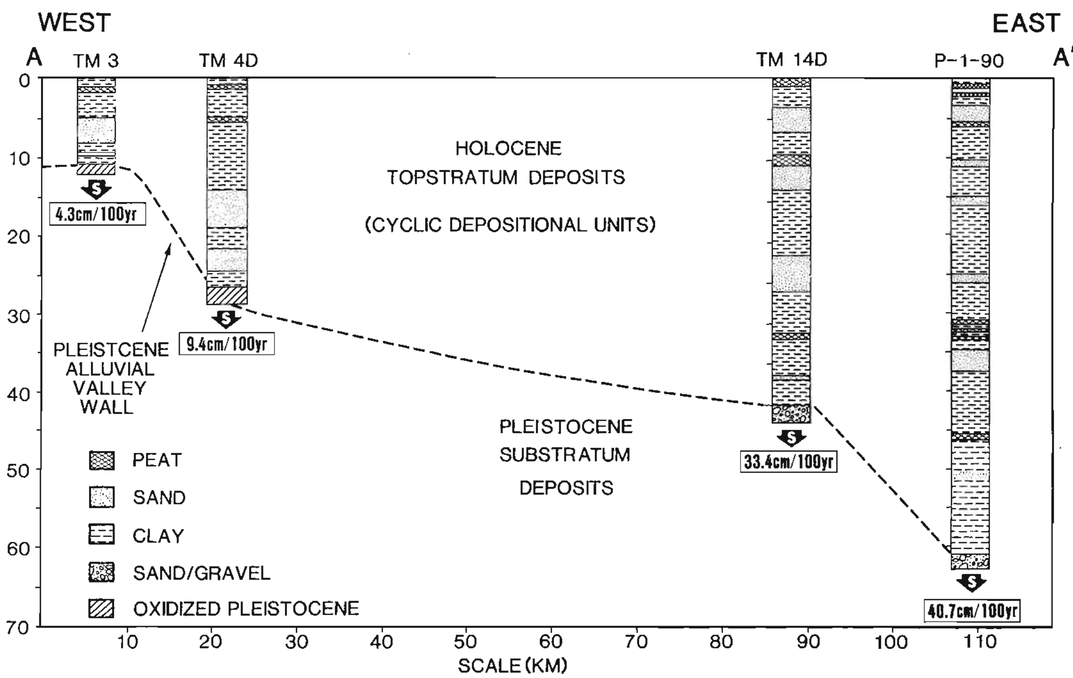


Figure 20. (Top) Map of the Mississippi River deltaic plain and southern alluvial valley showing the approximate position of the entrenched alluvial valley beneath delta plain deposits and the location of borings and cross section. (Bottom) A west-to-east transect of borings showing the influence of Holocene sediment thickness on subsidence rates as determined from ^{14}C dates (modified from Roberts *et al.,* 1994).

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the St. Bernard delta represent a late stage of the delta cycle, when the former delta surface has largely submerged beneath brackish-marine waters and a discontinuous barrier island arc stratigraphically overlies the distal part of the once active delta. (4) The final event in the delta cycle is submergence of the last barrier island remnant to become a submarine shoal. Ship Shoal of the former Maringouin delta is a good example of this final phase of the delta cycle.

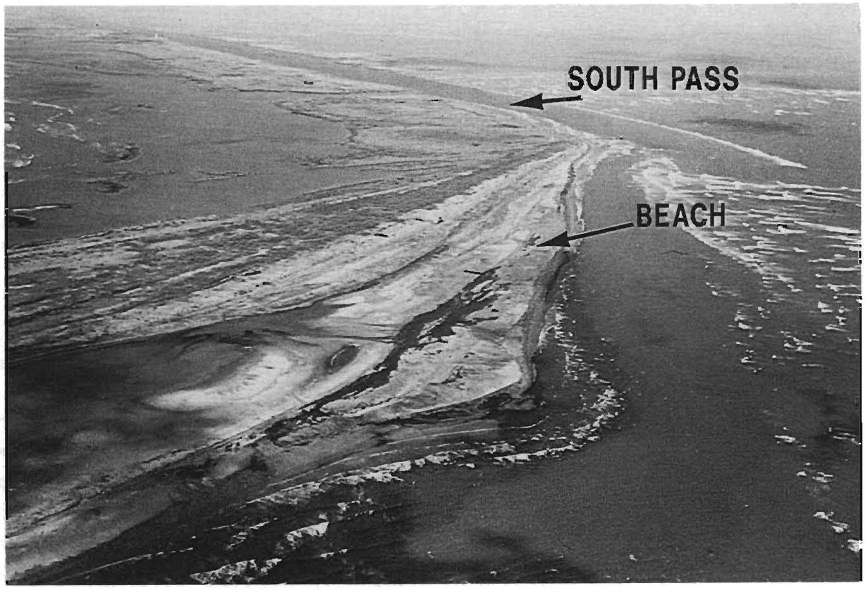

Figure 21. The beach at the mouth of South Pass in the modern Balize delta, which represents the wave-reworked top of the advancing distributary mouth bar.

bay tidal prism increases with time. Tidal passes shift laterally with migrating barrier islands. As KUECHER (1994) discovered, regressive sedimentary facies that filled interdistributary bays are more compaction-prone than those of the distributaries and their levees. Therefore, relative sea level rise, driven primarily by subsidence, occurs at a greater pace in these areas, which favors rapid opening of bays such as Timbalier and Barataria (Figure 19). As the tidal prism volume associated with these bays progressively increases with time, the volume of sediment stored in ebb-tidal and flood-tidal deltas effectively robs sediment from barrier islands, which are generally < 6 m thick (HOWARD, 1982). In the terminology of the transgressive model of PENLAND and BOYD (1981) the above events represent a stage 1 response.

Barrier Island Arc Formation

As the transgressive phase continues, it is evident from the St. Bernard delta example (Figure 19) that the marsh shoreline undergoes net displacment landward more rapidly than the wave- and subsidence-driven barrier islands. At the beginning of the transgressive phase of the delta cycle these shorelines start together. With time and the complicated processes of marshland deterioration driven by subsidence, lack of sediment input, and salt water intrusion, the complex perimeter of land behind the barrier islands retreats, leaving the barriers stranded in open water.

At this point in the evolutionary history of a delta lobe, transgressive sand bodies, reworked from the once active perimeter of the delta, have migrated landward and up-section over back-barrier brackish to marine bay deposits; that is, the transgressive sands have become stratigraphically detached from their source of sediment, the distributary mouth bar and channel sands of the underlying delta. As barrier islands move landward and sediments stored in flood-tidal and ebb-tidal deltas are reworked, a semi-continuous arcuate barrier develops.

The Chandeleur Islands of the St Bernard delta lobe represent the arcuate barrier stage of development (Figure 22). At present, the Chandeleur barrier island arc is approximately 75 km long and during an 84-year period (1885–1969) retreated at average rates of 9.1 m/yr in the south and 7.2 m/yr in the north (KAHN and ROBERTS, 1982). More recent research by MCBRIDE and BYRNES (this volume) on shoreline changes indicates that over the period 1855–1989 the Chandeleurs experienced retreat rates that increased from 1.5 to 18 m/yr south to north. This asymmetry in retreat rates resulted from the orientation of the barrier arc with reference to the prevailing southeasterly direction of wave approach. Waves from the south-southeast caused longshore drift of sediment toward the northern end of the barrier arc. An increase in sediment availability in the northern half of the arc encouraged dune development. The dunes extend 100–200 m landward and are vegetated with shrubs and grasses, grading landward into high salt marsh with *Avicennia germinans* (black mangrove) and *Spartina alterniflora* (salt marsh cordgrass) on the overwash lobes. The dunes tend to channelize overwash, whereas sheet-overwash processes dominate the low-profile southern part of the barrier arc.

Breaching and overwash during storm events causes segmentation of the barrier arc. For example, the Chandeleur arc was broken into many segments in response to Hurricane Camille on August 17, 1969. KAHN (1980) and KAHN and ROBERTS (1982) show that Hurricane Frederick in 1979 created 45 breaches in the barrier arc, 38 of which were reopened breaches originally created by Camille a decade earlier. The combined processes associated with tropical storms

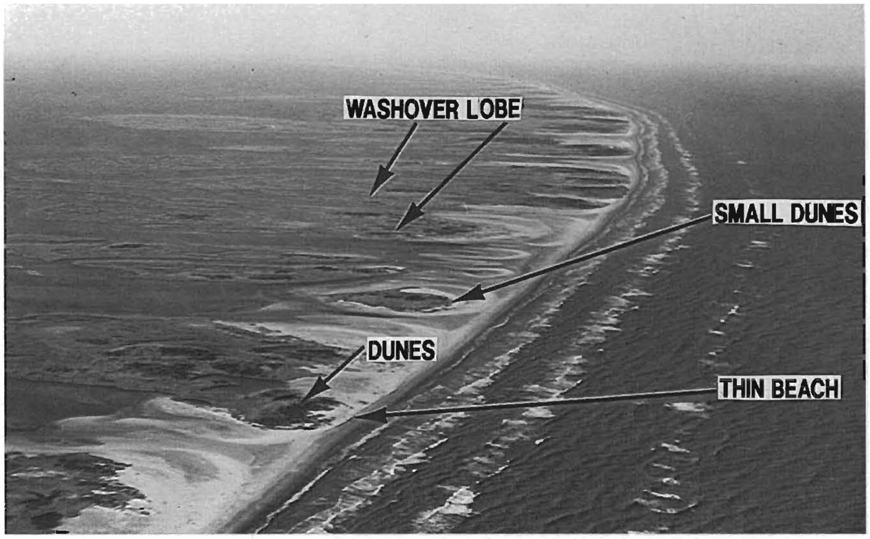

Figure 22. A low altitude oblique aerial photograph of the Chandeleur Island arc illustrating the thin recent beach that connects vegetated washover deposits and fills breaches between washover lobes (November, 1984). The view is toward the northern end of the island arc.

like Camille and Frederick produce a back-barrier sand sheet that is separated from a similar deposit seaward of the barrier arc marking the retreat path of the barriers. McBride and Byrnes (this volume) indicate that between 1855 and 1989 the Chandeleur Islands experienced land loss at an average rate of 7.6 ha/yr. Since no new sediment is being introduced into the system and the bay behind the islands is deepening owing to the on-going processes of subsidence, it has been predicted (Penland and Boyd, 1981) that continued transgression will deplete the reservoir of sediments necessary to maintain a subaerial form. The final stage in the marine-dominated transgressive phase of the delta cycle will be initiated when the subaerial barrier is eroded to become a submarine shoal.

Submarine Shoal Formation

By the time the Chandeleur Islands finally succumb to the forces of subsidence and marine reworking, most remnants of the St. Bernard marshlands will have disappeared and been replaced by a shallow marine embayment. This final stage of the delta cycle's transgressive phase is characterized by submergence of remaining barrier islands and creation of a submarine shoal, stage 3 of the transgressive model of Penland and Boyd (1981). A good example of a submarine shoal that evolved from drowned barrier islands is Ship Shoal, on the shallow shelf off the central Louisiana coast (Figure 19). This transgressive sand body is over 50 km long, ranges in width from 5 to 12 km, and, has a thickness of approximately 4–6 m. Penland *et al.* (1988) indicate that stratigraphic relationships derived from high resolution seismic profiles and shallow cores place Ship Shoal over the old Maringouin delta lobe, its probable original sediment source. The asymmetrical cross sectional profile of Ship Shoal indicates that it may still be actively moving shoreward. The shoreward face of this feature is much steeper than its seaward slope. Rates of landward movement estimated from historical bathymetric data range from 7 to 15 m/yr (Cuomo, 1982). Vibracores through the shoal indicate an upper section of clean, reworked sand (2–5 m thick) that is still being transported landward by physical processes of the inner shelf (Penland *et al.,* 1988). The basal part of the shoal contains rounded clasts of cemented sand, which probably formed in the barrier island stage (Roberts and Whelan, 1975), and fine-grained sediment containing shell debris. Shell and diagenetic clasts are common constituents of both the shoal and the thin transgressive deposits of the barrier retreat path to the present shoal location. At present, Ship Shoal is being buried in a thin blanket of fine-grained sediment from the Atchafalaya delta-building event. Future progradation of this new delta lobe will likely relegate Ship Shoal to the geologic record.

SUMMARY

Dynamic changes in component environments within the Holocene Mississippi River deltaic plain are related primarily to regressive and transgressive cycles as major deltas are built and abandoned. Each delta is composed of a nested series of thinner depositional features that evolve through regressive and transgressive stages involving shorter time and spatial scales than their larger deltaic counterparts. The delta cycle incorporates the evolutionary stages in the development and deterioration of a major delta lobe. This cycle provides a conceptual framework for understanding the present configuration of the Louisiana coastline and delta plain. It also provides an empirical basis for predicting future change in wetland distribution, barrier migration, and shoreline evolution.

The fundamental process of building a delta and then abandoning it in favor of a new site of deposition, delta switching, has been responsible for constructing Louisiana's coastal plain over the last 7000–8000 years, a period when the rate of sea level rise slowed considerably after the rapid rise from the latest Pleistocene glacial maximum. Within this framework, major regressive and transgressive events determine coastal and delta plain configuration and ultimately the products that are preserved in the geologic record.

The delta cycle, shown graphically in Figure 2, is separated into two major phases, a fluvially dominated regressive phase and a marine-dominated transgressive phase. Delta building starts with stream capture and the filling of an interior basin with lacustrine deltas and associated overbank and swamp deposits. This developmental stage is followed by rapid bayhead delta progradation as the interior basin fills with sediment and stream capture becomes progressively more efficient. Capture of Mississippi River water and sediment by the Atchafalaya River, its venerable distributary, has led to the filling of Atchafalaya Basin and initiation of the bayhead delta stage of a new major delta along the Louisiana coast. Since becoming subaerial, the Atchafalaya and Wax Lake deltas have been prograding across Atchafalaya Bay at a rate of approximately 400 m/yr to create thin, sand-rich deltas that will soon emerge onto the continental shelf, the final evolutionary phase of delta building.

The Holocene delta plain is constructed from two types of shelf-stage deltas, thin inner shelf deltas such as the St. Bernard and Lafourche and a thick, deeper water form, which is the Balize delta. Thin inner shelf deltas (a) prograde very rapidly, (b) develop many elongate and branched distributaries, (c) have thin widespread distributary mouth bar sands that may merge into sheet sands, and (d) accumulate a vertical sedimentary sequence that is usually less than 20–30 m thick. In contrast, the middle to outer shelf Balize delta has (a) built into relatively deep water, (b) constructed rather isolated elongate distributary mouth bar sands that thicken abnormally at the expense of underlying prodelta clay deposits which are deformed by this process, (c) developed a thick prodelta clay base over which coarser facies are prograding, (d) experienced slope instabilities on the delta front, which result in down-slope sediment transport, and (e) accumulated a vertical sedimentary sequence in excess of 100 m thick. The fluvially dominated character of all Holocene Mississippi delta lobes promotes rapid progradation onto the shelf of each major distributary, resulting in a complex shoreline configuration.

The marine-dominated transgressive phase of the delta cycle is characterized by fluvial abandonment of the delta, which is followed by subsidence and wave reworking of the delta perimeter. As marine processes rework deltaic headlands, sands derived primarily from distributary mouth bar and channel deposits are concentrated laterally into spits and barrier islands. Combined processes of subsidence submerge the delta surface, causing coastal bays to enlarge. The cumulative effect is that at any given time the bay shoreline is displaced landward of the barrier islands. The present configuration of the Lafourche and its associated spits and barriers reflects this stage of development. With continued subsidence and marine transgression, the bay shoreline and barrier islands continue to retreat landward at different rates. Barrier islands become separated from their source of sediment (the underlying delta). At this stage, the barriers form an arcuate configuration like today's Chandeleur Island Arc. Further delta shoreline retreat and submergence results in marine transgression over most of the delta surface and the formation of a shallow marine embayment where a subaerial delta once was located. By this stage in the transgressive phase, the barrier island arc has lost sufficient sediment to the retreat path and through storm overwash into a continually deepening back-barrier environment that it slowly transforms from a subaerial feature to a submerged shoal. At some other location along the coastal plain a new river course builds another delta lobe, which undergoes an evolutionary history similar to the one described above. Although the schematic delta cycle shown in Figure 2 illustrates regressive and transgressive phases of roughly equal duration, thin inner shelf deltas are likely to have a prolonged transgressive phase, whereas deeper shelf deltas, such as the modern Balize lobe, may actually have an abbreviated transgressive phase because of greater rates of subsidence related to the much thicker base of consolidation-prone sediments.

ACKNOWLEDGEMENTS

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 which 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 author thanks colleagues Mark Byrnes and Randy McBride of Coastal Studies Institute for helpful comments on the manuscript. Special thanks go to Dewitt Braud, who helped the author select LANDSAT TM images from his digital data base, that were used as illustrations in this manuscript.

LITERATURE CITED

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

BYRNES, M.R.; MCBRIDE, R.A.; TAO, Q., and DUVIC, L., 1995. Historical shoreline dynamics along the Chenier Plain of southwestern Louisiana. *Transactions Gulf Coast Association of Geological Societies,* 45, 113–122.

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.

COLEMAN, J.M. and WRIGHT, L.D., 1975. Modern river deltas: Variability of process and sand bodies. *In*: BROUSSARD, M.L. (ed.), *Deltas: Models for Exploration.* Houston Geological Society, pp. 99–149.

COLEMAN, J.M.; PRIOR, D.B., and GARRISON, L.E., 1980. Subaqueous sediment instabilities in the offshore Mississippi River delta.

New Orleans, Louisiana, Bureau of Land Management Open File Report 80–01.

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

COLEMAN, J.M.; ROBERTS, H.H., and BRYANT, W.R., 1991. Late Quaternary Sedimentation, *In*: SALVADOR A., (ed.), The Gulf of Mexico Basin. *Geological Society of America, The Geology of North America,* J, pp. 325–352.

CUOMO, R.F., 1982. The Geologic and Morphologic Evolution of Ship Shoal, Northern Gulf of Mexico. MS Thesis, Department of Geology, Louisiana State University, Baton Rouge, Louisiana, 249 p.

FISK, H.N., 1938. Geology of Grant and LaSalle Parishes. *Louisiana Department of Conservation, Geological Bulletin,* 10, 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, Mississippi, 78p.

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, Mississippi, 82p.

FISK, H.N., 1952. *Geologic Investigation of the Atchafalaya Basin and the Problem of Mississippi River Diversion.* U.S. Army Corps of Engineers, Mississippi River Commission, Vicksburg, Mississippi, 145p.

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

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

FISK, H.N. and MCFARLAN, E., JR., 1955. Late Quaternary deltaic deposits of the Mississippi River. *Geological Society of America Special Paper, no. 62,* pp. 279–302.

FISK, H.N.; MCFARLAN, E., JR.; KOLB, C.R., and WILBERT, L.J., JR., 1954. Sedimentary framework of the modern Mississippi delta. *Journal of Sedimentary Petrology,* 24, 76–99.

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.

GALLOWAY, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. *In*: BROUSSARD, M.L. (ed.), *Deltas: Models for Exploration.* Houston Geological Society, pp. 87–98.

GERDES, R.G., 1982. Stratigraphy and history of development of the Caminada-Moreau beach ridge plain, southeast Louisiana. MS Thesis, Department of Geology, Louisiana State University, 184p.

HOWARD, P.C. 1982. Quatre Bayou Pass, Louisiana: Analysis of currents, sediment, and history. MS Thesis, Department of Geology, Louisiana State University, 111p.

HUH, O.K.; ROBERTS, H.H.; ROUSE, L.J., and RICKMAN, D.A., 1991. Fine grain sediment transport and deposition in the Atchafalaya and Chenier Plain sedimentary system. *Proceedings Coastal Sediments '91* (Seattle, Washington), pp. 817–830.

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.

KEMP, G.P., 1986. Mud Deposition at the Shoreface: Wave and Sediment Dynamics of the Chenier Plain of Louisiana. Ph.D. dissertation, Marine Sciences Department, Louisiana State University, 146p.

KESEL, R.H., 1988. The decline in the suspended sediment load of the lower Mississippi River and its influence on adjacent wetlands. *Environmental Geology and Water Science,* 11, 271–281.

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.

KUECHER, G.J., 1994. Geologic Framework and Consolidation Settlement Potential of the Lafourche Delta, Topstratum Valley Fill; Implications for Wetland Loss in Terrebonne and Lafourche Parishes, Louisiana. PhD Dissertation, Department of Geology and Geophysics, Louisiana State University, 344p.

MCBRIDE, R.A.; PENLAND, P.S.; HILAND, M.; WILLIAMS, S.J.; WESTPHAL, K.A.; JAFFE, B., and SALLENGER, A.H., JR., 1992. Analysis of barrier shoreline change in Louisiana from 1853 to 1989. *In*: WILLIAMS, S.J., *et al.* (eds.), *Atlas of Barrier Island Changes in Louisiana.* Miscellaneous Investigations Series I-2150-A (color plates), U.S. Geological Survey, pp. 36–97.

MCBRIDE, R.A. and BYRNES, M.R., 1995. A megascale systems approach for shoreline change analysis and coastal management along the northern Gulf of Mexico. *Transactions Gulf Coast Association of Geological Societies,* 45, 405–414.

MCFARLAN, E., JR., 1961. Radiocarbon dating of Late Quaternary deposits, south Louisiana. *Geological Society of American Bulletin,* 72, 129–158.

MCINTIRE, W.G., 1954. Correlation of prehistoric settlements and delta development. *Louisiana State University, Coastal Studies Institute Technical Report 5,* 65p.

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. and LARIMORE, P.B., 1957. Changes in the Louisiana shoreline. *Transactions Gulf Coast Association of Geological Societies,* 7, 303–310.

MORGAN, J.P.; VAN LOPIK, J.R., and NICHOLS, L.G., 1953. Occurrence and development of mudflats along the western Louisiana coast. *Louisiana State University, Coastal Studies Institute Technical Report 2,* 34p.

MOSSA, J., 1990. Discharge-Suspended Sediment Relationships in the Mississippi-Atchafalaya River System, Louisiana. PhD dissertation, Department of Geography and Anthropology, Louisiana State University, Baton Rouge, Louisiana, 180p.

MOSSA, J. and ROBERTS, H.H., 1990. Synergism of riverine and winter storm-related sediment transport processes in Louisiana's coastal wetlands. *Transactions Gulf Coast Association of Geological Societies,* 40, 635–642.

NEESE, K.J., 1984. Stratigraphy and Geologic Evolution of Isles Dernieres, Terrebonne Parish, Louisiana. MS Thesis, Department of Geology, Louisiana State University, 127p.

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

PENLAND, S.; BOYD, R., and SUTER, J.R., 1988. Transgressive depositional systems of the Mississippi delta plain: A model for barrier shoreline and shelf sand development. *Journal of Sedimentary Petrology,* 58, 932–949.

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

ROBERTS, H.H., 1985. *A Study of Sedimentation and Subsidence in the South-Central Coastal Plain of Louisiana.* Final Report to U.S. Army Corps of Engineers, Waterways Experiment Station, 53p.

ROBERTS, H.H. and HUH, O.K., 1995. The eastern chenier plain: An update on downdrift coastal progradation associated with the building of a new Holocene delta lobe in the Mississippi River delta complex. *Transactions Gulf Coast Association of Geological Societies,* 45, 644–646.

ROBERTS, H.H. and VAN HEERDEN, I.L., 1992. Atchafalaya-Wax Lake delta complex: The new Mississippi River delta lobe. *Annual Coastal Studies Institute Industrial Associates Research Program, Research Report #1,* 45p.

ROBERTS, H.H. and WHELAN, T., III, 1975. Methane-derived cements in barrier and beach sands of a subtropical delta complex. *Geochimica et Cosmochimica Acta,* 39, 1085–1089.

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.

ROBERTS, H.H.; HUH, O.K.; HSU, S.A.; ROUSE, L.J., JR., and RICKMAN, D.A., 1989. Winter storm impacts on the Chenier Plain coast of southwestern Louisiana. *Transactions Gulf Coast Association of Geological Societies,* 39, 515–522.

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 phenomenon, and early diagenesis. *Transactions Gulf Coast Association of Geological Societies,* 44, 619–629.

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

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 HOWE, H.V., 1935. Cheniers of southwestern Louisiana. *Geographic Review,* 25, 449–461.

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

SAUCIER, R., 1963. Recent geomorphic history of the Pontchartrain basin: *Louisiana State University Coastal Studies Series 9,* 114p.

SCRUTON, P.C., 1960. Delta building and the deltaic sequence. *In*: TRASK, P.D., (ed.), *Recent Sediments, Northwest Gulf of Mexico.* Tulsa, Oklahoma: American Association of Petroleum Geologists, pp. 82–102.

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

SHLEMON, R.J., 1972. Development of the Atchafalaya delta—hydrologic and geologic studies of coastal Louisiana. *Report No. 8, Center for Wetlands Resources, Louisiana State University,* Baton Rouge, Louisiana, 51p.

SHLEMON, R.J., 1975. Subaqueous delta formation-Atchafalaya Bay, Louisiana. *In*: BROUSSARD, M.L. (ed.), *Delta: Models for Exploration.* Houston Geological Society, pp. 209–221.

TROWBRIDGE, A.C., 1930. Building of the Mississippi Delta. *American Association of Petroleum Geologists Bulletin,* 14, 867–901.

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

TYE, R.S. and COLEMAN, J.M., 1989b. Depositional processes and stratigraphy of fluvially dominated lacustrine deltas: Mississippi delta plain. *Journal of Sedimentary Petrology,* 59, 973–996.

U.S. ARMY CORPS OF ENGINEERS, 1974. *Preliminary Draft Environmental Impact Statement, Atchafalaya Basin Floodway.* U.S. Army Corps of Engineers, New Orleans, Louisiana, 324p.

U.S. ARMY CORPS OF ENGINEERS, 1975. Stages and Discharges of the Mississippi River and Tributaries in the New Orleans District, AnnualVolume 1973–1975. New Orleans, Louisiana, 1p.

VAN HEERDEN, I.L., 1983. Deltaic sedimentation in eastern Atchafalaya Bay, Louisiana. PhD dissertation. Department of Marine Sciences, Louisiana State University, Baton Rouge, Louisiana, 151p.

VAN HEERDEN, I.L. and ROBERTS, H.H., 1980. The Atchafalaya Delta: Rapid progradation along a traditionally retreating coast (south central Louisiana). *Zeitschrift für Geomorphologie,* 34, 188–201.

VAN HEERDEN, I.L.; WELLS, J.T., and ROBERTS, H.H., 1983. River-dominated suspended sediment deposition in a new Mississippi delta. *Canadian Journal of Fisheries and Aquatic Sciences Bulletin,* 40, 60–71.

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

WELLS, J.T. and ROBERTS, H.H., 1980. Fluid mud dynamics and shoreline stabilization: Louisiana Chenier Plain. *Proceedings 17th International Coastal Engineering Conference* (ASCE Sydney, Australia), pp. 1382–1401.

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

WOODBURY, H.D.; MURRAY, I.B., JR.; PICKFORD, P.J., and AKERS, W.H., 1973. Pliocene and Pleistocene depocenters, outer continental shelf, Louisiana and Texas. *American Association of Petroleum Geologists Bulletin,* 57, 2428–2439.

WRIGHT, L.D. and COLEMAN, J.M., 1972. River delta morphology: Wave climate and the role of the subaqueous profile. *Science,* 176, 282–284.

WRIGHT, L.D. and COLEMAN, J.M., 1973. Variations in morphology of major river deltas as functions of ocean wave and river discharge regimes. *American Association of Petroleum Geology Bulletin,* 57, 370–398.