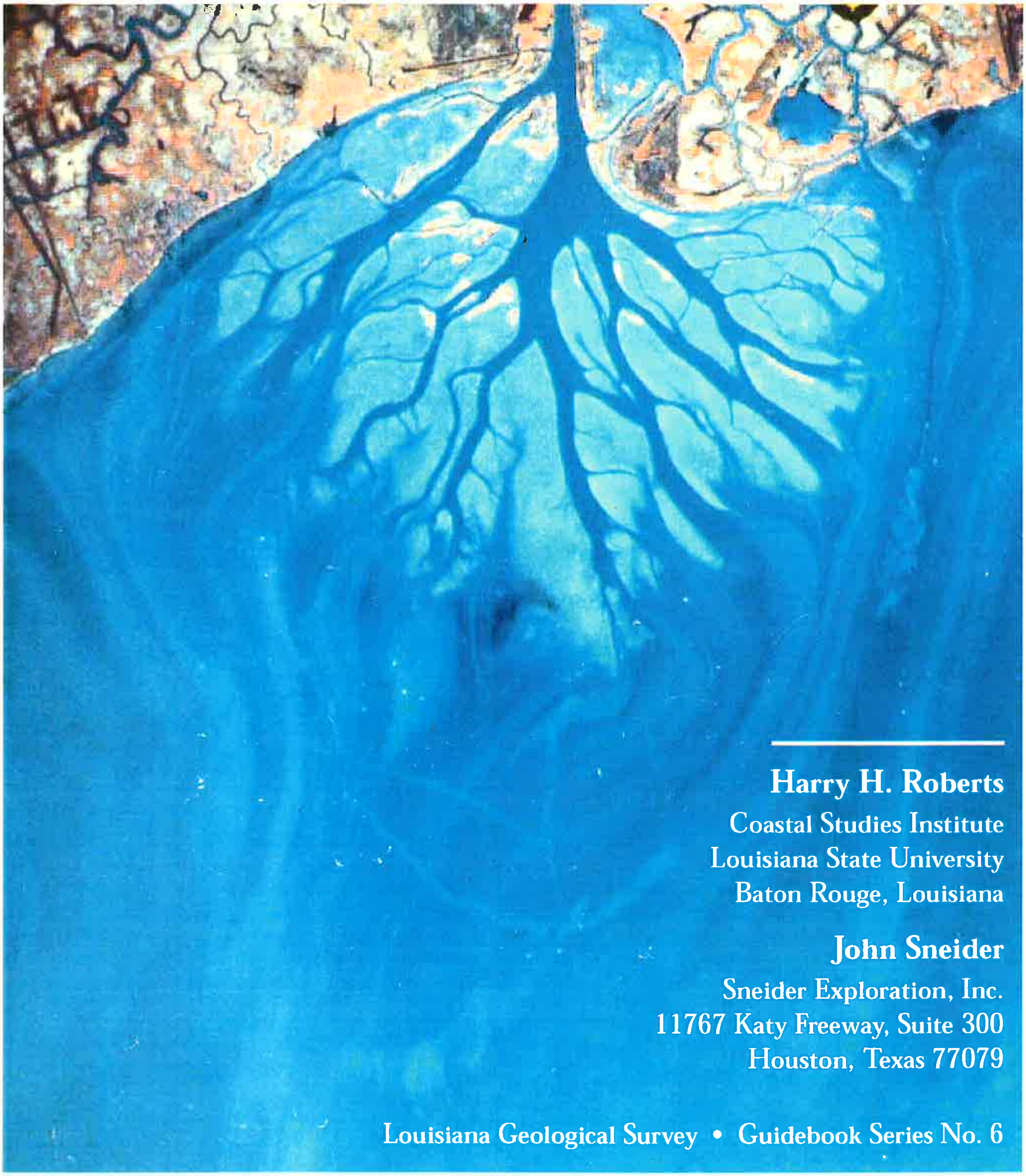
Atchafalaya-Wax Lake Deltas

The New Regressive Phase of the Mississippi River Delta Complex

A Field Seminar for the GCAGS 2003 Convention



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Louisiana State University
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PREFACE

This field trip is designed to acquaint you with a dynamic and geologically young part of the Mississippi River Delta Complex that has developed as a product of diversion of Mississippi River water and sediment down the Atchafalaya River course. This event, which the first European explorers documented was in progress in the 1500s, marks the initial stages of delta switching that will eventually lead to the development of a major delta lobe along the central Louisiana coast. The field trip will allow you to observe the important environments of deposition within the Atchafalaya Basin (lakes, lake deltas, and swamps) as well as one of the two bay-head deltas that are rapidly filling Atchafalaya Bay at the coast. In the evolution of a new delta lobe you will be shown through maps, satellite images, aerial photographs, and supporting posters the geologic framework for the Atchafalaya Basin and the progression of deposition that has led to rapid progradation at the coast since the early 1950s. In addition to the immediate deposition in Atchafalaya Bay, Atchafalaya River suspended sediments are making a substantial impact downdrift along the Chenier Plain coast. Although we will not be able to visit the prograding mud flats of the eastern Chenier Plain, your field trip leaders will discuss the impact of this latest delta switching event on nearshore environments to the west of Atchafalaya Bay. Satellite images, air photos, ground-level photographs, maps, and core logs will be used to emphasize the importance of the Atchafalaya River input of sediment and water to the coast. A highlight of the trip will be visiting one of the two bay-head deltas forming in Atchafalaya Bay, the Wax Lake delta, and discussing its sedimentary architecture and geomorphic evolution. The route we will be taking from New Orleans is illustrated in Figure 1. This route cuts across the fabric of the coastal plain and allows participants to view interdistributary basins and their depositional components.

Coastal progradation as forced by the diversion of Mississippi River sediment to the Atchafalaya channel is a positive scenario in the overall negative framework of landloss in Louisiana's delta plain. Constructive use of sediment to offset the effects of subsidence and landloss as well as other methods of mitigating the landloss problem will be discussed as we visit the various environments of the Atchafalaya Basin and adjacent coastal plain. As is characteristic of many of the world's deltas, man has drastically modified the natural system. The Mississippi River deltaic plain contains the very clear imprint of man's activities. The field trip leaders will point out modifications made by man and their impacts, both positive and negative, on this deltaic system.

HISTORY OF ATCHAFALAYA RIVER DIVERSION

The Atchafalaya River is a venerable distributary of the Mississippi River. It is a complex river that flows through an inland basin (Atchafalaya Basin) partly in its own channel and partly in channels inherited from other streams (Fisk, 1952), Figure 2. Old River, at the diversion point with the Mississippi, marks the lower arm of a cut off meander loop of the Mississippi River, as illustrated in Figure 2. This loop, initially named Turnbull Bend, extends approximately 10 km from its junction with the Mississippi to a point approximately 8 km above Simmesport, where it meets the Red River. At this point the Atchafalaya River descends south through the Atchafalaya Basin, channel depths in this part of the Atchafalaya River vary from approximately 18 to 40 m.

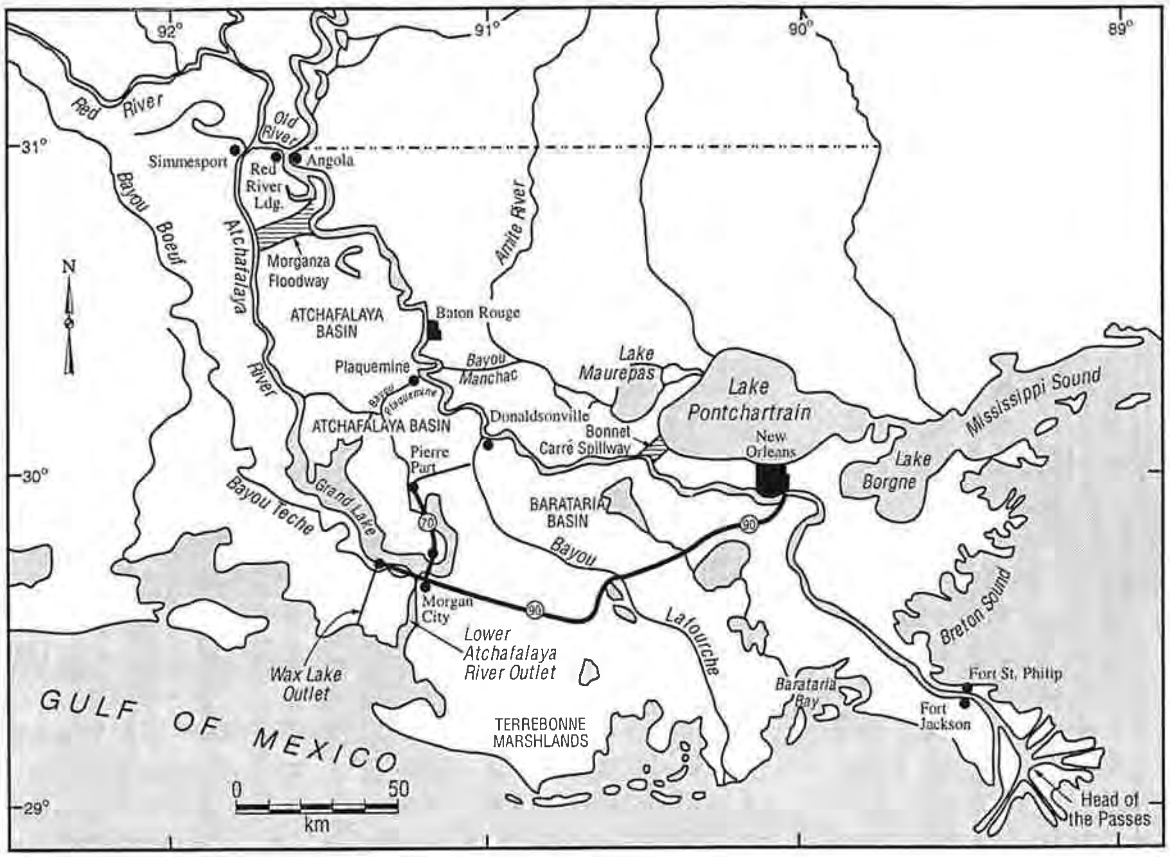

Figure 1. Field trip route from New Orleans to the Wax Lake Outlet and lower Atchafalaya Basin.

Westward migration or meander of the Mississippi River resulted in capture of the Red River by the Mississippi River at Turnbull Bend around 1805 (Figure 3). The Red River emptied into the northwest corner of the meander loop, while the inlet of the Atchafalaya River was located on the southwest corner of the meander loop. Captain Shreve in 1831 dredged a canal, a "cut-off," to shorten steamboat travel time across the narrow neck of Turnbull bend. The Mississippi River then scoured out the canal, converting it into the main Mississippi River channel. The ox-bow, Turnbull Bend, was renamed "Old River," since it was an "old" part of the Mississippi River. Large changes in water level height result in many bank failures along the Red River (Thorne 1982), and the trees supported by these failing banks fell into the river to be washed downstream into the mouth of the Red River. There they accumulated up until 1870 as a nested, impenetrable "raft" which plugged the channel. Shreve, in turn, cleared this log jam to allow colonization of the Red River. Removal of the channel plug enabled Mississippi River water to enter and deepen the channel. At the same time, flow from Red River also deepened the Atchafalaya River channel, setting the stage for flow capture of diversion of the Mississippi River through the Atchafalaya channel.

The diversion of Mississippi River water and sediment down the Atchafalaya course to the Gulf of Mexico has a definite gradient advantage over the Mississippi River. From the diversion to the Gulf of Mexico is approximately 220 km while the distance down the Mississippi River to the Gulf is approximately 320 km. Therefore, once initiated, it was inevitable that the Atchafalaya would

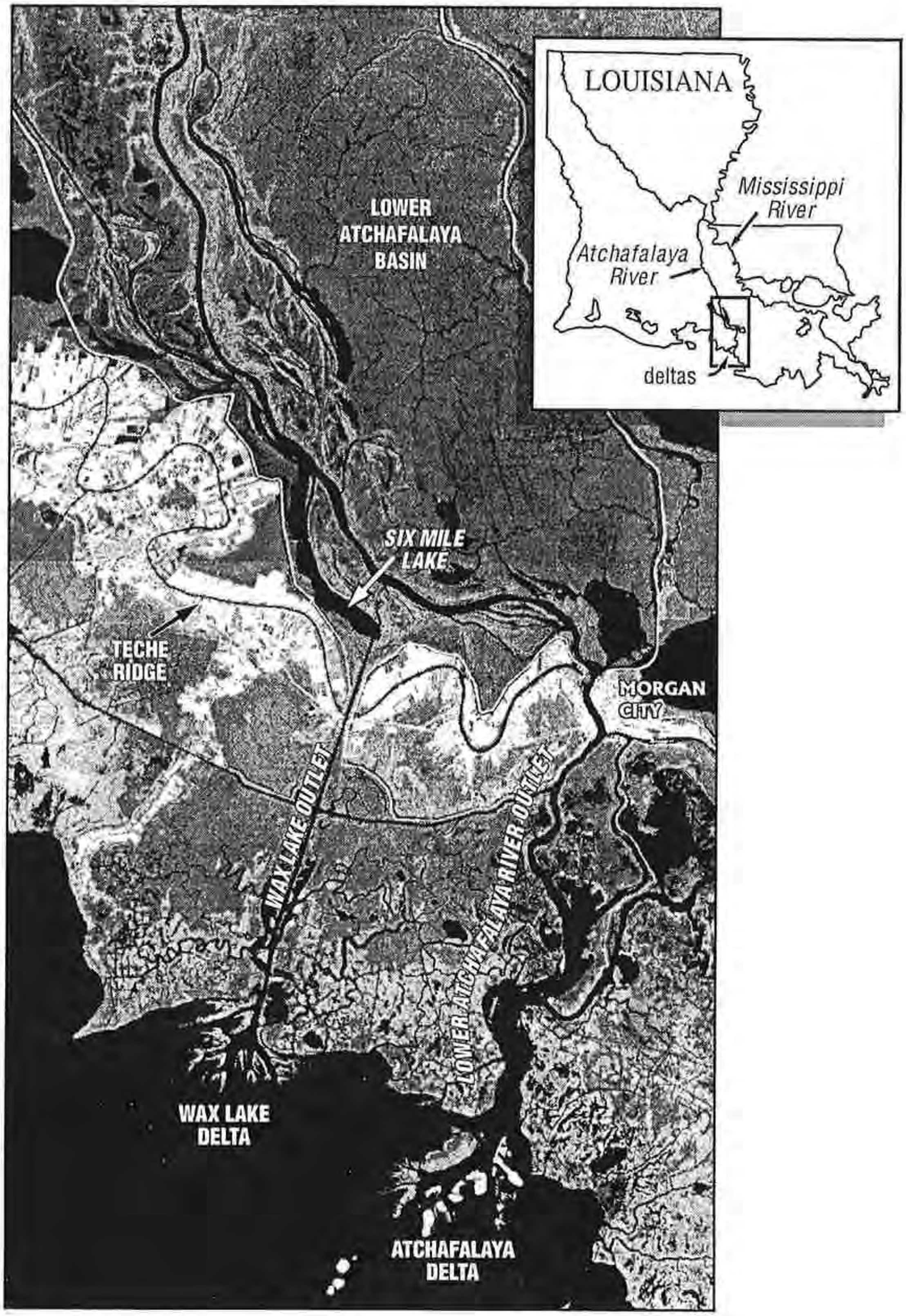

Figure 2. Field trip area of interest: (a) lower Atchafalaya Basin and (b) Wax Lake delta.

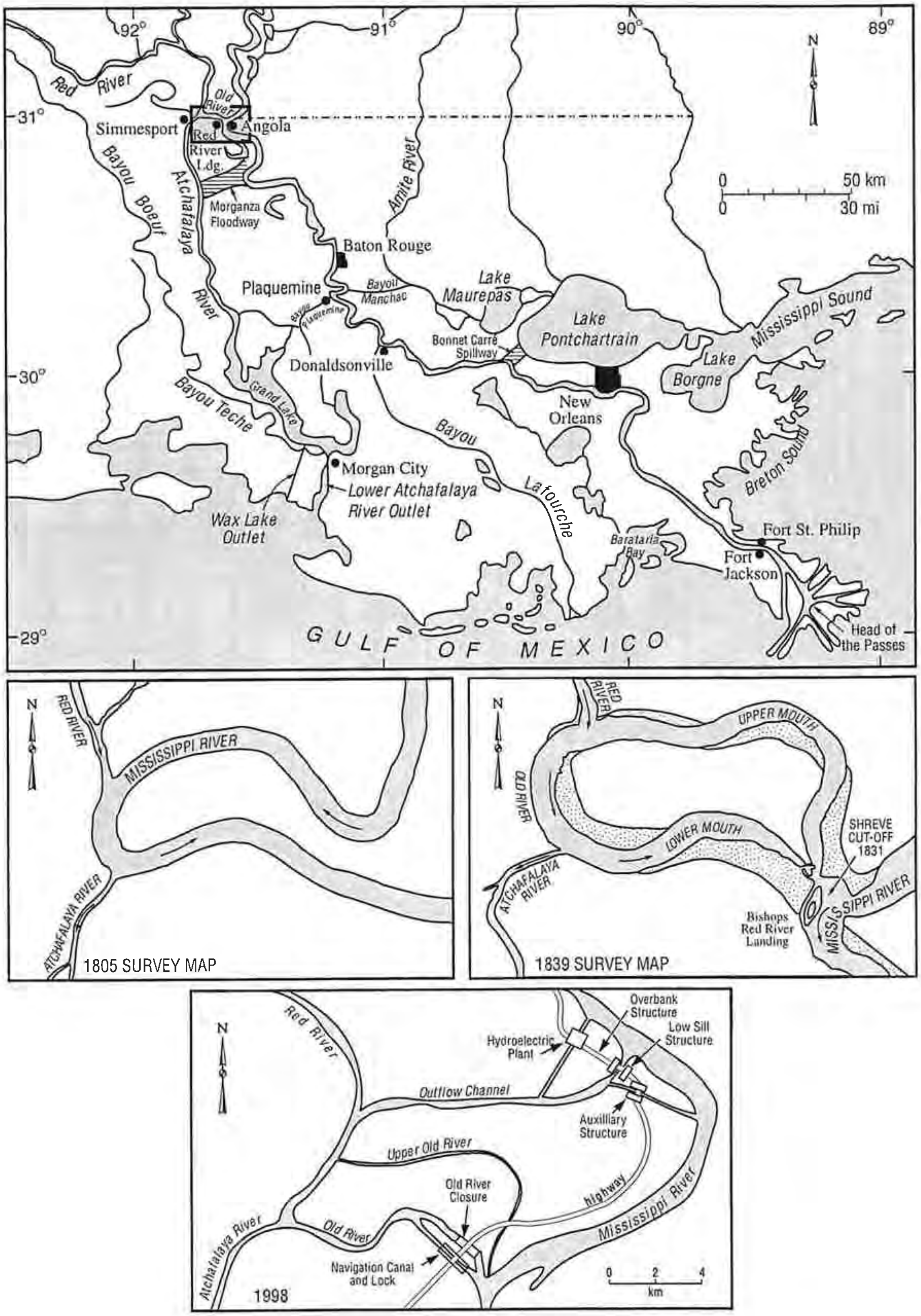

Figure 3. Historical development of the Atchafalaya River diversion channel and recently built man-made control structure.

one day capture the flow of the Mississippi River and build a new and major delta lobe along the central Louisiana coast. Fisk (1952) pointed out that the Atchafalaya was a distributary of the Atchafalaya as far back as the 1500s when the first European explorers documented its existence. However, flow down the Atchafalaya has been sporadic and has been periodically aided by dredging and the clearing of extensive log jams in the vicinity of Old River (Fisk, 1952). By the early 20th century, flow down the Atchafalaya was steadily increasing till in the mid-1900s the natural channel had become well-established and it was clear that total capture of the Mississippi would occur if man did not intervene. In order to prevent total capture, a control structure (Figure 3) was built by the U.S.Army Corps of Engineers at Old River in 1963. Since that time flow down the Atchafalaya has been regulated to 30% of the Mississippi River at the Old River cut-off plus the much smaller contribution by the Red River. Distribution of discharge throughout the Atchafalaya Basin to the two channels that lead to Atchafalaya Bay is illustrated in Figure 4.

The Atchafalaya Basin has historically been important to the state of Louisiana for lumbering and folk industries associated with fishing, crawfishing, crabbing, frogging and moss gathering. The basin has always been an important area for hunting and fishing. It also has been the site of oil and gas production during this century. With the recent development of 3D-seismic, the basin has become a site of renewed interest for oil and gas exploration.

ATCHAFALAYA BASIN

The river runs through an inland basin, the Atchafalaya Basin, defined by the alluvial ridges formed from two abandoned distributaries of the Mississippi River, the Teche-Mississippi ridge to the west and south, as well as the younger, modern Mississippi and the Lafourche ridges to the east (Figure 1). This route provides the shortest path to the sea, and the Mississippi River is attempting to divert by exchanging the Atchafalaya for its current channel (Fisk 1952). The Atchafalaya Basin is a wooded wetland (swamp) kept partly in its original state as a nature preserve and catchment area for excess Mississippi River flood waters. Atchafalaya River flow through the basin is completely divided between several channels (Figure 4). However, within the lower Atchafalaya Basin the Atchafalaya River bifurcates into shallow Six Mile Lake and deep Lower Atchafalaya River (Figure 4). Both branches independently flow to the Gulf of Mexico. Six Mile Lake flows to the Gulf of Mexico through an artificial channel, Wax Lake Outlet, that was dredged through the Teche ridge in 1943 by the US Army Corps of Engineers. Both this artificial channel and its natural counterpart to the east, the lower Atchafalaya River Outlet, deliver water and sediment to Atchafalaya Bay, where two bayhead deltas are presently forming (Figure 2).

The Atchafalaya basin contains nearly 8000 km^2 of swamplands and lakes. The basin was formed when the low central part of the lower Mississippi Alluvial Valley became completely surrounded by alluvial ridges of ancient river courses (Fisk, 1952). The surface lies at an approximate elevation of 14 m above mean sea level near Krotz Springs in the northern end of the basin and slopes seaward, reaching sea level near the southern termination of Grand Lake.

Although the Atchafalaya River discharges into the Gulf of Mexico via the Lower Atchafalaya River and Wax Lake Outlet (artificial) the bulk of the sediments carried by the stream are deposited in the numerous lakes that are present in the southern part of the basin. Thus, this river has

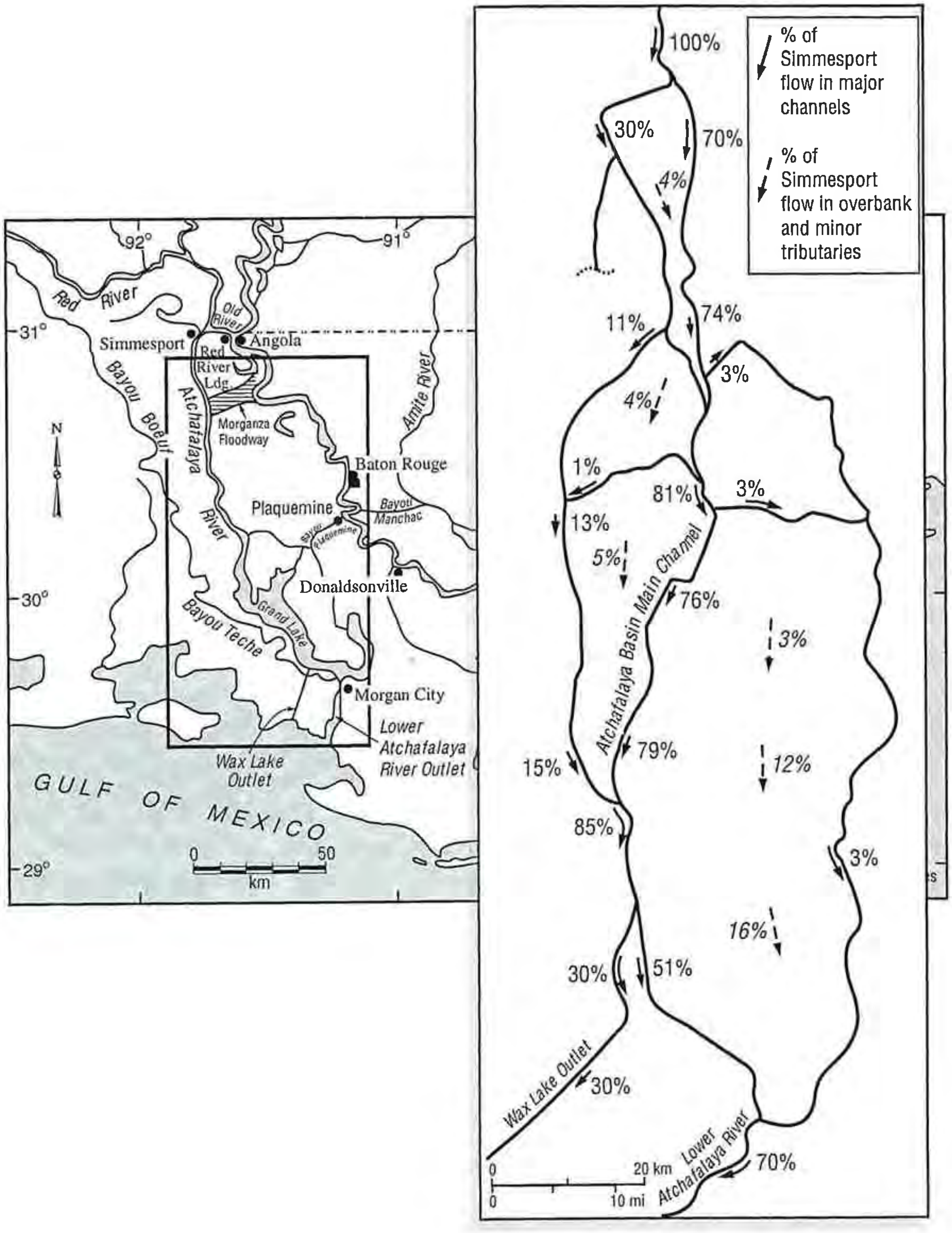

Figure 4. Distribution of discharge throughout Atchafalaya Basin.

constructed its delta within the basin as small interfingering lacustrine fill deposits (Figure 2). Fisk (1952) cites evidence that much of the land surface in the northern basin has been built by deposits that accumulated in a much larger ancestral Grand Lake. Today, approximately 390 km^2 of the southern part of the basin consists of shallow lakes, the major ones being Lake Fausse Point, Grand Lake, Six Mile Lake, Lake Polourde, and Lake Verret.

Borings in the basin reveal that two major units can be recognized overlying the buried Pleistocene terrace deposits, the coarse basal substratum and the upper fine-grained topstratum (Fisk, 1952). The basal unit consists of coarse sands and gravels laid down in the entrenched valley during the rising sea level stage. The deposits represent braided channel sequences and range in thickness from 48 m in the northern part of the basin to slightly greater than 105 m in the vicinity of Morgan City. Radiocarbon dating indicates that this unit ranges in age from 35,000 years B.P. (before present) near its base to about 10,000 years near the surface (McFarlan, 1961). Only the upper few feet of this unit was penetrated in the borings examined and consequently the lower material will not be dealt with in detail. However, this coarse alluvial valley fill represents deposits associated with multiple sea level cycles. Because of the coarseness of substratum sediments, coring is difficult and therefore less is known about this unit as compared to the finer grained topstratum.

The topstratum deposits of the Atchafalaya Basin include all materials overlying the coarse basal substratum and are distinguished by their finer-grained nature (Fisk, 1952). This unit forms a wedge-like body, increasing in average thickness from 27 m in the northern part of the basin to greater than 45 m in the vicinity of Morgan City at the southern end of the basin. The age of these deposits varies from one part of the basin to another but generally range from 12,000 year BP to contemporary deposits which form the surface of the present-day basin.

Topstratum deposits within the Atchafalaya Basin include facies that were deposited under several differing environments of deposition. These environments include natural levee, point bar, channel-fill, well drained and poorly drained swamp, lacustrine, and lacustrine delta fill. Facies representing the first three environments of deposition listed above have been well-described in the literature (Fisk et al., 1954; Kolb 1962; Coleman and Gagliano, 1965) and are generally closely associated with one another. They essentially form linear bodies of coarser sediment within the finer-grained more extensive deposits representing the swamp and lacustrine environments. The fine-grained clays of these environments exceed 30 m in thickness in several of the borings acquired by Fisk (1952) and Roberts (1986) and it is the areas exceedingly difficult to interpret their depositional environments without X-ray radiographing.

DEPOSITIONAL ENVIRONMENTS

Figure 5 illustrates characteristics of sediments that comprise the topstratum deposits in Atchafalaya as interpreted from a US Corps of Engineers boring taken within the north-central part of the basin (Roberts, 1986). This boring illustrates a rather cyclic repetition of deposition in environments interpreted as (a) well-drained swamps, (b) poorly-drained swamps, (c) lacustrine, and (d) lacustrine delta. At the base of the boring shown in Figure 4 braided channel deposits of the substratum (Fisk, 1952) were encountered, some 27 m below the modern surface.

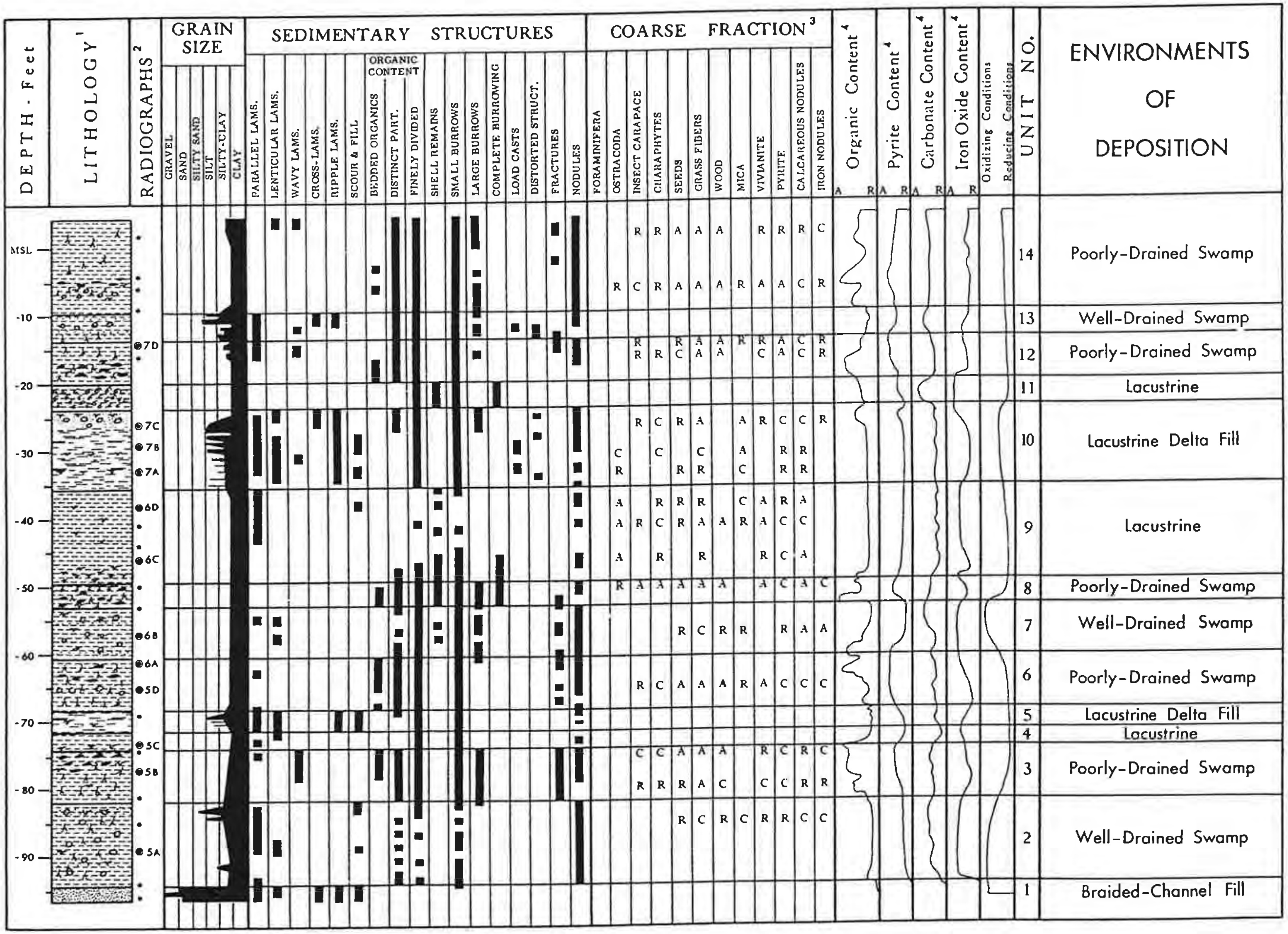

Figure 5. Boring through topstratum deposits of the Atchafalaya Basin with a tabulation of sedimentological characteristics and interpreted environments of deposition.

Figure 6. Swamp environments of the Atchafalaya Basin: (a) aerial view (b) ground-level view (poorly drained), (c) ground-level view (well-drained).

Braided Channel Deposits: Braided rivers generally display multiple channels which branch and rejoin in a variety of patterns. Flow is usually erratic in that there is a well defined flood season during which discharge increases many times greater than during low water stage. Usually, there is an overabundance of bedload material which is generally coarse and poorly sorted. Current patterns are mainly unidirectional but as a result of the multiple channel pattern, local current directions vary. In this environment, physical processes are usually responsible for most bedding features observed. Various types of cross-bedding are the most common sedimentary structures encountered. Variable intensities in current velocity, rapidly changing water depths, gain size and composition, and a heavily charged bedload are all responsible for a variety of bedforms which control the type of resulting bedding features. In the braided channel-fill deposits encountered at the base of the borings from the Atchafalaya Basin, planar and trough type cross-bedding is the dominant feature. Occasionally, graded beds (coarse to fine) are encountered but result from small migrating ripple trains. Clay ball inclusions, sometimes armored with a silt cover, are also present and are usually found in the forest beds of the larger cross-bedded units. Locally, small rounded wood particles commonly occur in the forest beds. Other less common structures include scour and fill, parallel and lenticular laminations, and plant burrows.

Conditions for braided stream deposition were met during the final stages of the period of glacial outwash as sea level rose following the last Pleistocene glacial maximum (Roberts, 1986). Relic braided stream patterns can still be observed in the middle-to-northern part of the alluvial valley.

Swamp Deposits: Swamps constitute low, flat area periodically covered or saturated with water and support a cover of woody vegetation with or without an undergrowth of shrubs. This environment is the most extensive one present within the Atchafalaya Basin and covers approximately 90% of the total area. Figure 6 shows both aerial and ground-level views of swamp environments of the Atchafalaya Basin. In areas adjacent to a river (natural levee system) excellent drainage conditions are usually present, whereas in areas isolated from these systems, standing water is present year round and drainage is poor. Therefore, in well-drained swamps alternate oxidizing and reducing conditions exist during accumulation of the sedimentary sequence. Whereas in poorly, drained swamps reducing conditions exist. The variations in the state of oxidizing or reducing environments impart distinctive characteristics to the deposits and with the aid of radiographs these features can readily be distinguished in the massive appearing clay cores obtained from swamp deposits. Common plant species found in Louisiana swamp environments are given in Table 1.

Poorly-Drained Swamp Deposits: Stagnant water conditions, resulting from an ineffective drainage network, is the major factor influencing the characteristics of sediments deposited in this environment. Water tolerant woody vegetation such as cypress (*Taxodium distichum*), tupelo gum (*Nyssa aquatica*), etc. form dense stands and other aquatics often form thick mats. Water levels are fairly stable and rarely exceed 0.5 - 1 m except in times of high floods. Anaerobic conditions are prevalent and hydrogen sulphide production can be quite high.

Lithologically, the deposits laid down under such conditions generally consist of highly

TABLE 1
Plant Species Composition in the Swamp

I. Bottomland Hardwood

Common name	Scientific name	% Frequency
Drummond red maple	Acer rubrum var. Drummondii	25.00
Water tupelo	Nyssa aquatica	11.43
Boxelder	Acer negundo	7.86
Cottonwood	Populus heterophylla	2.86
Bald cypress	Taxodium distichum	4.25
Roughleaf dogwood	Cornus drummondii	8.57
Black willow	Salix nigra	5.71
American elm	Ulmus americana	5.00
Shagbark hickory	Carya ovata	4.29
Pumpkin ash	Fraxinus tomentosa	3.57
Water oak	Quercus nigra	2.14
Hackberry	Celtis laevigata	2.14
Persimmon	Diospyros virginiana	3.57
Deciduous holly	Ilex decidua	2.86
Bitternut hickory	Carya cordiformis	1.43
Shumard red oak	Quercus shumardii	2.14
Sweetgum	Liquidambar styraciflua	1.43

II. Bald Cypress - Water Tupelo

Common name	Scientific name	% Frequency
Bald cypress	Taxodium distichum	33.33
Water tupelo	Nyssa aquatica	32.41
Drummond red maple	Acer rubrum var. Drummondii	19.44
Punkin ash	Fraxinus tomentosa	8.33
Buttonbush	Cephalanthus occidentalis	2.78

organic black clays with occasional thin laminations of silt introduced by floods. Woody peat beds are usually intercalated randomly throughout the sequence, but rarely attain any considerable thickness. Large wood fragments and laminations consisting of compressed leaves, twigs and seeds are common. As a consequence of the abundant plant life, root burrows are characteristic and often result in complete mixing of the sediment. Macro-faunal remains are usually scarce and, when present, consist of local concentrations of pulmonate gastropods or small fresh water gastrods. Microfaunal remains are likewise scarce, and the assemblage may comprise only one or two species of ostracods. Fresh water insect remains are generally present and many times concentrated along bedding planes containing abundant plant remains (leaves, twigs, etc.). Micro-plant remains are abundant, spores usually forming the major percentage of the assemblage. Charophytes are commonly encountered and those identified are represented by several species of *Chara* and *Nitella*. Diatoms vary in abundance from sample to sample, but were never exceptionally abundant.

The most characteristic features, however, consist of the various types of *syngenetic* and *epigenetic inclusions* (Figure 7). The most common inclusion consists of plant remains and since the material is formed in the basin, they must be considered as syngenetic. The organic remains deposited under such conditions are at first greatly modified by organisms, and decomposition proceeds rapidly.

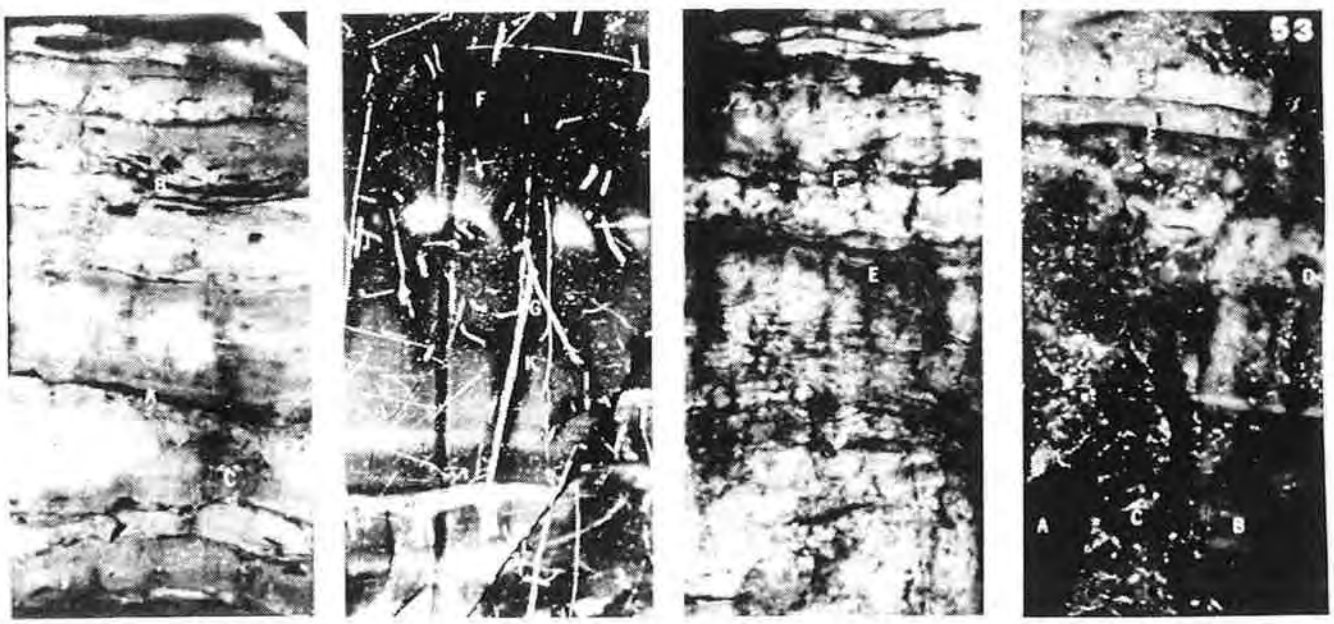

Figure 7. X-ray radiographs of poorly drained swamp deposits illustrating a variety of early diagenetic inclusions including pyrite, vivianite, and non-rich carbonates.

Upon burial, free oxygen is quickly exhausted but anaerobic bacteria continue the work of destruction and modification. Water stagnation however, results in more rapid concentration of the humic derivatives and high toxicity soon develops and decay is arrested. A high rate of organic accumulation leads to arresting decomposition at a very shallow depth in the accumulating deposit and large portions of the original organic fraction survive to be preserved. Thus, it can generally be stated that the floral remains represent the local vegetation growing in such an environment. This is important from an ecological standpoint. In other environments, such as a well drained swamp, decomposition and destruction result in selective preservation of floral remains. Consequently, those preserved do not represent actual floral environments at time of burial.

A second characteristic syngenetic inclusion is the high percentage of pyrite (FeS_2) and ferrous sulphide (FeS). These two compounds may be expected in all anaerobic sediments when sufficient reactive iron and sulphur are available Bailey et al. (1998). A controversy arises, however, as to the necessity of free oxygen to be present for the transformation of iron and sulphur compounds into pyrite. Pyrite content in the sediments examined from this environment range from slightly greater than 3.9 percent to less than 0.5 percent of the dry matter (Figure 7). Higher concentrations of pyrite could generally be correlated with high organic content. Three modes of occurrence are encountered: 1) small cubes, 2) isolated globular masses (framboids) and 3) replacement of small rootlets (Figure 8). The cubic form generally occurs as isolated single masses and rarely are intergrowths of several cubes observed. The cubes vary in size but range from 1 mm to less than 100 microns. More common are irregularly-shaped masses consisting of well-cemented small rounded (50 microns) pyrite balls. The globular masses are found scattered throughout the sequence and appear as small white spots on the radiographs (Figure 7). The highest percentage of pyrite occurs as replacement of the small organic rootlets. Root tubules as large as 2 mm in diameter are often found to be completely replaced by pyrite. In many instances the complete tubule is not replaced and the pyrite only forms an encrusting mass around the original organic remain (Figure 7). Although pyrite occurs in several other environments is reaches it highest abundance under the poorly-drained and reducing conditions found in this environment. The length of time required for its formation is not precisely known, but pyrite-replaced root tubules were found in shallow surface cores where the age of the deposits is most probably less than 100 years old. Therefore, it is believed that the process of in situ pyrite formation takes place rapidly.

Another common syngenetic inclusion in this environment is vivianite ($Fe_3P_2O_8 \cdot 8\ H_2O$, hydrous ferrous phosphate) and is often found in close association with pyrite. It occurs both as isolated masses in a clay matrix (Figure 7) or replacing organic rootlets. Although not restricted to this environment it reaches its highest percentage here, sometimes in excess of 2 percent. It is usually confined to certain zones or pockets rather than randomly scattered throughout the core. On a freshly open core, vivianite appears as small amorphous white masses, but upon prolonged exposure to air, the nodules turn to a bright blue color. The exact chemical reaction that causes the formation of this material is not well known.

Syngenetic calcium and magnesium (dolomite) carbonates also form in this environment but have a relatively lower content than in some of the other environments (i.e., well drained swamp). It generally occurs as both poorly cemented and well cemented nodules and as rims surrounding rootlets. The size of the nodules vary, being smaller in the younger units of this environment and increasing in size as older units. The shape varies, ranging from round flattened, lenticular-like masses to round and irregular masses. They are often concentrated within definite zones, but the lateral continuity of these has not been determined. The nodules range in cementation from poorly consolidated (incipient nodules) to well cemented concretions requiring a hammer to break open. Preliminary chemical analyses and X-ray diffraction indicate that they are composed predominantly of $CaCO_3$ but some manganese, magnesium, calcium, and iron carbonates are present. Within this environment iron carbonates (siderite) are abundant and are probably the result of diagenetic

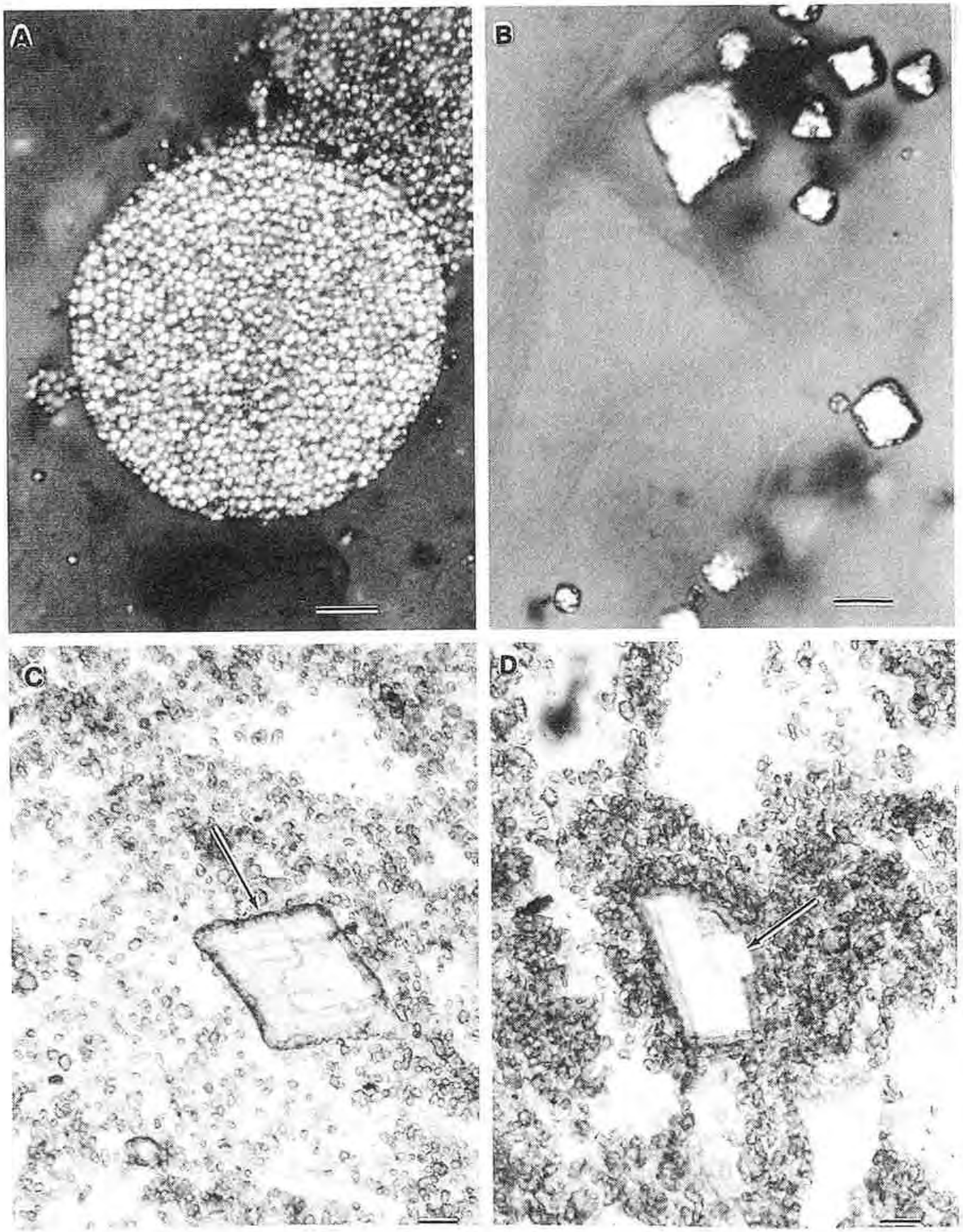

Figure 8. Micrographs of pyrite (A,B) and siderite concretions with other carbonates (C,D). A) Light micrograph of framboidal pyrite from Core 2D, depth = 6 m. Length of bar = 5 μm. B) Light micrograph of pyrite crystals in cell from Core 2D, depth = 6 m. Length of bar = 5 μm. C) Light micrograph of siderite concretion from Core 14D, depth = 18 m. The arrow points to dolomite with a siderite rim. Cark, granular material is the main siderite of the concretion. Length of bar = 10 μm. D) Light micrograph of siderite concretion from Core 14D, depth = 37 m. The arrow points to possible calcite with a siderite rim. Length of bar = 10 μm.

processes changing the original $CaCO_3$ nodules to iron carbonates (Figure 8). There is a higher percentage of calcium carbonate nodules in the younger units of this environment, whereas iron carbonates are more abundant in the deeper and older units.

Well-Drained Swamps Deposits: This environment is similar to the one described above except that drainage channels are more efficient, exposing the surface sediments during a large part of the year. Inundation only occurs during times of high flooding. This single process results in many different inclusions and completely changes the character of the resulting sedimentary sequence. Present day surface conditions in well drained areas differ from the poorly drained swamp only in that there are less aquatic plants. The deposits laid down in this environment consist predominantly of clay with scattered silt lenses but lack the high organic content of the environment described previously. Textural laminations are quite similar to those described in the poorly drained swamp (Figure 9). Faunal remains are very rare and are encountered in the samples examined. Foraminifera and ostracods are absent in the samples examined and only occasionally are insect carapace and charophytes observed. Seeds are present in some samples but consist of the more robust types and do not faithfully represent the local flora growing within the environment. Although an extensive pollen investigation has not been undertaken, the few samples examined show a very low content and most of the grains are badly corroded or fragmentary. *Taxodium distichum* (cypress), one of the most common trees found in the swamp is poorly represented. The organic content is usually very low and rarely are significant concentrations observed. The lack of these features can only be assumed to be the result of exposure to oxidizing conditions as organic material is available and can be seen in the upper few inches of present day, well drained swamp areas. Thus, much of the organic material is probably destroyed by oxidation and faunal remains are leached out because of a fluctuating water table much like conditions of a natural levee. In fact, many of the diagenetic inclusions found in well-drained swamp and levee deposits are similar.

The most significant difference between this environment and the poorly drained swamp environment described above is the number and type of inclusions. Pyrite is present but is usually confined to definite thin zones and is not especially abundant, rarely exceeding 1%. It generally occurs as drusy incrustations around plant fragments or as isolated globular masses (Figure 8). Vivianite is also rare and when present is associated with plant remains or zones of slightly coarser nature. One of the most common inclusions is calcium carbonate nodules (Figure 9). These are extremely abundant and occur both as large (2 cm) poorly cemented nodules and small (less than 5 mm) well-cemented nodules. Quite often, highly crystalline calcite nodules are extremely abundant. Much of the laminations observed on the radiographs are the result of concentration of carbonate cement within a particular layer. Some appear to form in cavities probably caused by insect burrowing.

Iron oxide nodules are particularly abundant. They most commonly occur as small (½ to 6 m), fairly well cemented masses that vary in shape from extremely irregular masses to well-rounded nodules. They are usually scattered throughout the sequence, but the large ones appear to be confined to definite zones. Iron oxides also occur as rims around plant rootlets (Figure 9). In many cases, the original organic fragments are completely destroyed and the rim remains as a small hollow tube. The inner portion of the rim is generally well cemented but cementation gradually decreases outward. Although both iron oxide and carbonate compounds are readily available, iron carbonate

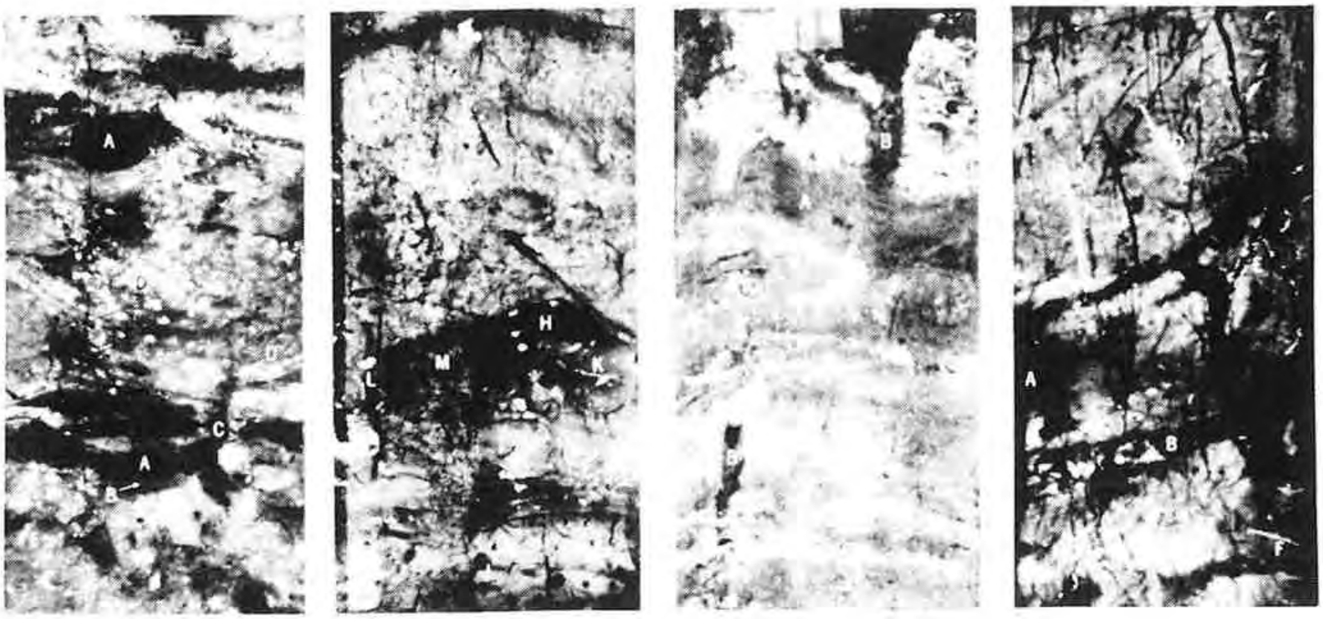

Figure 9. X-ray radiographs of well-drained swamp deposits illustrating a variety of early diagenetic inclusions including iron oxides, calcium carbonate nodules, and other metalic oxides.

nodules (siderite) are relatively rare. The most plausible explanation for this lies in the fact that the iron oxides are quite stable compounds and since the iron is in a tri-valent state, it will not readily combine with $CaCO_3$. Therefore, it appears that reducing conditions are more likely needed for the formation of the iron carbonate nodules.

Lacustrine Deposits: Shallow, restricted, inland bodies of fresh water constitute an important environment within the Atchafalaya Basin (Figure 10). Well over 520 km^2 of the present basin consist of these shallow water lakes. They range in size from those as large as Grand Lake or Six Mile Lake (16 to 20 km long) to very small unnamed bodies of water barely exceeding 0.5 km in diameter. Most of the lakes are very shoal, even the larger ones rarely attain depths greater than 5.5 m deep. The process by which these lakes form has not been investigated in any great detail but they are obviously closely related to local subsidence and compaction. Once a low depression is formed and standing water accumulates at that site, further enlargement is made possible by wind initiated wave action. Undoubtedly, both subsidence and wave action are important in the formation and enlargement of these lakes. A halt in growth and deterioration of the lake system is usually brought about by stream diversion into the lake. Such an influx of sediments introduces many new processes and changes the character of the lacustrine deposits. For this reason the sedimentary fill introduced by the streams is not included as part of the lacustrine facies but is described separately below and referred to as lacustrine delta fill. It should be realized, however, that no sharp line exists between the two facies and lacustrine facies merges transitionally upward with the overlying delta fill.

Figure 10. Shallow lake in the lower Atchafalaya Basin.

Quite water deposition, reducing conditions, burrowing organisms (especially polychaete worms), and occasional wave and current action are characteristic of this environment. The deposits consist of dark gray to black, soft, highly organic clays that commonly contain a few scattered silt lenses. Stratification appears to be poorly developed on an open core face, but when examined by the radiograph technique a variety of stratification types is apparent (Figure 11). Most prominent are parallel and lenticular laminations, burrowing, and distorted primary structures. In the lower sections of the lacustrine facies a highly disturbed, burrowed zone is commonly encountered. In many cases, only a few traces of the original stratification remain. Most of the burrowing is the result of worms, hence few faunal remains are encountered. Occasionally, a few fresh water micro-mollusks (Figure 11) and the pelecypods *Rangia* and *Unio* are encountered. Proceeding vertically upward within the facies less burrowing disturbance is encountered. The exact cause of this is unknown, but it is possible the result of one or two processes: 1) increase sedimentation rates because of a prograding stream and filling of the lake or 2) toxic conditions develop whereby the fauna cannot exist. Fish kills in south Louisiana lake are frequent events related to the development of anoxic conditions in these organic-rich environments. The first process is the more likely as several factors indicate an increased rate of sedimentation as the lake begins to fill.

The most common sedimentary structure encountered is parallel laminations (Figure 11). Several factors cause the laminations: a) size differences, b) concentrations of minerals and colloids within certain layers, and c) flocculated and non-flocculated layers. Size differences account for only a small number of the parallel lamination seen in the cores. As most of these deposits contain only a small percentage of silt, the size differences between layers fall mainly within the clay range. Of the samples from different layers tested, only one or two show a significant difference in size, therefore, it is felt that size is a minor factor in producing the resulting laminations. Concentrations of minerals and colloids within certain layers account for a much higher percentage of the laminations. Colloidal organics tend to accumulate within certain layers and these layers have a low X-ray absorption. Layers containing these colloidal organics range in thickness from 200 microns to 10 mm or more. They are very distinct and have sharp upper and lower boundaries. Concentration of $CaCO_3$ and iron hydroxide cement also cause the laminations. One feature, although probably an early diagenetic effect, is the formation of a very thin layer, 100 microns to 1 mm thick, of crystalline $CaCO_3$ and siderite along certain bedding planes. This layer generally continues completely across the 13 cm core width. The thin, extremely white laminations (Figure 11) of this nature. The cause of this feature is not exactly known but probably can be correlated with water movement along bedding planes after deposition. Undoubtedly other mineral concentrations also contribute in the formation of the laminations but this detection awaits further chemical determinations.

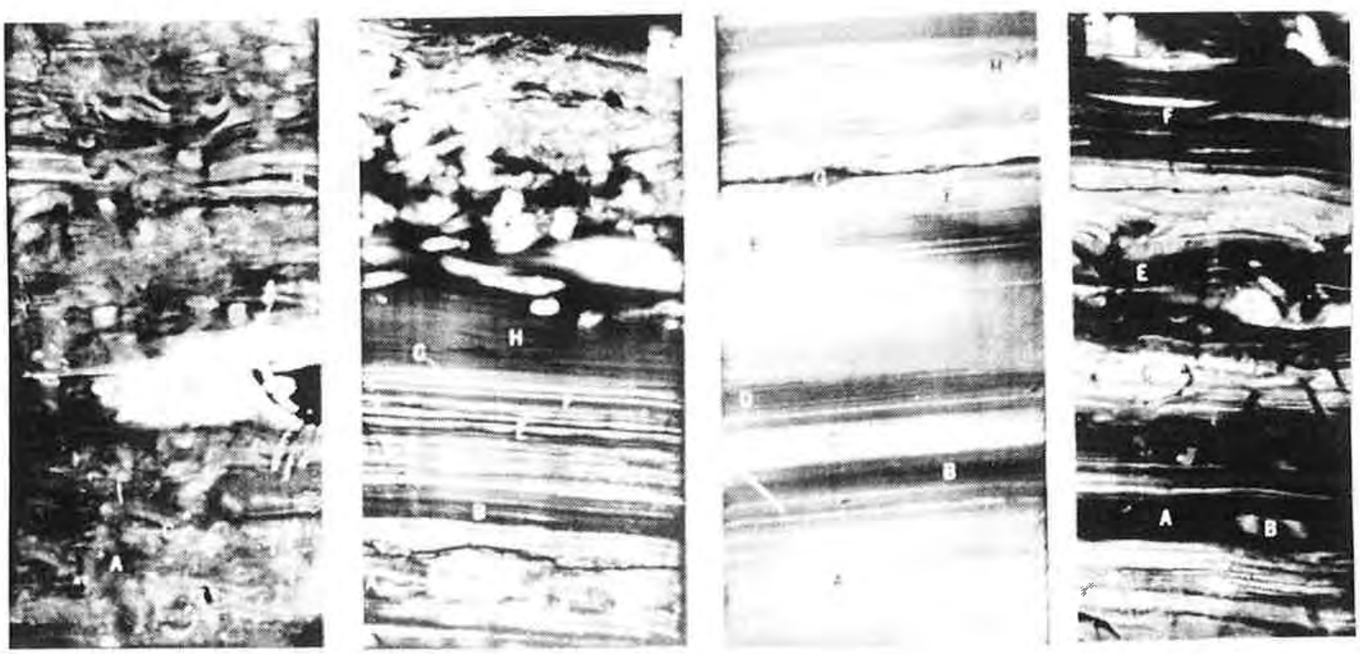

Figure 11. X-ray radiographs of lacustrine deposits illustrating lamination types and early diagenetic inclusions, primarily siderite.

A common cause of parallel laminations however, is the result of altering flocculated and non flocculated layers. Normal gravity settled clay particles from suspension tend to be deposited with parallel orientations, whereas flocculated particles generally settle randomly. Thus, the non-flocculated layers freely transmit X-rays whereas the flocculated layers tend to have high absorption values.

Micro faunal remains are usually abundant within the lacustrine facies but consist of only a small number of species of ostracods. Foraminifera are entirely absent. Charophytes are encountered in some samples but do not occur in significant quantities. Vivianite is abundant and closely associated with drifted plant remains or in burrow-fill. Pyrite is also common but occurred mostly as small cubes and isolated drusy masses rather than replacing plant fibers. Iron nodules are completely absent but some carbonate nodules are layers are apparent. Small carbonate nodules are not as abundant as in the well drained swamp facies, but do occur. Large (1-4 cm), well consolidated $CaCO_3$ nodules are most common.

Lacustrine Delta Deposits: The history of deposition in the Atchafalaya Basin clearly incorporates the filling of lakes of various sized by deposition from the Atchafalaya River and its secondary channels creating lacustrine deltas. The diversion of a stream into one of the lake basins causes an appreciable increase in the sedimentation rate. This, combined with increased current action and coarser grained particles, impacts different characteristics to the delta fill. No sharp boundary exists between normal lacustrine and lacustrine delta fill facies. Sedimentation rates gradually increase within the lake sequence and both grain size and thickness of laminations increase vertically upward. The process of fill is apparently rapid if judged by present-day fill of the lake in the Atchafalaya Basin. Fisk (1952) illustrates the phenomenal rate of growth of the delta into Grand Lake in recent years (Figure 12). In a period of slightly greater than 20 years more than 155 km^2 of additional land surface has been formed in the lake area. Figure 13 shows the latest lacustrine deltas in this area and a schematic representation of lake deltas in general. The delta fill varies in thickness, ranging from a few feet in the smaller lakes to greater than 4.5 m in the larger ones.

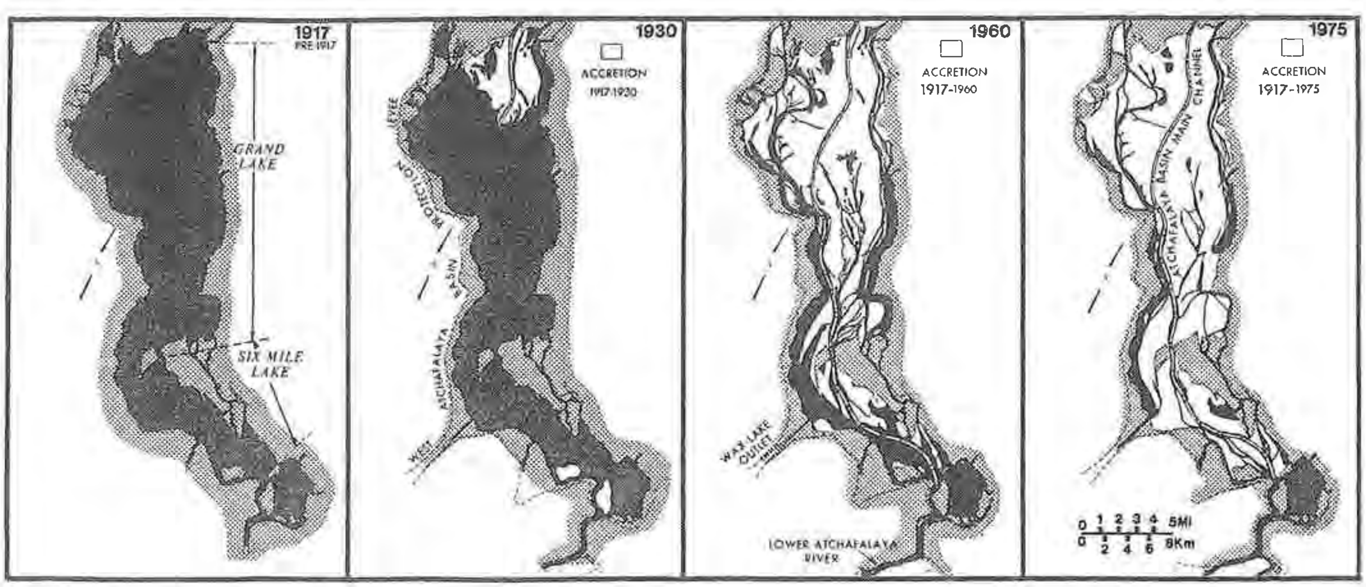

Figure 12. A record of filling of Grand Lake-Six Mile Lake in the southern Atchafalaya Basin with sand-rich lacustrine delta (modified from Roberts et al., 1980).

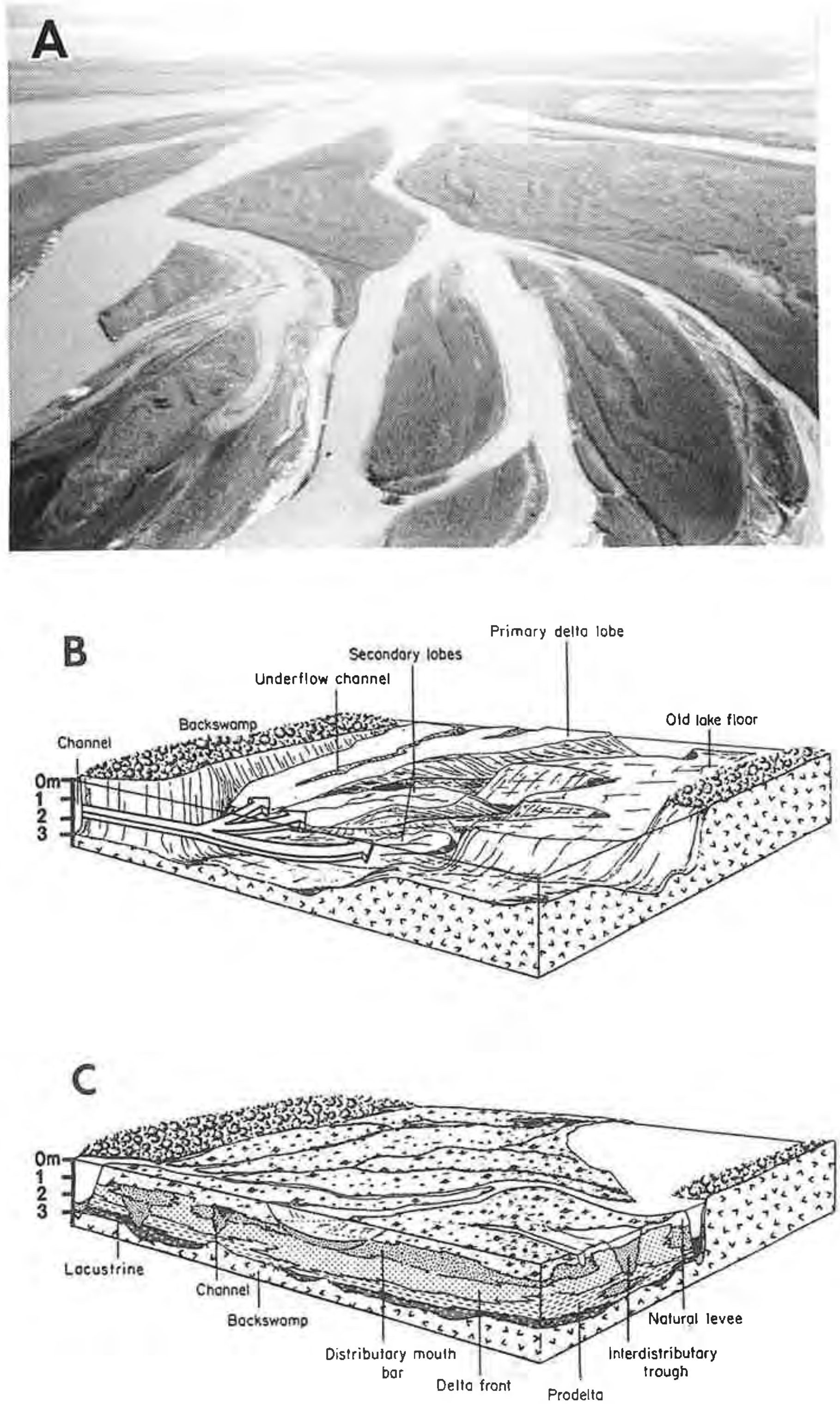

Figure 13. Atchafalaya Basin and (a) an aerial photo of a lacustrine delta in the Grand Lake-Six Mile Lake area of the lower schematic representation of lacustrine delta evolution illustrating (b) morphology of elongate lobes characteristic of these delta types and (c) sedimentary architecture of a fully developed delta (modified from Tye and Coleman, 1989).

The deposits vary considerably in grain size, but generally range from silty clays in the lower portion of the section to fine sand in the upper portion. Parallel laminations consisting of colored clay layers, flocculated and non-flocculated layers, and alternating silt and clay layers (Figure 14) dominate the lower portion of the fill. Scour and fill structures, load casts, distorted structures, lenticular laminations, and isolated ripple laminations are occasionally encountered. Further up the section, massive appearing silts with a few thin clay lamination are found. Radiographs reveal small scale ripple laminations to be the dominant sedimentary structure. Within this zone, especially near the top, organic remains, scattered pyrite, and calcium carbonate nodules become abundant. The occurrence of these inclusions is probably the result of burrowing by plant roots that are established on top of the fill. The coarser grained nature of these deposits allow free movement of percolating ground water and this probably accounts for the zone of early diagenesis.

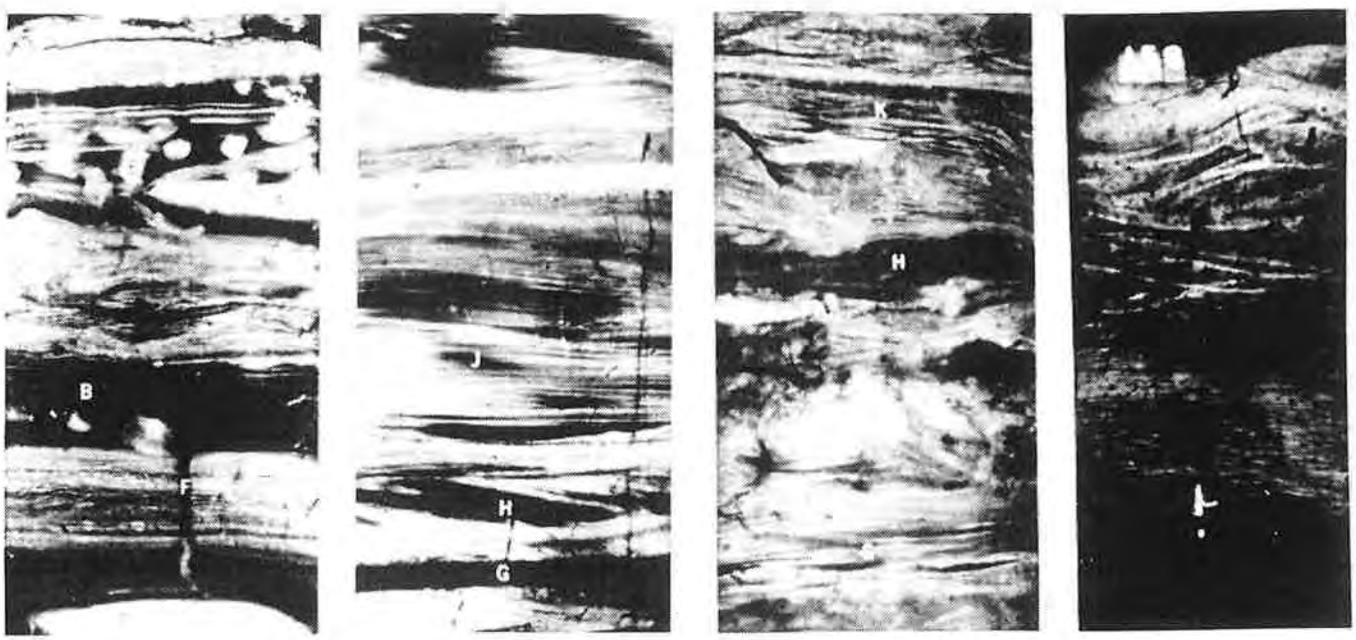

Figure 14. X-ray radiographs of lacustrine delta deposits.

The total sequence of deposits laid down in this environment contains a sporatic faunal content. Some samples examined lack microfunal remains while others showed a high percentage of ostracods. Foraminifera were not observed in any of the samples examined. Charophytes are not especially abundant, except very near the top of the lacustrine delta fill unit. Seeds and other macro-plant remains vary in abundance from sample to sample and most of them can be accounted for by drift rather than in situ formation. Vivianite never attains significant amounts. With the exception of the upper few feet of the fill, nodules, both iron and carbonate, are not abundant. Pyrite, when present, occurs as small drusy incrustations around and within root fragments. One of the most important features of this facies, when compared to the others, is the high content of mica. Since the detritus laid down within this environment represents both bed load and suspended load of the river system, this probably accounts for its high content. Tye and Coleman (1989) suggest that lacustrine delta-building is a very rapid process (Figure 13). 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 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 elongated lobes that sometimes scour into underlying lacustrine deposits (Figure 13). These sands are categorized as distributary mouth bar and subaqueous levee deposits by Tye and Coleman (1989). Although there is considerable sedimentologic variation in lacustrine deltas, a coarsening-upward sequence over laminated and bioturbated lacustrine clays, silty-clays, and silts in 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, 1989). 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. The presence of two small but well-developed deltas at the cost, Atchafalaya and Wax Lake deltas in Atchafalaya Bay (Figure 2), 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.

Floating Marshes (Flotants): Although the Atchafalaya Basin does not contain extensive freshwater marshes, other interdistributary basins like Barataria Basin between the levees of the old Lafourche distributaries and those of the modern Mississippi support abundant freshwater marsh environments. Freshwater marshes are important and widespread sedimentary environments of the Mississippi River's upper deltaic plain (Russell, 1942; Fisk, 1958; Frazier, 1967). In the vicinity of Lac Des Allemands there is an abrupt transition from swamp forest to the rather featureless grassy carpet of the fresh marsh (Figure 15). This environment extends south to the landward limit of tidal influence, which is marked by brackish water marsh.

Louisiana's freshwater marshlands are characterized by four observable features: (1) the dominant grass, maiden cane *(Panicum hemitomon)*; (2) standing water of less than 5 percent salinity; (3) thick and durable marsh root mats under which one can find sediments ranging from peat to homogeneous steel-gray clay; and (4) large expanses of fresh marsh that are actually floating (flotant of Russell, 1942). Subordinate plants in the freshwater marshes are bull tongue (*Sagittaria falcata*), spike rush (*Eleocharis sp.*), and bullwhip (*Scurpies californicus)*. The flotant's diverse plant community also includes abundant ferns, *Thelypteris palustris* and *Osmunda regalis*. Sasser and Gosselink (1984) show that the above-ground primary production for a Barataria Basin flotant is 1,960 g m^{-2} y^{-1} dry weight. Compared to figures of Day and Conner (in press) for a poorly drained swamp, 900 g m^{-2} y^{-1}, the flotant has twice the primary production.

Flotant is formed when dense mats of roots and minor amounts of detritus are separated from the terrigenous sediment substrate beneath the marsh (Figure 15). These living rafts are up may be over a meter thick and certainly have proved strong enough to support a large party of field trip participants. Flotant appears to invade open water bodies. Anoxic conditions sometimes form at the

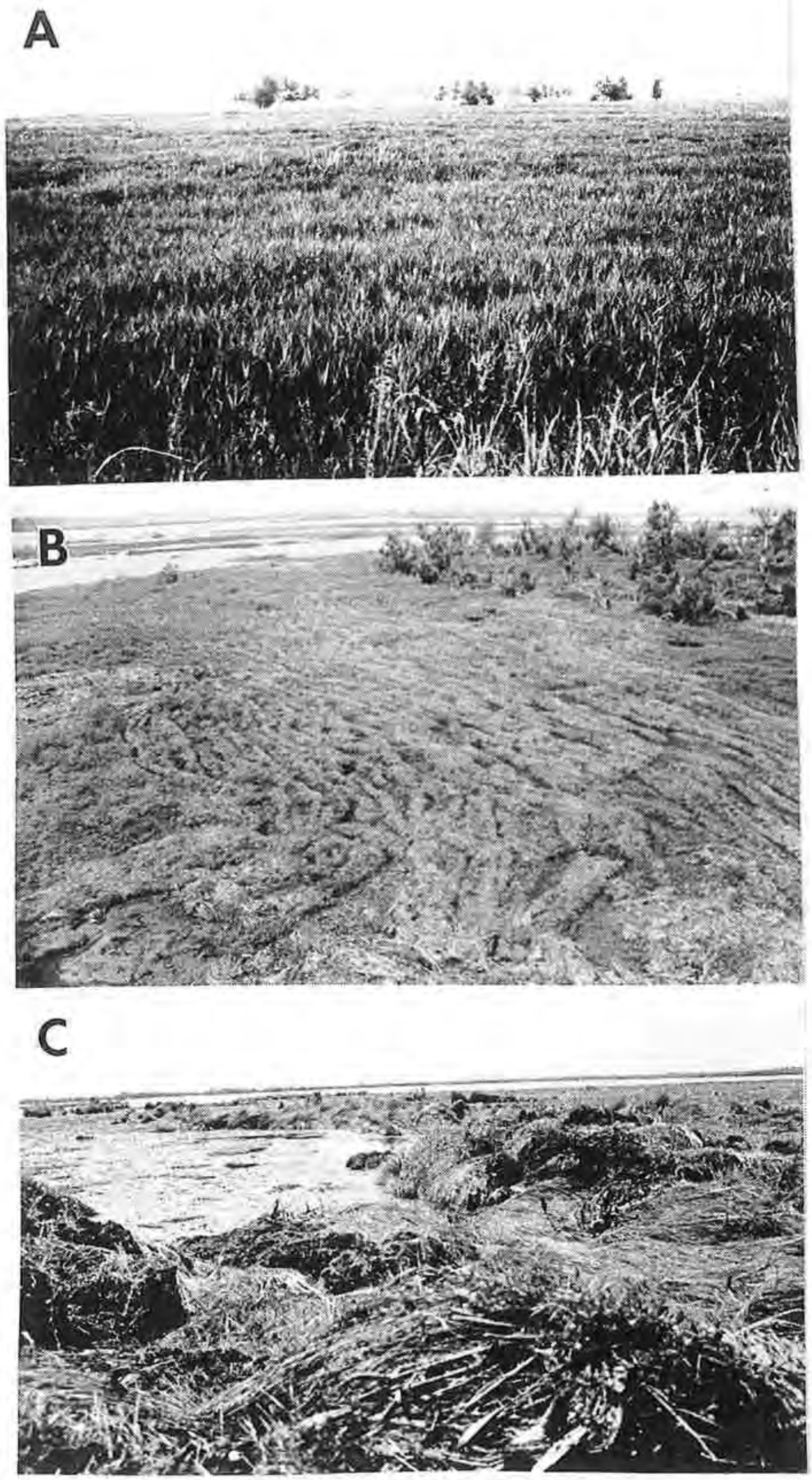

Figure 15. (A) A large area of flotant in Barataria Basin. (B) Flotant push against the shoreline during the passage of Hurricane Andrew. (C) Fragments of flotant transported to the shoreline during Hurricane Andrew.

substrate beneath the floating mat. In this setting organic detritus collects on the lake bottom and in time this accumulation is thought to merge with the organic mat of the flotant.

As a result of the high primary productivity of the marsh community, large quantities of organic matter are trapped in this environment. Freshwater peats that result from this process can be up to 3-4 m thick in the Barataria Basin (Kosters and Bailey, 1983). Acting over the past several thousand years, freshwater marshes have led to the formation of extensive peaty-clay deposits in the upper deltaic plain. These organic deposits can be quite thick (to 3-4 m) and can cover large geographic areas, thus having the potential to be good stratigraphic markers (e.g., Tertiary lignites in the Wilcox Fm) in the subsurface.

THE ATCHAFALAYA-WAX LAKE BAYHEAD DELTAS: THE NEW LOBE IN THE MISSISSIPPI RIVER DELTA COMPLEX

INTRODUCTION

Two bayhead deltas are developing in Atchafalaya Bay as a product of capture of Mississippi River flow by the Atchafalaya River several hundred years ago (Figure 16). Rapid sedimentation has been occurring in the bay since the Atchafalaya River Basin (an area characterized by swamps and lakes) filled with lacustrine deltas and overbank deposits. In the late 1940s and early 1950s the basin filled to near capacity, and sediment carried by the river passed through to the coast. This increased sedimentation in Atchafalaya Bay and initiated the delta-building process. In 1963, the U.S. Army Corps of Engineers established a control structure at the confluence of the Atchafalaya and Mississippi rivers, and since then flow down the Atchafalaya has been regulated to ~30% of the Mississippi discharge combined with input from the Red River.

There was little awareness of the delta-building event until a few lobes from the emerging delta became marginally subaerial in 1972 (Shlemon 1975) and gained full exposure in 1973 (Roberts et al., 1980). The abnormally high flood of 1973 scoured sand from the lower Atchafalaya River course and deposited it in Atchafalaya Bay. Systematic subaerial growth has continued from these early stages. Van Heerden (1983) provided the first detailed analysis of the important response features. Early works of Shlemon (1975), Roberts et al. (1980), and van Heerden (1983) are built on to produce an up-to-date view of the incipient stages of this important developing lobe of the Mississippi Delta Complex.

The reasons for the study of the Atchafalaya - Wax Lake system include the following:

a) Together these deltas represent the next major lobe of the Mississippi complex,
b) Initiation of delta growth in Atchafalaya Bay offers an opportunity to study and investigate major delta lobe progradation from infancy,
c) It is now possible to understand the sedimentary fabric of a deltaic high-stand bayhead deltas.
d) Application of knowledge gained to the practical problems of sediment distribution, that is management of sediment sources for environmental restoration,

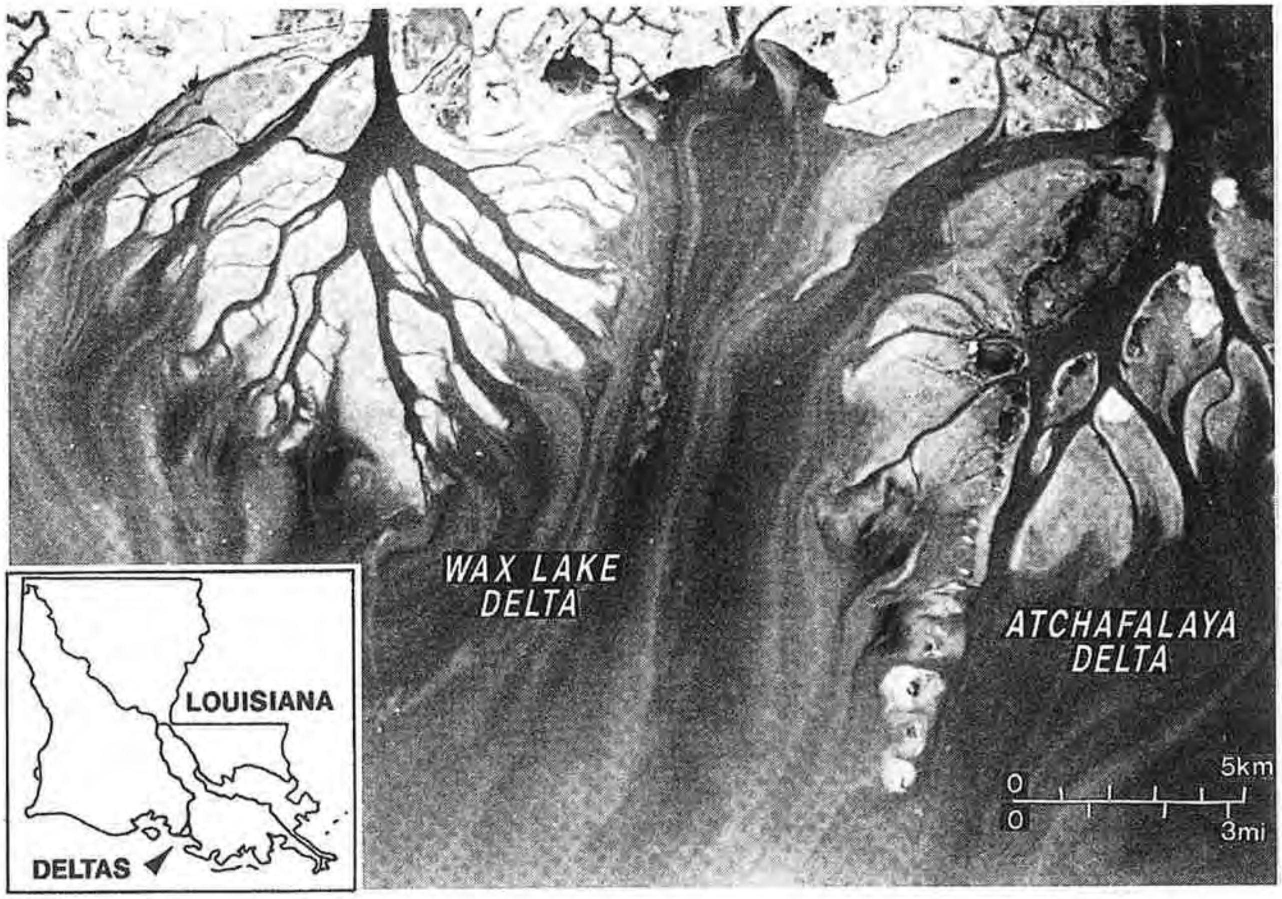

Figure 16. High altitude photograph of the Wax Lake and Atchafalaya bayhead delta (Dec. 1990).

e) Understanding the scale and mode of sedimentation, at the scale of crevasse splays, and

f) Details of the Atchafalaya and Wax Lake delta lobes are applicable to exploration for thin, sand-rich deltas and subdeltas commonly found in the subsurface of the northern Gulf of Mexico.

EVOLUTION OF THE HYDROLOGICAL REGIME

Both the Mississippi and Atchafalaya rivers provide immense contributions of fresh water and sediment to coastal Louisiana (Figure 17). The Mississippi River is the largest river on the North American continent, draining approximately 6559,600 km^2.

Because of extensive progradation during the last 800 years, the course of the modern Mississippi River in coastal Louisiana has undergone a reduction in gradient and general flow efficiency to the point that a new major channel, the Atchafalaya River, is now favored. The Atchafalaya River is 300 km shorter than the Mississippi, and was a definite distributary of the Mississippi in 1542 (Fisk 1952), but discharges were small and sporadic until 1839 (Morgan et al. 1953). At this time, major log jams in the Atchafalaya were cleared. After 1839, Atchafalaya River discharges were aided by dredging, and by 1900 the Atchafalaya carried 13% of the

Figure 17. Location of the Mississippi and Atchafalaya Rivers in southern Louisiana. The Atchafalaya floodway levees are identified.

Mississippi's flow (Morgan et al. 1953). Discharges continued to increase so that by 1952 the river carried almost 30% of the Mississippi's flow (Fisk 1952; Shlemon 1972). In 1963, however, increased capture of the Mississippi waters was terminated by the construction of a control structure at the point of diversion. Since then, Atchafalaya River discharge has been held to 30% of the combined Mississippi River and Red River 1950 flow regime (Roberts et al. 1980), Figure 18.

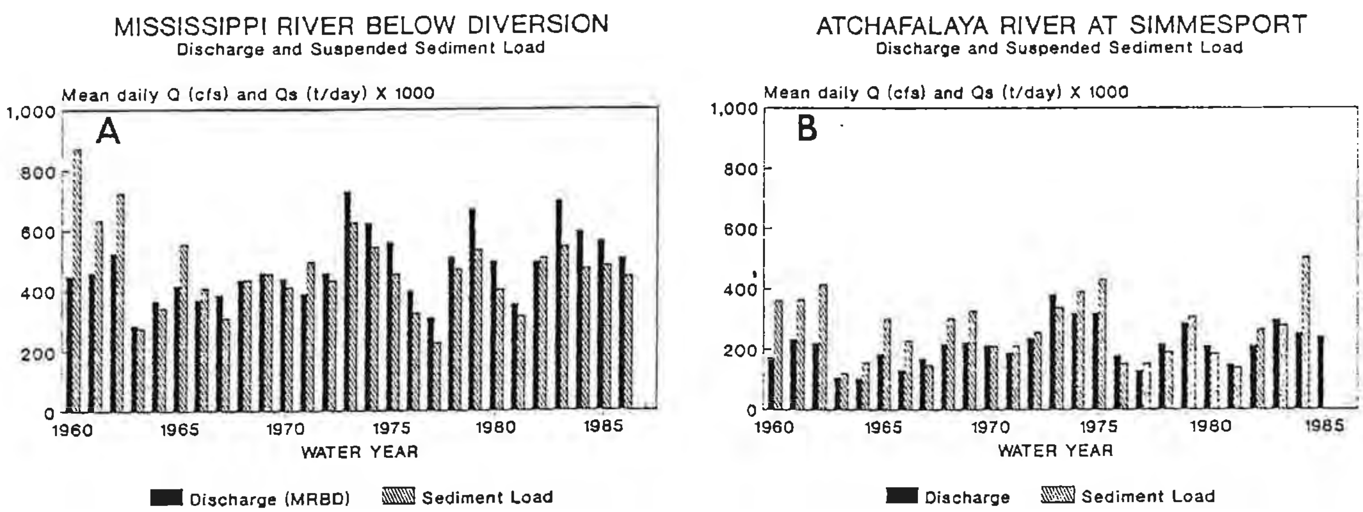

Figure 18. Mean discharges and sediment loads: (a) Mississippi River below diversion, (b) Atchafalaya River at Simmesport, Louisiana: 1960-1985.

The Red River has a drainage area of 227,531 km^2. River discharge data collected on the Atchafalaya at Simmesport, located below the control structure and confluence of the Red River, and data from the Mississippi River downstream of the control structure reveal that the Atchafalaya presently averages about 50% of the discharge and over 60% of the suspended load of the Mississippi (Mossa and Roberts 1990). Thus, the Atchafalaya River has substantial delta building capacity.

The average discharge of the Atchafalaya River at Simmesport is 226,760 cfs. High flows generally occur between January and June, and the average annual peak flow is 428,000 cfs. Approximately 70% of the flow at Simmesport now passes through the lower Atchafalaya River to eastern Atchafalaya Bay, and the remainder passes through the 20.9 km shortcut to the western part of the bay created by Wax Lake outlet.

When compared to approximately the past 40 years (Table 2), 1973-75 were years of abnormally high water. During these years flows averaged 313,000 cfs (8,863 cms) at Simmesport; peak flows of over 700,000 cfs (19,824 cms) were recorded in April 1973, and 600,000 cfs (16,992 cms) in April 1975 (USACOE 1975). Similar high-flow averages and peak flows were recorded at Morgan City, on the lower Atchafalaya River, during the spring of 1973. Peak flows at Morgan City exceeded 600,000 cfs (16,992 cms) during 1973, and exceeded the normal 300,000 cfs (8,496 cms) peak flows during 8 months of 1973—75. Proportionally high flows were recorded at Wax Lake outlet during the same period. Accompanying these abnormally high discharges were unusually high concentrations of sediment carried as suspended load. Discharges in 1979, 1983, 1990, 1991, and 1993 could be classified as above average floods.

SEDIMENT FLUX

The average annual sediment load of the Atchafalaya River at Simmesport for the period 1952—1989 was 88,223,000 tons (Table 2).

Sediment reaching Atchafalaya Bay changed from a dominance of silt and clay to silt and fine sand between the mid-1950s and mid-1970s. With increased efficiency of the main channel the lower parts of the basin are being filled by an assemblage of channel, lacustrine delta fill, and overbank deposits ranging in size from clay to fine sand.

The material carried as bedload in the lower part of the Atchafalaya Basin is capable of reentrainment as suspended load. Confinement of the river in the lower basin to a single channel in the 1960s for navigation efficiency has resulted in scouring of previously deposited channel, levee, and lake fill sediment, as evidenced by channel deepening (Roberts et al. 1980). High-water years 1973—75 greatly accelerated this process, and fine sands began to reach the bay in significant quantities. The increased sand transport in suspended load during the high-water periods of 1973 and 1975 is linked to rapid accretion of distributary-mouth bar sand bodies, as confirmed by aerial photography, satellite imagery, hydrographic surveys, and grain-size distribution data.

Both the volume and the size distribution of sediment reaching Atchafalaya Bay through the lower Atchafalaya River outlet changed dramatically during the high-water period of the early 1970s. Prior to this event, periodic sampling of the lower Atchafalaya River indicated an average annual sediment load of 47 x 10^6 tons (42.6 x 10^6 metric tons) for the period 1965—71 (USACOE 1974). The annual suspended sediment load during the 3 high-water years (1973—75) nearly

TABLE 2 Summary of Measured Suspended Sediment Loads for the Atchafalaya River at Simmesport, Louisiana

YEAR (OCT-SEPT)	TOTAL SED. LOAD (TONSx10^3)	SAND-SILT RATIO SAND (TONSx10^3)	%	SILT (TONSx10^3)	%	DISCHARGE (DSFx10^3)	AVG SED CONCEN (PPM)
1951-52	196,460	48,890	25	147,570	75	80,800	900
1952-53	135,230	28,440	21	106,790	79	56,960	880
1953-54	54,130	13,110	24	41,020	76	31,980	627
1954-55	93,360	24,080	26	69,280	74	50,425	686
1955-56	67,175	15,540	23	51,730	77	49,080	507
1956-57	225,474	55,700	25	169,774	75	74,059	1,126
1957-58	214,390	48,082	22	166,308	78	89,413	887
1958-59	83,230	20,944	25	62,286	75	55,729	553
1959-60	131,878	24,153	18	107,725	82	69,333	704
1960-61	133,372	40,524	30	92,848	70	76,814	643
1961-62	151,913	57,675	38	94,238	62	88,881	663
1962-63	44,876	8,610	19	36,266	81	47,060	353
1963-64	52,591	10,414	20	42,177	80	33,117	588
1964-65	108,871	27,472	25	81,399	75	66,444	607
1965-66	88,522	17,468	20	71,055	80	51,024	642
1966-67	55,710	6,794	12	48,916	88	57,314	360
1967-68	121,351	16,727	14	104,624	86	80,105	561
1968-69	115,245	27,170	24	88,075	76	83,329	512
1069-70	75,098	19,790	26	55,308	74	74,278	374
1970-71	72,441	19,625	27	52,816	73	71,721	374
1971-72	89,587	18,732	21	70,855	79	75,407	440
1972-73	124,468	45,363	36	79,105	64	139,951	329
1973-74	142,994	32,235	23	110,759	77	116,972	453
1974-75	157,938	35,106	22	122,832	78	117,129	499
1975-76	56,113	8,464	15	47,649	85	65,925	315
1976-77	57,137	6,050	11	51,087	89	47,800	443
1977-78	71,194	12,497	18	58,697	82	79,737	331
1978-79	112,343	25,548	23	86,795	77	104,824	397
1979-80	67,801	10,652	16	57,149	84	77,609	312
1980-81	51,079	5,343	10	45,736	90	54,995	277
1981-82	104,102	11,403	11	92,699	89	77,494	481
1982-83	100,894	25,055	25	75,839	75	108,584	345
1983-84	73,213	12,349	17	60,864	83	93,081	292
1984-85	116,757	16,995	15	99,762	85	88,848	487
1985-86	81,794	9,289	11	72,505	89	78,649	386
1986-87	71,855	4,173	6	67,682	94	80,288	332
1987-88	57,780	6,556	11	51,224	89	59,347	361
1988-89	52,228	2,545	5	49,683	95	87,867	220
Average*	88,223	16,455	17	71,768	83	83,533	386

*Average based on period 1966-67 to 1989.

doubled, the lower Atchafalaya River outlet carrying 93 x 10^6 tons (88.9 x 10^6 metric tons).

Table 3 represents average sediment budgets of suspended-load volumes and size characteristics for the periods 1965—71 and 1973—75 (USACOE 1974). The 1973—75 sediment balance indicated a dramatic increase, particularly in the amount of sand transported in the suspended load and conveyed through the basin to Atchafalaya Bay. It should be noted that only 25% of the sand in the suspended load was transported to Atchafalaya Bay in the earlier period, whereas 90% of the sand was conveyed to the bay during the later high-water period.

TABLE 3 Average Annual Suspended Load Budget, Atchafalaya River

	Input		Distribution of Input								
	Simmesport (Near Diversion Point	%	Basin Retention	%	Wax Lake Outlet	%	L. Atchafalaya River	%		Total (%)
1967-1971										
Sand	19,342 (17,543)	22	14,491 (13,143)	75	1,153 (1,046)	6	3,968 (3,354)	19	=	100 Sand
Silt/clay	67,905 (61,590)	78	10,179 (9,232)	15	15,590 (14,140)	23	42,136 (38,217)	62	=	100 Silt/clay
Total	87,247 (79,133)	100	24,670 (22,376)	29	16,743 (15,186)	19	45,834 (41,571)	52	=	100 Total
1973-1975										
Sand	37,506 (34,018)	25	3,668 (3,327)	10	5,748 (5,213)	15	28,090 (25,478)	75	=	100 Sand
Silt/clay	100,704 (100,409)	75	21,256 (19,279)	19	21,789 (19,771)	20	67,650 (61,359)	61	=	100 Silt/clay
Total	148,210 (134,426)	100	24,924 (22,606)	17	27,546 (24,984)	19	95,740 (86,836)	65	=	100 Total

NOTE: Computations from measured data and sediment rating curves, USACOE files. Values are expressed in tons x 10^3 (metric ton equivalents are given in parentheses).

It is estimated that much of this increase in suspended sand concentration is related to scouring and resuspension of previously deposited material. Table 3 shows that 37.5 x 10^6 tons (34.0 x 10^6 metric tons) of sand-sized material introduced at Simmesport during 1973—75 represents a twofold increase over values from the earlier period. During the same period 33.8 x 10^6 tons (30.7 x 10^6 metric tons) were introduced into Atchafalaya Bay through lower Atchafalaya River and Wax Lake outlet, which represents a seven-fold increase, implying scour in the lower reaches of the Atchafalaya River system

Total measured sediment load at Simmesport exceeded 100,000,000 tons in the years 1979, 1983, 1985, 1990, and 1991. During the latter 2 years the high sediment load resulted in significant delta growth.

SEDIMENTATION PATTERNS AND DELTA GROWTH

Subaerial Growth Curves

The Atchafalaya and Wax Lake deltas developing in Atchafalaya Bay represent the only real area of land/wetland growth at present in coastal Louisiana (Figure 19). The most recent data from air photo analysis reveal that by the end of 1990, 23.3 mi^2 (64.7 km^2) of new land had developed since inception during the spring flood of 1973. The growth curves for each delta are however quite different. From 1973 to 1980 the Wax Lake delta had only attained 1.33 mi^2 (3.4 km^2) subaerial expression at a rate of 0.17 mi^2/yr. Thereafter the rate increased dramatically to 1.02 mi^2/yr (2.62 km^2/yr), for a total area in 1990 of 11.56 mi^2 (29.6 km^2 or 7,315 acres). The dramatic increase in rate reflects that by the end of 1980 Wax Lake and the surrounding and adjoining open water bodies had attained a sediment-filled state, and as a consequence sediment could now pass straight down Wax Lake outlet to the bay. Maintenance dredging activities in Wax Lake delta ceased in the early 1980s, so delta growth has since proceeded "naturally." If the status quo remains, by the year 2000 Wax Lake delta should cover an area of 21.63 mi^2 (56 km^2 or 13,840 acres). At a growth rate of 650 acres a year. Wax Lake delta reduces Louisiana's coastal wetland loss by +/-3 percent per annum - small but significant and constant.

Unfortunately, the Atchafalaya delta's growth curve is less spectacular even though the lower Atchafalaya River's discharge exceeds that of Wax Lake outlet. The Atchafalaya curve is somewhat flatter and displays marked fluctuations (Figure 18). These differences to the Wax Lake curve reflect the activities of man.

Looking at the Atchafalaya growth curve in detail reveals that from emergence in 1973 to mid-1976, the growth rate was a very rapid 1.84 mi^2/yr (5.1 km^2/yr). Rapid delta progradation reflects that large floods occurred in 1973, 1974 and 1975. Mid-1976 the subaerial expression was 8.0 mi^2 (20.5 km^2) and after the large flood in 1990 land area had increased to 13.71 mi^2 (35.1 km^2), at a rate of 0.41 mi^2/yr (1.04 km^2/yr). This rate is 20 percent of that of the 1973 to 1976 period, but more significantly, is only 39 percent of the Atchafalaya's smaller sister, the Wax Lake.

Mapping sequential sets of aerial photographs and satellite images have provided a means of tracking subaerial delta growth and changes in the geomorphic character of each bayhead delta (Figure 19a). Although this method has advantage regarding development of an understanding of the geomorphie evolution of these features, there are problems choosing a datum for comparisons of data sets. An alternative method is the use of a terrain model based on cross-bay transects of bathymetry and land elevations. This procedure is explained in detail by Cunningham et al. (1996). The advantage of this method is that a common datum can be established between data sets making quantification of growth and erosion much easier. The growth curve of Figure 19b was constructed using this method.

Table 4 illustrates areas per year and rates of change of each delta based on terrain model results (Majersky et al., 1997). Using the terrain model approach with a -0.6 m (2.0 ft) datum, steady expansion of delta area is seen for each of the bayhead deltas between the years 1981,

TABLE 4 Growth Values (modified from Majersky et al., 1997)

Growth Values (modified from Majersky et al. 1997)

DELTA	1981		1989		1994		2000*		Rate Used for Prediction
	mi^2	km^2	mi^2	km^2	mi^2	km^2	mi^2	km^2	
WAX LAKE	7.6	19.7	18.5	47.9	20.1	52.1	32.5	84.2	pre-1990 rate
ATCHAFALAYA	26.0	67.3	32.9	85.2	39.2	101.5	44.4	115.0	pre-1990 rate
							42.98	111.3	Halved '89 -'94 rate

1989, and 1994, although a weir established in 1988 diminished the sediment load of the Wax Lake Outlet until its removal in 1994. Using pre-weir rates of growth for both the Wax Lake and Atchafalaya deltas, it is anticipated that by the year 2000 Wax Lake delta will have 84.2 km^2 (32.5 mi^2) of land above the -0.6 m datum while the Atchafalaya delta will have 115.0 km^2 (44.4 mi^2). These estimates suggest a total of 197 km^2 (76 mi^2) of tidal/subaerial land, not present prior to ~ 1973, will occupy Atchafalaya Bay. A total of 43% of this new land will be associated with the Wax Lake delta while 57% will belong to the Atchafalaya delta. That is, the intertidal and subaerial parts of Wax Lake delta will occupy 18% of Atchafalaya Bay while the Atchafalaya delta will occupy about 25%. Vibracoring of these deltas indicates that they are sand-rich sedimentary sequences. Sand percentages of the total delta vary from about 35% in the distal parts to over 85% in proximal areas. Sand bodies vary in thickness depending on position within the delta. They vary in thickness from 1.3 - 5.2 m (4.3 - 17.1 ft.).

Subaerial Growth Patterns

Atchafalaya Delta

Due to dredging activities in the western half of the Atchafalaya delta, the following discussion will only address the eastern half of this delta.

Systematic monitoring of delta growth in the eastern Atchafalaya delta by mapping subaerial lobes revealed two entirely different growth responses: one involving channel elongation and bifurcation and the other related to channel abandonment, leading to lobe fusion and upstream accretion of lobes.

1. Channel Elongation and Bifurcation

Since inception of subaerial growth, a three-level hierarchy of channels has developed. Broad primary channels, wider than 900 m and approximately 3 m deep at the upstream ends bifurcated to form secondary channels with widths less than 300 m and depths of 2 m. Narrow tertiary channels, 150 m wide or less and about 1 m deep, evolved in subsequent bifurcations.

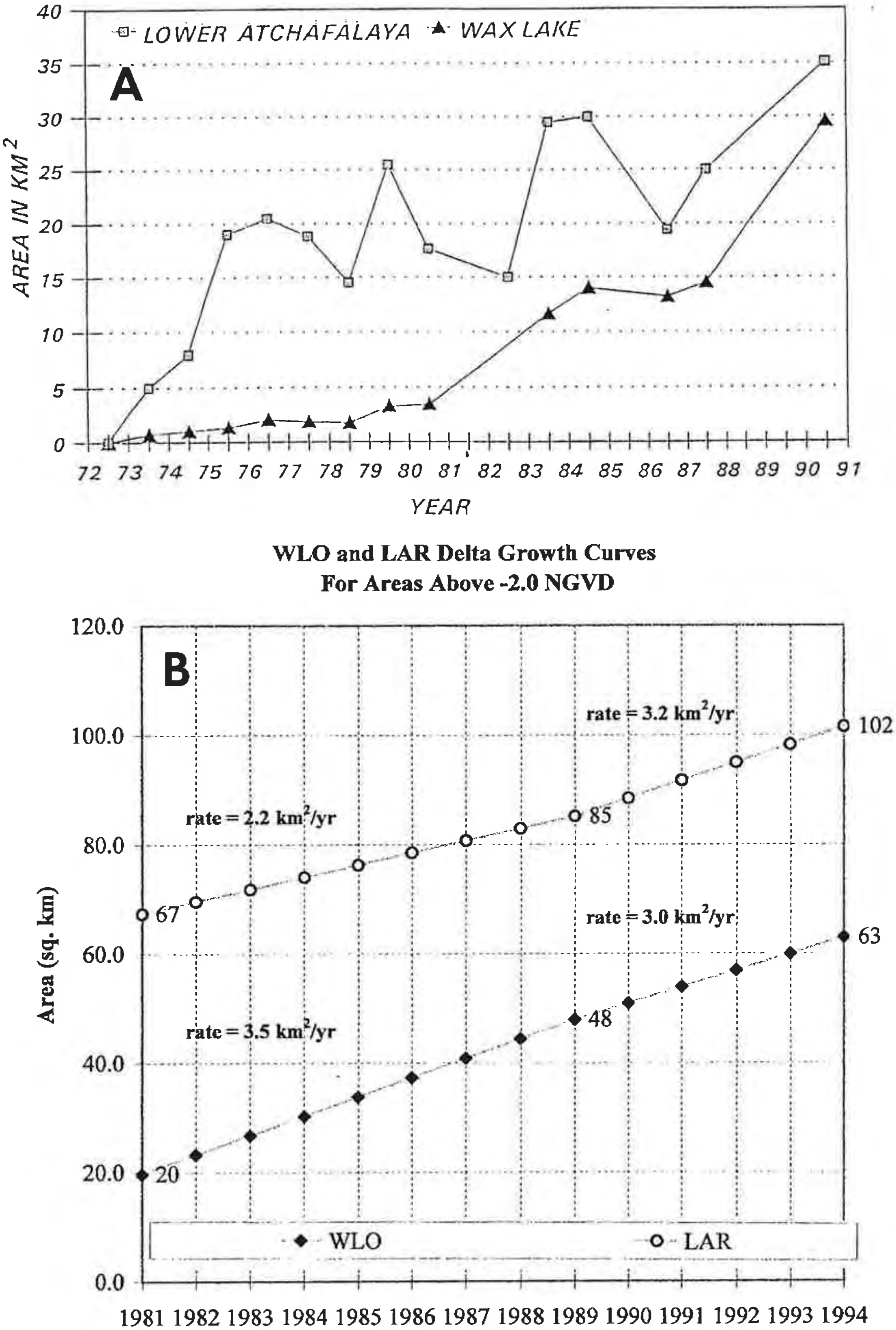

Figure 19. Growth history of Atchafalaya and Wax Lake Deltas: (a) calculated from areas measured from air photos and satellite images, and (b) calculated from an -0.6 m (-2.0 ft.) Datum using terrain analysis with elevations established by standard survey techniques.

Subaqueous delta growth started in the early 1950s as a major bifurcation between East Pass and West Pass in the area now known as the Poule D'eaux Islands (Figure 20) (Shlemon 1972). By 1972 East Pass had developed to a well defined primary channel opening into a shallow bay area. However, after the 1973 flood a number of broad secondary channels, for example Natal Channel (Figure 20a) branched from East Pass. During the next 3 years, the secondary channels extended seaward as they underwent a series of major bifurcations that produced channels of generally unequal size. The larger channels developed as linear continuations of parent channels and retained, for the most part, secondary channel sizes. However, these linear continuations did undergo stepwise reductions in width (Figure 20b). The smaller, tertiary-sized channels produced in bifurcations branched at acute angles to the parent channels and did not undergo further bifurcations.

Concurrent with secondary channel bifurcation was the establishment of a network of small "overbank" channels. These channels were narrower than tertiary channels and originated as breaks in the subaqueous levees of the secondary channels.

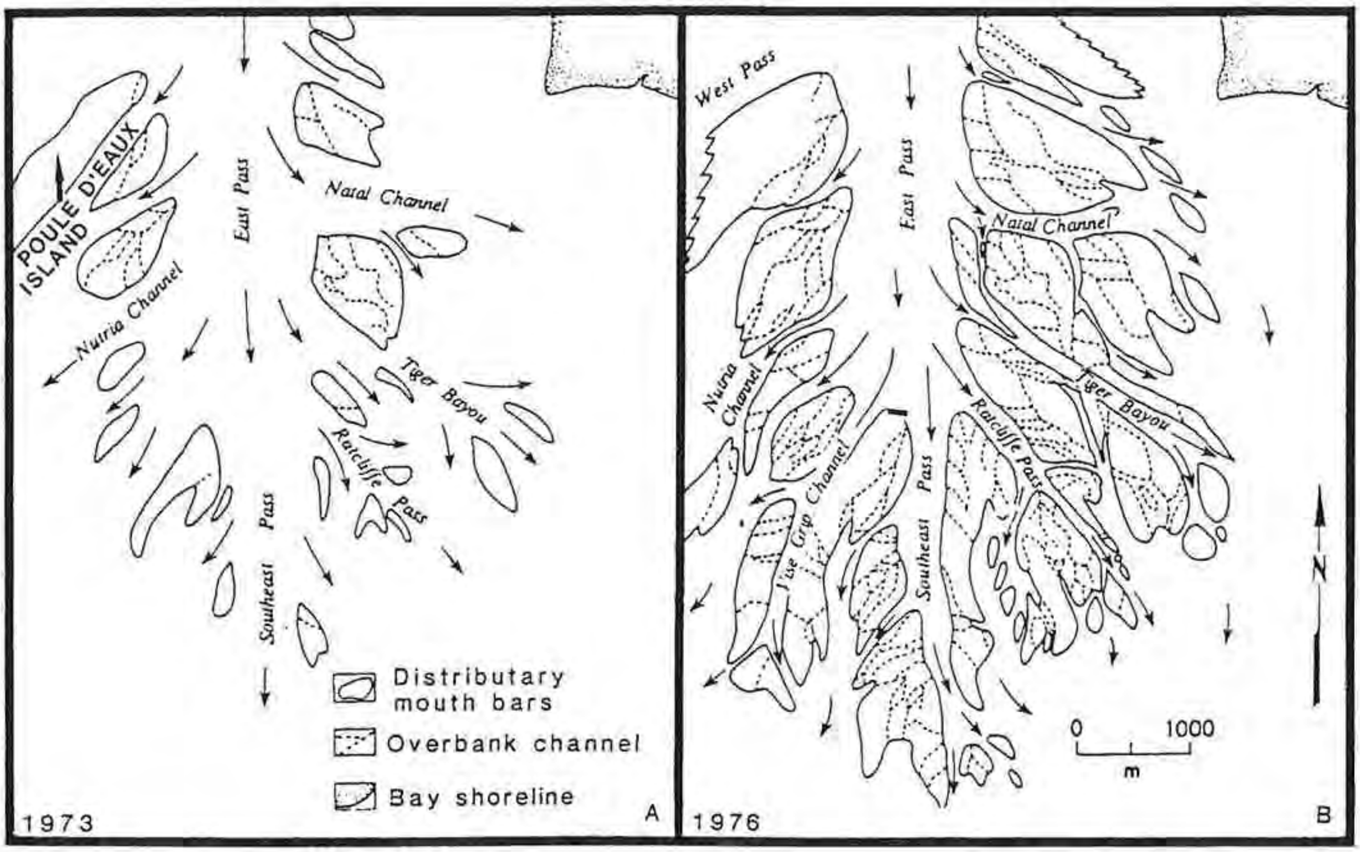

Figure 20. Comparison of delta lobes and channel patterns, 1973 and 1976. Secondary channels are named.

2. Channel Abandonment and Lobe Fusion

Aerial photography and LANDSAT interpretation revealed no significant seaward extension or channel bifurcation after 1977 in the eastern Atchafalaya delta (Figure 21). Delta area, expressed as subaerial land, increased, during this period through two processes; lobe fusion by channel abandonment and accretion of the upstream ends of some subaerial units.

Since 1976, upstream subaqueous growth occurred at all lobes adjacent to East Pass (Figure 21). Channel cross sections over the period 1977-1981 indicate that vertical accretion and upstream lobe growth are rapid processes. Between May 1977 and May 1979 the subaqueous upstream portion of the lobe in the lower portion of East Pass (Figure 21b) accreted at a rate of 0.25 m yr^{-1} (Figure 22). Unfortunately, a shell dredger operating in the area during the latter half of 1979, deepened the channel and increased the cross-sectional area monitored in March 1982. Nevertheless, accretion continued in the central part of the channel, where the effects of the shell dredger were minimal (Figure 22). By June 1992 the central portion of this cross section had aggraded to a few inches above mean sea level, while the western channel had almost completely sealed. As Figure 8 shows, upstream accretion of lobes is a process common to the entire eastern delta area.

Channel cross section data reveal that between 1977 and 1982 the majority of tertiary channels became steadily narrower. The rate of cross section reduction increased slightly during

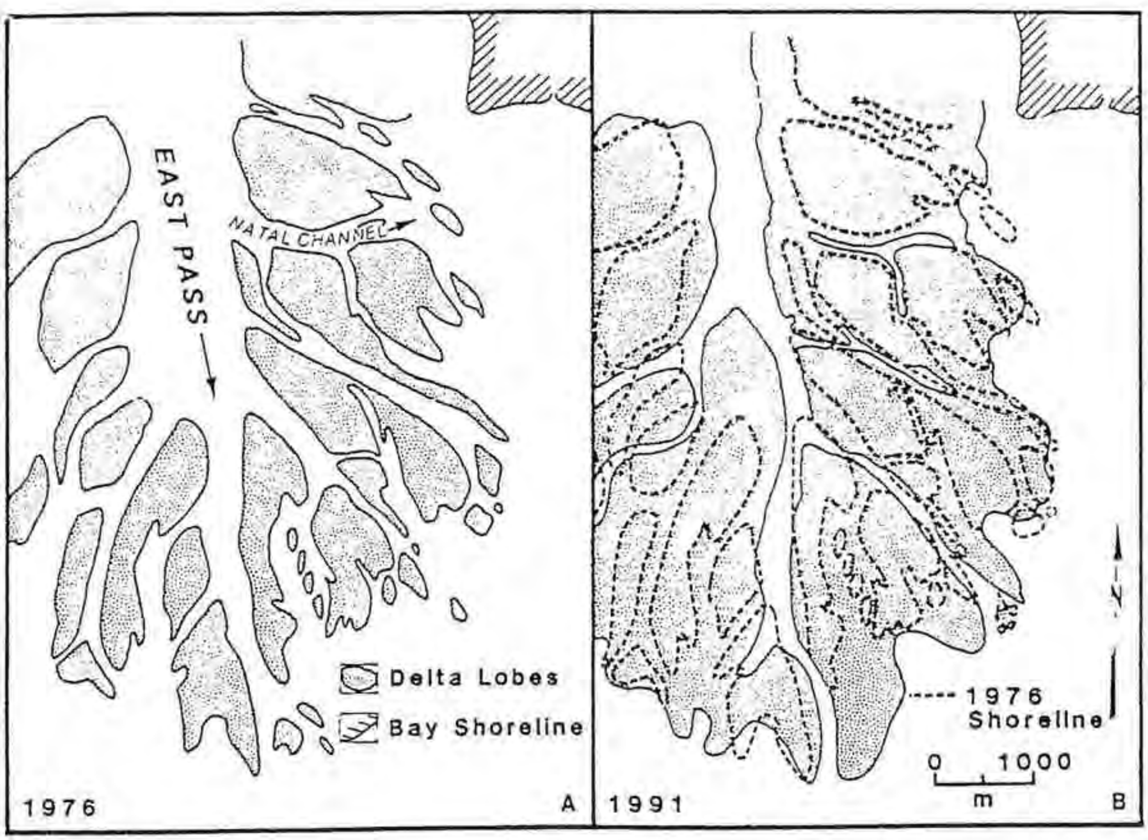

Figure 21. Comparison of delta lobes in 1976 and 1991. Note the upstream migration of lobes during this period.

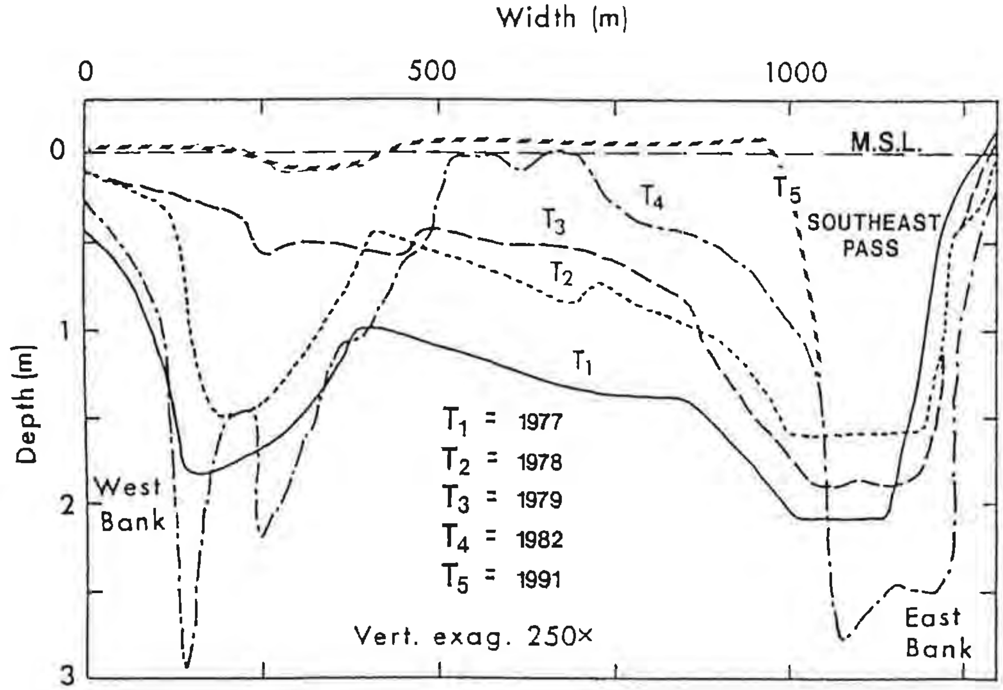

Figure 22. Cross-channel profiles of a primary channel exhibiting upstream growth of adjacent sediment lobes and channel filling.

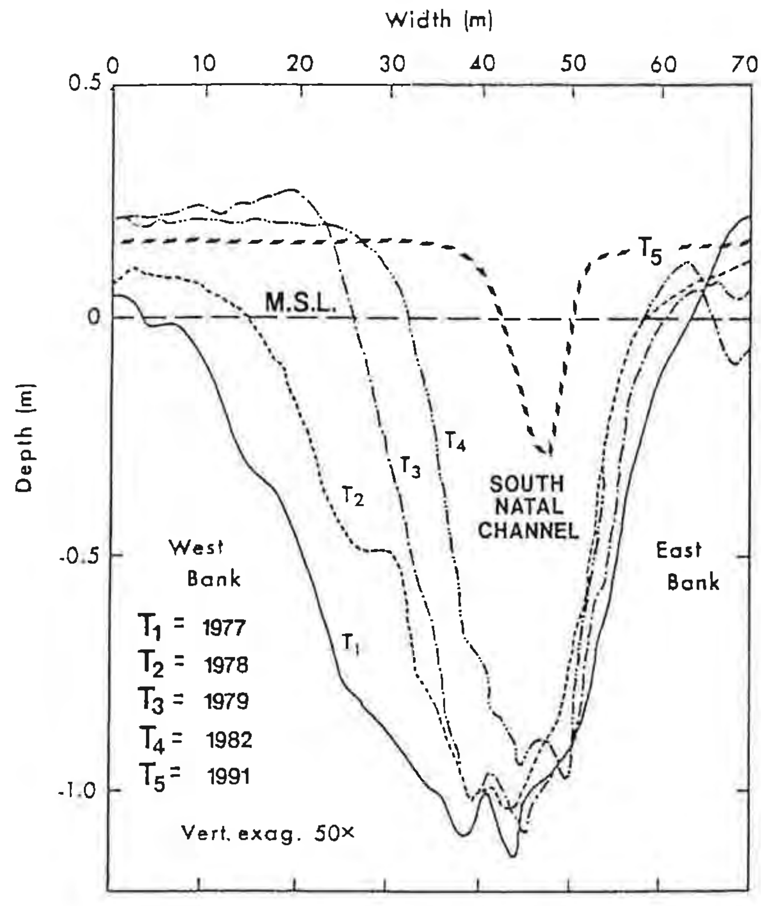

Figure 23. Cross-channel profiles of a typical tertiary channel in the eastern Atchafalaya delta.

this period as a consequence of the 1979 flood (Figure 23). Tertiary channel narrowing eventually reached a stage where discharges were so reduced that channel mouths closed as a result of subaqueous levee construction in the parent channel. Sealed channels slowly filled with fine sediment. Between 1982 and 1992, the majority of the tertiary channels in the eastern delta filled, fusing adjacent lobes into larger features.

Overbank channels present after the 1976 flood filled with sediment and were overgrown with vegetation. In contrast, secondary channels maintained their depth or even deepened over the 1977-1982 period even though they narrowed slightly through aggradation of the channel flanks (Figure 24). After 1982, the months of a majority of secondary channels sealed due to subaqueous levee development in East Pass and by 1992, most of these had filled to now have dimensions of tertiary channels.

At present, the growth rate of the eastern delta is minimal. The Navigation Channel that bisects the Atchafalaya delta is a very efficient conduit for Atchafalaya sediment from the river mouth to the Gulf of Mexico. As a consequence the eastern Atchafalaya delta is being by-passed.

Wax Lake Delta

Navigation dredging activities in the Wax Lake delta ceased in the 1980s. The discussion of growth patterns will include the whole delta.

1. Channel Elongation And Bifurcation

Since inception of this delta a similar hierarchy of channel sizes, to the eastern Atchafalaya delta, has developed. Growth patterns vary across the delta. In the western third of the delta, tertiary sized channels have formed at bifurcations of secondary channels. As in the Atchafalaya case, the bifurcation with the orientation most similar to the parent channel assumes dominance (Figure 25). With time this channel enlarges in size at the expense of its distributary, and its orientation aligns that of the parent channel. Through a succession of such bifurcations, the secondary channels in the western Wax Lake delta have prograded since 1973, and continue to date.

Progradation of the mid section of the delta is also through secondary channel elongation. However, here the channels extend through linear subaqueous levee growth, rather than through bifurcations (Figure 25). The progradation pattern in the eastern third of Wax Lake delta is similar to the eastern Atchafalaya delta. Contrary to the Atchafalaya delta case, channel elongation seems to have continued past 1976 and seems to have terminated in 1983.

2. Channel Abandonment And Lobe Fusion

Upstream growth of delta lobes has been one of the growth processes in the Wax Lake delta since 1978. Additionally, channel infilling and lobe fusion has occurred throughout the delta, but not at the scale that characterized the eastern Atchafalaya delta after 1976.

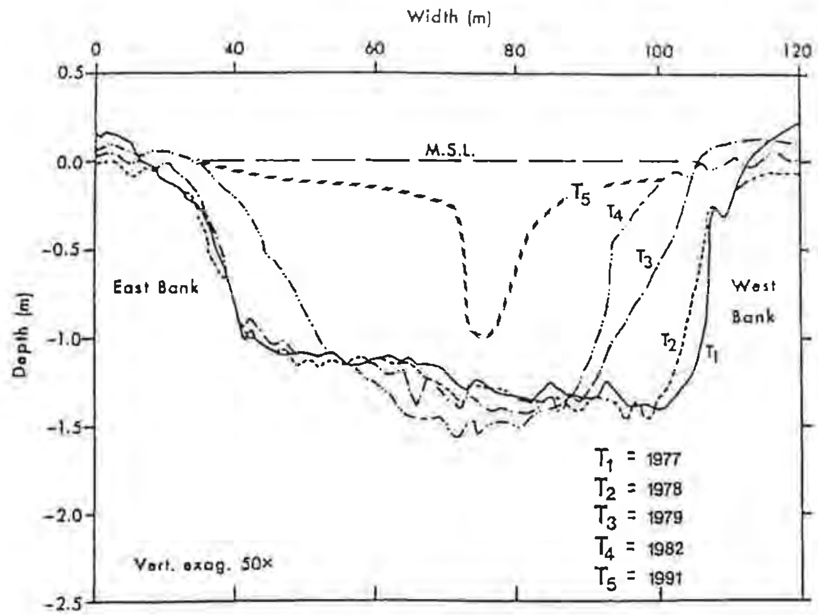

Figure 24. Cross-channel profiles of a secondary channel showing lateral accretion and channel filling.

Channel abandonment and lobe fusion in the eastern Atchafalaya delta become the dominant process once channel bifurcation and progradation ceased. However, in the Wax Lake delta progradation and lobe fusion occur concurrently. The marked difference between the two deltas growth patterns reflects that the eastern Atchafalaya delta is slowly being bypassed because of the navigation channel, whereas the Wax Lake is in a more natural state.

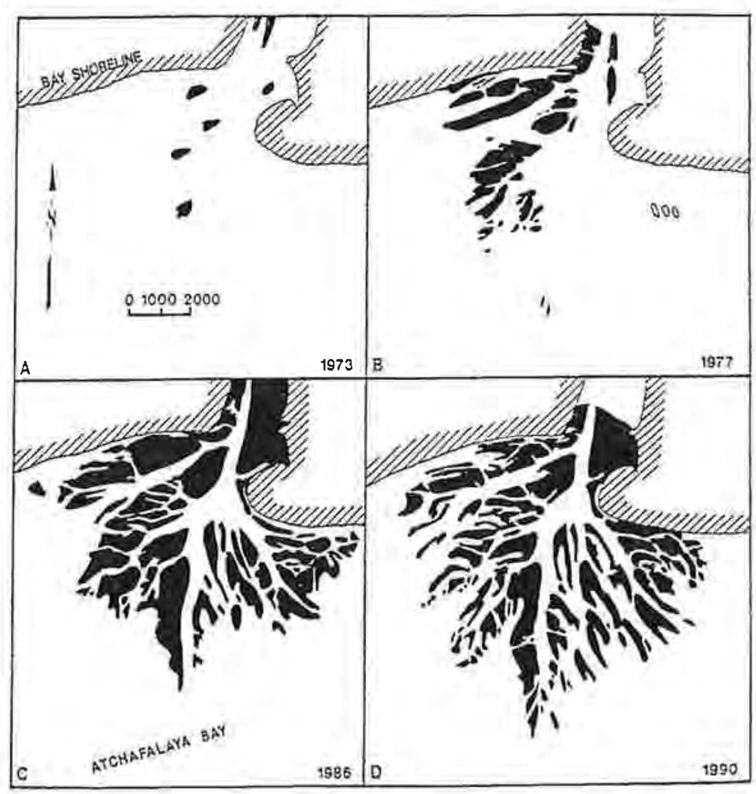

Figure 25. Progressive subaerial growth of the Wax Lake delta lobe from 1973 to 1990.

DEPOSITIONAL MODEL FOR DELTA GROWTH

Channel Elongation And Bifurcation

The configuration of bifurcations and the mechanisms of channel extension are determined by river mouth processes. In shallow Atchafalaya Bay, inertial and frictional factors are most important. Buoyant forces are not a factor since the bay waters are essentially fresh. The inertia of the issuing water is mostly dependent on river stage, but can be influenced by prevailing wind and tides. Frictional drag is dependent upon bottom type, bed roughness, and also whether there is any preexisting relief on the bay bed bottom.

Geomorphic components of the Atchafalaya and Wax Lake deltas suggest that the rapid expansion of effluent seaward of a confined distributary mouth initially produces a broad, accurate bar with the central positions of this bar shoaling most rapidly. Presumably, during floods maximum current velocity and highest concentrations of suspended load occur in the central portion of the distributary channel. As the sediment load passes from the deep, confined channel to the unconfined shallow bay, there is a dramatic reduction in current velocity. The central portions of the issuing stream can no longer support its high suspended load and the coarse fraction is deposited with most deposition in the central part of the bar.

Subaqueous levees develop beneath the lateral boundaries of the expanding stream due to sedimentation associated with flow reductions caused by friction between the issuing and ambient waters. Relief created by these "proto" subaqueous levees increases the bottom drag effects on the flow, enhancing deposition and as a consequence levee development. This in turn restricts effluent expansion. Constriction of the stream now occurs between the subaqueous mid-channel bar and levees, leading to localized mid-stream scour and channelization. As the mid-channel bar and levees accrete, the frictional drag they offer to flow increases, which encourages sedimentation on these features. Thus, once initiated, channel bifurcation in such settings becomes a self-generating mechanism. When a bifurcation is well established, or even as it reaches a well established state, new bifurcations are initiated at the seaward end of the recently created channels.

This discussion suggests a continuous-hierarchy of bifurcations, which certainly is not the case in the Atchafalaya delta. Because the bifurcation process creates a greater wetted perimeter through which an original volume of water must flow, efficiency of the flow decreases. Thus, the numerous bifurcations in the eastern Atchafalaya delta coupled with the efficient Navigation Channel has seriously reduced flow efficiency, decreasing the progradation rate of delta building. Certainly, by mid-1977, flow efficiencies were so reduced that progradation and bifurcation processes had ceased.

An idealized bifurcation would result in equal-sized channels. However, this is rarely the case. Channel asymmetry appears to reflect flow regime asymmetry induced by the tidal cycle (Figure 26a). In the eastern Atchafalaya delta strongest outflows in a developing bifurcation tend to follow the most northerly oriented channel as this would be more in line with the preferred orientation of the flood tide currents. Higher velocities in this channel inhibit sedimentation by flushing sediments farther bayward. Conversely, during ebbing tide discharge velocities tend to be lower, enhancing the possibility of deposition in the newly created channels and specifically in the most southerly of the bifurcation forks since this would be more in the line with the orientation of ebb flows. During a complete river flood event, the more northerly oriented fork of any developing bifurcation tends to maintain its cross sectional area, to the detriment of the most southerly oriented fork. In plan view, bifurcations result in one fork, the most northerly, being a well defined continuation of the parent channel, while the more southerly is smaller, and branches at an acute angle (Figures 26b, c and d). Elsewhere in the Atchafalaya delta, and in the Wax Lake delta, differences in channel pattern reflects the orientation of the channel trends in relation to tidal currents and prevailing wind directions.

Channel Abandonment And Lobe Fusion

Lack of seaward delta growth is generally thought to reflect abandonment of the distributary channel network caused by a marked reduction in outflow efficiency (Coleman and Prior 1982). This phenomenon is certainly true of the eastern Atchafalaya Delta, which is in essence a crevasse off the main flow down the navigation channel. However, it may also reflect the fact that most of the sediment entering the eastern delta area by way of East Pass is being deposited before it reaches seaward extremes of the distributary channel network.

As suspended sediment-rich flood waters are transported through the eastern delta complex, frictional drag on the sides of the channel levees and at midchannel bars induces sedimentation (Figure 27). Thus, even though there may be strong flows down distributary mouths, the waters may be so impoverished of relatively coarse sediment by the time they reach distributary mouth, that bifurcation processes are not active and the remaining fine-grained sediments are flushed into the bay.

The above mechanism explains why delta growth has been dominated by upstream accretion and channel abandonment. The former reflects deposition on top of and upstream accretion of the flanks of preexisting mid channel lobes and bars. Channel abandonment reflects the sealing of channels by subaqueous levee formation at their mouths and subsequent infilling by levee overtopping.

3 - D SEDIMENTARY ARCHITECTURE

a) Depositional Environments And Sediment Characteristics

The following discussion is based on 50 short cores and 44 vibracores obtained from the Atchafalaya delta (Figure 28) and 12 vibracores from the Wax Lake delta (Figure 29).

1. <u>Subaqueous Depositional Environment</u>

Old Bay Bottom

Highly bioturbated blue-gray clays and silty clays, with numerous oyster shell fragments

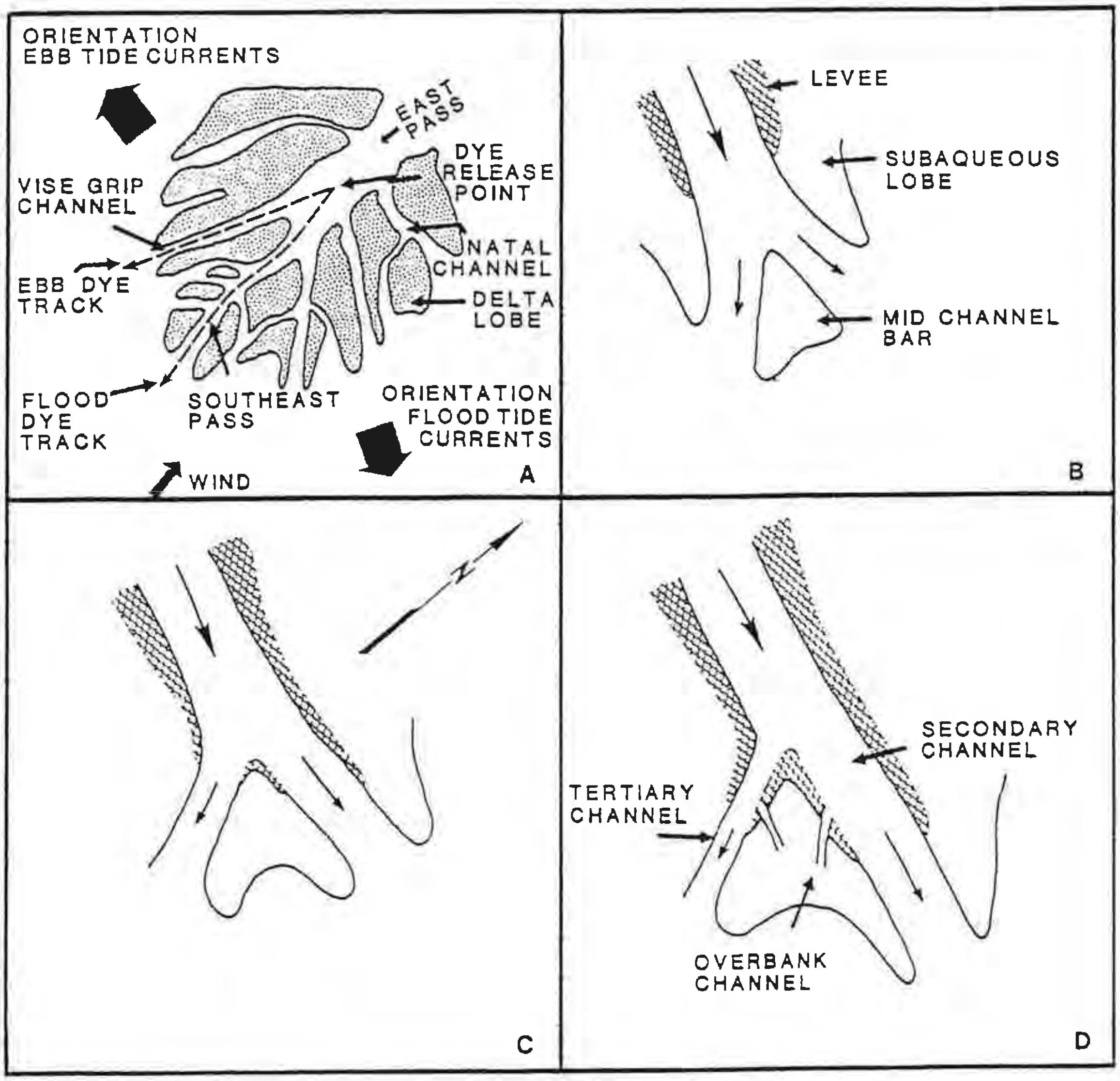

Figure 26. Channel bifurcation of the Eastern Atchafalaya Delta. (a) orientation of tidal currents and results of dye release experiment (van Heerden, 1978), (b)-(d) successive stages in development of a bifurcation.

identify the old-bay-bottom material. Disruption through bioturbation has destroyed most of the primary sedimentary structures; although, weakly graded beds are sometimes present and probably represent reworking during violent storms.

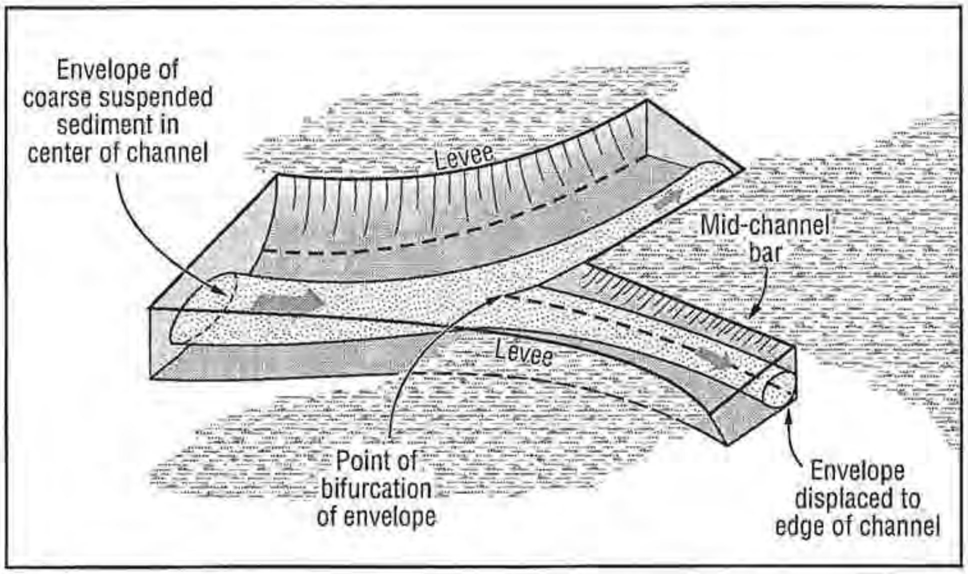

Figure 27. Schematic view of an envelope of coarse suspended sediment (assumed to be in mid-channel) as it is split by a mid-channel bar.

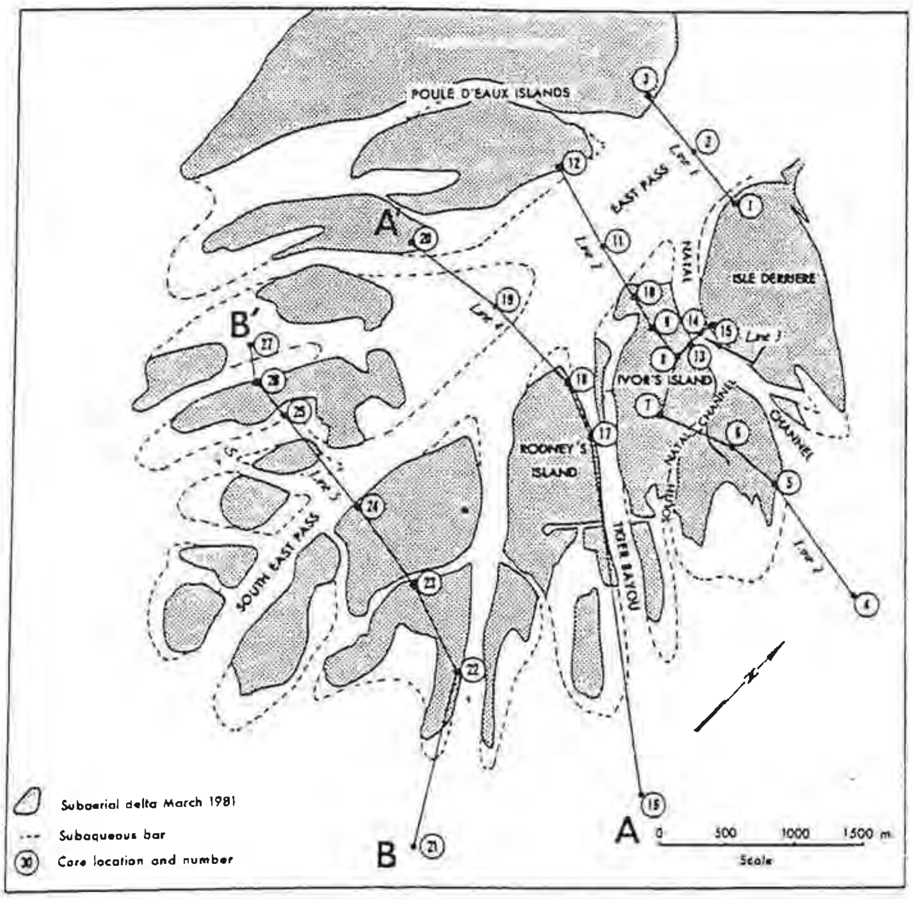

Figure 28. Transects of deep vibracores in the eastern Atchafalaya delta. These lines of cores are used in determining sedimentary facies relationships and stratigraphic reconstructions of the delta.

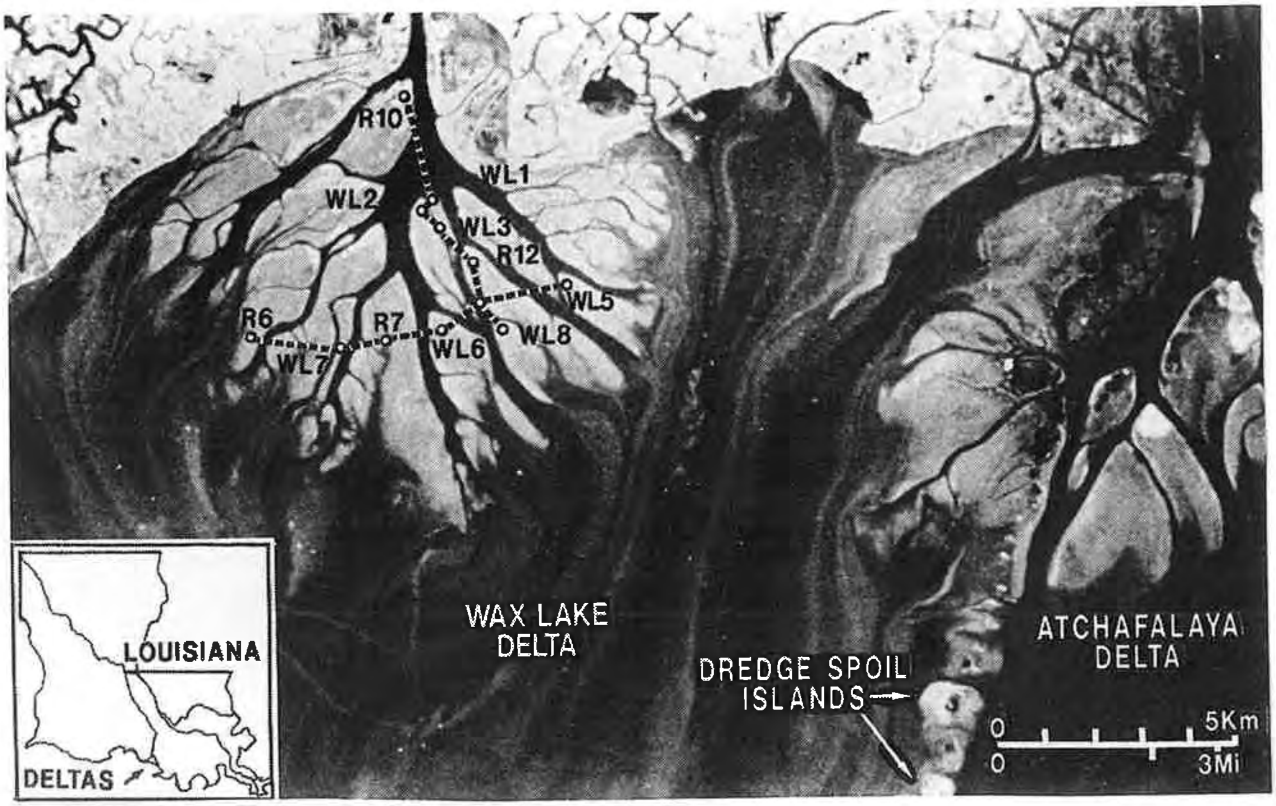

Figure 29. Vibracore locations used for illustrating the sedimentary architecture of the Wax Lake delta.

Micro-fossil examination reveals that old-bay-bottom deposits are dominated by the brackish water ostracod, Perissocytheridea brachyfonna. The transition from old bay sediment to lower prodelta deposits is rather abrupt and is accompanied by less evidence of biogenic activity in the prodelta sediment.

Prodelta

Because sedimentary structure associations differ, prodelta deposits can be divided into two distinct subenvironments. Lower prodelta sediment consists of highly bioturbated brown-grey clays and silty clays and contain one or two layers of shell lag that are generally about 4 in. (10 cm) thick. Brackish water Rangia and Mulinia shells and casts of the freshwater ostracods, Candona lactea and Cypridopsis vidua, (Engel and Swain 1967) are common. The foraminifera, Ammonia beccarii and Elphidium sp., showed marked reductions in numbers from old bay to lower prodelta sediments.

The upper prodelta sequence consists of vertically stacked cycles 4 in.(10cm) thick of red-brown, parallel-laminated silty clays and clays separated by thin (2 to 3 mm) silt lenses that may contain clam shell fragments. Small, polychaete worm burrows originate in the silts and penetrate into the underlying material. A distinguishing characteristic of the upper prodelta facies is its high lateral continuity and low lithologic variation. Upper prodelta median grain size is smaller (~12 microns), and the sorting is better than the underlying lower prodelta and old-bay-bottom sediment. Unlike prodelta deposits of the modern Mississippi delta these deposits are thin and laminated, as compared to thick and massive.

Distal Bar

Overlying prodelta facies is a coarsening-upward sequence that varies from silty clays to coarse silt (median grain size, 20 microns). These deposits constitute the distal bar, which is characterized by textually variable parallel laminations and lenticular laminations. Individual lamination may be 0.7 in. (2 cm) thick. Closer to the individual river mouths, distal-bar deposits become coarser, with small scale cross-laminations, scour and fill and other similar sedimentary structures. Distinct, vertical textural contrasts are present throughout the distal-bar facies; although, lateral continuity is lower than in the prodelta environment. Deformation structures are common in distal-bar sediments. Like the prodelta deposits this facies is thin, less than 3 to 5 ft (<1 m 1.5 m).

Distributary Mouth Bar

Close to distributary mouths, distal-bar sediments grade upward into a shallower and coarser distributary-mouth-bar facies. Although the distributary-mouth bar deposits also coarsen upward, they consist of upward fining cycles of cross and parallel-laminated fine sands, silts, and clayey silts which alternate with parallel-laminated silty clays. The distributary-bar cycles vary in thickness from 1 to 3.5 in. (3 to 9 cm). Some upper horizons of distributary-mouth-bar deposits contain up to 4 in. (10 cm) thick layers of parallel-laminated silts and clays with numerous erosional surfaces (lenticular bedding, Reineck and Wunderlick 1968).

Deformation structures are common in these deposits. Highly structured and sand-rich subaqueous levee deposits are difficult to distinguish from the coarsest distributary-mouth-bar facies in thin deltas like the Atchafalaya and Wax Lake.

Channel Fill

Clayey, silty, and sandy channel fill have been recognized. Clayey channel fill is generally found in small abandoned channels that are usually flanked by vegetated levees (van Heerden 1983). Parallel laminations are the most common primary structures.

The large, primary and secondary distributary channels in the eastern delta are undergoing reductions in cross-sectional area by aggradation of channel flanks and general shallowing of the channels. The silty fill material deposited in these channels consists of parallel-laminated silts and clays. Erosional surfaces and worm burrows are common. Occasionally, thin lenses of cross-laminated silts that represent starved ripples are present.

Sandy channel fill consists of parallel- and cross-laminated, gray, silty sand which acts as a capping layer in channels of the eastern delta area and is part of the lobe-fusion process.

2. Subaerial Depositional Environments

Natural Levee

Because subaqueous and subaerial natural levee deposits are similar and gradational, they have been considered one environment. Natural levee deposits are composed of silts and fine sands, with minor amounts of clay, and display various sedimentary structures that reflect differing intensities of flood-related sedimentation. Trough and climbing-ripple cross laminations are the dominant structures because of high sedimentation rates associated with high flood conditions. When minimal sedimentation occurs during low floods, simple cross laminations are the most common structures found.

Back-Bar Algal Flats

Algal flats form the central part of lobes between subaerial levees. Generally, algal flat sediment is highly organic and consists of parallel-laminated silts and clays interbedded with thin reduced organic layers. Algal flat sand lobes and sand sheets are situated within the algal sequence. Sand lobes consist of thin, cross-laminated, sandy material that occurs near overbank channel mouths. Sand sheets, as the name suggests, are laterally continuous although thin deposits. Generally, they are made up of clean, cross-laminated, fine sands.

Back-bar algal flats are sites of algal production, specifically during summer and fall. Slow deposition accompanied by low turbidity and shallow waters can result in the accumulation of laterally extensive, thick algal layers. Once buried, they compress readily and are discernible in cores as dark organic rich layers no more than 1m (3 cm) thick. Algal layers tend to bind the surface sediment and offer protection against storm erosion mechanisms, especially in the fall and early winter. Eventually, back-bar algal flats attain enough elevation for colonization by marsh plants. Algal flats overlie distributary-mouth-bar deposits and may attain thickness in excess of 3 ft (1 m).

b) Stratigraphic Relationships

Stratigraphic relationships are discussed beginning with the old-bay-bottom sediment that functions as the platform over which the delta prograded. Figure 28 shows the locations of stratigraphic cross sections of the natural eastern lobes of the Atchafalaya delta. Core control for constructing the interpreted stratigraphic relationships is shown in Figures 30 and 31. Input data from vibracores were used to determine the styles of vertical stacking of facies and sediment characteristics for the Atchafalaya delta.

The old-bay-bottom sediment, which underlies the prodelta deposits, is shell rich, burrowed, and interpreted as having been primarily derived from shoreline erosion of the bay perimeter. Morgan et al. (1953) estimated that coastal retreat in this area was around 6 to 8 ft/yr (2 to 3 m/year), prior to significant delta growth in the bay in the early 1950s.

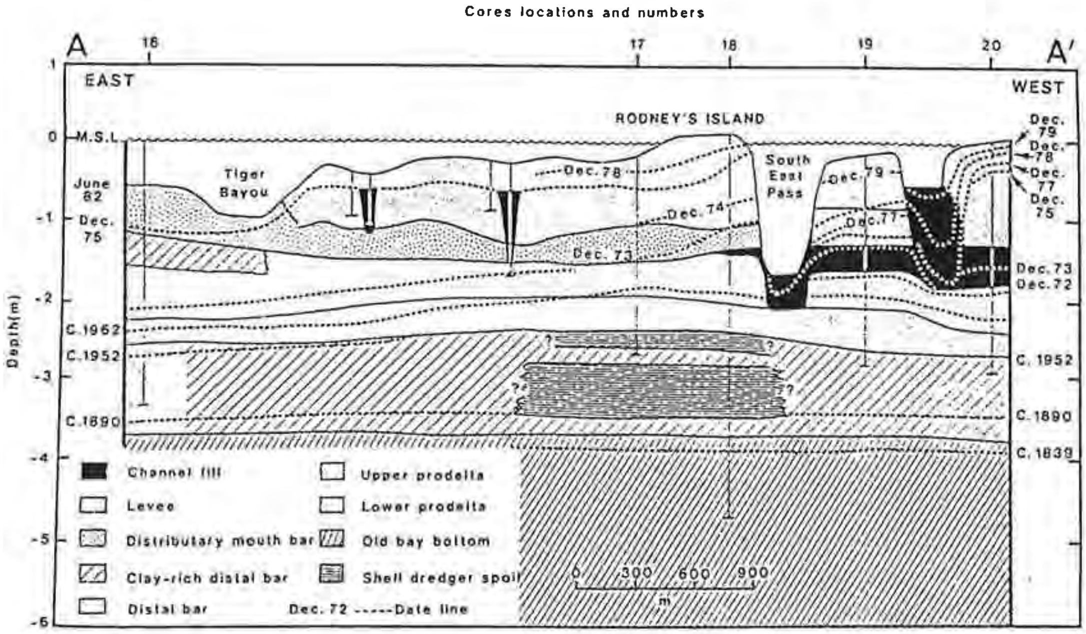

Figure 30. Interpreted stratigraphic cross section (profile A-A' of Figure 28) from the eastern lobe of the Atchafalaya delta. Core control is shown on the cross section.

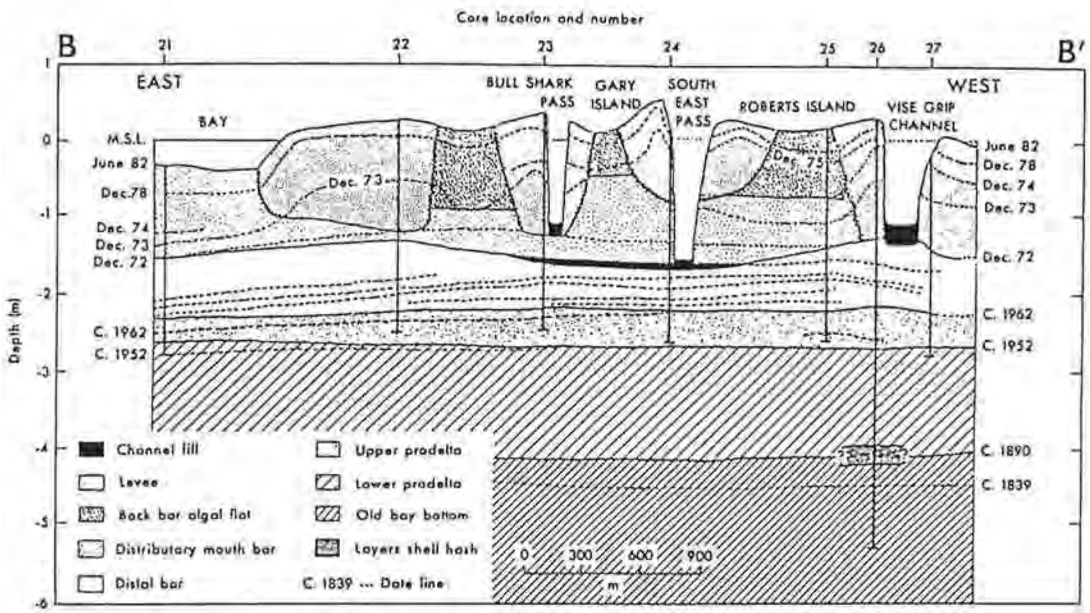

Figure 31. Interpreted stratigraphic cross section (profile B-B' of Figure 28) from the eastern lobe of the Atchafalaya delta. Core control is shown on the cross section.

The lower prodelta clay unit was initiated as a consequence of high discharge that occurred when major log jams were cleared in 1839 (van Heerden 1983). However, initial stages of delta growth are recorded in the upper prodelta sediment (Figures 30 and 31), which began continuous bay floor aggradation in 1952. Upper prodelta deposits appeared as a seaward-thinning wedge of sediment, fronting the lower Atchafalaya River mouth. Establishment of an embryonic channel network in the bay provided the conduits for the distribution of coarser sediment. This transition as a consequence of channel development forced deposition of a slit-rich, distal bar-facies, overlying the fine-grained prodelta deposits.

As subaqueous delta growth continued, distal-bar material was overlaid by distributary-mouth-bar sediment (Figure 30). Stratigraphic relationships show this change occurred in the early 1970s. The overall coarsening-upward sequence of distributary mouth bars consists of repeated upward-fining cycles of parallel-and cross-laminated silts and fine sands that pass upward into parallel-laminated clay (van Heerden 1983). Cycles range between 1 to 4 in. (3 to 10 cm) in thickness. These structures are quite distinct from the textually more variable and parallel-laminated, distal-bar sediments. In contrast to older facies, distributary mouth bars are initially restricted to sites of channel bifurcation.

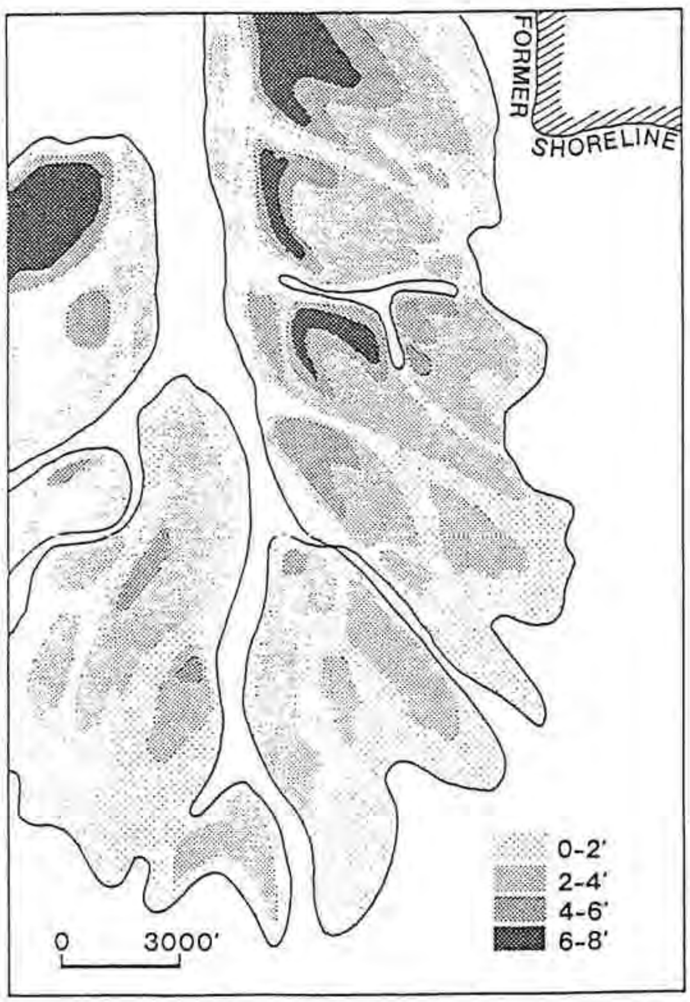

Figure 32. Net sand map of the eastern lobe of the Atchafalaya delta based on vibracores throughout the study area.

Upper prodelta, distal-bar, and distributary-mouth-bar facies aggraded the delta over 20 years (1952-1972) to prepare for progradation of coarser grained facies, which eventually led to subaerial exposure of the delta lobes.

Transport of substantial silt and sand-sized sediment during the unusually high flood of 1973 was responsible for the emergence of coarse delta lobes, initiating the subaerial phase of delta development (Roberts et al. 1980). Much of the sand-rich sediment deposited during this flood was retained in the construction of thick subaqueous and subaerial natural levees, which were apparent on post-flood air photographs as well as in cores. Net sand for the eastern lobe of the Atchafalaya delta is shown in Figure 32.

Both the Atchafalaya and Wax Lake deltas have experienced similar morphological evolution and facies development (Roberts and van Heerden, 1992). Although most sedimentological work to date has focused on the Atchafalaya delta, it is appropriate for this paper to concentrate on new data from the more natural Wax Lake delta. Both deltas are represented by relatively coarse facies considering the high volume of suspended load sediments delivered to Atchafalaya Bay through both the lower Atchafalaya River and Wax Lake Outlets. As previously discussed, much of this suspended load is by-passing the bay and is being transported to the shelf and downdrift coasts. Indications are that most of the coarse sediment (medium to fine sand and coarse silt) remains in the bay as part of the deltas, especially in the western Wax Lake delta system. Figures 33 and 34 illustrate cross sections constructed from vibracore data in both strike and dip directions through the Wax Lake delta. Sedimentary facies of the delta are subdivided into three types (1) sand-rich, (2) interlaminated sands, silts, and clays, and (3) clay-rich (Fig. 33).The bay bottom sediments over which the delta has prograded are distinguished by their fine-grained sediments, extensive burrowing, and abundant shell debris. An important observation to make concerning the sedimentary framework for the Wax Lake lobe is that there is very little clay-rich prodelta facies at the base of this delta. Van Heerden and Roberts (1988) report, also from vibracore data sets, that the Atchafalaya delta displays a similar pattern of a limited clay-rich base assuming delta-building started in the early 1950's. As Figures 33 and 34 illustrate, deltaic deposits in the Wax Lake lobe may be up to 5 m thick with nominal - thickness of 3.0-3.5 m. Maximum sand body thicknesses reach 4.5 m (Figure 34, core R7) in the strike section, which probably represents the result of the process of lobe fusion and upstream accretion identified by van Heerden (1983). This process essentially fills the channel network established during the early stages of delta development with coarse sediment as sand-rich sublobes of the delta fuse and build upchannel to form larger subaerial components. Figure 35 show dominant facies that make up this delta. Using the core data in strike and dip cross sections (Figs. 33 and 34), Table 6 was constructed to emphasize sand body thicknesses and sand thickness as a percentage of the overall delta sequence. On average, the sand-rich facies (distributary mouth bar and subaqueous levee deposits), occupy about 67% of the Wax Lake delta's sedimentary framework. In comparison, data presented by van Heerden (1983) suggests the same sand-rich facies accounted for 55% of the total deltaic sequence. Although it is difficult to determine accretion rates from 1973 because of a lack of dependable bathymetric data on the largely submerged Wax Lake delta, data presented by Majersky et al. (1997) suggest that the Wax Lake delta has vertically accreted at an average rate of approximately 2.7 cm/yr. since 1981 (note the overlain 1981 surface in Figs. 33 and 34).

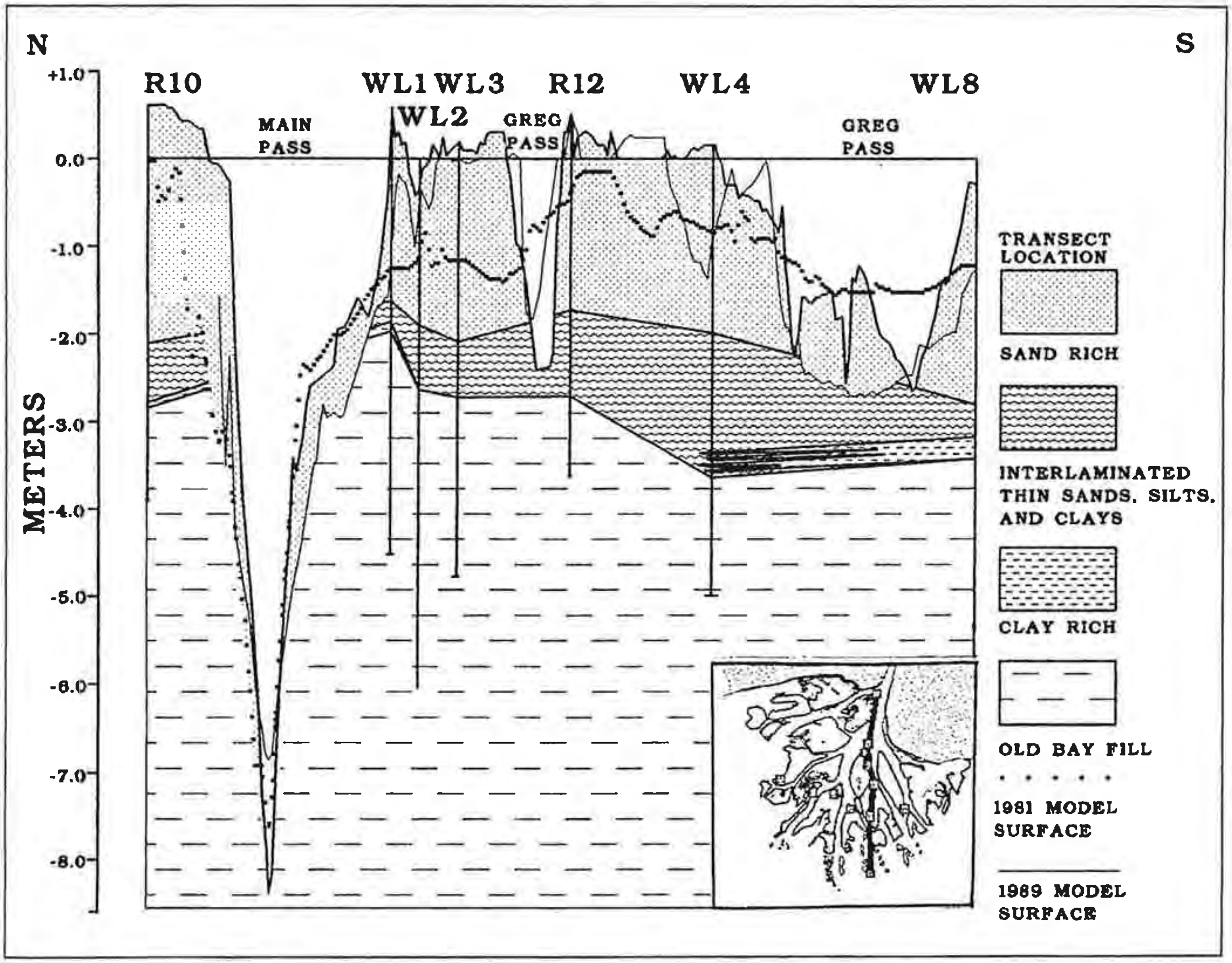

Figure 33. Dip-oriented cross section of the Wax Lake delta showing the distribution of sedimentary facies as determined from vibracore data. See Figure 29 for core locations.

Fisk (1955) described the thin, inner shelf Lafourche delta as one with many distributaries and semi-continuous sheet sands formed by the coalescence of distributary mouth bar deposits from closely spaced distributaries. The strike and dip cross sections through the Wax Lake delta and its eastern Atchafalaya delta counterpart (van Heerden and Roberts, 1988) suggest a similar merging of sand bodies to form a semi-continuous sand trend. In addition, Fisk (1955) indicated that channels that built thin inner shelf deltas, like the Lafourche, frequently cut through the entire delta sequence into underlying sediments. This relationship currently exists in the Atchafalaya and Wax Lake bayhead deltas (e.g. Fig. 6), especially in the proximal parts of the system. Like the inner shelf deltas of the Mississippi Delta plain, the Wax Lake delta is a sand-rich system (Table 5).

The growth patterns of the Atchafalaya and Wax Lake deltas have followed a similar trend, but because of the delayed subaerial growth of the Wax Lake delta, its morphology reflects a younger stage of development. As outlined by van Heerden and Roberts (1988), the Atchafalaya delta was characterized by numerous channels and small subaerial lobes in the 1970s but through the process of lobe fusion and upstream accretion the delta evolved toward a simpler morphology. This morphology is characterized by fewer channels and both fewer and larger subaerial lobes. By contrast, the Wax Lake delta still has a complex channel network and numerous subaerial lobes. It is still prograding through the process of channel elongation and bifurcation as compared to the Atchafalaya delta where channel abandonment and lobe fusion is forcing dominance on a few channels. The Atchafalaya delta also has the added feature of being modified by periodic dredging of the navigation channel and the placement of spoil along the channel margins.

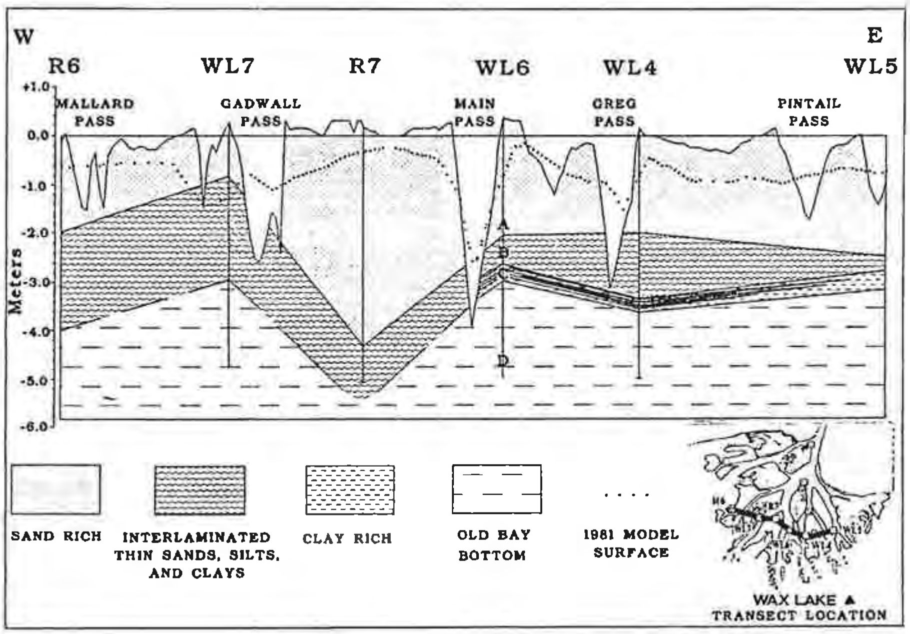

Figure 34. Strike-oriented cross section of the Wax Lake delta showing the distribution of sedimentary facies as determined from vibracore data. See Figure 29 for core locations and Figure 35 for vibracore X-ray radiographs.

TABLE 5 Sand Thickness-Wax Lake Delta

Transect	Core	Sand Body Thickness (m)	Sand Thickness (% of Delta Sequence)
Down-dip	R10	2.7	78
	WL1	2.2	86
	WL2	1.9	61
	WL3	2.5	78
	R12	2.5	70
	WL4	2.1	57
	WL8	2.2	78
Cross-strike	R6	1.8	63
	WL7	2.6	34
	R7	4.5	*
	WL6	2.4	72
	WL4	2.1	57
	WL5	1.3	67
Average		2.4	67

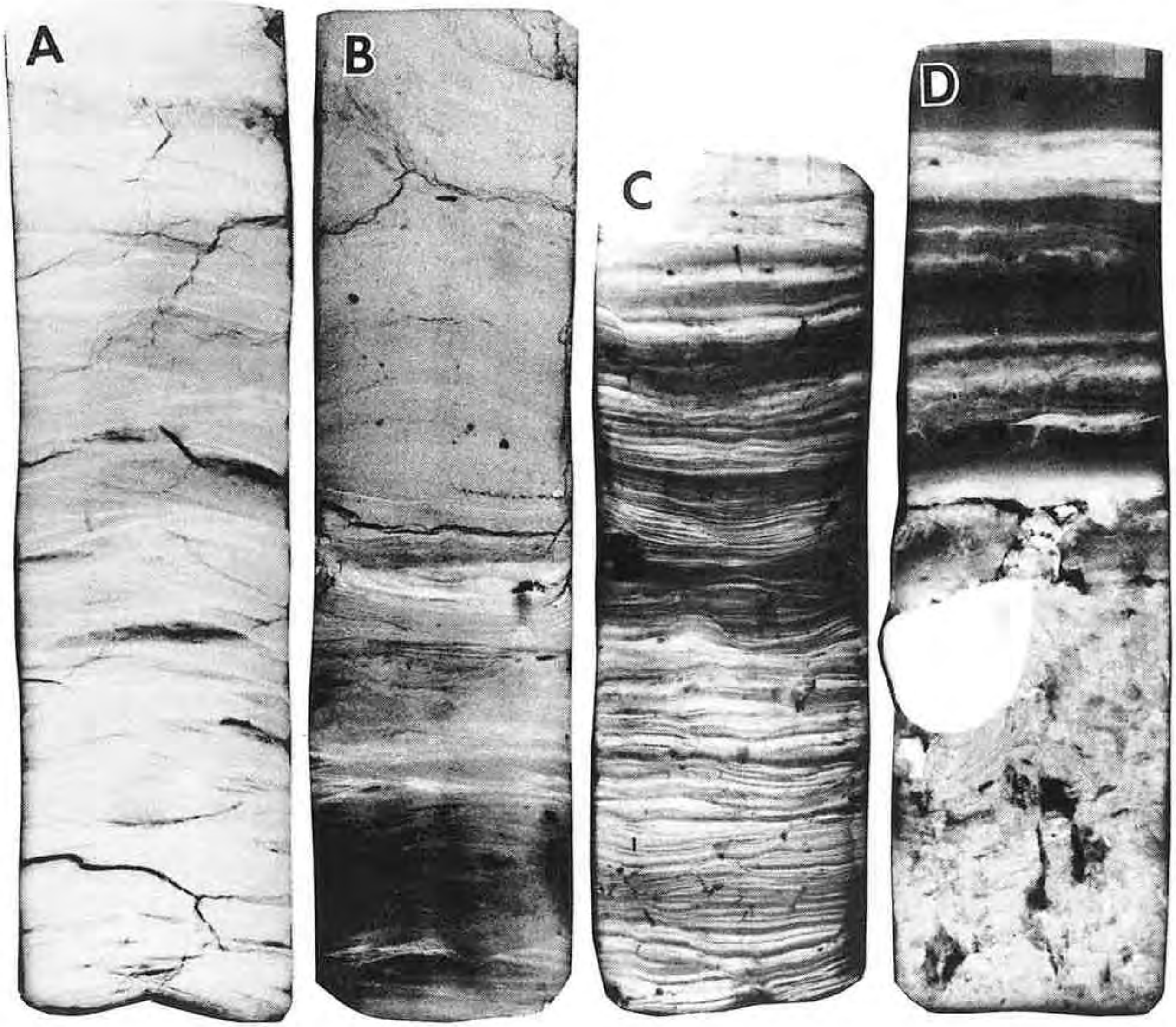

Figure 35. X-ray radiographs of selected subsamples from vibracores R6, Figure 24, illustrating the dominant sedimentary facies: (a) Sand rich (upper), (b) interlaminated thin sands, silts, and clays (upper part), (c) interlaminated thin sands, silts, and clays (lower part), and (d) old bay fill.

JUMP STARTING THE ATCHAFALAYA DELTA - A MANAGEMENT PLAN TO REINSTATE DELTA GROWTH

Sediment delivery to the Atchafalaya delta averages 61,000,000 tons every year (van Heerden 1980). The subaqueous phase of delta growth was initiated in 1962 and the delta became a subaerial feature in 1973 (van Heerden 1983). Initial subaerial growth amounted to 477 hectares per year, but since the late 1970's the growth rate has dramatically diminished to 102 hectares per annum (van Heerden 1994a).

Lack of delta development reflects that a navigation channel bisects the Atchafalaya Delta Figure 36). This channel is maintained at a depth deeper than would exist in totally natural conditions. Van Heerden (1994a) has tied the slow pace of Atchafalaya Delta development, as well as the rising costs of navigation channel maintenance, to the unnaturally large cross-section of the navigation channel passing through the delta. Further, it is almost continuously bounded on its west bank by high artificial levees and, to a lesser extent, by dredged material deposits along the east side. The consequence of this form is that the channel is an efficient collector for sand-sized sediment that would otherwise be naturally distributed across deltaic surfaces. The enlargement of the navigation channel and the pre-1990s program for placing dredged material led to early senescence of the natural distributary system. Van Heerden (1994a) has projected based on sediment supply that wetlands in the Atchafalaya Delta could expand at a rate of 650 $ha\text{-}y^{-1}$, approximately twice the current level, if this landscape were managed to optimize emergent habitat creation.

Louisiana loses about 8,000 hectares of wetlands p.a.. The long-term solution to this wetland loss problem is tied to reestablishing the hydrologic processes that created the wetlands (CWPPRA 1993, van Heerden 1994b). Against this background, the State should plan to maximize wetland creation in the Atchafalaya complex. A long-term management plan had not been formulated for the delta and in 1993 the Environmental Protection Agency funded us to develop an initial plan. In developing a plan, a number of projects were designed to aid in delta (wetland) growth. This spring two projects, funded by the Coastal Wetlands Planning, Protection and Restoration Act (Breaux Bill) are to be constructed in the Atchafalaya Delta in an attempt to spread river sediment over a wider area (Figure 36). Construction and programmed monitoring costs exceed $8.0 million, but these two projects have the potential to create more wetland habitat over the next 20 years than all projects presently authorized during the seven year life of the Breaux Bill ($250 million expended to date). Additionally, a mechanism for the beneficial use of the navigation maintenance dredge material was developed.

a.) Reestablishment of Natural Sediment Delivery System

The first project is to reestablish the natural sediment delivery system on the east side of the delta (Figure 37). Two channels previously closed by unrestricted dredge material disposal will be dredged 3m deep with bottom widths of 60m. One channel will be dredged for 1550 m, with a channel bifurcation present at its downstream end. The other will be dredged for 810 m. These dimensions are similar to natural secondary sized distributary channels (van Heerden 1993). A total of 543,000 cubic meters of material is to be dredged with which 260 hectares of new delta lobes will be created (Figure 37). All created delta lobes are expected to settle to an elevation suitable for emergent marsh vegetation. Reactivation of these two channels is expected to improve sediment supply to approximately 400 ha of existing wetlands and an additional 400 ha of shallow delta platform. An additional 600 hectares of new marsh could accrete over the next 20 years because of natural delta building associated with the two distributary channels.

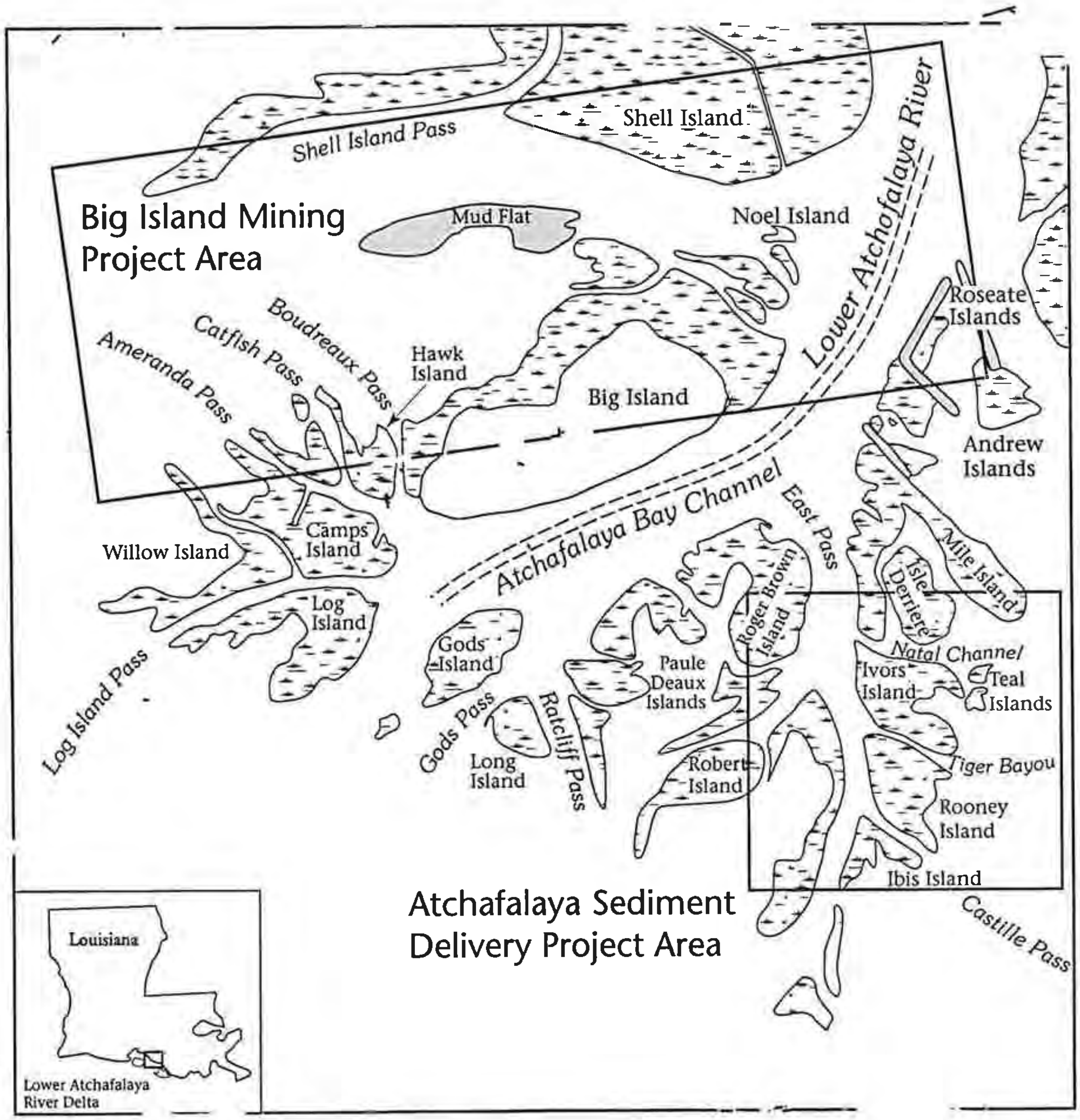

Figure 36. Location map of Atchafalaya delta Big Island Mining and Sediment Delivery project areas.

b.) Marsh Creation, Big Island Mining

The second project is more ambitious ands aims to enhance natural delta building on the west side of the delta in the vicinity of Big Island (Figure 38). This island consists of millions of cubic meters of dredge spoil placed in a linear mound up to 5m. in elevation. As such it is the highest land for tens of kilometers and has limited wetland value. The project, presently under construction, will mine some of this dredge spoil and use it beneficially. The Big Island Mining project is designed to enhance natural delta building processes by creating an avenue for sediment transport to areas north and west of Big Island. The Big Island Mining project consists of dredging a 6400m distributary channel with four smaller tertiary distributary channels to emulate an emerging delta lobe.

The main distributary channel starts with a bottom width of 240m and a depth of 6m, which is similar to the maintained depth of the navigation channel. The restored channel narrows and shoals to a 120 m bottom width and depth of -3 m. This longitudinal shoaling of the thalweg is designed to mimic a natural distributary channel by creating a venturi effect to keep velocities high enough to convey suspended sand as far as possible. A total of 2.5 million m^3 of dredged material will be placed in 11 disposal sites at elevations create 344 hectares of new wetlands beside the channel (Figure 38). The "proto" delta formed is expected to expand over time and the associated natural delta building processes will create many additional acres of wetlands.

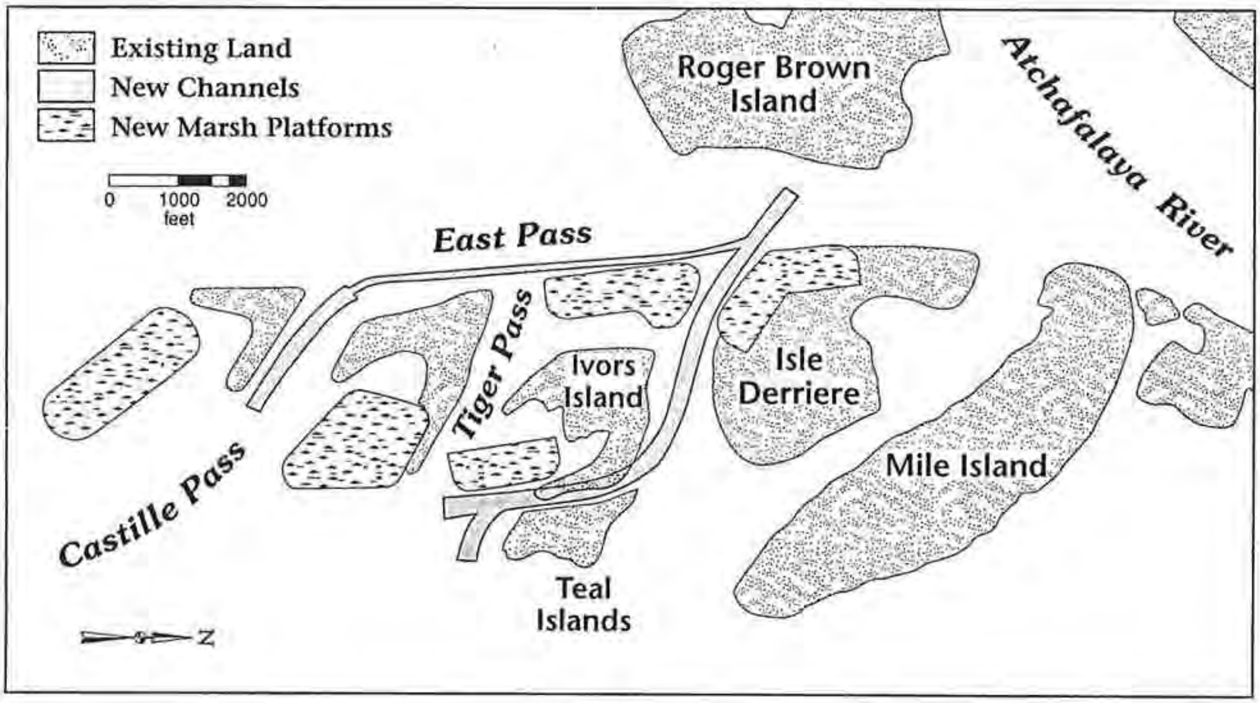

Figure 37. New land to be created in the eastern Atchafalaya delta by dredge spoil placement.

c.) Beneficial Use of Dredge Material

Each year the U.S. Army Corps of Engineers dredges approximately three million cubic metres of material from the navigation channel to maintain its depth. In the past they deposited this sediment in large spoil piles with limited wetland value. A new approach to disposal was designed. A "fan tail" spray fitting is attached to the discharge pipe nozzle and the sediment sprayed over a wide area. By successively lengthening the discharge pipe, they can construct a low elevated and flat lobe. These new disposal features were designed to mimic crescentic delta lobes and associated distributary channels. Mile Island (Figure 37) is an example of one such lobe. This program has been extremely successful and has resulted in the gain of hundreds of hectares of new wetlands while not affecting shipping needs.

The above combination of projects should stimulate natural delta growth and estimates are that within a few years subaerial delta growth should exceed 370 hectares per annum, a 350% increase over the present rate.

d.) Benefits to Coastal Wetland Dependent Fish and Wildlife Populations

The Atchafalaya Delta winters up to 250,000 water fowl. These projects will immediately increase the marsh area by five percent with associated benefits to the water fowl. Additionally, ducks, ibises, herons and skimmers, and other birds have breeding colonies in Atchafalaya Delta. The new delta lobes will provide suitable habitat for additional breeding colonies.

Fish populations will benefit from the shallow protected environments associated with delta lobe creation. These areas will provide forage and nursery habitats and an additional source of plant detritus. Detrital material will contribute to increased inshore and near shore fishery productivity.

Increasing discharge laterally from the delta will enhance sediment introduction to marshes surrounding Atchafalaya Bay, aiding in their maintenance.

The new distributary channel will enhance recreational access. Additionally, new fishing and hunting grounds will be established. These activities are extremely important to local economies.

IMPACTS OF ATCHAFALAYA RIVER SEDIMENTS ON DOWNDRIFT COASTS

As discussed earlier, significant quantities of primarily fine-grained sediment started arriving in Atchafalaya Bay in the early 1950s, initiating the subaqueous phase of Atchafalaya delta development (Shlemon 1975). Of equal importance, the Chenier Plain renewed growth at about this same time. Morgan et al. (1953) documented the appearance of new mudflats along the eastern part of the Chenier Plain at Chenier Au Tigre. Fine-grained sediment from the Atchafalaya appears to have largely bypassed the bay and was carried westward (Figure 39). Morgan and Larimore (1957), in a study which focused on annual rates of shoreline change, found that although most of the Chenier Plain coast was retreating at an average rate of over 18 ft/yr (5.6 m/yr), the Chenier Au Tigre area was accreting at about 13 ft/yr (4.0 m/yr). This coastal progradation was the first sign of reversal in the trend of shoreline retreat that had been operative for centuries along the western and central Louisiana coast.

Since the early 1950s when Atchafalaya sediment started nourishing down-drift coasts, the Chenier Plain has been in the early stages of a progradational phase. Figure 40 illustrates a time series record (1969-1979) of mudflat appearance and migration along the Chenier Plain shoreline. During this period several patterns emerged: (a) simultaneous erosion and accretion of adjacent stretches of shoreline, (b) an increasing length of shoreline fronted by newly emergent mudflats, and (c) a shift of mudflat accretion to the west. Since these data were compiled, it has become apparent that the patterns observed during the 1969-1979 period are continuing and accretion along

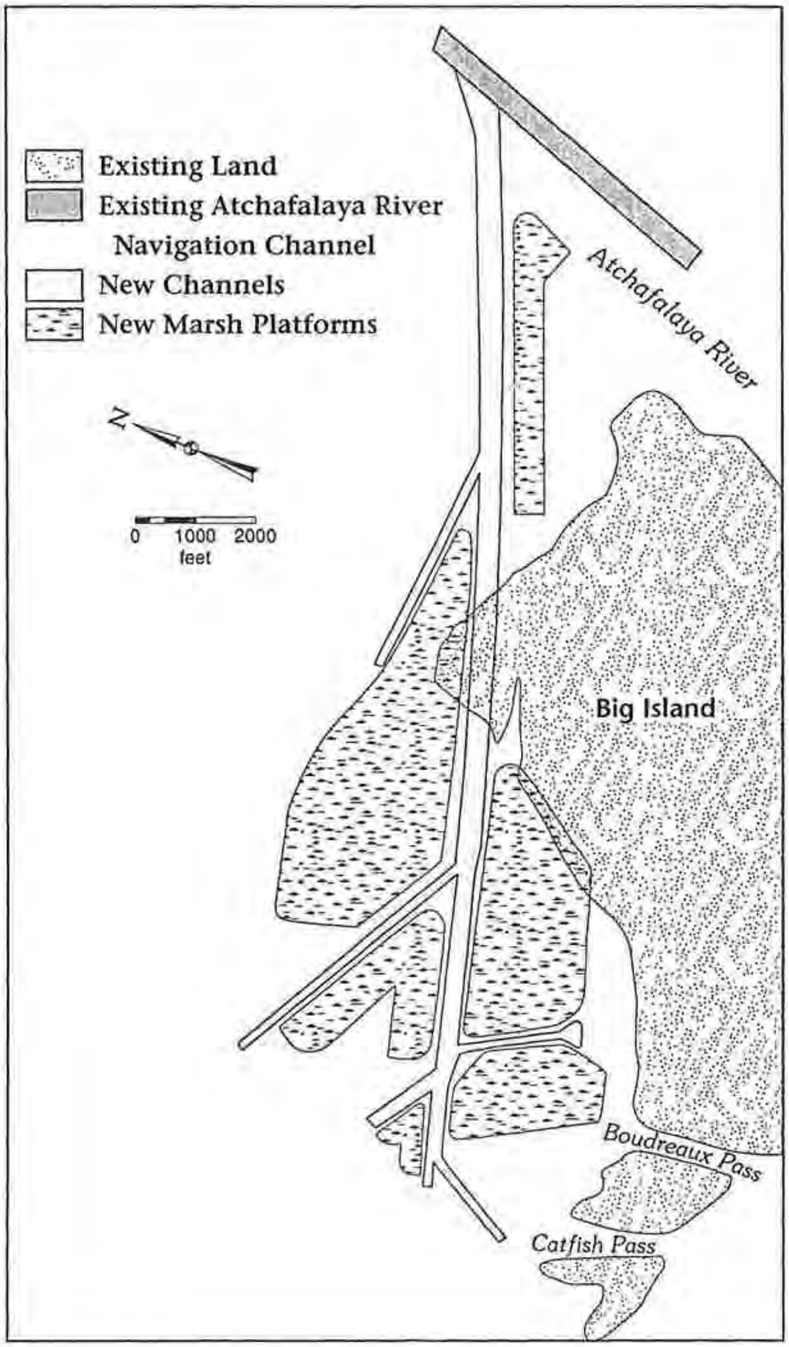

Figure 38. Proposed natural enhancement of the natural delta-building process in the vicinity of Big Island, western Atchafalaya delta.

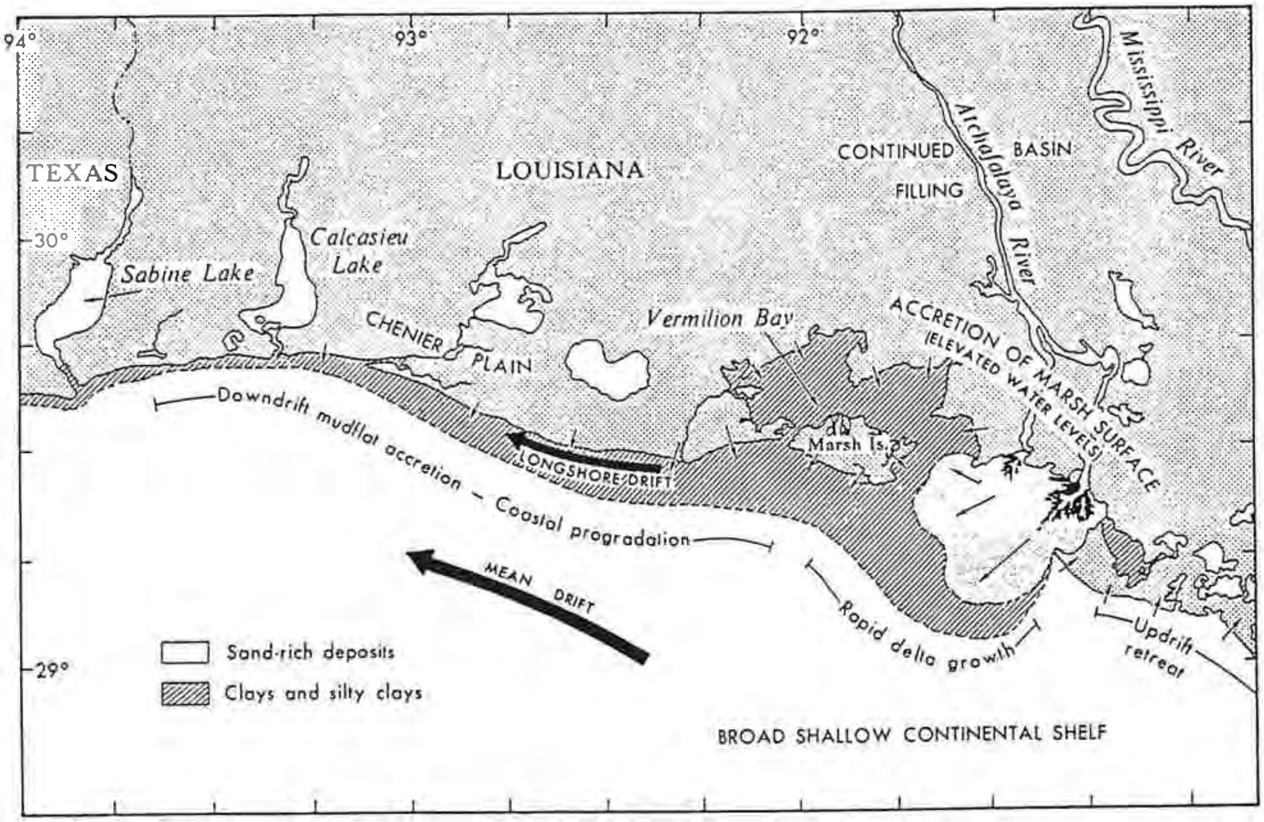

Figure 39. Map of central-to-western Louisiana coast showing the impacts of Atchafalaya River sedimentation.

the eastern Chenier Plain is accelerating. Along an 11 ml stretch of coast from Freshwater Bayou westwards, shoreline progradation rates have varied from 180-240 feet/yr (60-80 m/yr) for the past 10 years.

Although it is clear that fine-grained sediments from the Atchafalaya River are the source of material for renewed progradation of the Chenier Plain, the actual processes of sediment transport to the shore face and preservation of that sediment as a permanent part of the coast are still poorly understood. Kemp (1986) is responsible for the definitive work to date. He postulated that progressive nearshore attenuation of incident waves decreased shear stress on mud bottoms and promoted deposition. Thus, significant diabathic transport of fluid mud would occur on the nearshore shelf. This is the reverse of the response by sandy surf-dominated coasts. In addition, Kemp et al. (1980) also found low frequency flows were associated with shore-amplified water level oscillations which have characteristics of a standing wave with an antinode at the shoreline. The onshore decreasing shear stress gradient developed under attenuating waves causes mud deposition close to shore. Water level fluctuations, in combination with wave states, wind speed and direction, and atmospheric conditions associated with the passage of winter cold fronts (Robert et al. 1987) force cross-shore fluid mud transport that stabilizes mudflats.

Stormy conditions associated with periodic winter cold front passages are closely related to transport of suspended sediment to the continental shelf, coastal erosion, and coastal

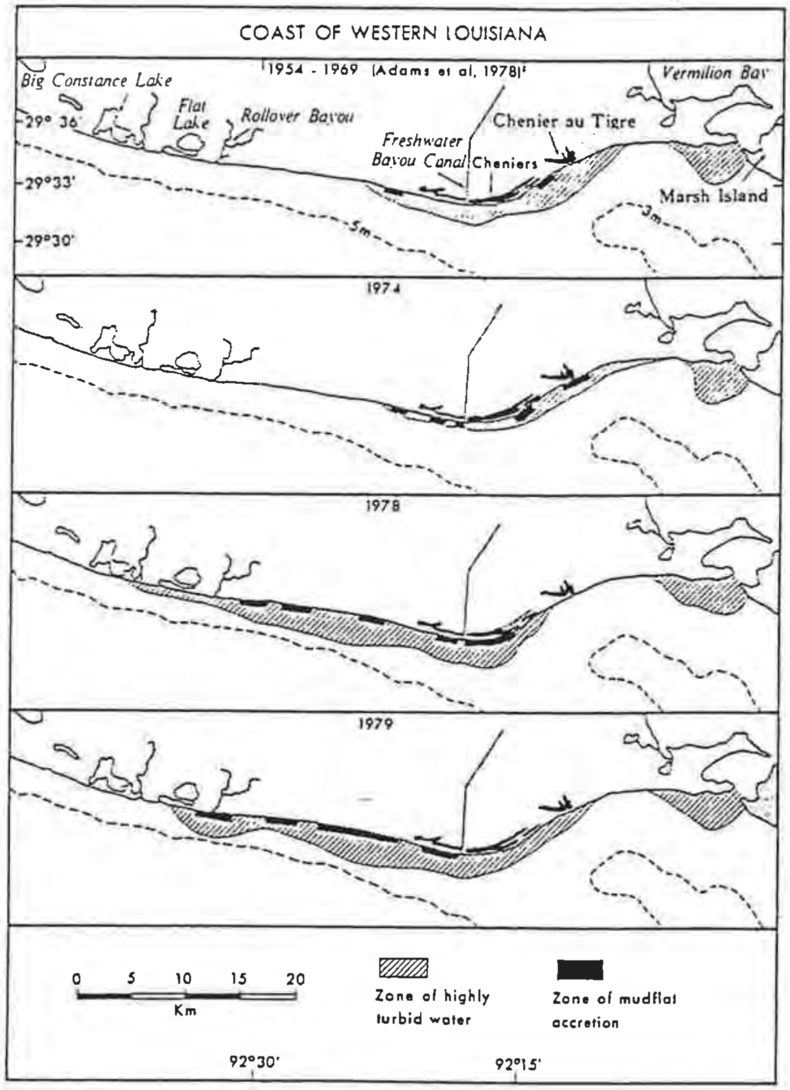

Figure 40. Areas of mudflat accretion from 1969 to 1979, Louisiana Chenier Plain. Segments of coast between mudflats are generally eroding. Note shift in sedimentation to the west.

progradation along shoreline sectors where abundant fine-grained sediments are stored on the inner shelf. Cold front passages occur between October and April on three- to five-day cycles. Their typical NW to SE direction of approach, large spatial scales, and numerous yearly occurrences (20-30 events/year) drive physical processes that cause significant coastal change.

Recently both remotely sensed multispectral and high quality photographic data have been collected from altitudes of 0.9 mi (1500 m), 5.6 mi (9000 m), and 13 mi (21,000 m) before and after cold front passages to form a data base for evaluating coastal change and suspended sediment transport pathways. Remotely sensed data sets are augmented with ground truth measurements of coastal configuration, sedimentology, and water quality to better understand the mudflat accretion processes.

Physical processes active in the prefrontal phases of a winter cold front passage are considerably different from those of the post frontal phase. Along the Chenier Plain coast prefrontal stages are characterized by prolonged periods (on the order of several days) of high wave action from the southerly quadrants, water level setup along the coast, and strong alongshore as well as onshore sediment transport. At these times mud from the Atchafalaya River, stored on the nearshore shelf, is transported onshore and alongshore to slightly prograde the Chenier coast. Post-frontal conditions bring dry, cold winds from the northerly quadrants causing water-level setdown along the coast, a significant reduction in nearshore wave energy, and drying of the newly deposited mudflats fronting the Chenier Plain. Rapid drying causes an important increase in sediment strength, mud crack formation, and effective armoring of the mud flats by dried mud clasts that resist erosion in subsequent cycles. Figure 41 illustrates the sequential progradation of the eastern chenier plain coast from 1987-1993. Figure 42 is a ground shot.

Summary of Impact on Downdrift Coasts

Activation of Atchafalaya River sediment input to the northern Gulf of Mexico coast in the early 1950s initiated a new era in the Mississippi River Delta complex. Not only did delta-building start in Atchafalaya Bay, but substantial impacts from suspended load transport started occurring in marshlands surrounding the bay and along downdrift coasts. For centuries the Atchafalaya Bay area and adjacent Chenier Plain coast were regions characterized by marshland loss and coastal retreat. In the classic paper by Morgan and Larimore (1957) the shoreline of Atchafalaya Bay was estimated to be retreating at an annual rate of 2-3 m/yr (6-9 ft/yr) while parts of the Chenier Plain coast were eroding at rates estimated at up to 7 m/yr (22 ft/yr). With diversion of Mississippi River water and sediment down the Atchafalaya River coupled to filling of the Atchafalaya Basin with sediment in the 1950s, sediments became available to reverse these trends of coastal retreat and to some extent interior marsh landloss.

High suspended sediment loads in Atchafalaya Bay waters are conducive to sediment transport to marshlands around the bay perimeter under the proper physical process conditions. Mossa and Roberts (1990) pointed out that there is a synergism between peaks in suspended sediment concentration and physical process conditions that enhance suspended sediment transport to surrounding marshlands. In late winter and early spring when suspend sediment is maximized in the Atchafalaya River, cold fronts are still actively impacting Louisiana. These cyclic events accompanied by strong winds cause waves and resuspension of bay sediments as well as water level setup against the coast. Elevation of bay water levels by as much as 1-2 feet establishes a gradient that forces highly turbid water into the marshlands where sedimentation occurs before wind reversals force water out of the marsh. This sediment not only builds the marsh substrate, but provides nutrients for healthy plant communities. The end result is to offset the destructive effects of subsidence and nutrient imbalance. Consequently, the marshlands around Atchafalaya and Fourleague bays have been revitalized by the introduction of Atchafalaya River suspended sediments.

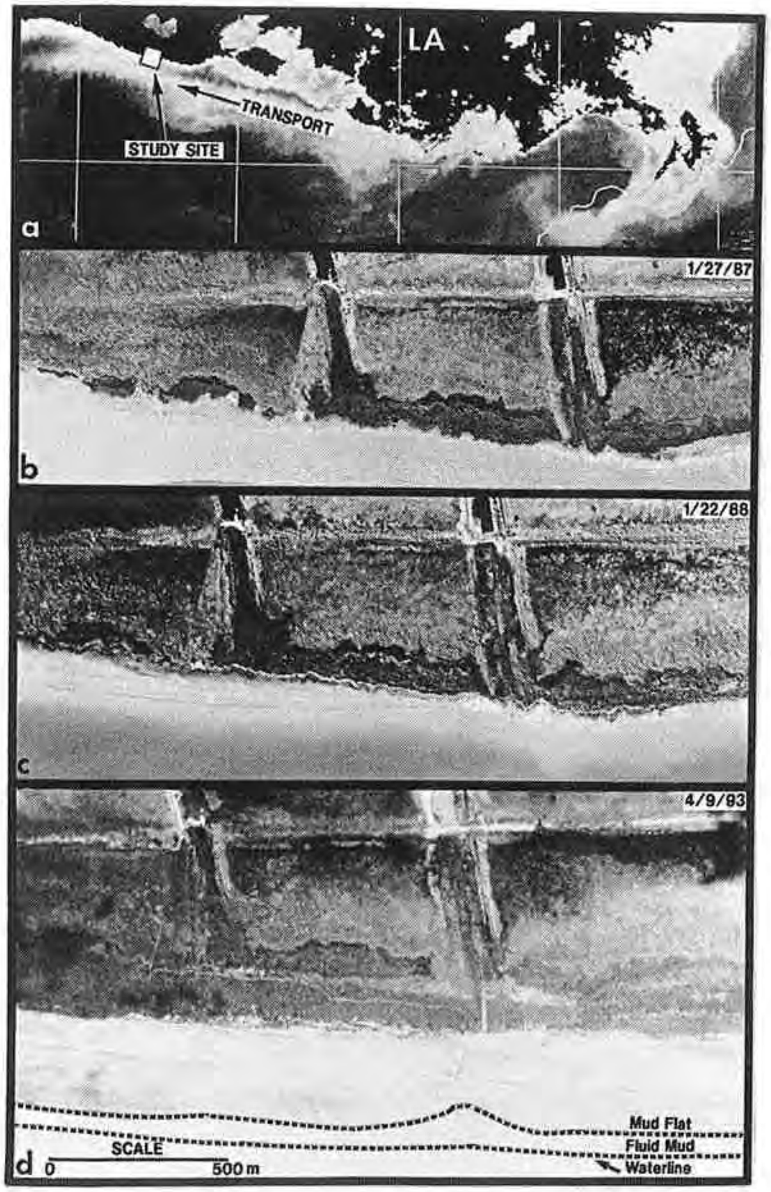

Figure 41. Sequential progradation of the eastern chenier plain shoreline between 1987-1993.

Along the Chenier Plain, sediments from the Atchafalaya are forced westward and coast-parallel. This coastal current system supplies fluid mud to the nearshore shelf for transport to the shoreface. Again, initial work on these environments suggests that cold front-related processes are responsible for cross-shelf shoreward sediment transport and coastal accretion. Some parts of the eastern Chenier Plain are presently prograding at rates measured in 10s of m/yr (100s of ft/yr). Although the most dramatic changes are occurring on the eastern part of the Chenier Plain coast which is closest to the sediment source, impacts are now being felt as far downdrift as east Texas.

Capture of Mississippi River water by the Atchafalaya River is perhaps the most important event to occur in the Mississippi River Delta Complex in historical times because it marks the

Figure 42. Ground-level photograph of a sun baked and cracked layer of mud along the eastern Chenier Plain coast.

beginning of a new delta lobe. By studying the emerging delta from this event we have the opportunity to witness a significant highstand parasequence in the making and determine the evolutionary strategy responsible for its stratigraphic and sedimentologic complexity. Lessons learned in this setting should be transferable to many thin deltas both modern and in the subsurface.

REFERENCES

Adams, R.D., P.J. Banas, R.H. Baumann, J.H. Blackman, and B.W.G. McIntire, 1978. Shoreline erosion in coastal Louisiana; inventory and assessment. Final Report to Louisiana Department of Transportation and Development: 139pp.

Adams, C.E., Jr., J.T. Wells, and J.M. Coleman, 1982. Sediment transport on the central Louisiana continental shelf: implications for the developing Atchafalaya River delta. Contr. Mar. Sci., 25:133-148.

Angelovic, J.W., 1976, Environmental Studies of the South Texas Outer Continental Shelf, 1975, 2: Physical Oceanography, U.S. Department of Commerce, NOAA, Washington, D.C.

Bagnold, R.A., 1966. An approach to the sediment transport problem from general physics. U.S. Geol. Surv. Prof. Pap. 4221.

Becker, R.E., 1972. Wave energy studies along the Louisiana coast. Report Number 12, Coastal Resources Unit, Center for Wetland Resources, Louisiana State University, Baton Rouge, Louisiana: 22pp.

Brower, W.A., J.M. Meserve, and R.G. Quayle, 1972. Environmental Guide for the U.S. Gulf Coast. Prepared for U.S. Army Corps of Engineers by National Oceanic and Atmospheric Administration, EOS, NCC, Asheville, NC.

Byrne, J.V., D.O.S. Leroy, and C.M. Riley, 1959. The Chenier Plain and its stratigraphy, southwestern Louisiana. Trans. Gulf Coast Assoc. of Geol. Soc., 9:237-260.

Bailey, A.M., H.H. Roberts, and J.H. Blackson, 1998. Early diagenetic minerals and variables influencing their distributions in two long borings (> 40 m), Mississippi river delta plain: Journal of Sedimentary Research, 68:185-197.

Breland, P.L., D.M. Patrick, and L.M. Smith, 1988. The sedimentary texture, structure, and framework of lacustrine deltaic deposits in the Atchafalaya Basin. Transactions Gulf Coast Association of Geological Societies, 38:351-359

Chabreck, R., 1972. Vegetation, water, and soil characteristics of the Louisiana coastal region: Louisiana State University Agricultural Experiment Station Bull., 72 pp.

Chuang, W. and W.J. Wiseman, 1983. Coastal sea level response to frontal passages on the Louisiana-Texas shelf, Journal of Geophysical Research, 88(c4):2615-2620.

Coastal Wetlands Planning, Protection and Restoration Act, 1993. Louisiana Coastal Wetlands Restoration Plan, 11 vols.

Coleman, J.M., and S.M. Gagliano, 1965. Sedimentary structures: Mississippi River deltaic plain. _In_: Middleton, G.V. (Editor) Primary sedimentary structures and their hydrodynamic interpretation. Society of Economic Paleonlogists and Mineralogists, Special Publication, 12:133-148.

Coleman, J.M., 1966. Ecological changes in an massive fresh-water clay sequence. Transactions Gulf Coast Association of Geological Societies, 16:159-174.

Coleman, J.M., 1976, Deltas: Processes of deposition and models for exploration: Continuing Education Publication Company, Inc., Champaign, IL. 102 p.

Comeaux, M.L., 1972. Atchafalaya swamp life-settlement and folk occupations: Geoscience and Man, School of Geoscience, Louisiana State University, 111 p.

Crout, R.L. and R.D. Hamiter, 1981. Response of bottom waters on the west Louisiana shelf to transient wind events and resulting sediment transport. Gulf Coast Association of Geological Societies Transactions, 31:273-278.

Cunningham, R., S. Majersky, and L. Xu. 1996a, Compilation of the 1981, 1989, and 1994 USACE, NOD hydrosurveys and associated aerial photography of Atchafalaya Bay: Project completion report: DACW 29-M-1664: US Army Corps of Engineers (New

Orleans District).

Cunningham, R., S. Majersky, F. Jones. 1996b, Compilation of the U.S. Army Corps of Engineers Hydrosurveys and Associated Aerial Photography of Atchafalaya Bay, LA., in Proceedings of the United States Intergraph Graphics Users Group Conference: New Orleans, LA, September, 1996.

Daddio, E., W.J. Wiseman, Jr., and S.P. Murray, 1978. Inertial currents over the inner shelf near 30 North. Journal Physical Oceanography, 8:728-733.

Fernandez-Partegas, J. and C.N.K. Mooers, 1975. Some front characteristics over the eastern Gulf of Mexico and surrounding land areas, Final report to the Bureau of Land Management under contract 08550-CT4-L6.

Fisk, H.N., 1944. Geological investigation of the alluvial valley of the Lower Mississippi River. U.S. Army Corps Eng., Vicksburg, Miss. 78pp.

Fisk, H.N., 1948. Geology of lower Mermentau River basin and control structure sites: definitive project report, Mermentau River, Louisiana. U.S. Army Corps Eng., Mississippi River Com., Vicksburg, Miss.

Fisk, H.N., 1952, Geologic investigation of the Atchafalaya Basin and the problem of Mississippi River diversion: U.S. Corps of Engineers, Mississippi River Commission, Vicksburg, Mississippi, 1:145 p.

Fisk, H.N., 1955, Sand facies of recent Mississippi delta deposits: Proceedings 4th World Petroleum Congress, Rome, Italy, Section 1-c, p. 377-398.

Fisk, H.N., 1961, Bar-finger sands of the Mississippi delta, in Modern Deltas, American Association of Petroleum Geologists, reprint series No. 18, 1976, p. 62-92.

Fisk, H.N., E., McFarlan, Jr., C.R. Kolb, and L.J. Wilbert, 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.

Gould, H.R. and E. McFarlan, 1959. Geological history of the Chenier Plain, southwestern Louisiana. Trans. Gulf Coast Assoc. Geol. Soc., 9:261-272.

Howe, H.V., R.J. Russell, and J.H. McGuirt, 1935. Physiography of coastal southwest Louisiana. Dep. Conserv. Geol. Surv. Geol. Bull., 6:242

Hoyt, H.H., 1969. Chenier versus barrier, genetic, and stratigraphic distinction. Bull. Am. Assoc. Pet. Geol., 53:299-306.

Hsu, S.A., 1988, Coastal Meteorology. Academic, San Diego, CA: 260pp.

Hsu, S.A., 1992. Effects of surface baroclinicity on frontal overrunning along the central Gulf coast. Journal of Applied Meteorology, 31(8):900-907.

Hsu, S.A., 1993. The Gulf of Mexico a breeding ground for winter storms. Mariners Weather Log, 37(2):4-11.

Hsu, S.A. and B.W. Blanchard, 1991. Shear velocity and eolian sand transport on a barrier island, in Coastal Sediments 1991. Am. Society of Civil Engineers, 1:220-234.

Humphreys, H., 1971. Photographic of Red River raft, 1873: Louisiana History, 12:101-108.

Johnson, G.A., E.A. Meindl, E.B. Mortimer, and J.S. Lynch, 1984. Features associated with repeated strong cyclogenesis in the western Gulf of Mexico during the winter of 1982-83, Postprints, Third Conference on Meteorology of the Coastal Zone, Jan. 9-13, 1984, Miami, Fl. American Meteorological Society, Boston, MA: 110-117.

Kaczarowski, R.T. and R.E. Gernant, 1980. Stratigraphy and coastal processes of the Louisiana Chenier Plain. Gulf Coast Assoc. Geol. Soc. Field Guide: 72pp.

Kemp, G.P., J.T. Wells, and I. Ll. van Heerden, 1980, Frontal passages affect delta development in Louisiana: Coastal Oceanographic and Climatological News, 3:4-5.

Kemp, G.P., 1986. Mud deposition at the shoreface: wave and sediment dynamics on the Chenier Plain of Louisiana. Thesis, Louisiana State University, Baton Rouge: 148pp.

Kemp, G.P., J.N. Suhayda, H.S. Mashriqui, I. Ll. van Heerden, and O. Marlbrough. 1995, Development of a long-term water and sediment distribution plan for the lower Atchafalaya basin to minimize flooding to local communities and to determine the impacts of the present Wax Lake Outlet weir, Phase 1, Task 2: Assessment of the impact of the Wax Lake Outlet weir on the water levels and sedimentation within the lower Atchafalaya River: Report submitted to the mayors of the City of Morgan City, and the City of Berwick, Louisiana.

Kolb, C.R., 1962. Distribution of soils bordering the Mississippi River from Donaldsonville to Head of Passes: US Army Corps of Engineers Waterways Experiment Station, Technical Report No. 3-601, Vicksburg, Mississippi, 61pp.

Kosters, E.C., and A. Bailey, 1983. Characteristics of peat deposits in the Mississippi River delta plain: Trans. Gulf Coast Geol. Soc., 33:311-325.

Latimer, R.A., and C.W. Schweitzer. 1951, The Atchafalaya River study: A report based upon engineering and geological studies of the enlargement of Old and Atchafalaya rivers: US

Army Corps of Engineers, Mississippi River Commission, Vicksburg, Mississippi, v. 1 and 3.

LeBlanc, R.J. and H.A. Bernard, 1954. Resume of late recent geological history of the gulf coastal. Geologie en Mijnbouv, 16:185-194.

Majersky, S. H.H. Roberts, R. Cunningham, G.P. Kemp, and C. John. (In Press), Facies development in the Wax Lake Outlet Delta: Present and future trends: Basin Research Institute Bulletin, Louisiana State University.

McCave, I.N., 1973. Some boundary-layer characteristics of tidal currents bearing sand in suspension. Mem. Soc. R. Sci. Liege, 6 ser., 6:187-206.

McFarlan, E., Jr., 1961. Radiocarbon dating of Late Quaternary deposits, south Louisiana. Geological Society of American Bulletin, 72:129-158.

McIntire, W.G., 1958. Prehistoric indian settlements in the changing Mississippi River delta. State Univ. Coastal. Stud. Ser., 1:65pp.

Milliman, J.D. and R.H. Meade, 1983. World-wide delivery of river sediment to the ocean, Journal of Geology, 91(1):1-21.

Moeller, C.C., O.K. Huh, H.H. Roberts, L.E. Gumley and W.P. Menzel, 1993, Response of Louisiana coastal environments to a cold front passage: Journal of Geophysical Research, p. 434-447.

Morgan, J.P., J.R. Van Lopik, and J.G. Nicholas, 1953. Occurrences and development of mudflats along the western Louisiana coast. Louisiana State University, Coastal Studies Institute, Tech. Rep. 2:34pp.

Morgan, J.P. and P.B. Larimore, 1957. Changes in the Louisiana shoreline. Trans. Gulf Coast Assoc. Geol. Soc., 7:303-310.

Mossa, J. 1990, Discharge-suspended sediment relationships in the Mississippi-Atchafalaya River system, Louisiana: Ph.D. dissertation, Department of Geography and Anthropology, Louisiana State University, 180 pp.

Mossa, J. and H.H. Roberts, 1990, Synergism of riverine and winter storm-related sediment transport processes in Louisiana's coastal wetlands: Gulf Coast Association of Geological Societies, 40:635-642.

Murray, S.P., 1976. Currents and circulation in the coastal waters of Louisiana. Sea Grant Publ. 210, Baton Rouge, LA, Center for Wetland Resources, Louisiana State University.

Murty, T.S., G.A. McBean, and B. McKee, 1983. Explosive cyclogenesis over the northeast

Pacific Ocean. Monthly Weather Review, 111:1131-1135.

Muller, R.A. and J.E. Willis, 1983. New Orleans Weather 1961-80: A climatology by means of synoptic weather types. School of GeoScience, Miscellaneous Publication 83-1, Louisiana State University, Baton Rouge: 70pp.

Otvos, E.G. and W.A. Price, 1979. Problems of chenier genesis and terminology-and overview. Mar. Geol., 31:252-263.

Penland, S., J.R. Suter, and R.A. McBride, 1987c. Delta plain development and sea level history in the Terrebonne coastal region, Louisiana. In: Coastal Sediments '87. Am. Soc. Civ. Eng., New York: 1689-1705.

Penland, S. and J.R. Suter, 1989. The geomorphology of the Mississippi River Chenier Plain. Marine Geology, 90:231-258.

Penland, S., K.A. Westphal, C. Zganjar, P. Connor, L. Wayne, R. Seal, L. Mathies, B. Nord, and J. Flanagan, 1995, Beneficial use monitoring program annual report, part 2: Results of monitoring the beneficial use of dredge material at the lower Atchafalaya River bay and bar navigation channel: US Army Corps of Engineers, New Orleans District, 42 p.

Price, W.A., 1955. Environment and formation of the Chenier Plain Quaternaria, 2:75-86.

Quirox, R. S., 1983. The climate of the :El Niño" winter of 1982-83-a season of extraordinary climate anomalies. Monthly Weather Review, 111:1685-1706.

Rhodes, R.C. , A.J. Wallcraft, and J.D. Thompson, 1985. Navy-corrected geostrophic wind set for the Gulf of Mexico, NORDA Technical Note 310:103 pp.

Roberts, H.H., D.W. Cratsley and T. Whelan, 1976, Stability of Mississippi Delta sediments as evaluated by analysis of structural features in sediment borings: Eighth Annual Offshore Technical Conference, Houston, Texas, p. 9-28.

Roberts, H.H., R.D. Adams, and R.H. Cunningham, 1980, Evolution of sand-dominant subaerial phase, Atchafalaya Delta, Louisiana: American Association of Petroleum Geologists Bulletin, 64:264-279.

Roberts, H.H., 1986, A study of sedimentation and subsidence in the south-central coastal plain of Louisiana: Final Report to US Army Corps of Engineers, Waterways Experiement Station, 53 p.

Roberts, H.H., O.K. Huh, S.A. Hsu, L.J. Rouse, and D. Rickman, 1987. Impact of cold-front passages on geomorphic evolution and sediment dynamics of the complex Louisiana coast in Coastal Sediments 1987. Am. Society of Civil Engineers, 2:1950-1963.

Roberts, H.H., O.K. Huh, S.A. Hsu, L.J. Rouse, Jr. and D.A. Rickman, 1989, Winter storm impacts on the Chenier Plain coast of Southwestern Louisiana: Gulf Coast Association of Geological Societies Transactions, 39:515-522.

Roberts, H.H. and I.Ll. van Heerden, 1992, Atchafalaya - Wax Lake Delta complex: The new Mississippi River delta lobe. Coastal Studies Institute: Annual Industrial Associates Research Program Meeting, Nov. 12, 1992: Coastal Studies Institute, Louisiana State University, Baton Rouge, 45 p.

Russell, R.J. and H.V. Howe, 1935. Cheniers of southwestern Louisiana. Geogr. Rev., 25:449-461.

Russell, R.J., 1942. Flotant: Geographic Review, 32:74-98.

Sasser, C.E., and J.G. Gosselink, 1984. Vegetation and primary production in a floating freshwater marsh in Louisiana: Aquatic Botany, 20:245-255.

Saucier, W.J., 1949. Texas-West Gulf cyclones. Monthly Weather Review, 77:219-231.

Shlemon, R.J., 1972, Development of the Atchafalaya Delta, Louisiana - Hydrologic and Geologic Studies of Coastal Louisiana, Report 8: Center for Wetland Resources, Louisiana State University, Baton Rouge, 51 p.

Shlemon, R.J., 1975, Subaqueous delta formation - Atchafalaya Bay, Louisiana, in M.L. Broussard, ed., Deltas: Houston Geological Society, p. 209-221.

Smith, J.D., 1977. Modeling of sediment on continental shelves. In, The Sea: Marine Modeling, vol. 6, E.D. Goldberg, I.N. McCave, J.J. O'Brien, and J.H. Steele (eds), New York, Wiley Interscience: 539-577.

Smith, D.G., 1984, Vibracoring fluvial and deltaic sediments: Tips on improving penetration and recovery: Journal of Sedimentary Petrology, 54:660-663.

Stow, D.A.V. and A.J. Bowen, 1980. A physical model for the transport and sorting of fine-grained sediment by turbidity currents. Sedimentology, 27:31-46.

Stumpf, R.P., 1992, Remote sensing of water quality in coastal waters, Proceedings of the 1st Thematic Conference on Remote Sensing for Marine and Coastal Environments, SPIE 1930, 293-305, New Orleans, LA, p. 15-17.

Thompson, W.C., 1951. Oceanographic analysis of Atchafalaya Bay, Louisiana and adjacent continental shelf area marine pipeline problems. Texas A&M Research Foundation, Department of Oceanography, sec. 2, Project 25, 31p.

Thorne, C., 1982. Processes and mechanisms of river bank erosion *In* R.D. Hey, J.C. Bethurst, and C.R. Thorne (eds), Gravel Bed Rivers, Wiley, New York, p. 227-272.

Tye, R.S., and J.M. Coleman, 1989. Depositional processes and stratigraphy of fluvially dominated lacustrine deltas: Mississippi delta plain. Journal of Sedimentary Petrology, 59:973-996.

US Army Corps of Engineers, 1995, Atchafalaya Basin, Louisiana Wax Lake Outlet control structure: Emergency removal of weir and connecting levees, emergency dredging in Grand and Sixmile Lakes, St. Mary and St. Martin Parishes, Louisiana: Environmental assessment #213. New Orleans District.

van Heerden, I. Ll., 1980. Sedimentary responses during flood and non-flood conditions, New Atchafalaya Delta, Louisiana, M. Sc. Thesis, Department of Marine Sciences, Louisiana State University, 76 pp.

van Heerden, I.L., 1983, Deltaic sedimentation in eastern Atchafalaya Bay, Louisiana: Ph.D. Dissertation, Department of Marine Sciences, Louisiana State University, Baton Rouge, Louisiana, 161 p.

van Heerden, I.L. and H.H. Roberts, 1988, Facies development of Atchafalaya Delta, Louisiana: A modern bayhead delta: American Association of Petroleum Geologists Bulletin, 72: 439-453.

van Heerden, I. Ll., 1994a. Natural and Dredged Material Sedimentation in Atchafalaya Delta, Louisiana. A contract report for the Environmental Protection Agency, Region 6, Dallas, Texas.

Walker, N.D., L.J. Rouse, Jr., O.K. Huh, D.E. Wilensky and Varis Ransibrahmanakul, 1992, Assessing the spatial characteristics and temporal variabilities of the Mississippi and Atchafalaya River plumes: Proceedings of the First Thematic Conference on Remote Sensing for Marine and Coastal Environments, New Orleans, LA, 15-17 June, 1992, p. 719-728.

Walker N.D. and L.J. Rouse, Satellite Assessment of Mississippi River Discharge Plume Variability, 1993. Draft Final Report, Minerals Management Service, Gulf of Mexico OCS Regional Office, New Orleans, LA: 50pp.

Walker, N., J. Day, N. Rabalais, O. Huh, and A. Hammack, and R. Lane, 1997, Circulation, Suspended sediment and Chlorophyll Distributions associated with the Atchafalaya River discharge plume, Louisiana, Extended Abstract, Proceedings of the Fourth International Conference on Remote Sensing for Marine and Coastal Environments, I-277 - I-286, Orlando, Florida, 17-19 March, 1997.

Welder, F.A., 1959, Processes of deltaic sedimentation in the lower Mississippi River, Technical report No. 12: Coastal Studies Institute, Louisiana State University, Baton Rouge, 90 p.

Wells, J.T. and H.H. Roberts, 1980. Fluid mud dynamics and shoreline stabilization: Louisiana chenier plain. American Society of Civil Engineers, Proceedings 17th International Coastal Engineering Conference: p. 1382-1401.

Well, J.T., and G.P. Kemp, 1981, Atchafalaya mud stream and recent mudflat progradation: Louisiana chenier plain: Gulf Coast Association of Geological Societies Transactions, 31st Annual Meeting, 21-23 October, 1981, Corpus Christi, Texas, p. 409-416.

Wells, J.T., S.J. Chinburg, and J.M. Coleman, 1982, Development of the Atchafalaya River deltas: Generic analysis: Contract report to Waterways Experiment Station, Vicksburg, Mississippi, 91 p.