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Delta Switching: Early Responses to the Atchafalaya River Diversion

Harry H. Roberts

Coastal Studies Institute
Louisiana State University
Baton Rouge, Louisiana 70803

ABSTRACT

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Repeated shifting of the locus of deltaic deposition (delta switching) has been the fundamental process by which the complex delta plain of the Mississippi River has been built. The latest in a series of major Holocene diversions of the river has taken place down the Atchafalaya River course. From the diversion point, this course is approximately 300 km shorter to the Gulf of Mexico than the present Mississippi River course, producing an obvious gradient advantage. Even though control structures presently limit flow down the Atchafalaya to 30% of the Mississippi plus the Red River contribution, dramatic changes have occurred along the central Louisiana coast since Richard J. Russell, James P. Morgan, and their colleagues first reported, in the early 1950s, impressive shoreline adjustments related to the introduction of Atchafalaya sediment. To date, sediment delivered by the Atchafalaya River has (a) filled the Atchafalaya Basin to capacity with lacustrine deltas and swamp deposits; (b) created two bay-head deltas in Atchafalaya Bay (> 150 km^2 of new land above the -0.6 m isobath); and, (c) started a new progradational chapter in the history of the downdrift chenier plain. Since the early 1950s when investigators documented the first accretion along the eastern chenier plain coast, the whole of Atchafalaya Bay, surrounding marshlands, adjacent shelf, and downdrift coasts have experienced a dynamic influx of sediment as a product of the latest Holocene delta switching event.

ADDITIONAL INDEX WORDS: *Delta switching, delta growth, chenier plain, shoreline change.*

INTRODUCTION

By the 1930s several researchers had identified abandoned courses of the Mississippi River (TROWBRIDGE, 1930; RUSSELL, 1936, 1939, and 1940; FISK, 1938; and RUSSELL and RUSSELL, 1939). During this period the role of delta switching in construction of the Mississippi River delta plain was first clearly identified by RUSSELL (1940) and later popularized by FISK (1944). Their observations concerning multiple meander belts within the alluvial valley and upper delta plain led to the conclusion that the Mississippi River had changed its position through time, resulting in down-dip deltas that coalesced to form the complex, low-relief environments of the present delta plain. In his report summarizing the Mississippi River alluvial valley study, FISK (1944) made the first comprehensive attempt to join river courses with their deltaic deposits. Even though he had the ages of the Lafourche and St. Bernard deltas reversed, his initial maps of the deltaic plain identified a series of delta lobes connected to up-dip meander belts of the present and former Mississippi River courses. FISK (1944) and his team of researchers, as well as KOLB and VAN LOPIK (1958, 1966) popularized this new concept of delta-building. Results from archaeological studies of the delta plain published by MCINTIRE (1954) clarified the initial problem of establishing a relative chronology for the delta lobes. An absolute chronology using ^{14}C dating was later established by FISK and MCFARLAN (1955), FRAZIER (1967), and most recently by TORNQVIST *et al.* (1996).

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The diversion of Mississippi River water and sediment down the Atchafalaya River course is the only delta switching event within historical times (Figure 1). As FISK (1952) noted in his study of the Atchafalaya River and its basin, explorers recognized the Atchafalaya as a distributary of the Mississippi River as early as the 1500s. These and later accounts suggest that the Atchafalaya was intermittently closed at the diversion point with massive log jams. However, during the first half of this century, flow down the Atchafalaya steadily increased, as shown in Figure 2. The Atchafalaya basin and river study by FISK (1952) clearly identified the Atchafalaya River diversion as the next Holocene delta-switching event and, if left unchecked, the Atchafalaya would eventually capture the entire discharge of the Mississippi, a conclusion that eventually led congress to appropriate funding for a control structure at the Old River diversion site. This structure was built in 1963 and an auxillary control structure was installed in 1986 after the abnormally high flood in 1973 damaged the Old River diversion structure. Since the original control structure was installed, discharge to the Atchafalaya has been at 30% of the Mississippi discharge at the diversion point plus the contribution from the Red River.

In addition to identifying a new delta-switching event, FISK (1952) and his co-workers provided a detailed understanding of the interdistributary basin-filling process. He identified the latest sedimentary facies that developed as the Atchafalaya River progressively captured more of the Mississippi River discharge. This landmark study set the stage for understanding important depositional events that have oc-

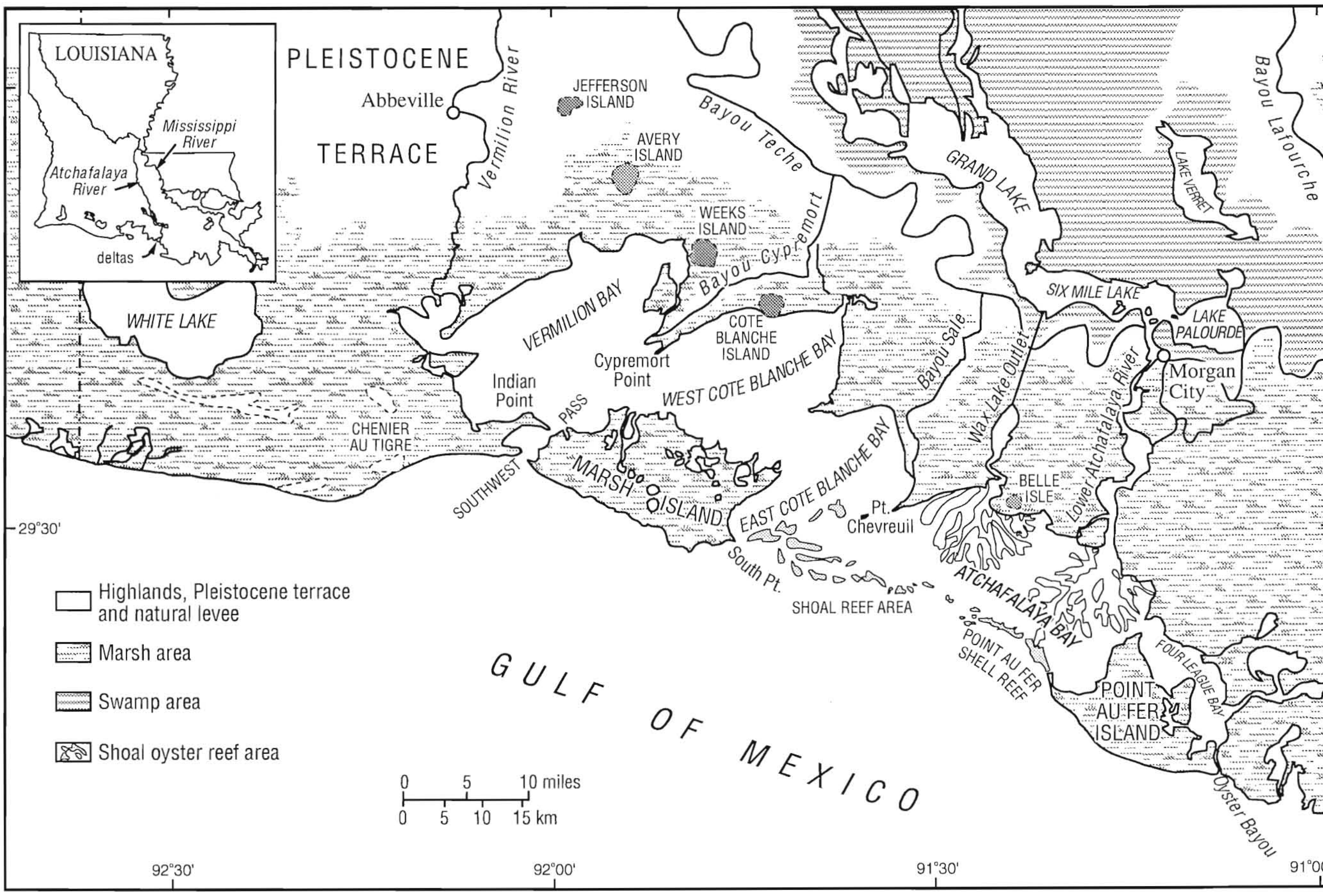

Figure 1. Location map showing the central and western Louisiana coast currently being impacted by diversion of Mississippi River water and sediment down the Atchafalaya River course. Note the bayhead deltas forming in Atchafalaya Bay and down-drift eastern chenier plain where coastal progradation is underway, (modified from Fisk, 1952).

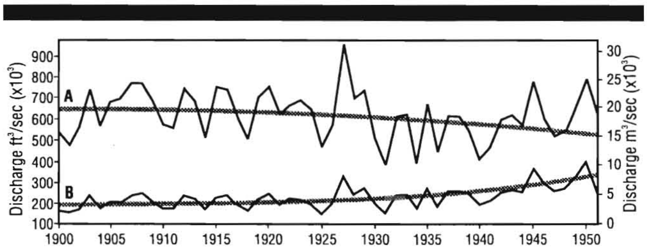

Figure 2. Graphs of Mississippi River discharge (measured at Red River Landing) and Atchafalaya River discharge (measured at Simmesport) over the period 1900–1950. Note the steady increase in Atchafalaya discharge (graph B) at the expense of the Mississippi (graph A) (adapted from Morgan *et al.,* 1953). This trend continued until 1963 when a control structure was installed at the diversion point and input to the Atchafalaya River from the Mississippi was limited to 30% of the Mississippi discharge.

curred along the central and western Louisiana coasts as a product of the Atchafalaya River diversion.

The purpose of this paper is to present a current appraisal of the latest Holocene delta-switching event and its impact on the Atchafalaya Basin, Atchafalaya Bay, and the down-drift chenier plain coast (Figure 1).

EVOLUTION OF ATCHAFALAYA RIVER DELTA-BUILDING

As recently summarized by ROBERTS (1997), the process of delta building proceeds in an orderly and predictable manner after a major Mississippi River diversion takes place. This process begins with the filling of interdistributary basins with lacustrine deltas (TYE and COLEMAN, 1989; BRELAND *et al.,* 1988) and swamp deposits (COLEMAN, 1966). When the basin becomes filled, sediments are by-passed to the open coast to develop bayhead deltas. Finally, progradation of a delta onto the continental shelf creates the final shelf phase of delta development. In the case of the Atchafalaya diversion, this evolution from lacustrine—bayhead—shelf deltas has progressed to the bayhead delta phase.

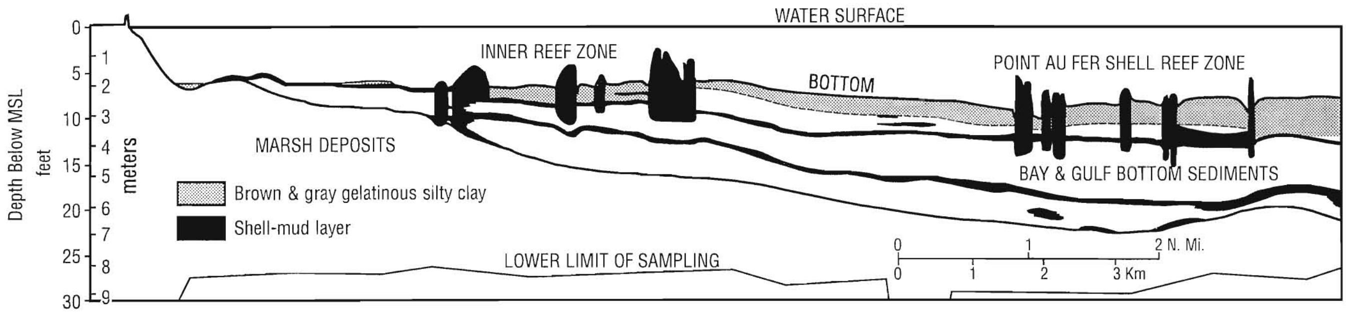

Figure 3. Cross section of Atchafalaya Bay from Pt. Chevreuil to the inner continental shelf south of the Point Au Fer shell reefs (see Figure 1 for general location). Note the abundance of oyster reefs along this transect and the seaward thickening wedge of "gelatinous mud" that equates to the first significant sedimentary deposits measured in Atchafalaya Bay and on the adjacent inner shelf associated with the Atchafalaya diversion (modified from Thompson, 1951).

Basin Filling

From the beginning of the Atchafalaya diversion, sediments have been transported into the Atchafalaya Basin, where until recently, they remained as part of the recent history of basin-filling. As part of the geologic investigation of the Atchafalaya Basin and the problem of increasing capture of Mississippi River discharge (FISK, 1952), it was discovered through an extensive soil boring program that sediments filling the Atchafalaya Basin were mostly fine-grained swamp deposits and coarser lacustrine delta sediments. The lacustrine and swamp environments of the interdistributary basin provide a natural setting that encourages sediment deposition. These natural settling basins prevent sediment from bypassing through the basin in quantities sufficient to significantly impact the coast. Although MORGAN *et al.* (1953) present evidence of slight progradation of the eastern chenier plain coast between surveys conducted in 1837 and 1927, two significant events occurred in the 1940s and 1950s that dramatically changed sediment input to coastal environments of central and western Louisiana. First, the last of the major lakes in the southern Atchafalaya Basin (Grand Lake and Six-Mile Lake) were rapidly being filled with sand-rich lacustrine delta deposits (ROBERTS *et al.,* 1980). Second, an artificial channel, the Wax-Lake Outlet, was dredged by the Corps of Engineers in 1942 from Six-Mile Lake into Atchafalaya Bay to help reduce rising flood levels on the lower Atchafalaya River course near Morgan City. Both these events encouraged more efficient transport of Atchafalaya sediments, primarily suspended load, to Atchafalaya Bay, the adjacent continental shelf, and downdrift coasts (Figure 1). Following these events, THOMPSON (1951) noted an increase in fine-grained sediment deposition on the inner shelf, while MORGAN and LARIMORE (1957) indicated that the eastern part of the chenier plain was beginning to prograde at a rate estimated at 3.9 m/year, even though the perimeter of Atchafalaya Bay was still retreating at a rate of approximately 2.3 m/year. This shelf deposition outside of Atchafalaya Bay and the progradation at Chenier au Tigre (RUSSELL and MORGAN, 1952) were the first substantial data points related to the impact of Atchafalaya River sediments on the shelf and open coast.

Initiation of Bay-Head Delta Building

The earliest detailed report of sedimentation in Atchafalaya Bay is by THOMPSON (1951). At that time, he described the bay as having a rather uniform average depth of ~2 m, with the uppermost 0.5 to 1 m of sediment composed of "mud with a jelly-like consistency" (Figure 3). Within this gelatinous silty clay, oyster reefs with relief of up to 1m above the surrounding bay floor were found (Figure 4). Two groupings of these oyster reefs occurred, one composed of isolated buildups that trended easterly from Pt. Chevreuil across the middle part of Atchafalaya Bay and another more massive reef, the Point Au Fer Shell Reef, that essentially formed the seaward boundary between Atchafalaya Bay and the open shelf (Figure 3). Subsequent shell dredging activities and increased sedimentation in Atchafalaya Bay have largely eliminated the topographic significance of these oyster reefs. However, in the early 1950s, they still had dramatic relief above the bay bottom (Figure 4). Although THOMPSON (1951) identified the gelatinous mud covering the bottom of Atchafalaya Bay as coming from the Atchafalaya River by way of both the Lower Atchafalaya River and Wax-Lake Outlet (Figure 1), he states that Atchafalaya Bay experienced no prominent depth change between surveys in 1889 and 1935, which he interpreted as a balance between deposition, erosion, compaction, and subsidence. MORGAN *et al.* (1953) did, however, indicate that fine-grained sediment (silty clay) was accumulating in the southeast corner of the bay to thicknesses of nearly 2 m. These two studies suggest that most of the bay was not rapidly changing and that Atchafalaya sediments were by-passing the bay where they were being deposited on the shelf beyond the Point Au Fer Shelf Reef. In fact, THOMPSON (1951) indicated that within the 46-year period between 1889 and 1935, U.S. Coast and Geodetic Surveys of the Atchafalaya Bay and adjacent shelf areas showed as much as 2 m of new sediment added to the inner continental shelf beyond the Point Au Fer Reef along the western part of Atchafalaya Bay (Figure 5).

Following the work of THOMPSON (1951) and MORGAN *et al.* (1953), SHLEMON (1975) was the first to call attention to a dramatic change in the balance of sedimentation in Atchafalaya Bay that led to rapid subaqueous delta develop-

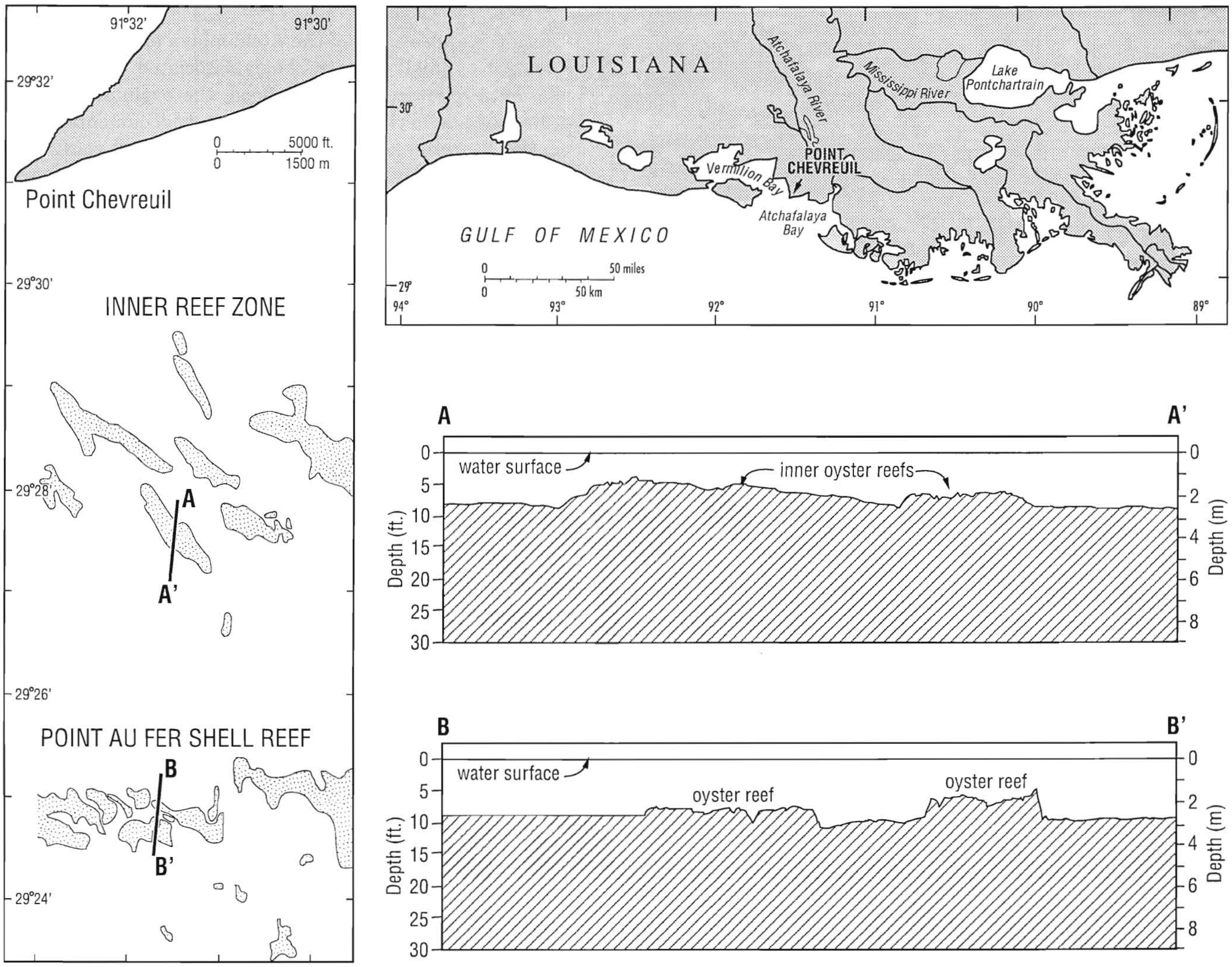

Figure 4. A plan-view map of western Atchafalaya Bay area showing the positive relief on both the inner oyster reef trend as well as the Point Au Fer shell reefs as represented on echo sounder profiles across these features (Thompson, 1951).

ment, especially opposite the mouth of the lower Atchafalaya River. In roughly two decades (1951–1972) both the Lower Atchafalaya River and the Wax-Lake Outlet had transported sufficient sediment to Atchafalaya Bay to radically change its bathymetry from average depths ranging from 2 to 3 m to large areas with depths of less than 1 m. Figure 6 illustrates the shoaling of the bay bottom prior to the enormous flood of 1973 that converted the subaqueous bayhead deltas at both the Lower Atchafalaya River mouth and at the Wax-Lake Outlet into subaerial features. From 1938 to 1972, the average annual discharge down the Atchafalaya River was 5126 cm/s and the average peak discharge for those years was 12,121 cm/s (USCOE, 1974). During the 1973 flood, peak discharges exceeded 19,824 cm. In addition, 1974 and 1975 were also high water years. During these three high water years the average annual suspended sediment load more than doubled in the lower Atchafalaya River, to 88.9×10^6 metric tons (USACOE, 1975). Given flow velocities during flood conditions, the coarsest particles (fine-to-medium-sized sand) available to the lower Atchafalaya River were capable of being transported as suspended load (ROBERTS, 1997). Figure 7 illustrates the increase in surficial sand-sized sediment in Atchafalaya Bay before and after the high water years of 1972–1975. ROBERTS *et al.* (1980) indicated that during this period an estimated 30.7×10^6 metric tons of sand were introduced to the bay from combined discharge through the lower Atchafalaya River and Wax Lake Outlet, a seven-fold increase over previous years (1967–1971). These figures and U.S. Army Corps of Engineers (USACOE, 1974) observations of the lower Atchafalaya River channel deepening after the 1973 flood suggested scouring of channel sands and deposition in the bayhead deltas, initiating the subaerial phase of bayhead delta development that is presently continuing.

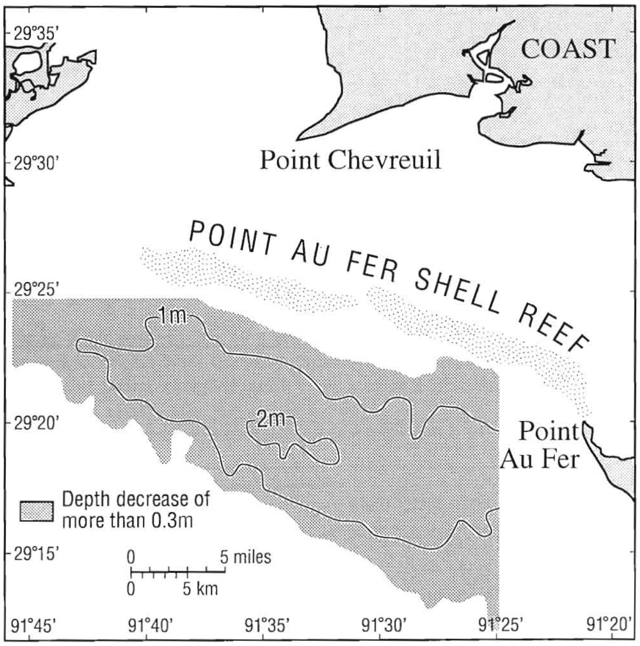

Figure 5. This figure illustrates the general thickness of "gelatinous muds" seaward of the Point Au Fer shell reef trend, interpreted as newly deposited Atchafalaya River sediment (modified from Thompson, 1951). Note that these deposits were approximately 2 m thick in the area of data collection just seaward of the Point Au Fer shell reef.

Sediment Delivery and Delta Growth

Since the appearance of the Atchafalaya delta and the development of small exposed shoals associated with the Wax Lake delta following the 1973 flood, the evolution of these two bayhead deltas has been progressively documented in the scientific literature (ROUSE *et al.*, 1978; ROBERTS *et al.*, 1980; VAN HEERDEN, 1980, 1983; VAN HEERDEN and ROBERTS, 1988; ROBERTS *et al.*, 1997; MAJERSKY *et al.*, 1997; and MAJERSKY-FITZGERALD, 1998). Because the Atchafalaya River delta experienced a more rapid initial development, attention in the 1970s and 1980s was focused on it, particularly the eastern lobe, which was largely unmodified by human activities, such as dredging and dredge spoil placement. However, following the filling of Wax Lake, which lies on the man-made canal between the Grand Lake-Six Mile Lake area in Atchafalaya Basin and Atchafalaya Bay, the Wax Lake delta experienced a rapid growth phase between approximately 1980 and 1989 (Figure 8). In fact, growth of the Wax Lake delta between these years occurred at a greater rate for the Wax Lake delta (3.5 km^2/yr) than the Atchafalaya delta (2.2 km^2/yr) (ROBERTS *et al.*, 1997). Delta growth is directly related to sediment supply, and the period between 1989 and 1994 suggests a decrease in sediment supply to the Wax Lake delta and a simultaneous increase to the Atchafalaya delta. This change resulted from human intervention into the sediment supply system. In 1988, a weir was installed by the USACOE in Six Mile Lake above the entrance to the Wax Lake Outlet (KEMP *et al.*, 1995). The purpose of this weir was to decrease the steadily increasing capture of Atchafalaya River discharge by the Wax Lake Outlet. Table 1 clearly

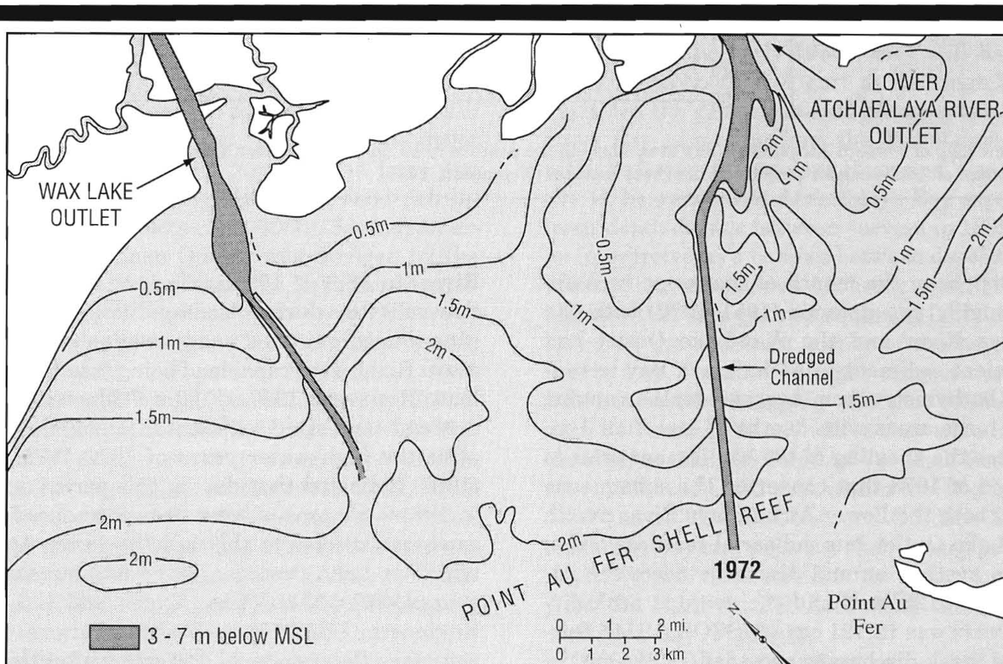

Figure 6. Bathymetry map of Atchafalaya Bay compiled from USACOE and Coastal Studies Institute data collected in 1972. Note the well-defined subaqueous shoals forming opposite the Atchafalaya River and Wax Lake Outlets.

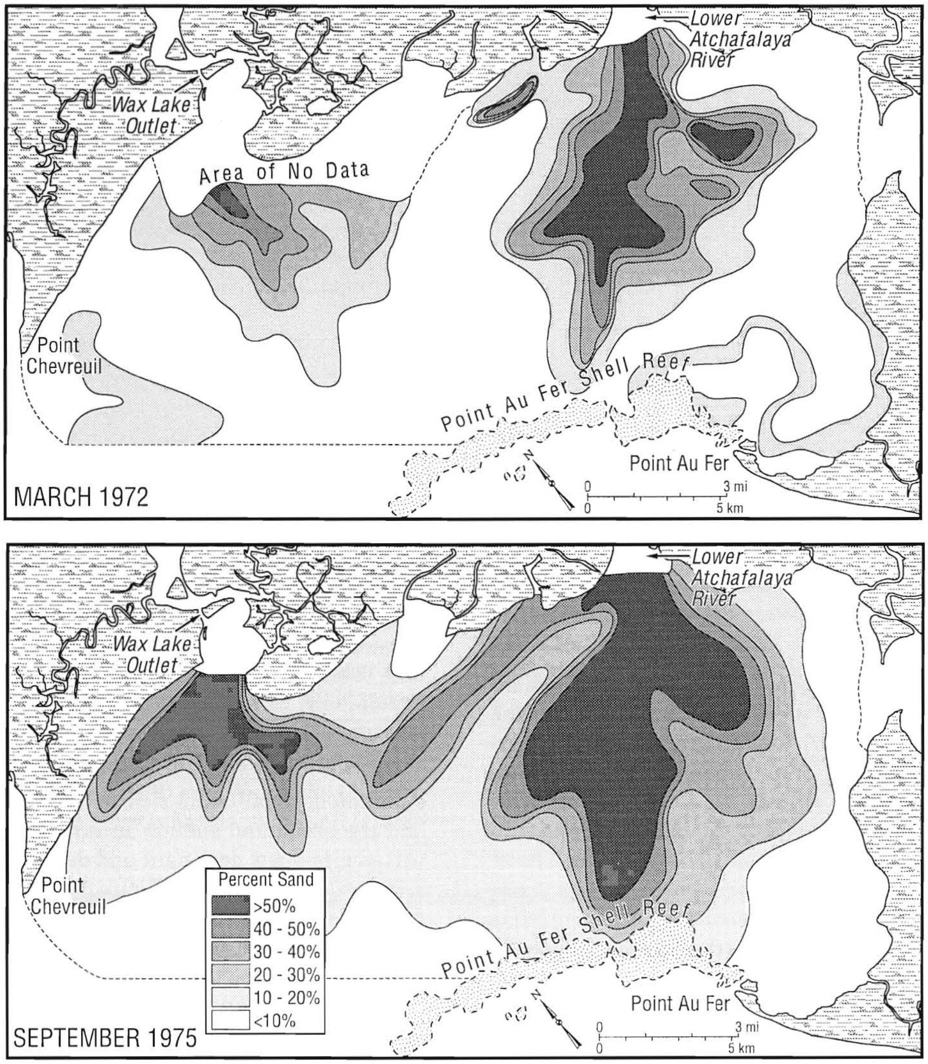

Figure 7. Distribution of sand concentration for Atchafalaya Bay bottom sediments as determined from USACOE (New Orleans District) samples (477 samples in 1972 and 160 samples in 1975), (Adapted from Roberts *et al.,* 1980).

shows the effect of this weir on suspended sediment distribution down the Wax Lake and Atchafalaya channels. The pathway for water and sediment down the Wax Lake Outlet is approximately 21 km shorter to Atchafalaya Bay than by way of the Lower Atchafalaya River course, a decided gradient advantage. As SHLEMON (1975) initially pointed out, the Wax Lake Outlet cross-sectional area steadily increased from its original 1942 configuration to 1975, while the Lower Atchafalaya River channel decreased slightly. Originally, the Wax Lake Outlet was designed to transport 20% of the project flood (42.5×10^3 cm/s). However, over time, flow down this man-made course increased so that by the 1990s it carried 30% of the project flood and up to 45% of average discharges (15,580 cm/s or less) (USACOE, 1995), resulting in a Wax Lake Outlet delta that now approaches the size of the Atchafalaya River delta (Figure 9). As Figure 8 illustrates, installation of the weir decreased the capture of Atchafalaya River discharge by the Wax Lake Outlet and had an obvious affect on delta growth during the period 1989–1994. The weir caused the rate of change of growth to increase for the Atchafalaya delta and decrease for the Wax Lake delta. Problems with increased flood stages at Morgan City forced removal of the weir in 1994 (USACOE, 1995). Discharge down the Wax Lake Outlet has now returned to pre-weir conditions, and an increase in the rate of Wax Lake delta growth is currently underway. A simultaneous decrease in the rate of Atchafalaya delta growth is expected.

Morphology and Sedimentology

The morphological evolution of the Atchafalaya and Wax Lake deltas has followed the general trends first described by WELDER (1959) for the Cubits' Gap subdelta of the modern Mississippi Balize delta (birdfoot). A man-made crevasse

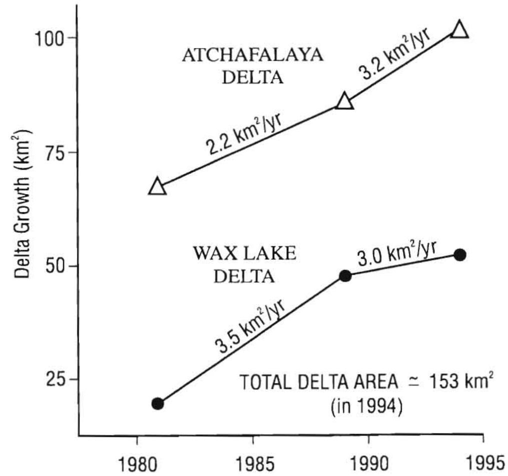

Figure 8. Growth of both the Atchafalaya and Wax Lake deltas measured in km² above the −0.6 m isobath. Measurements were made for 1981, 1989, and 1994. Rates of change are indicated in km/yr between the measurement years (modified from Majersky *et al.*, 1997).

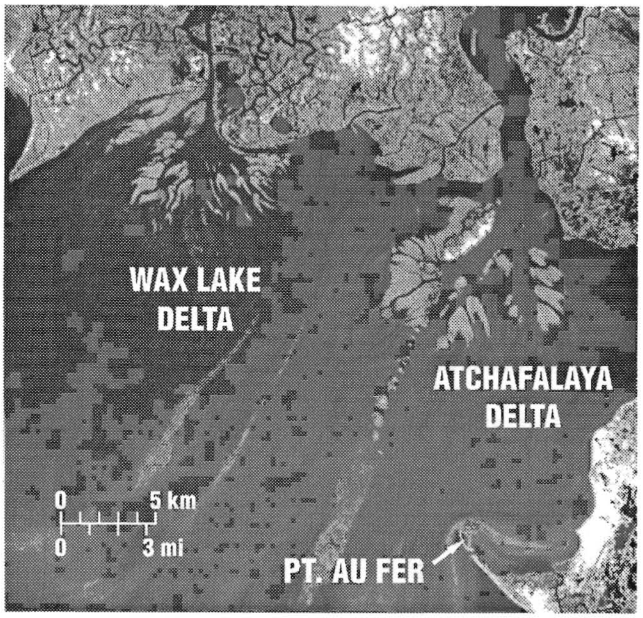

Figure 9. A SPOT satellite image (HRV3, near infra-red) taken 22 January 1988 (1704GMT) of Atchafalaya Bay showing the subaerial morphology of the Wax Lake and Atchafalaya bayhead deltas.

through the levee bordering the main Mississippi River channel forced the development of the Cubits' Gap subdelta. The early stages of subaerial growth and progradation were characterized by the development of mid-channel bars and channel bifurcation. This basic process was observed by VAN HEERDEN (1980) in the early stages of Atchafalaya delta subaerial development. During the period 1973–1975 when flood levels were above normal, delta growth proceeded by seaward channel extension, through the construction of subaqueous levees, and channel bifurcation. The next growth phase, as recognized by VAN HEERDEN (1980), occurred after those high water years from 1975 to the early 1980s, when average-to-below average floods occurred. From this period and extending to the present, Atchafalaya delta growth has been characterized by the combined processes of lobe fusion and upstream accretion (VAN HEERDEN and ROBERTS, 1988). During this evolutionary period, many small channels were eliminated, small sand-rich lobes merged into larger ones, and the broad and shallow initial channel network was converted into a few dominant and deeper channels that conduct flow through the delta (Figure 10). Although the Wax Lake delta has evolved through the same stages of seaward channel extension and bifurcation, as well as by lobe fusion and upstream growth, these growth patterns occurred simultaneously in the Wax Lake delta which suggests more efficient sediment retention in the system (ROBERTS and VAN HEERDEN, 1992). Perhaps this trend is related to the frequent dredging of a navigation channel through the Atchafalaya delta since the delta-building process was initiated. Rapid growth of the Wax Lake delta was delayed until about 1980

Table 1. *Total suspended sediments (tons) supplied to Atchafalaya Bay during the years 1980–1994 (adapted from Roberts* et al., *1997).*

Year	Atchafalaya Bay Total Suspended Sediment (tons)	Wax Lake Outlet Contribution (%)	Lower Atchafalaya River Contribution (%)
1980	58,382,867	38.0	62.0
1981	46,334,975	40.9	59.1
1982	94,012,474	35.4	64.6
1983	119,764,928	36.3	63.7
1984	88,019,253	43.3	56.7
1985	70,400,486	43.2	56.8
1986	53,358,810	43.5	56.5
1987	71,855,000	40.0	60.0
1988	63,410,000	45.3	54.7
1989	75,047,838	37.4	62.6
1990	89,136,596	30.4	69.6
1991	55,940,694	24.7	75.3
1992	69,596,000	30.0	70.0
1993	89,037,557	36.1	63.9
1994	60,188,033	31.4	68.6

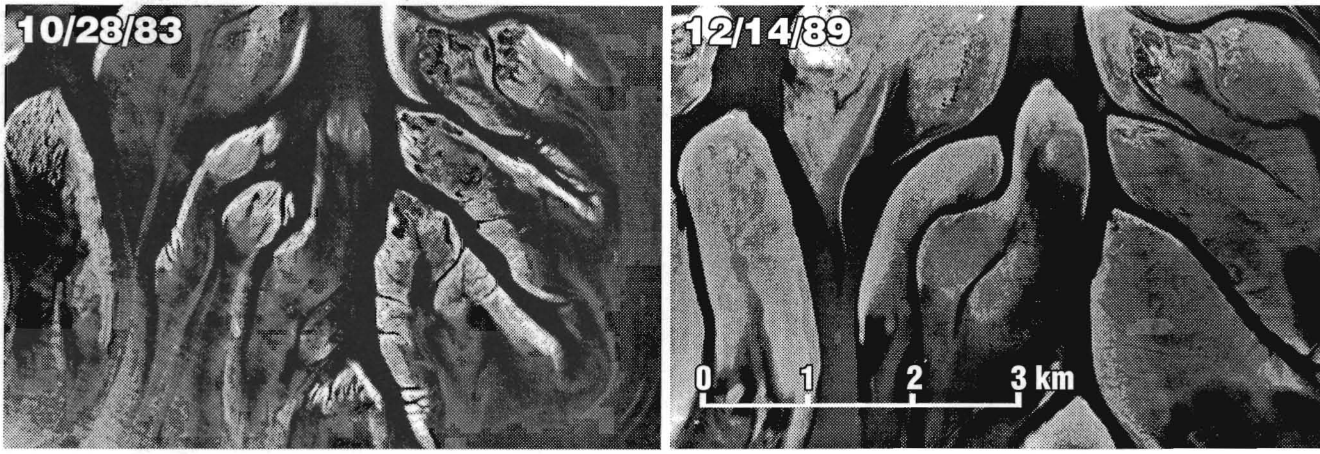

Figure 10. These two images show the same part of the eastern lobe of the Atchafalaya delta in two different years, 1983 and 1989. The latest image illustrates growth of the delta by vertical accretion, lobe fusion, and upstream growth.

because of sediment loss to upstream basins along the outlet (*e.g.*, Wax Lake). When these small basins became sediment-filled in the late 1970s, both traction load and suspended load sediments were more efficiently transported to Atchafalaya Bay, and a sharp increase in growth rate occurred (Figure 8).

A sedimentological examination of both the Atchafalaya (VAN HEERDEN and ROBERTS, 1988) and Wax Lake (MAJERSKY *et al.*, 1997; MAJERSKY-FITZGERALD, 1998) deltas indicates that they are very similar with regard to sedimentary architecture. Each is thin (~3 m thick), has a thin clay-rich prodelta-distal bar unit at the base, and is dominantly composed of a sand-rich distributary mouth bar and subaqueous levee facies.

Figure 11 represents a strike-section through the Wax Lake delta as reconstructed from vibracores. This cross section is also typical of an Atchafalaya River bayhead delta.

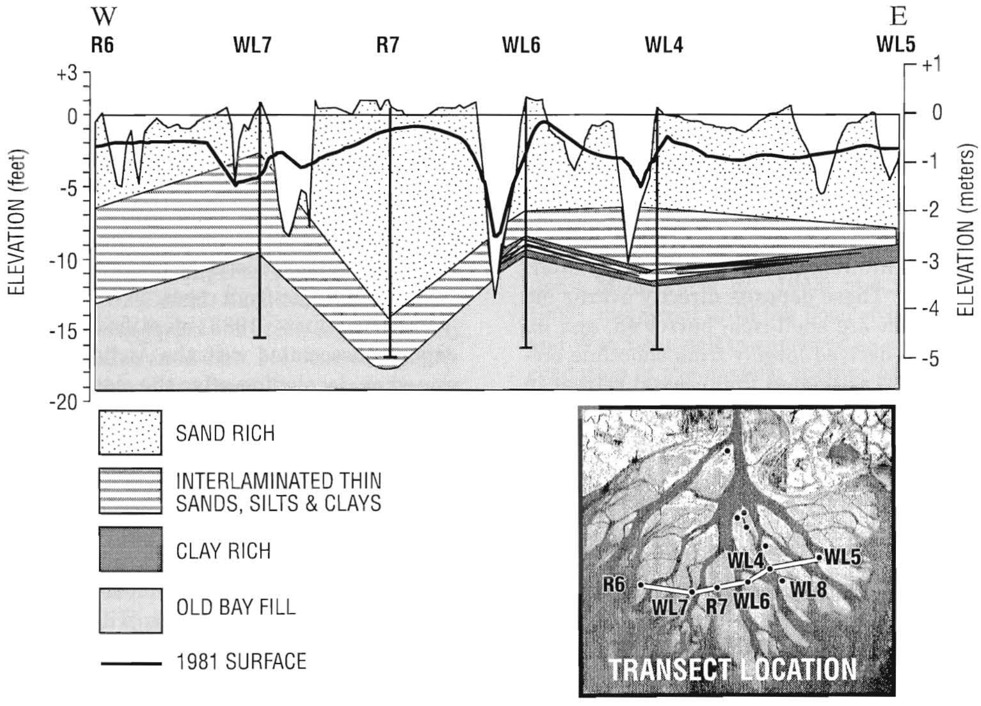

Figure 11. An interpretive strike-oriented cross section of the Wax Lake delta as compiled from vibracores (modified from Roberts *et al.*, 1997). Note the dominance of sand-rich facies and the thin fine-grained base of this delta.

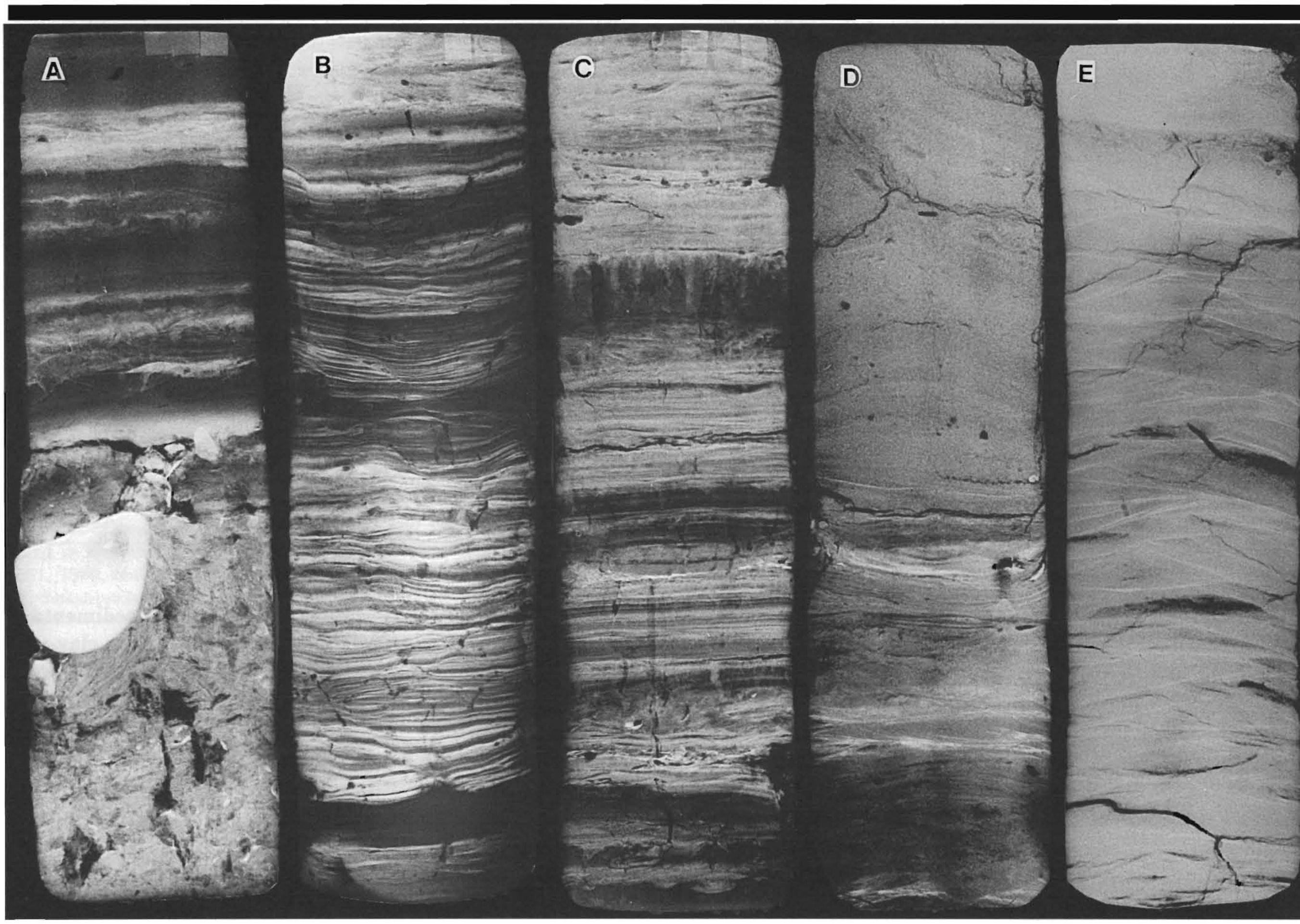

Figure 12. X-ray radiographs of subsamples of a vibracore through the Wax Lake delta illustrating the sedimentary facies and their characteristics. These cores represent (a) the contact between shell-rich old bay bottom sediments and overlying prodelta deposits composed of alternating clays and silty clays; (b) prodelta-distal bar deposits composed of thin silty layers that alternate with clay and silty-clay layers; (c) distal bar deposits composed of alternating sand, silty, and clay layers with burrows; (d) massive and cross-stratified distributary mouth bar sand; and, (e) cross-stratified fine sand of the subaqueous levee.

The bases of these deltas are represented primarily by interlaminated silts and clays. These deposits directly overlie old bay-bottom sediments that are shell-rich, burrowed, and interpreted as having been derived largely from shoreline erosion. MORGAN *et al.* (1953) estimated that coastal retreat in this area was 2 to 5 m/yr prior to the introduction of Atchafalaya sediments, which had a significant impact on central Louisiana's bays and coasts in the 1940s and early 1950s.

Bay bottom sediments that were present before delta-building began are typically composed of silty-clays that display little primary structure because of the intense burrowing by a variety of benthic organisms, particularly bivalves (Figure 12a). Weakly graded units are sometimes present, and remnants of starved ripples are present. These sedimentary structures are probably related to the reworking of the shallow bay floor during storm events. Oyster shells (*Crassostrea virginica*) and brackish water clams (*Rangia cuneata*) are common. The transition from bay bottom sediments to overlying prodelta deposits is usually rather abrupt and quite easy to interpret from cores.

VAN HEERDEN (1983) identified very early lower prodelta deposits associated with the Atchafalaya delta that he interpreted as developing after the clearing of a major log jam on the river in 1839. These deposits are composed of alternating clays and silty-clays that contain burrowed horizons. They do not contain abundant shell debris and definitely mark a change in sedimentation style within the bay. Figure 12b represents these deposits that, at least in part, are probably equivalent to the "gelatinous mud" in western Atchafalaya Bay and on the adjacent shelf identified by THOMPSON (1951) (Figures 3 and 4). However, with continuous bay floor aggradation, which was underway in the early 1950s, a silt-rich prodelta-distal bar facies was deposited as a seaward thinning wedge of sediment. The initial channel networks that later provided conduits for the development of coarser facies from both the lower Atchafalaya River and Wax Lake Outlets, were etched into these deposits. This transition, punctuated by channel development, forced deposition of coarser facies over prodelta deposits.

The upper prodelta-distal bar deposits (Figure 12c) are characterized by alternating parallel laminated clays and fine silts. Some thin and apparently horizontal silt units are, on closer inspection, actually very low-angle cross-laminated horizons. Starved ripples of silt-rich sediment are also found in distal bar deposits.

The sand-rich facies are comprised primarily of distributary mouth bar, channel, and subaqueous deposits as well as more elevated natural levee sediments. As illustrated in Figure 12d and 12e these sediments contain a variety of structures. The distributary mouth bar facies generally consists of upward fining units of cross-laminated and parallel laminated fine-to-medium-sized sands with thin intervals of silts and silty clays. Occasionally, distributary mouth bar sediments contain massive sand-rich units, while subaqueous and intermittently exposed natural levee deposits typically contain trough and climbing ripple cross-laminations. These structures indicate high sedimentation rates associated with active discharge conditions. Climbing ripples are replaced by simple cross-laminations when sediment supply decreases significantly during waning flood conditions or periods of low discharge. Intermittently exposed levees contain alternating clays, silts, and fine sands, while subaqueous levees are mostly composed of sand. Exposed levee deposits contain parallel laminations as well as cross-laminations. These deposits are quickly colonized by plant communities once they build above the low tide level. Root burrows and particulate organic horizons are frequently found in intermittently exposed or subaerial natural levee deposits.

A summary of sand body thicknesses in the Wax Lake delta, as measured from vibracores, is presented by MAJERSKY *et al.* (1997). On average, the sand-rich facies (distributary mouth bar, channel, and levee deposits) account for about 67% of the Wax Lake delta's sedimentary framework. By comparison, VAN HEERDEN (1983) estimates, from numerous vibracores of the eastern delta, that the same facies account for about 55% of the Atchafalaya delta. However, a new evaluation of sand body geometries in the Atchafalaya delta by MAJERSKY-FITZGERALD (1998) suggests that the delta is composed of approximately 62% sand. Earlier studies by FISK (1955) on the Lafourche delta found that this comparatively thin inner shelf delta was also sand-rich. He described a process by which semi-continuous delta front sheet sands formed through the coalescence of distributary mouth bar deposits from closely spaced distributaries. Strike and dip sections through the Atchafalaya delta (VAN HEERDEN and ROBERTS, 1988) and the Wax Lake delta (MAJERSKY *et al.*, 1997) suggest a similar process involving the fusion of sand bodies, primarily composed of distributary mouth bar and subaqueous levee deposits, to produce a semi-continuous sand trend. FISK (1955) also indicated that the distributaries of these thin inner shelf deltas, like the Lafourche, frequently cut well below their own deltaic deposits. Cross sections through both the Wax Lake and Atchafalaya deltas indicate that distributaries in the proximal parts of these bayhead deltas have cut well into the old bay-bottom sediments below more recent deltaic deposits. These similarities suggest that the formation of bayhead and thin inner shelf deltas, like the Lafourche or St. Bernard deltas of the Mississippi River delta plain, even though their spatial scales are quite different, derive from very similar processes.

DOWNDRIFT IMPACTS

The impact of a delta switching event similar to the diversion of Mississippi River water and sediment down the Atchafalaya River is not confined to the delta-building area alone, but downdrift coastlines and shelves are also dramatically affected. Research on shoreline change and mudflat development along the Louisiana coast west of Atchafalaya Bay by MORGAN *et al.* (1953), VAN LOPIK (1955), MORGAN and LARIMORE (1957), and MORGAN (1963) noted that the coast was beginning to undergo a rapid transition from erosion or near equilibrium to local progradation. MORGAN *et al.* (1953) indicated that local inhabitants identified these changes along the coast as starting in the 1946–1948 time frame and that these changes affected about 25 km of the eastern chenier plain coast. The increasing and steady capture of Mississippi River discharge by the Atchafalaya distributary (Figure 1), as well as the more efficient transport of sediment through the Atchafalaya Basin, because of its near sediment-filled state has obviously enhanced deposition of suspended load sediment both in Atchafalaya Bay and beyond. As discussed previously concerning the early stage of Atchafalaya sediment deposition, clays carried in turbid Atchafalaya River plumes beyond the Point Au Fer Shell Reefs flocculated when they encountered more marine inner shelf waters, thus causing the buildup of "gelatinous clays" described initially by THOMPSON (1951) (Figure 5). MORGAN *et al.* (1953) identified the Point Au Fer Shell Reef (Figure 1) as a barrier to free intrusion and mixing of salt water with fresher water in Atchafalaya Bay, thus limiting the flocculation of clays within the bay. However, research by Morgan and his colleagues clearly identified fluid mud deposits up to 2 m thick in the nearshore area off the eastern chenier plain coast and the appearance of a mudflat at Chenier Au Tigre (Figure 13).

Although Atchafalaya River sediments were clearly implicated in coastal change as early as the 1950s (THOMPSON, 1951; MORGAN *et al.*, 1953; and MORGAN and LARIMORE, 1957), it was not until the flood of 1973 when the Atchafalaya and Wax Lake deltas appeared as subaerial features that progradation of the eastern chenier plain was rediscovered, and once again scientific attention focused on the effects of downdrift sedimentation from the Atchafalaya River (ADAMS *et al.*, 1978; ROBERTS, *et al.*, 1980; VAN HEERDEN, 1980; WELLS and ROBERTS, 1980; KEMP, 1986).

Important Role of Cold Front Passages

Cold fronts, boundary zones between cold and dry polar air surging southward and warm maritime air moving northward, are common drivers of weather patterns in the autumn and winter months. Along the mid-latitude Gulf of Mexico coast, these fronts most frequently approach from a northwesterly direction and move generally west to east, producing orderly spatial and temporal changes in wind speed, wind

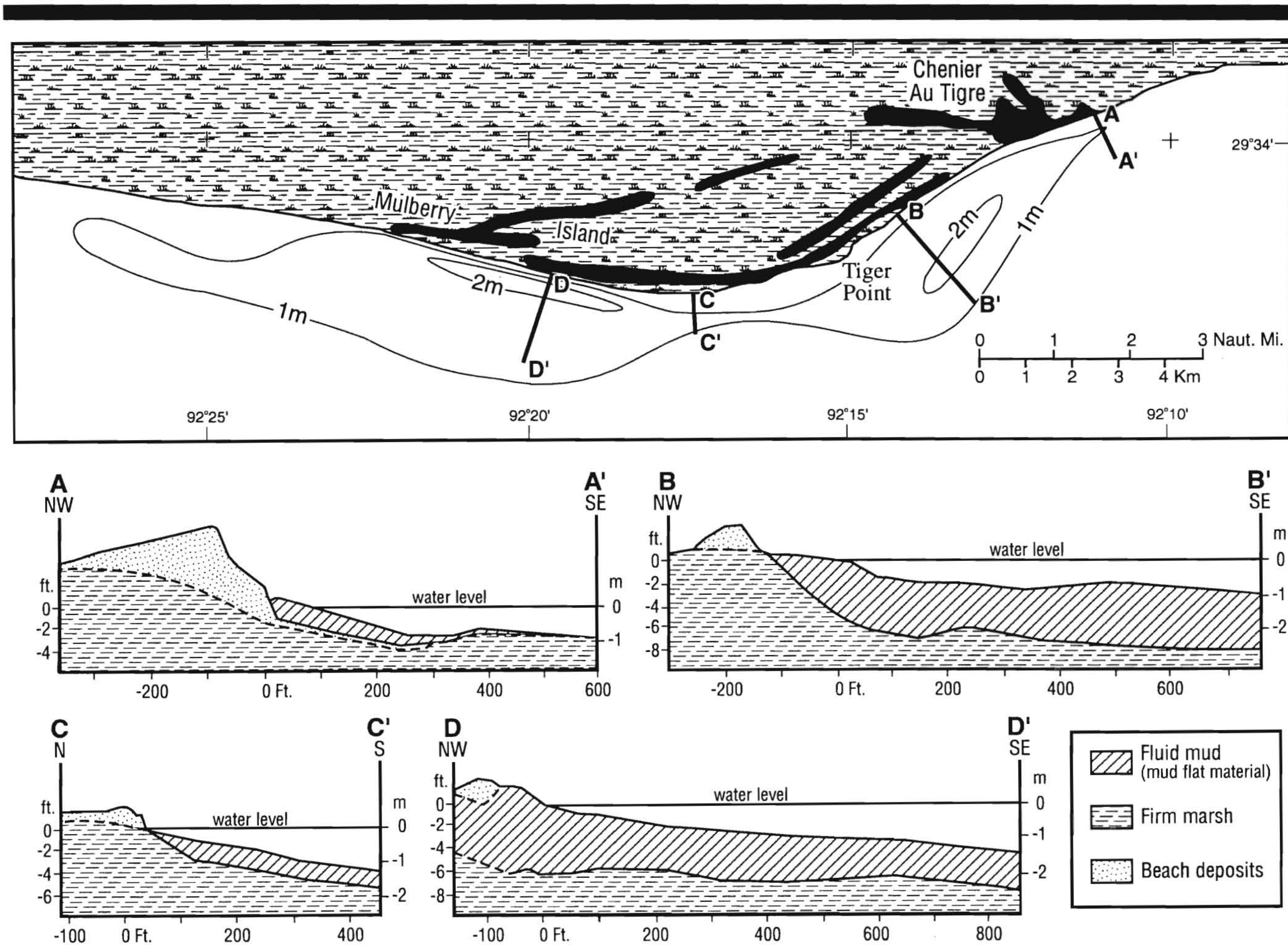

Figure 13. Map and selected cross sections showing the thicknesses of fluid mud deposits along the eastern chenier plain (modified from Morgan *et al.*, 1953). In the map view, distances from the shoreline have been exaggerated 9x for illustration purposes. Note that all cross sections except D-D' start at the shoreline in coarse-grained chenier ridge-beach deposits. At this time fluid mud from the Atchafalaya diversion was just starting to prograde the eastern chenier plain coast.

direction, barometric pressure, air temperature, and humidity. Intensity of the front's pressure system and speed of movement are the main factors that regulate energy transfer to the coast and ultimately impact sediment transport and processes of coastal erosion and deposition. Figure 14 illustrates changes in barometric pressure, wind speed direction, and water levels (inshore and offshore) associated with a cold front passage measured on the inner shelf offshore of the chenier plain. Changes in these parameters, as well as sedimentary responses along the chenier plain, can be conveniently discussed in terms of two sets of conditions, prefrontal and postfrontal.

During the prefrontal phase, before a cold front obliquely crosses the western Louisiana coast, moist maritime winds blow onshore from the Gulf of Mexico toward the advancing front. If the front approaches from the common northwesterly direction, winds will blow toward the coast from the south-southeast. Regardless of front orientation, oblique or parallel to the coast, long fetch prefrontal winds cause water level set-up at the shoreline. If the front moves slowly toward the coast or stalls inland and onshore winds persist, bay water levels may be elevated by as much as 0.6 m (ROBERTS *et al.*, 1989) and sediments on the nearshore shelf and in coastal bays are resuspended (WALKER *et al.*, 1992). Over prolonged prefrontal periods, tidal modulation of already elevated water levels forces water with a high suspended sediment load into surrounding marshlands where these terrigenous sediments build substrates and provide a source of nutrients for coastal plant communities, a process that helps offset subsidence and leads to a healthy coastal marsh ecosystem (MOSSA and ROBERTS, 1990). This process applies particularly to the marshes around Atchafalaya Bay. Since increased Atchafalaya discharge started in the late 1940s, the marshland perimeter of Atchafalaya Bay and those bays adjacent to Atchafalaya Bay (Figure 1) have received an increase in clay-rich sediment.

Prevailing currents set to the west on the inner shelf opposite Atchafalaya Bay, as noted by both THOMPSON (1951) and MORGAN *et al.* (1953). New research on the Mississippi-

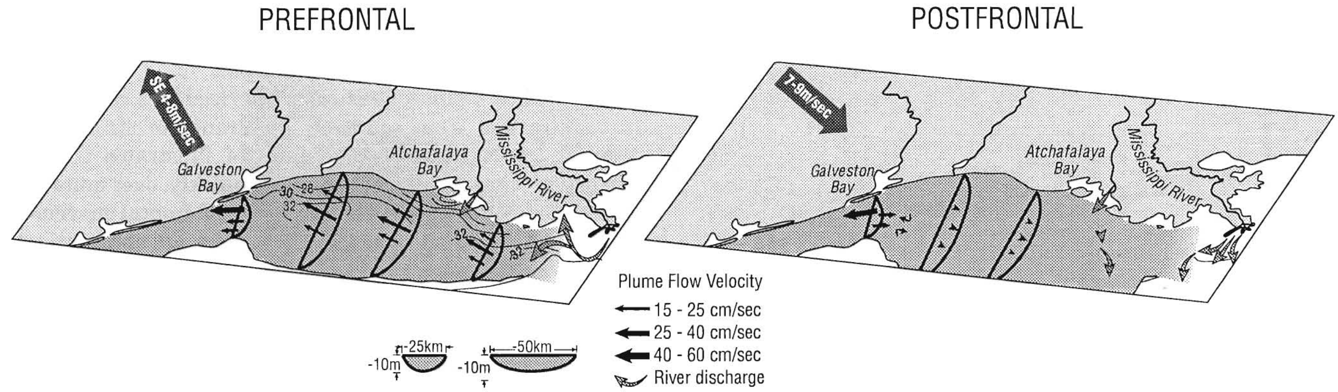

Figure 14. Inner shelf flow off the coast of Louisiana as forced by input from the Mississippi and Atchafalaya Rivers under pre-frontal and immediate post-frontal conditions (modified from Murray, in press).

Atchafalaya coastal plume indicates that the combined peak discharge of these rivers is in excess of 30 × 10^3 m^3/s during flood conditions and about 10 × 10^3 m^3/s during the low water months of the fall, resulting in a brackish, turbid band of coastal water that is identifiable all the way to the Texas-Mexico border (MURRAY, in press). Results of this new study indicate, as others have observed (WELLS and ROBERTS, 1980; ADAMS *et al.*, 1982; ROBERTS *et al.*, 1987), that the advection of suspended sediment in this plume is strongly modulated and sometimes even reversed by the annual wind cycles, especially the wind reversals associated with the passage of winter cold fronts (Figure 15). Strong northerly winds associated with frontal passages, which start in the fall and disappear in early spring, disrupt the prevailing westward transport of Atchafalaya River water and its suspended sediments. ADAMS *et al.* (1982) conclude, from sediment transport studies on the inner shelf opposite Atchafalaya Bay, that the coarsest material available (very fine sand, 3.5Φ) is transported to the southeast by intense flow resulting from cold front passages. Their results suggest that sand-sized materials are currently being selectively transported east-southeastward and offshore, while most of the suspended load of finer sediments is moved down current (westward) with the mean flow to provide sediments that impact downdrift coasts. Therefore,on average, sediments are rather continuously supplied to Louisiana western coasts by the mean westward drift that manifests itself opposite Atchafalaya Bay and near the chenier plain coast as a very turbid band of water near the coast, locally termed the mudstream. The result of this westward drift of sediments, which has been identified since the late 1940's, has been deposition of fluid mud on the inner shelf and simultaneous progradation of the shoreline along sections of the downdrift eastern chenier plain coast. Although ADAMS *et al.* (1978) illustrated that the number of new chenier plain mud flats was increasing and that the belt of active coastal progradation was migrating westward, the actual processes responsible for cross-shelf transport of mud to the shoreface were poorly understood at that time. KEMP (1986) has thus far provided the most comprehensive appraisal of the fundamental processes responsible for onshore sediment transport. Like earlier work off the Surinam coast of South America (WELLS *et al.*, 1978), he found that progressive nearshore attenuation of solitary-like waves, which efficiently transport suspended sediment, promoted deposition at or near the shoreline. He also found that shore-amplified water level oscillations, which have the characteristics of standing waves with an antinode at the shoreline, caused shoreward transport of low-frequency flows. Later, ROBERTS *et al.* (1987) and ROBERTS *et al.* (1989) focused on the significance of wave states and water level fluctuations forced by winter cold fronts as part of the fundamental process of mudflat accretion and coastal progradation.

Along the chenier plain coast, prefrontal conditions are most frequently associated with persistent wave approach from the southeast, which drives the westerly coastal mudstream and elevates water levels, as much as 0.3 m, (Figure 14). WELLS and ROBERTS (1980) indicate that waves from the southeast, the most frequent wave approach direction, have periods that range from 4.5 to 6.0 seconds. Analysis of remotely sensed data (satellite images, airborne multispectral scanner data, and air photos) clearly identify the trend of westward alongshore movement of turbid inner shelf water during prefrontal conditions, as recently confirmed by extensive current meter data for the entire coastal boundary current (MURRAY, in press), Figure 15.

The inner shelf, along prograding parts of the eastern chenier plain, is blanketed with fluid mud as originally discussed by MORGAN *et al.* (1953) and confirmed again later by WELLS and ROBERTS (1980), KEMP (1986), and ROBERTS *et al.* (1987). The muds have a very low density (1.10–1.35 g/cm^3) and high water content (61–89%), a sediment that should easily be eroded. However, as previously observed in the field, sectors of the coast fronted by fluid muds accrete rather than erode when under attack by waves. Figure 16 schematically illustrates response of the eastern chenier plain coast to both prefrontal and post frontal conditions. Wave-related processes, as described by KEMP (1986), cause nearshore fluid mud to be transported over a flooded mudflat surface. Waves transiting fluid wind bottoms are progressively attenuated as they approach the shoreline and they do not break. The at-

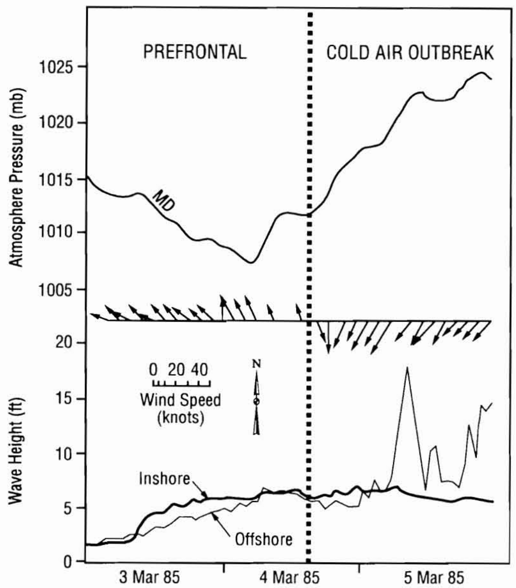

Figure 15. Surface measurements of barometric pressure, wind speed and direction and wave height made at 50 km (inshore) and 111 km (offshore) seaward of the eastern chenier plain during the passage of a cold front in March 1987 (modified from Roberts *et al.*, 1987). Note the onshore winds blowing from a southeasterly direction and low barometric pressure in the prefrontal phase while high pressure and strong northerly winds occur directly after the front passes.

tenuation causes an onshore decrease in wave shear stress at the bed that promotes deposition of fluid mud on the shoreface or on the flooded mudflat surface. Transport processes are modulated by tide as well as wave state. However, the mudflats are flooded primarily by wind-forced water level setup along with tidal oscillations. Field observations suggest that distinct lobes of fluid mud are transported to the mudflat surface after unusually strong prefrontal wind and wave activity. These localized sediment transport events are not well understood, but perhaps they are related to the standing waves identified by KEMP (1986). Like KEMP (1986), HUH *et al.* (1996) suggest that sediment delivery takes place during sea level oscillations on a variety of scales. These water level changes are forced by a variety of events ranging from hurricanes and winter storms to wave run-up. However, cold front passages appear to provide the primary conditions for sedimentation and coastal progradation.

Post-frontal conditions are characterized by a rapid shift in wind direction from southerly quadrants to strong winds from the north-northwest. Figure 14 illustrates that this change in wind direction takes place quickly, over minutes to a few hours depending on the speed of frontal movement. This wind direction change, followed by an abrupt rise in barometric pressure, clear skies, brisk northerly winds, and a drop in air temperature. These events cause the water level at the coast to drop quickly and wave action to markedly diminish near the coast. At the same time, turbid bay water is flushed seaward in plumes that generally trend toward the southeast. As Figure 14 shows, however, wave state offshore quickly increases as fetch for the strong northerly winds increases seaward of the coast. Under rapid setdown conditions, the coastal mudflats drain seaward and are exposed to clear skies and cold, dry winds, usually for several days. Newly deposited fluid muds exposed to these conditions quickly dewater through evaporation, increasing sediment cohesion and eventually producing a mud-cracked surface (Figure 17). This process, if the post-frontal phase is prolonged, will transform a sedimentary unit composed of initial particles of clay in the 2–5 micron size range to sun-baked clasts in cobble-to-boulder size range. Newly deposited sediments are stabilized in the short-term by the desiccation process described earlier. Sun-baked polygons of mud averaging 20–30 cm wide and 8–10 cm thick commonly result from this process, which armor the mud flat surface against physical erosion. In the longer term, the newly deposited mud flat surface is quickly colonized by plant communities typically consisting of *Spartina* and/or *Panicum*. These plants not only stabilize the mudflat and resist erosion but the marsh plants also enhance sedimention by functioning as baffles for new sediment introduced during periods of mudflat flooding. Armoring of the accreting mudflats by this desiccation process and rapid colonization by marsh plants helps protect against erosion during infrequent, but sometimes intense, storm wave attack.

Record of Sedimentation and Coastal Progradation

Even though cold front passages cannot be compared with hurricanes in terms of energy transfer at the coast, they have

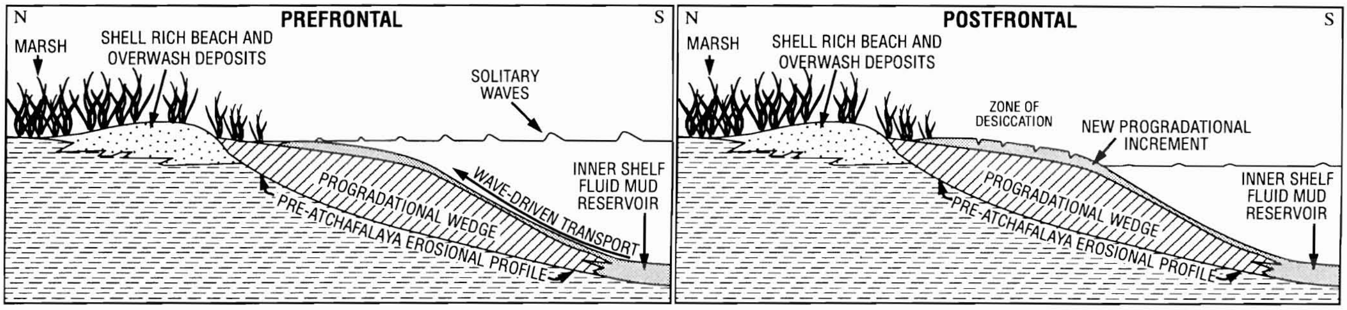

Figure 16. Schematic representation of processes of mudflat accretion and stabilization during pre-frontal and post-frontal conditions.

Figure 17. View of the newly accreted and mud-cracked mudflat along the eastern chenier plain. Note the size of individual clasts that have developed from post-frontal desiccation of fluid mud deposited on the mudflat surface.

more uniform directions of approach, repeated patterns of wind and wave forcing, occur at larger spatial scales, and have a much higher repeat frequency (30–40 each year). Along the chenier plain coast, the cyclic forcing associated with cold fronts has more of a sedimentologic and geomorphic impact than the occasional hurricane. HUH *et al.* (1991) implicate cold fronts in these combined processes that have initiated steady progradation of the eastern chenier plain coast in recent years. Unlike the transitory mudflats and mud arcs first documented by MORGAN *et al.* (1953) and later studied by WELLS and KEMP (1981) and KEMP (1986), coastal progradation has increased since 1987 in overall scale and rate. Repeated low and high altitude color infrared photography between 1987 and 1994 (HUH, *et al.,* 1996) indicated that over large areas of the eastern chenier plain, the muddy shoreface has prograded rapidly and persistently, with rates averaging ~50 m/yr. Figure 18 illustrates sections of the coast where progradation has been particularly impressive over the 1987 to 1990 time frame. Progradation in these areas has exceeded the ~50 m/yr average.

Deposition of fluid mud layers are the building blocks of coastal progradation along the eastern chenier plain. Vibracores through newly accreted mudflats indicate that these deposits are composed of couplets of cohesive and non-cohesive sediments (Figure 19). Rapid deposition of these fluid mud layers, as proposed by KEMP (1986), involves a process of "boundary layer dumping" that occurs when the yield strength of the fluid mud layer supported above the wave boundary layer reaches equivalence with wave boundary layer shear stress, process similar to the one described by STOW and BOWEN (1980) for sediment sorting in turbidites. An onshore decreasing shear stress gradient under attenuating waves gives rise to deposition close to shore, even on the mudflat surface when coastal water levels are elevated. As Figure 19 illustrates, these coastal mud deposits are composed of vertically stacked couplets, 2–10 cm thick, composed of rather homogeneous mud and thin shelly silt units. These incremental units are systematically being added to parts of the chenier plain coast that are fronted by inner shelf reservoirs of fluid mud. In time, fluid mud deposits will migrate westward until the entire chenier plain shoreline is transformed from the centuries old erosional phase to a new episode of coastal progradation forced by the fundamental process of delta-switching that is currently providing an abundant supply of sediments from the Atchafalaya diversion of Mississippi River water and sediment.

CONCLUSIONS

Effects of perhaps the most important geological event in Louisiana in historical times, transport of water and sediment down the Atchafalaya River course, are now being clearly observed in Atchafalaya Bay and surrounding coastal environments, as well as along the downdrift chenier plain coast. This latest delta-switching event is attempting to abandon the modern Balize (birdfoot) delta of the Mississippi in favor of a new delta in Atchafalaya Bay and on the adjacent continental shelf. At present, this embryonic stage of delta-building is represented by two bayhead deltas, one at the mouth of the Atchafalaya River, and another at Wax Lake Outlet, a man-made canal that diverts part of the Atchafalaya River discharge. In addition to delta-building this latest episode of delta-switching has affected the downdrift coast so that the centuries old state of coastal erosion and retreat is in the process of being reversed. Since the early documentation of Atchafalaya River sedimentation at the coast by THOMPSON (1951), MORGAN *et al.* (1953), and MORGAN and LARIMORE (1957), dramatic changes related to increased sed-

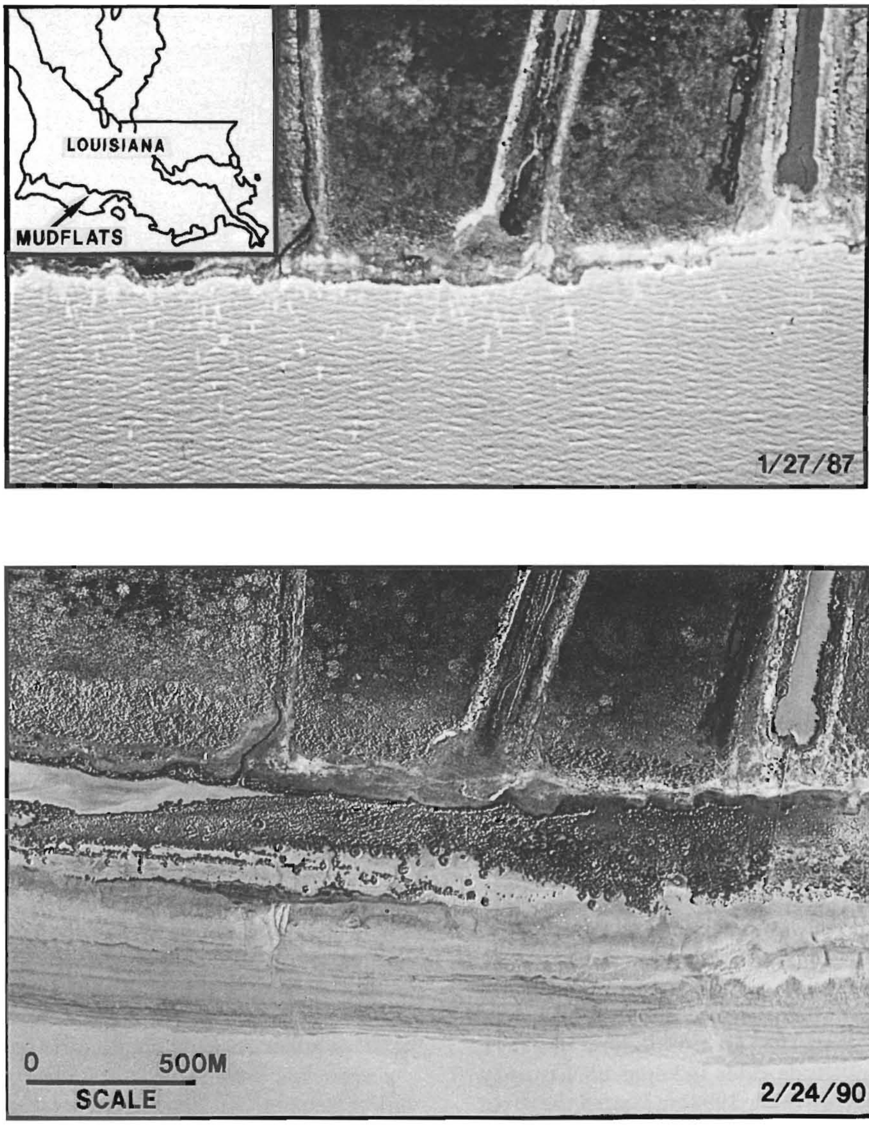

Figure 18. These two plates of the eastern chenier plain coast (1987 and 1990) indicate the rapid progradation characteristic of a new era of growth forced by the Atchafalaya River diversion of Mississippi River water and sediment.

iment transport and deposition have occurred. These changes are summarized as follows:

(1) Following increasing capture of Mississippi River water and sediment in the 1940s and 1950s, which coincided with the sediment filling of Atchafalaya Basin, suspended sediments arrived at the coast in increasing quantities. THOMPSON (1951) and MORGAN *et al.* (1953) recognized and documented the first major coastal and shelf changes related to these events.

(2) In 1963 the Old River control structure was built at the point of stream capture of Mississippi flow down the Atchafalaya River course. Discharge down the Atchafalaya was regulated at 30% of the Mississippi plus the added contribution from the Red River.

(3) By 1972 the bottom of Atchafalaya Bay had accreted to near exposure at low tide over considerable areas opposite the Atchafalaya River mouth and to a lesser extent opposite the Wax Lake Outlet, and it was clear that a new phase of bayhead delta-building was underway. In addition, transient mudflats were appearing and disappearing along the eastern chenier plain coast.

(4) In 1973, an abnormally high flood year, the Atchafalaya and Wax Lake deltas became subaerial features and started a new sand-rich part of their development. Subaerial evolution of the Wax Lake delta lagged behind the Atchafalaya because small inland basin (*e.g.,* Wax Lake) had to be filled before coarse sediments were efficiently by-passed to Atchafalaya Bay.

(5) Both the Atchafalaya and Wax Lake deltas have rapidly evolved through the processes of seaward channel exten-

Figure 19. X-ray radiograph of a stacked series of cohesive and non-cohesive sediment couplets interpreted as having been deposited as a product of boundary layer sorting (Stow and Bowen, 1980) associated with sediment transport events during cold front passages. The core from which these subsamples were taken was acquired from the newly accreted mudflat illustrated in Figure 18b.

sion and bifurcation as well as lobe fusion and upstream growth by coarse sediments (primarily fine sand). Both deltas are composed primarily of sand-rich facies (mostly distributary mouth bar and subaqueous levee deposits). Estimates of sand content made from vibracores are 62% for the eastern Atchafalaya delta and 67% for the Wax Lake delta. At present, these deltas account for over 150 km^2 of new land (above a -0.6 m isobath).

(6) Since THOMPSON (1951) documented deposition on the shelf opposite Atchafalaya Bay and MORGAN *et al.* (1953) studied new mudflats at Chenier Au Tigre, dramatic changes have occurred along the eastern chenier plain coast as a product of sediments supplied from the Atchafalaya River. From the 1950s to the mid-1980s linear mudflats and mud arcs along the eastern chenier plain coast were transient features that basically increased in number and appeared farther and farther westward during this period. By 1987 the ~20 km stretch of eastern chenier plain coast west of Freshwater Bayou started a phase of very rapid progradation, averaging about 50 m/yr.

(7) Deposition of fluid mud along the chenier plain coast was found to be strongly linked to the passage of cold fronts (30–40/yr). Prefrontal winds cause resuspension of sediment and water level setup along the coast. During this time sediments are transported by water level oscillations on a variety of temporal and spatial scales. Post frontal winds cause water level setdown at the coast, transport of turbid plumes out of coastal bays, and exposure and desiccation of newly deposited sediment on mudflats. Development of sun-baked mud clasts and rapid colonization of mud flats by

marsh vegetation collectively stabilize these deposits against erosion.

(8) Cross-shelf transport of fluid muds to the shoreface and flooded mudflats result in growth increments composed of complete fluid mud with a thin silty and sometimes shell-rich base. These fundamental depositional units appear to be the products of a decreasing shear stress gradient developed under attenuating waves.

(9) In the future, the Atchafalaya and Wax Lake bayhead deltas will merge, fill Atchafalaya Bay, and emerge on the adjacent continental shelf as a shelf phase delta. Influence of Atchafalaya sediments will be felt farther south on the continental shelf and sediment supply to downdrift coasts will increase. As a product of the Atchafalaya delta-switching event, the eastern chenier plain will continue to rapidly prograde, and the zone of progradation will systematically move westward until the entire chenier plain coast has made the transition from long-standing transgressive to a regressive state.

ACKNOWLEDGMENTS

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