5-18-2007

Long and Short-Term Morphologic Evolution and Stratigraphic Architecture of a Transgressive Tidal Inlet, Little Pass Timbalier, Louisiana

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Long and Short-Term Morphologic Evolution and Stratigraphic Architecture of a Transgressive Tidal Inlet, Little Pass Timbalier, Louisiana

A Dissertation

Submitted to the Graduate Faculty of the
University of New Orleans
in partial fulfillment of the
requirements for the degree of

Doctor of Philosophy
in
Engineering and Applied Science
Geology

by

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B.S. The University of Mississippi, 1999
M.S. The University of Mississippi, 2003

May, 2007

ACKNOWLEDGEMENTS

Funding was provided through the New Orleans Geological Society's Scholarship Foundation and Geological Society of America Student Research Grant no. 8075-05.

I would like to thank my major advisor, Mark Kulp, for the guidance, insight, motivational support, and friendship. Your enthusiastic attitude towards scientific endeavors has been inspirational. A big thanks goes to: Duncan FitzGerald for the encouragement, advice, and rapid turnaround on draft revisions; Shea Penland for believing in me and giving me the opportunity to fulfill my dreams to pursue a career as a coastal scientist in Louisiana; Ioannis Georgiou for the technical suggestions and advice; and Alex McCorquodale for helping bridge the gap between my inner scientist and engineer. I look forward to future collaborations with you all.

Thanks go to Jeff Motti, Phil McCarty, and Mike Brown at the UNO Coastal Research Lab for introducing me to Louisiana coastal field methods, field work assistance, and for keeping the boats afloat.

Thanks to the U.S. Geological Survey for providing a platform and resources for the collection of vibracore and shallow subbottom profiles aboard the *R/V Gilbert* with Jim Flocks, Capt. Dave Bennett, Capt. Rich Young, Dana Wiese, and Chandra Dreher. Thanks to Nancy DeWitt with the U.S.G.S. for instruction on bathymetric surveying and data processing methods.

Thanks to Wilton Delronde at the LUMCON field camp in Port Fourchon for the hospitality and fantastic cooking.

A very special thanks goes to Mom and Dad for providing me with a strong educational foundation, continuing emotional support throughout my educational career (including providing me with a temporary lab space and office in the flooded house while the UNO facilities were condemned after Katrina), and for understanding that my career path is somewhat nontraditional.

And most importantly, thank you Nikki for the love, support, and for having the understanding necessary to put up with me throughout this dissertation process.

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ABSTRACT

The majority of changes to barrier island shorelines can be attributed to tidal inlet processes, and therefore an understanding of these processes is important to effectively manage barrier systems. High rates of relative sea-level rise within the Mississippi River delta plain have resulted in rapid landward-migration of barrier island and tidal inlet systems. Moreover, ongoing conversion of back barrier and interior wetlands to open water increases tidal exchange. Enlarging tidal prisms, together with the landward migration of the barrier systems, results in a dynamic environment within which tidal inlets undergo vast changes in position, geometry, and shoreline morphology.

Historic bathymetric maps (dating to the 1880's) and newly acquired bathymetric data for Little Pass Timbalier have been assembled to construct an evolutionary model for the region. The evolution of Little Pass Timbalier is complex and encompasses landward migrating ebb channel at rates of 33 m/yr, lateral channel migration at rates of 23 m/yr, and avulsion to new breaching sites along the adjacent barrier shoreline. Increasing backbarrier tidal prism results in seaward progradation of the ebb tidal delta as the inlet throat migrates landward.

Following the active 2005 hurricane season, a post-storm bathymetric survey was conducted. A sediment volume change analysis determined that 10.6 x 10^6 m^3 of sediment were removed from the study area.

Vibracores and subbottom profiles taken along the inlet retreat path at locations where relic channel depth was determined to be deeper than the depth of wave ravinement reveal an inlet fill sedimentary package bounded by scour surfaces separating underlying and adjacent fluvio-deltaic deposits. The inlet channel fill consists of a coarsening upward interval of shelly clayey sands that are lenticular to wavy bedded and grade upward into ebb tidal delta shelly sands. The inlet fill geometry is in the form of an erosionally bounded dib-elongate channel fill that thins seaward and pinches out at the location of inlet formation (storm breach). The inlet fill developed as a result of landward migration (dip elongate geometry) and associated with a transgressive barrier system differs from inlet fills developed along stable coastlines at laterally migrating tidal inlets (strike elongate geometry).

CHAPTER 1

INTRODUCTION

A tidal inlet is an opening along a barrier shoreline that connects the ocean with bays, lagoons, marsh, and tidal creeks (Davis and FitzGerald, 2004). Tidal currents maintain the inlet channel by shore perpendicular flushing of sediment that is transported alongshore by waves (Brown, 1928; Escoffier, 1940). Tidal inlets have long been of interest to coastal scientists and engineers because they act as a conduit for the daily exchange of tidal flow and provide a navigable route between the open ocean and sheltered waters. A transgressive tidal inlet is a tidal inlet linked to a transgressive barrier island system. Transgressive barriers migrate landward in response to relative sea-level rise (RSLR) and maintain subaerial exposure by the landward transfer of sand at tidal inlets (Armon, 1979) and storm overwash processes (Boyd and Penland, 1981; Ritchie and Penland, 1985).

The Mississippi River delta plain (MRDP) is undergoing the highest rates of RSLR in North America with rates that range between 1.03 and 1.19 cm/yr as indicated by a 40-year tide gauge record (1942-1982) from Grand Isle (Penland and Ramsey, 1990). Land subsidence accounts for 67 to 90% of the RSLR and the remaining portion is attributed to a eustatic rise rate of 0.10 to 0.12 cm/yr (Gornitz and Lebedeff, 1987; Penland and Ramsey, 1990). This high rate of RSLR coupled with the effects of tropical cyclones and passages of frontal systems results in a highly transgressive regime that has produced landward-migrating, overwash-dominated barrier systems. Moreover, ongoing conversion of back barrier and interior wetlands to open water bays and lagoons increases bay-tidal prisms, which in turn has enlarged the flow area of the associated tidal inlets (O'Brien, 1931; 1969; FitzGerald et al., 1984; FitzGerald et al., 2004). The continually increasing tidal prism, with the landward migration of a transgressive barrier system results in a dynamic environment within which new tidal inlets are formed and existing inlets are subject to changes in cross-sectional area (deepening and/or widening of throat) and position.

Because the Mississippi River delta plain is undergoing transgression, it provides an ideal location to study transgressive processes and the resultant development of transgressive stratigraphic architectures. Additionally, the land loss and shoreline retreat along many areas of the delta plain directly affects a population of more than 2 million people including metropolitan New Orleans, sustainability of one of the largest ecosystems on the North American continent, and national economic concerns associated with oil and gas, petrochemical, shipping, and fishery industries. Attempts are under way by local, state, and federal interests, to manage this land loss and protect the population, ecology, and economic assets from increased susceptibility to storm impacts. A concise understanding of the barrier island-tidal inlet system is crucial if these attempts are to be successful.

Many of the mitigation attempts are focused on barrier island restoration. As interior wetlands deteriorate, open water area increases, resulting in an increased volume of water (tidal prism) that passes through the tidal inlets during each portion of the tidal cycle. In order to adjust to the increased tidal prism, tidal inlets widen and deepen, and additional inlets form along the shoreline. Moreover, as tidal prism increases, ebb tidal deltas (shoals that form at the seaward terminus of a tidal inlet) increase in sediment volume. Increasing tidal prism, driven by interior wetland loss, results in barrier degradation because of increased inlet cross-sectional area (widening of existing inlets and formation of new inlets). Sediment that is stored in the enlarging ebb tidal deltas due to increasing tidal prism, would otherwise be available in the littoral system and contribute toward barrier island stability. Management of the barrier islands must be in concert with mitigation of increasing tidal prism size in order to be effective. The controls on tidal inlet morphology within relatively short time periods across the Mississippi River delta plain are not well defined, and an understanding of the inlet system response to these processes requires refinement if accurate models are to be constructed. The utility of such models is an increased ability to effectively manage transgressive barrier shorelines of the MRDP.

The objectives of this study are to: 1) develop a long-term morphological (<150 yrs) evolutionary model for Little Pass Timbalier tidal inlet, 2) develop a short-term (seasonal), storm impact model for the inlet system, 3) define the stratigraphic framework of a transgressive tidal inlet, and 4) apply the morphological evolution and stratigraphic framework developed in preceding chapters to define a process-response evolutionary model for a MRDP transgressive tidal inlet system.

Chapter 2 covers the basic background information necessary for developing an understanding of transgressive tidal inlets in the MRDP.

Chapter 3 is a long-term morphologic evolution study of Little Pass Timbalier. The dataset consists of bathymetric surveys covering four time periods (1880's, 1930's, 1980's, and 2005). Digital elevation models are produced for each time period and the time-series is used to construct a morphological evolutionary model for the inlet system.

Chapter 4 is a short-term seafloor change analysis at Little Pass Timbalier that occurred as a result of the 2005 hurricane season. Bathymetric surveys were conducted in June 2005 prior to storm impact, and in November 2005 after the passage of 3 major tropical cyclones, Hurricanes Cindy, Katrina, and Rita. DEMs are produced from the bathymetric data and a seafloor bathymetric change analysis is carried out between the two DEMs. Also, a sediment volumetric change analysis is conducted in order to determine sediment transport trends that develop as a result of storm impact.

Chapter 5 is a sedimentologic and stratigraphic analysis of Little Pass Timbalier. Specifically, this section focuses on the stratigraphic architecture of the inlet fill that develops along the transgressive tidal inlet landward retreat pathway. The historical bathymetric data and morphological evolutionary model presented in Chapter 3 are used to determine the inlet throat position since 1880. Vibracores and high-resolution shallow subbottom profiles were taken along transects that intersect the historical position of the inlet throat for the 1880's, 1930's, and 1980's. A stratigraphic model for transgressive tidal inlet fill geometry is presented.

Chapter 6 presents a summary of the study and the overall conclusions of the previous chapters. Chapter 6 additionally provides suggestions for future research directions that can provide needed insight to barrier/tidal inlet system stratigraphic architecture, forcing parameters, and increased ability to effectively manage transgressive shoreline systems of the MRDP.

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CHAPTER 2

BACKGROUND

STUDY AREA

Little Pass Timbalier separates East Timbalier and Timbalier Islands and is the conduit for daily tidal exchange between Timbalier Bay and the Gulf of Mexico (Fig. 1). It is located approximately 90 km west of the active Balize delta complex of the Mississippi River and 100 km south-southwest of New Orleans, Louisiana. The Timbalier Islands are downdrift flanking deltaic barriers that are located west of the Caminada-Moreau erosional headland. This headland is a result of distributary progradation and delta lobe development of the Lafourche subdelta that began progradation 1,500 yrs BP (McFarlan, 1961; Törnqvist et al., 1996). Approximately 300 yrs BP, the once active distributary system waned and the previously active depocenter became reworked by marine processes to generate the erosional headland and flanking transgressive barriers (Morgan, 1974; Penland et al., 1988).

Physical Coastal Processes

The Timbalier shoreline is subject to diurnal tides with a microtidal range of 0.12 m during neap tidal conditions that increases to as much as 0.60 m during spring tides (Georgiou et al., 2005). Meteorological tides often have a profound effect on water levels in the area, especially during the fall and winter months when 10 to 30 frontal passages per year elevate water levels by 0.3 to 0.9 m (Boyd and Penland, 1981). Associated with the passage of these frontal systems are southeast onshore winds that can generate waves with heights of 2.0 to 3.0 m (Boyd and Penland, 1981). Subsequent to the passage of a frontal system, strong northerly winds are generated. Tropical cyclones, with a recurrence interval of 1.6 years, generate storm surges of 1.0 to 5.0 m, and deepwater wave heights can be as much as 5.0 to 10.0 m

(Ritchie and Penland, 1985). Wave height and water level data (for a period from May 2001 to February 2002) from a monitoring station located 2 km offshore of Timbalier Island at a 5 m water depth,

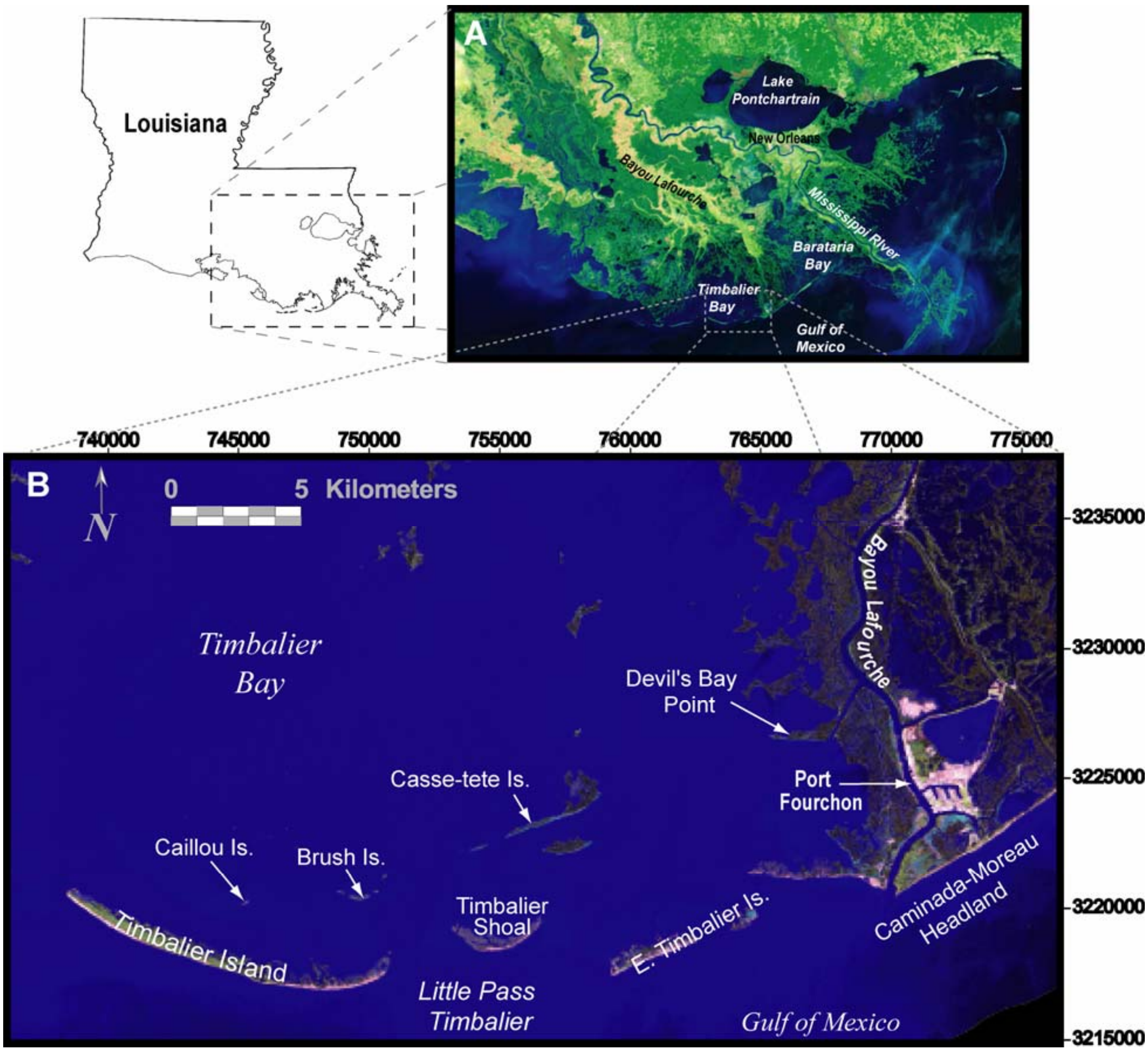

Figure 1. Satellite images showing the study area of the Mississippi River Delta Plain (A) and the Timbalier Island shoreline (B). Little Pass Timbalier is the tidal inlet that is the focus of this study. It separates Timbalier Island from East Timbalier Island and is the primary conduit for daily tidal exchange between Timbalier Bay and the Gulf of Mexico. Note the arc-shaped shoal situated landward of the throat of Little Pass Timbalier. This shoal separates the two ebb dominant channels within the tidal inlet system. Image A of the delta plain was taken in February 2005 and Image B was taken in 2002. Coordinate grid on Image B is in meters, UTM Zone 15.

show an average wave height of 0.07 to 0.8 m and during the passage of frontal systems within this time frame wave height increased to approximately 1 to 2 m (Georgiou et al., 2005). Net sediment transport along the Timbalier Shoreline is to the west; however a localized reversal occurs along the easternmost spit of Timbalier Island at Little Pass Timbalier's marginal flood channel.

Mean relative sea-level rise (RSLR) rates in coastal Louisiana are approximately five times greater than average rates for the northern Gulf of Mexico (Gornitz and Lebedeff, 1987; Penland and Ramsey, 1990). This rapid RSLR is driven primarily by compactional subsidence of Holocene strata (Kolb and Van Lopik, 1958; Penland and Ramsey, 1990; Törnqvist et al., 2006). However, other natural factors such as isostatic adjustment to regional crustal loading, faulting, and eustatic sea-level rise also contribute to the regional subsidence (Kolb and Van Lopik, 1958; Penland et al., 1987; Kulp, 2000; Dokka, 2006). Anthropogenic effects that include subsurface fluid withdrawal (Morton et al., 2005) and draining of wetlands for urban development (Snowden et al., 1980) amplify the problem in localized subsidence "hot spots". It has been determined, on the basis of tide gauge data, that rates of RSLR in the delta plain are 1.09 cm/yr at Houma (1946 – 1988), 1.17 cm/yr at Eugene Island (1942 – 1988), and 1.11 cm/yr at Grand Isle (1949 – 1986) (Penland and Ramsey, 1990). Recent data acquired from the NOAA tide gauge at Grand Isle show a slowing of RSLR rates in recent years with a long term (1947 – 2006) rate of 0.92 cm/yr (Fig. 2).

The rapid rate of RSLR results in a transgressive regime within which interior wetlands are converted to open water and barrier shorelines migrate landward. Moreover, anthropogenic alterations to delta plain hydrology, such as confinement of the Mississippi River to its channel by artificial levees, oil and gas access and navigation canal excavation, and indirect effects associated with canal excavation that lead to altered salinity regimes and increased wave fetch, have added to increased open water area and in turn an increase in the volume of water (tidal prism) moving into and out of the bays through tidal inlets during each tidal cycle. The increases in tidal prism sizes have direct impacts on tidal inlet geometry and distribution, as well as coastal zone sediment-dispersal patterns. Tidal inlets are undergoing rapid morphological evolution by increasing throat cross-sectional area, formation of additional ebb channels, and expansion of ebb tidal deltas; all of these processes occur at the expense of barrier island sediment volume and integrity (FitzGerald et al., 2003; 2004; Miner et al., 2005).

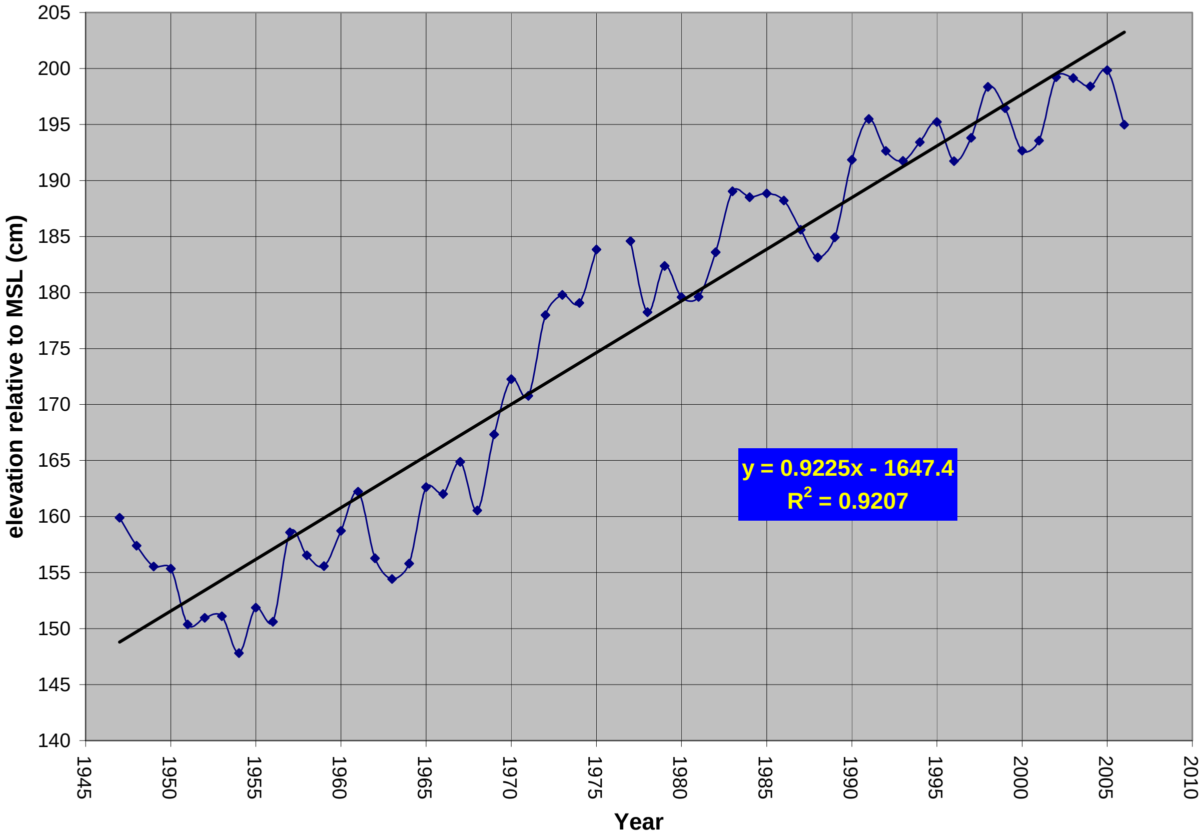

Figure 2. Relative sea-level curve for Grand Isle based on NOAA tide gauge (# 8761724) data for the period from 1947 – 2006. The plot shows the annual mean sea level for each year (curved line and diamonds) and a best-fit trend line. Plotted values are relative to the 1983 – 2001 mean sea-level datum.

REGIONAL GEOMORPHIC EVOLUTION AND STRATIGRAPHY

The Holocene MRDP is the product of deposition by multiple, spatially and temporally offset, fluvio-deltaic depocenters fed by distributary systems of the lower Mississippi River drainage basin (Russell, 1936; Fisk, 1944). Chronological alterations in the location of these depocenters arise from upstream avulsions of the Mississippi River and its distributaries. With each avulsion event, a new distributary network and attendant delta complex is formed. In total, the Holocene delta plain consists of six delta complexes: Maringouin (7,500 - 5,000 yrs BP), Teche (5,500 – 3,800 yrs BP), St. Bernard (4,000

– 2,000 yrs BP), Lafourche (2,500 – 400 yrs BP), Balize (1,000 yrs BP – present), and Atchafalaya (400 yrs BP – present) (Fig. 3) (Kolb and Van Lopik, 1958; Frazier, 1967; Coleman, 1988; Penland et al., 1988; Törnqvist et al., 1996; Roberts, 1997). Each delta complex consists of smaller scale delta lobes.

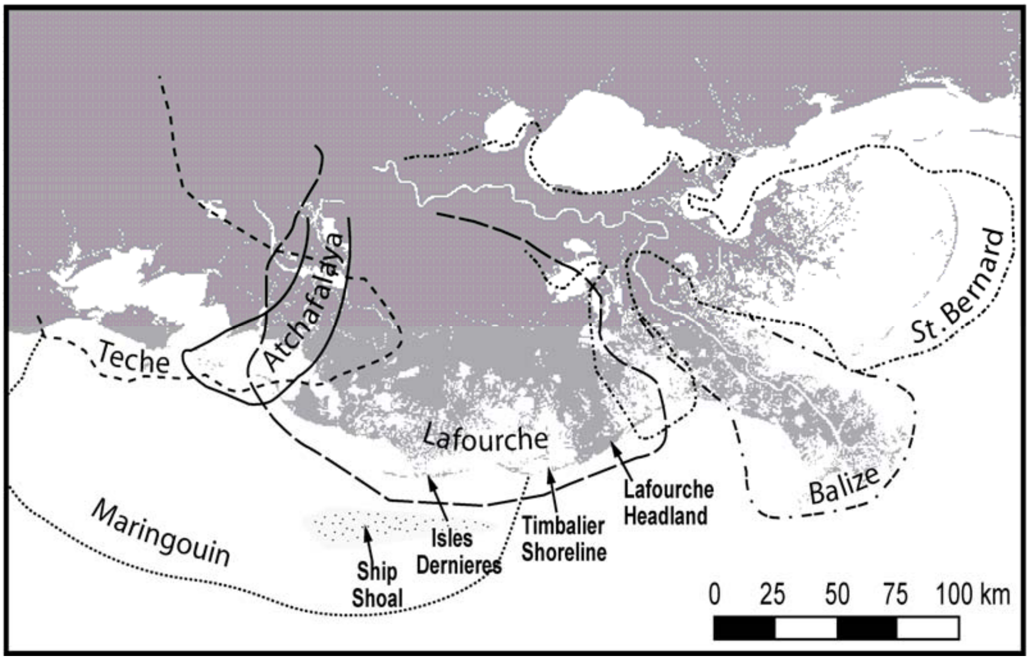

Figure 3. Map of the Holocene Mississippi River delta plain that shows the multiple, spatially offset depocenters for each delta complex. Depocenter shifts result from upstream fluvial avulsions, the infilling of accommodation space within interdistributary basins, and ultimately deltaic progradation. Mid Holocene deposition started with the Maringouin-Teche complexes (7,500 – 3,800 yrs BP), followed by St. Bernard (4,000 – 2,000 yrs BP), Lafourche (2,500 – 400 yrs BP), and modern deposition at the Balize (1,000 yrs BP – present) and the Atchafalaya (400 yrs BP – present). Names, location, and chronology for delta complexes are derived from Frazier (1967), Penland et al. (1988), Törnqvist et al. (1996), Roberts (1997), and Kulp et al. (2005a).

Delta plain formation is the result of a cyclic set of events, the delta cycle, that starts with stream avulsion and delta building, and ends with abandonment and delta deterioration by marine processes and subsidence (Coleman et al., 1998). Major avulsion events are a product of decreasing gradient and hydraulic efficiency as the main channel lengthens by means of deltaic progradation. While many gradient advantages exist along the lower Mississippi floodplain, erodable substrate (e.g., abandoned channel sand) and favorable floodplain topography (e.g., active and abandoned floodplain channels) are also critical factors influencing avulsions (Mohrig et al., 2000; Aslan et al., 2005). If these criteria are met, a river flood or a tropical cyclone may trigger the avulsion event (Slingerland and Smith, 1998;

Mohrig et al., 2000). The avulsion results in stream capture by a previously less significant distributary and a delta-switching event, causing a gradual abandonment of the formerly active delta lobe in favor of the more efficient route. The delta cycle can be divided into two phases, the fluvial-dominated regressive phase, and the marine-dominated transgressive phase (Roberts, 1997). Products of this autocyclic process of delta lobe progradation and subsequent abandonment are the transgressive components of the delta plain that include barrier island/tidal inlet systems, inner-shelf sand shoals, tidal channels, and interdistributary bays (Roberts, 1997).

Subsequent to deltaic abandonment, previously active delta lobes become erosional headlands, and subsidence and marine reworking results in the landward migration of the shoreline. Sediment comprising the headland is reworked laterally by waves and storm impacts to form barrier islands, and eventually inner-shelf shoals (Kwon, 1969; Penland et al., 1988). A three-stage conceptual model depicting the evolution from deltaic abandonment to barrier island formation to inner-shelf shoal formation was conceived by Penland et al. (1988) (Fig. 4). During Stage 1, the abandoned deltaic headland is reworked to form an erosional headland with flanking barrier islands. Submergence due to RSLR and decreased fluvial sediment supply leads to mainland detachment and formation of a Stage 2 transgressive barrier island arc. In Stage 3, continued RSLR results in transgressive submergence of the island arc to form an inner-shelf barrier shoal (Penland et al., 1988).

Lafourche Delta Complex and Timbalier Barrier Shoreline Development

The Lafourche delta complex formed as the Mississippi River prograded across the earlier formed Teche delta complex approximately 2,500 yr BP (Frazier, 1967; Coleman, 1988). The oldest Lafourche delta lobe that prograded the study area was the Bayou Terrebonne distributary network, active between 830 and 1,270 yr BP (Fig. 5) (Penland et al., 1988; Kulp et al., 2005a). The modern course of Bayou Lafourche represents the position of the last major distributary channel of the Lafourche complex that was actively forming meander belt ridges no later than 800 yr BP (Frazier, 1967; Saucier, 1994). Active progradation of delta lobes in the Lafourche complex continued until approximately 300 yr BP (Frazier, 1967; Morgan, 1974; Penland et al., 1988; Kulp et al., 2005a).

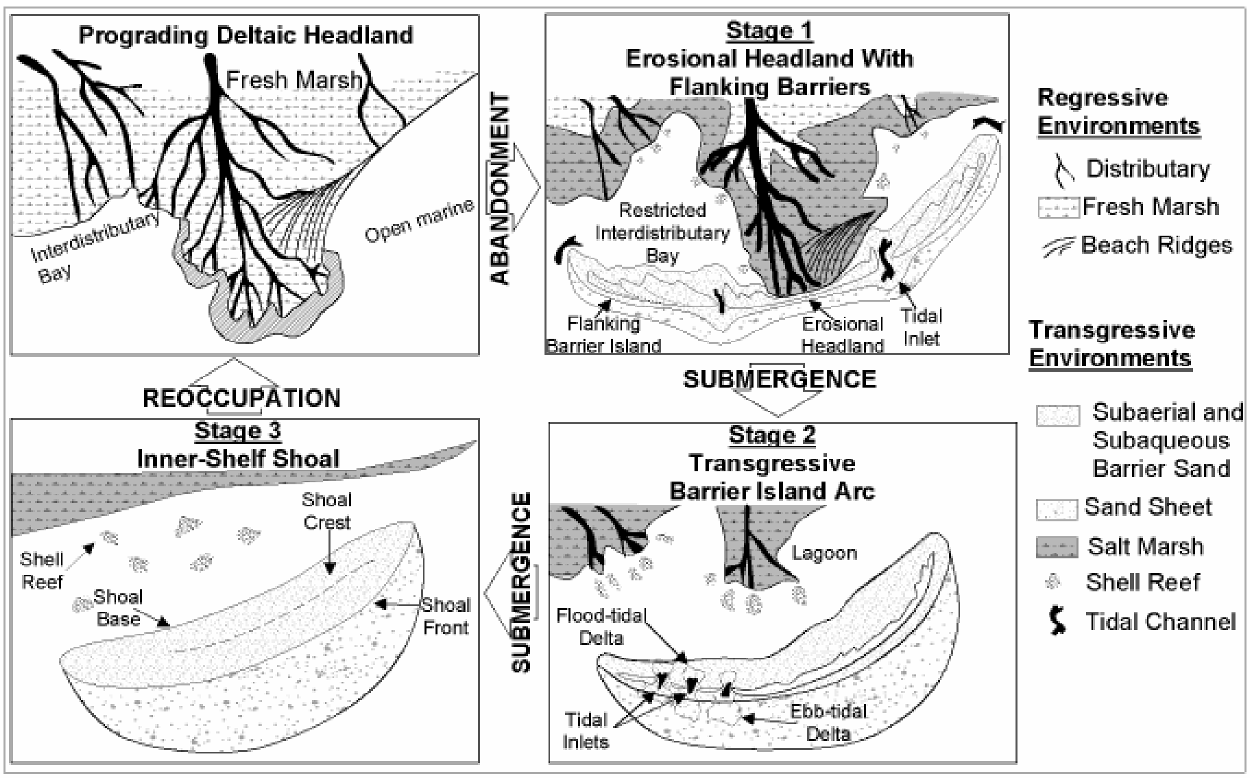

Figure 4. Three-stage model conceived by Penland et al. (1988) for the formation and evolution of transgressive Mississippi River delta barrier islands. Deltaic abandonment results in the formation of a Stage 1 erosional headland with flanking barriers separated by tidal inlets. RSLR results in mainland detachment and the formation of a Stage 2 transgressive barrier island arc. Continued RSLR results in transgressive submergence and the formation of a transgressive inner-shelf shoal. From Kulp et al. (2005b) modified from Penland et al. (1988).

Subsequent to the abandonment of the Terrebonne distributaries, marine transgressive processes became dominant and the abandoned lobe became an erosional headland. During the transgressive phase continual reworking of the distributary mouth bars and relict shorelines by shoreface retreat (Swift, 1968) provided a sand source for a sandy barrier shoreline that is backed by bays and lagoons (Kwon, 1969). The Terrebonne shoreline formed during this transgressive event and is evident in a linear trend that consists of Casse Tete Island, Devil’s Bay Point, the landward limit of the Cheniere Caminada beach ridges, and Fifi Island north of Grand Isle (Figs. 1 and 5) (Gerdes, 1982; 1985).

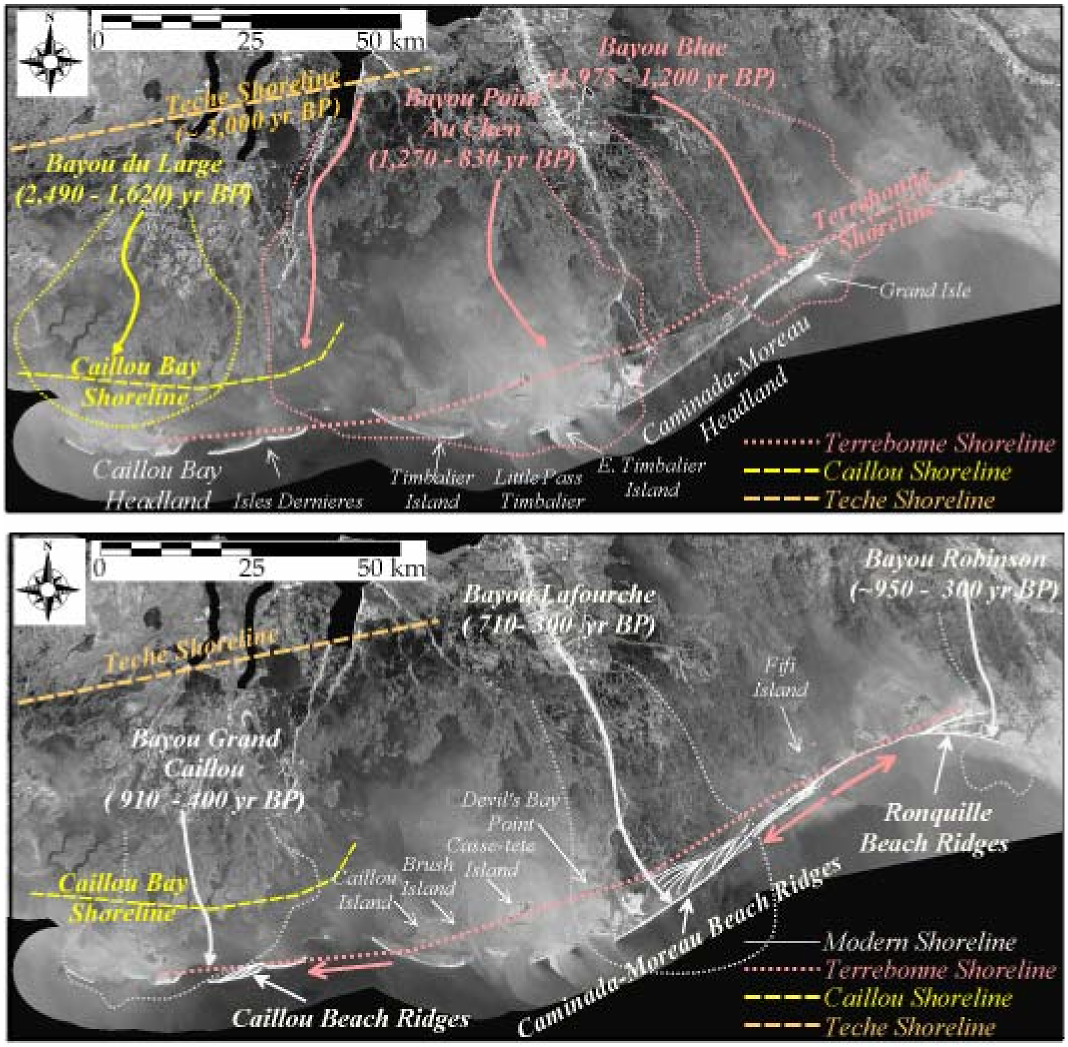

Figure 5. Aerial photograph showing the distribution of delta lobe depocenters during two separate progradational episodes after which subsequent transgressions led to the development of the Terrebonne Shoreline (A) and the Caminada-Moreau beach ridges and modern shoreline that includes the Timbalier Islands (B). Figure from Kulp et al. (2005a) based on information from Kolb and Van Lopik (1958), Frazier (1967), Gerdes (1982), Penland et al. (1987), Levin (1991), and Kosters and Suter (1993).

Following fluvial abandonment and the subsequent transgression of the Terrebonne shoreline, distributary reoccupation of the Lafourche complex took place as the Bayou Lafourche distributary network began to prograde approximately 710 yr BP and bypassed the seaward extent of the Terrebonne transgressive shoreline (Gerdes, 1985; Kulp et al., 2005a). Seaward progradation of the Bayou Lafourche distributaries imparted a “groin effect” to the updrift side of the headland. Sand derived through longshore transport from the eastern part of the Terrebonne shoreline (Fifi Island) and Grand Terre Island farther east contributed toward the Caminada-Moreau regressive beach ridges abutting the protruding deltaic headland (Gerdes, 1985; Kulp et al. 2005a) (Fig. 5). Abandonment of the Lafourche distributary network 300 yr BP, resulted in transgression and marine reworking of the previously progradational Lafourche delta lobe, thereby forming the present-day Caminada-Moreau erosional headland and associated flanking barrier islands (Figs. 4 and 5) (Penland et al., 1988; Kulp et al., 2005a).

Within the present transgressive phase, the Caminada-Moreau beach ridge plain has become the major sand source for lateral spit accretion east and west of the headland. Breaching of these spits has resulted in the formation of tidal inlets and nearly symmetrical flanking barrier island systems representing a Stage 1 erosional headland and flanking barrier islands based on the Mississippi Delta barrier island evolutionary model (Penland et al., 1988). The flanking barrier islands consist of the Timbalier Islands to the west and Grand Isle to the east. Seventy-five percent of the Caminada-Moreau coastline is overwashed an average of 15 times per year during cold fronts and tropical cyclones (Ritchie and Penland, 1985). As a result more than 50% of the shoreline consists of a thin, continuous washover sheet approximately 1 m above mean sea level (Boyd and Penland, 1981).

Regional Stratigraphic Framework

Figure 6 shows a simplified dip-oriented stratigraphic cross-section for the Holocene MRDP that includes late Holocene transgressive and modern high stand systems tracts that developed as a result of late Holocene eustatic sea-level rise and stabilization, respectively. During the waning phases of Holocene sea-level rise the early and late Holocene delta plains were deposited as shelf-phase deltas (Penland, 1990) and represent retrogradationally stacked, backstepping parasequences of the upper transgressive systems tract (terminology from Van Wagoner et al., 1987). Transgressive salt marsh, interdistributary bay, lagoon, and transgressive sands (green in Fig. 6) overlie regressive deltaic muds, peats, and distributary deposits (grey in Fig. 6). As the shoreline migrates landward during a transgressive phase, there is a landward shift in paralic environments (brackish marsh, inner-distributary bay, saline marsh, lagoonal, and barrier). The marine flooding surface of a transgressive event is marked by a

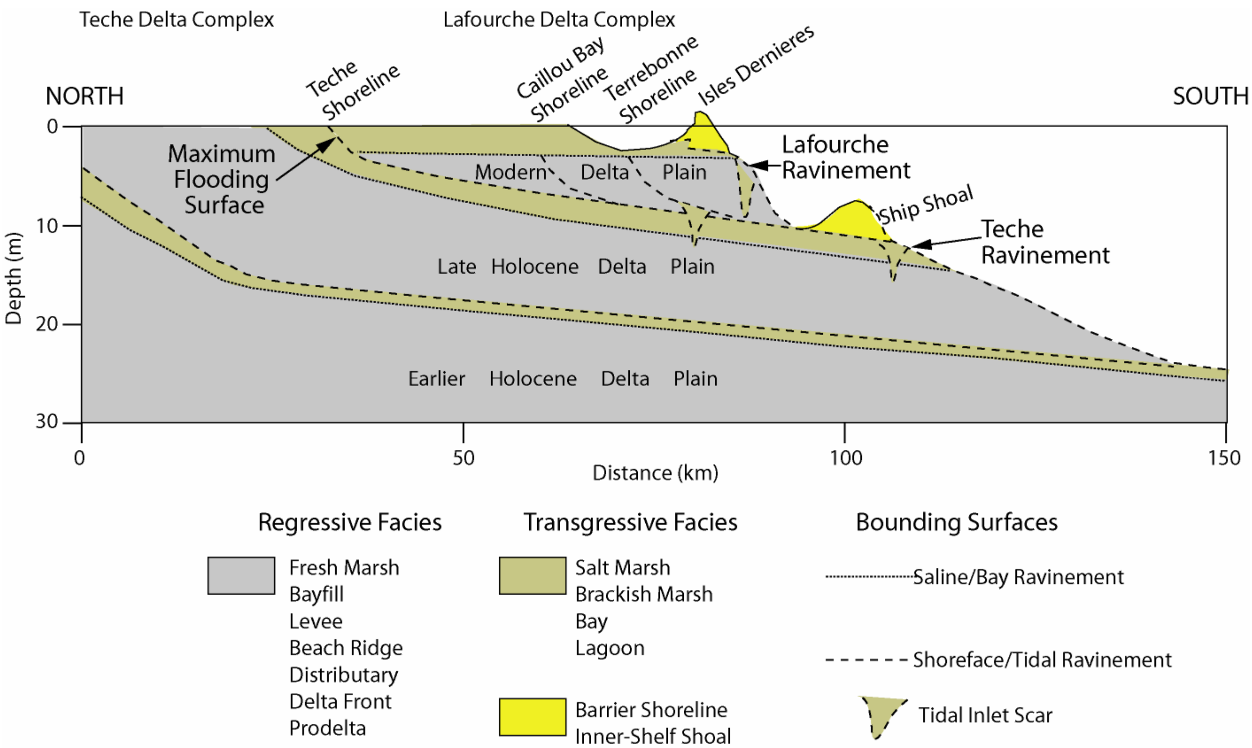

Figure 6. Idealized dip-oriented stratigraphic cross section of the Holocene Mississippi River delta plain. The early Holocene delta plain and late Holocene delta plain are retrogradationally stacked, backstepping parasequences of the transgressive systems tract deposited during the waning stages of Holocene glacio-eustatic sea-level rise. The maximum landward position of the Teche Ravinement surface represents the maximum flooding surface and the stabilization of glacio-eustatic sea-level to modern conditions. Ship shoal is a stage 3 inner-shelf shoal that underwent transgressive submergence at the end of late Holocene time (Penland et al., 1988). The modern delta plain represents the highstand systems tract. Note the ravinement surfaces within the modern delta plain separating highstand progradational parasequences (delta complexes and delta lobes). These ravinement surfaces mark transgressive episodes when delta deposition was focused elsewhere in the delta plain, and RSLR resulted in shoreface retreat across the formerly prograded delta complex. The saline/bay ravinement surface represents the marine flooding surface for each parasequence set and separates regressive fresh marsh, bay-fill, and fluvial facies from transgressive inner-distributary bay, lagoon, saline and brackish marsh, and barrier/tidal inlet deposits. The shoreface/tidal ravinement is represented by a sharp contact indicated by shell lag and/or a transgressive sand sheet. Modified from Penland et al. (1987).

transition from freshwater marsh, swamp, or fluvio-deltaic depositional environments to overlying paralic environments through open marine. The marine flooding surfaces separate parasequences within the transgressive systems tract. The Teche Ravinement Surface is the maximum flooding surface and separates the transgressive (early and late Holocene delta plains) from the highstand (modern delta plain) systems tracts. During the present highstand of eustatic sea-level, delta switching has led to the development of progradational parasequences separated by transgressive ravinement surfaces. The St.

Bernard delta complex which began to prograde approximately 4,000 yr BP is the first of the highstand delta complexes (Boyd et al., 1989). However, transgression continued in the study area due to subsidence-driven RSLR and deltaic progradation did not occur for another 1,000 yrs when the Lafourche complex began to form (Figs. 3 and 6). The Terrebonne shoreline marks the maximum landward limit of the Terrebonne ravinement, and the modern Timbalier Island and Caminada-Moreau shorelines are actively undergoing shoreface and tidal ravinement processes. Barrier sand deposits along the Caminada-Moreau headland and Timbalier Islands average 1-2 m thick in the central headland and thicken to a maximum of 6 m at the western tip of Timbalier Island at Cat Island Pass (Fig. 7).

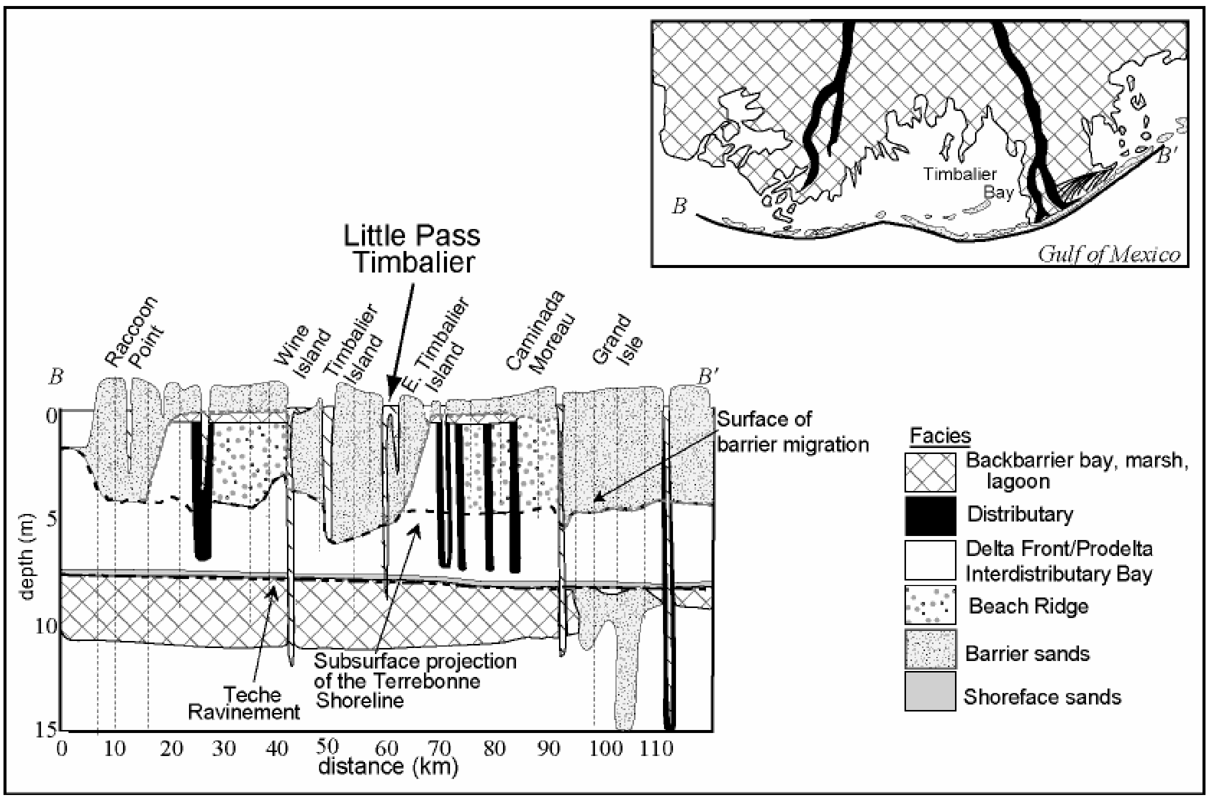

Figure 7. Strike-oriented cross section that trends along the modern Timbalier/Isles Dernieres barrier shoreline. Note the thin barrier sands that thicken at inlets due to tidal ravinement and are separated from underlying deltaic deposits by shoreface ravinement surfaces away from the inlets. Also note the thick, regressive beach ridges that form on the updrift side of a prograding distributary and during transgressive phases become a significant sediment source for flanking barrier nourishment. Figure from Kulp et al. (2005a) based on data presented in Penland et al. (1988), May et al. (1984), Neese (1984), Gerdes (1982), Isacks (1983), SJB Group (2003), and unpublished Louisiana Geological Survey data.

PREVIOUS STUDIES

Previous investigators working along the Louisiana coast all note that tidal inlet systems are anomalous when compared to those discussed in literature for the Atlantic coast (e.g. Hayes, 1975; FitzGerald 1976; 1984). Many of the previous works are in agreement that the stratigraphy of these systems varies greatly from those presented in the literature of coarse-grained, stable coastlines due to the dominantly fine-grained, transgressive environment and stability of the inlet throat. The main factor contributing to the atypical morphology and evolution of the Louisiana tidal inlets is attributed to their highly transgressive nature and the extensive backbarrier wetland loss producing increasing tidal prism. All of the inlet systems of the Louisiana coastal zone display an evolutionary style characterized by increasing bay tidal prism and cross-sectional area, which aid barrier breaching, inlet formation, and a general degradation of the barrier coast (Howard, 1985; Shamban, 1985; Suter and Penland, 1987; Levin, 1993; Kulp et al., 2006; FitzGerald et al., 2004). However, inlets along the Chandeleur Islands, which constitute a late Stage 2 transgressive barrier island arc, have undergone a decrease in tidal prism and have become smaller in cross-section. The expansion of Chandeleur Sound now allows the exchange of tidal waters northeast and southwest around the edges of the barrier, lessening tidal flow through the inlets (Levin, 1993).

Larger inlets of the MRDP such as Barataria Pass and Cat Island Pass are exceptions to the classification scheme based on wave energy versus tidal range as proposed by Hayes (1979) because they are tide-dominated inlets located in a microtidal environment (Shamban, 1985; Suter and Penland, 1987). Ebb-tidal deltas of these systems increase in volume and thickness over time as a result of increasing bay-tidal prism (Walton and Adams, 1976; Howard, 1985; FitzGerald et al., 2004). The work of FitzGerald et al. (2004) concluded that the fine-grained ebb-tidal deltas of the Barataria coast do not display a stratigraphy dominated by channel cut and fills, large scale landward dipping foresets, and shallow dipping strata of the sand-rich ebb tidal deltas reported in the literature (e.g., FitzGerald and Nummedal, 1977; Davis et al., 2003). Instead they are dominated by coarsening upward units consisting of muddy fine sands to clean fine sands (FitzGerald et al., 2004).

Results from a stratigraphic investigation conducted by Suter and Penland (1987) in the area just offshore Cat Island Pass, Louisiana, revealed an acoustic package on high-resolution shallow seismic profiles characterized by northwest dipping, high-angle clinoform reflectors. The sedimentary package corresponding to the geophysical record contains shell-rich, fine sand with multiple scour surfaces (Suter and Penland, 1987). The authors interpreted this lithosome as inlet channel fill within the inlet migration path of Cat Island Pass (Suter and Penland, 1987). This is the only study that attempted to classify inlet fill in the MRDP. However, Cat Island Pass is migrating laterally due to a set of conditions unique for a MRDP tidal inlet, including an abundant longshore-derived sand source and minimal landward translation of the ebb channel.

With the exception of Cat Island Pass the tidal inlets of the MRDP do not appear to migrate laterally. The stability of an inlet is often associated with tidal dominance over longshore processes, however wave dominated inlets on the Louisiana coast such as Raccoon Pass also appear to be stable through time (Kulp et al., 2006). There are also numerous workers that have proposed that Louisiana tidal inlets occupy former distributaries (Howard, 1985; Levin, 1995; Kulp et al., 2006). However, no clear evolutionary model, stratigraphic model, or descriptions of preservation potential of these transgressive inlet systems are offered in the current literature.

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CHAPTER 3

MORPHOLOGIC EVOLUTION OF A TRANSGRESSIVE TIDAL INLET SYSTEM, LITTLE PASS TIMBALIER, LOUISIANA

INTRODUCTION

The Mississippi River delta plain (MRDP) is undergoing the highest rates of relative sea-level rise (RSLR) in North America, ranging between 1.03 and 1.19 cm/yr as indicated by a 40 year tide gauge record (1942-1982) from Grand Isle (Penland et al., 1988a; Penland and Ramsey, 1990). Land subsidence accounts for 67 to 90% of the RSLR and the remaining portion is attributed to a eustatic rise rate of 0.10 to 0.12 cm/yr (Gornitz et al., 1982; Gornitz and Lebedeff, 1987; Penland et al., 1988a; Penland and Ramsey, 1990). This high rate of RSLR coupled with the effects of tropical cyclones and passages of frontal systems results in a highly transgressive regime that has produced landward-migrating, overwash-dominated barrier systems. Moreover, ongoing conversion of back barrier and interior wetlands to open water bays and lagoons increases bay-tidal prisms, which in turn has enlarged the flow area of the associated tidal inlets (O'Brien, 1931; 1969; FitzGerald et al., 1984a; FitzGerald et al., 2004). The continuing increasing bay size-tidal prism together with the landward migration of the barrier systems results in a dynamic environment within which new tidal inlets are formed and existing inlets are subject to changes in cross-sectional area (deepening and/or widening of throat) and position.

Most of the erosional and depositional changes along barrier island shorelines occur at the ends of the barrier. These changes are directly attributable to tidal inlet processes both in the inlet and along the adjacent barrier shoreline (FitzGerald, 1984; FitzGerald et al., 1984b). Along transgressive barrier islands, most of the landward movement of sediment occurs at tidal inlets (Armon, 1979) therefore, an understanding of these tidal inlet processes is crucial to understanding transgressive barrier island evolution. In Louisiana, knowledge of inlet processes is imperative for formulating barrier stabilization projects, determining sediment budgets, and predicting future changes. Currently, large scale coastal restoration initiatives are being formulated that might require inlet management. In comparison to many well-studied inlets, such as those along the Atlantic coast of North America, the tidal inlets of the MRDP are unique because of their location along a microtidal, transgressive coast that is dominantly fine-grained in textural character. The dominance of storm processes and overall fine-grained composition of the barriers and tidal shoals compared to the well studied inlet systems elsewhere in the world indicate that a different set of factors be considered when managing Louisiana tidal inlets.

The rapid evolution and transgressive nature of the MRDP provide an opportunity to correlate the historical morphological shoreline changes with the landward retreat, lateral migration, and avulsion of the tidal inlets. In this way, the evolution of the inlet can be traced using historical data and can be related to the actual channel morphology and depositional processes. This work will result in the development of process-response models that will be used to improve understanding of transgressive tidal inlet morphology and evolution, as well as an exploration tool for sand resource surveys and barrier/inlet system management approaches.

METHODOLOGY

Historical and recent bathymetric surveys are the primary datasets used in the analysis of Little Pass Timbalier. Historical surveys (dating from the 1880's –1980's) compiled by List et al. (1994) provide the framework for examining long-term trends. Details of data collection methods, processing techniques, and error assessment for the historical surveys can be found in List et al. (1994). These data were used in early phases of this investigation to create contour maps of Little Pass Timbalier, providing an understanding of the inlet morphological evolution during the 100 yr time period covered by the dataset.

Recent (2005) bathymetric data of the study area were gathered using the University of New Orleans Coastal Research Laboratory single-beam bathymetric rig mounted on the 21-foot *R/V Mudlump*. This bathymetric survey rig consists of an *Odom Hydrographics Hydrotrac* system with a factory specified vertical resolution of 1.0 cm. Depth soundings are collected through a side-mounted *Odom*

Hydrographics 200 kHz transducer with a beam width of 3°. The fathometer is equipped with a *Starlink Invicta* 210L differential global positioning system (DGPS) for navigation. Heave, pitch, and roll of the vessel, hence transducer and DGPS antenna, are recorded using a *VT TSS Dynamic Motion Sensor Series-25* that is mounted vertically in-line with the DGPS antenna and the transducer. Thus, lateral offset errors between the DGPS antenna readings, transducer soundings, and vessel motion are cancelled minimizing vertical and horizontal errors in depth and navigation recordings. The bathymetric, motion correction, and navigation data are recorded and integrated using *Coastal Oceanographics Hypack Max* hydrographic survey software run on an *Amrel Rocky Unlimited* field notebook computer.

The survey lines were programmed in *Hypack* with a line spacing of approximately 800 m for both shore normal and shore parallel lines. During the actual survey, the planned line spacing was not followed in areas where shallow depths (less than 0.40 m) limited survey vessel accessibility or where shoal and island shorelines interfered with the bearing of a planned line (Fig. 1). When shallow depths along a shoal or island shoreline were encountered, the perimeter was mapped at the minimum depth accessible by the survey vessel. Synthetic data points with a Z value of 0.5 m were digitized for the islands and subaerial portions of the shoals based on aerial photography taken within a month of the bathymetric survey. A tightly spaced zigzag survey trajectory along the axis of the inlet channel throat was employed to define the abrupt (severe) bathymetric changes in that area. Hence, the data points acquired during the survey does not totally adhere to programmed line spacing, but rather the distribution was modified in the field based on a knowledge of the geomorphology of the tidal inlet system.

The 2005 bathymetric data were processed using *Hypack Single Beam Editor* module and tide corrections were integrated using 6-minute interval data the NOAA tide gauge station (# 8762075) at Port Fourchon, LA. The water level elevation from the tide gauge was measured relative to mean lower low water (MLLW), a tidal datum based on the National Tidal Datum Epoch 1983 –2001.

Figure 1. Data coverage for the 2005 single-beam bathymetric survey of Little Pass Timbalier. Note the tight coverage through the inlet throat and the non-continuity of some of the survey lines, indicating the distribution of shoals encountered while surveying. Aerial photo is from 2004 and grid coordinates are in meters UTM zone 15.

After processing, the bathymetric data and historical datasets were used to make a series grids and ultimately digital elevation models (DEMs) for each date or time period (1880's, 1930's, 1980's, and 2005). The grids and DEMs were constructed using *Golden Software Sufer 8* contouring software. A kriging geostatistical algorithm was used to create the grid. Kriging is a distance weighting, moving average method that takes into account naturally occurring regional variables that are continuous from place to place (such as a linear bar or inlet channel), and assigns optimal weights based on the geographic arrangement of data point Z values taken from a variogram (Davis, 1986; Krajewski and Gibbs, 2003). Kriging was determined to be the most appropriate contouring method because it takes into account spatial characteristics of the local geomorphology and provides the best linear estimate that can be obtained from and irregular arrangement of data samples. Each DEM was then rectified and scaled relative to the other DEMs, allowing for the construction of a time series model that shows the morphological evolution of Little Pass Timbalier for the period from 1880 to 2005.

RESULTS

The results of the bathymetric change analysis are presented as a series of DEMs, one representing each time period covered by the study. Inlet morphology for each time period is described based on the terminology of Hayes (1975, 1980). Each DEM is described in the context of the previous time period in order to best interpret and present the morphological evolution of Little Pass Timbalier since 1880.

Inlet Morphology and Evolution

1880's

During the 1880's Little Pass Timbalier consisted of a relatively narrow, 1.5 km-wide tidal inlet with a single, 7 m-deep channel (Fig. 2) (List et al., 1994). The DEM for the 1880's indicates the presence of prominent flood and ebb tidal delta sediment bodies. The flood tidal delta was highly prominent during this early period and became less evident during subsequent stages. The flood delta morphology for the 1880's is comparable to those described by Hayes (1975) for Atlantic coast inlets and includes a flood ramp, flood channels, ebb shield, ebb spit, and spillover lobe (Fig 2). Noteworthy, is the fact that the ebb tidal delta is not as prominent at this stage as it is during subsequent stages. Ebb tidal volume for the 1880's was estimated to be 8 x 10^6 m^3, using the method proposed by Dean and Walton (1975). Inlet throat cross section area for this time period was 3,177 m^2.

1930's

Between 1880 and 1930 Little Pass Timbalier underwent a series of changes that led to breaching of the downdrift shoreline. According to U.S. Coast and Geodetic Survey maps, this process appears to

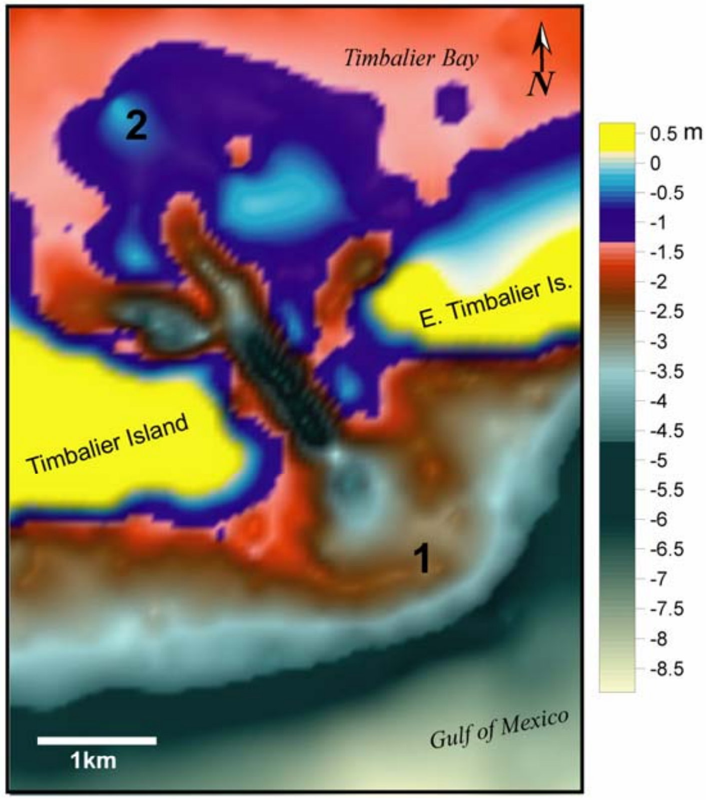

Figure 2. Digital Elevation Model (DEM) of Little Pass Timbalier for the 1880's. Note that the inlet consists of a single ebb channel, marginal flood channels, and pronounced ebb (1) and flood (2) tidal deltas with morphologies typical of those described by Hayes (1975) for Atlantic coast inlets. Bathymetric data from List et al. (1994).

have occurred prior to 1925 (U.S Coast and Geodetic Survey, 1925) and possibly took place during a 1909hurricane in which winds of 200 km/hr were recorded on the Louisiana coast and a tidal surge of 5 m was measured at Timbalier Island (Williams et al., 1992). The breaching of the adjacent shoreline resulted in an avulsion of the inlet and a displacement of the main channel 4.7 km updrift (west) of the 1880 channel thalweg location. These changes contributed toward a widening of Little Pass Timbalier, from 1.5 km in 1880 to 8.6 km by 1930. The wider inlet actually consisted of multiple channels separated by shoals, rather than a single, well-defined ebb channel (Fig. 3). The main ebb channel that formed at the site of the new breach was the deepest of the channels (7 m). Updrift, toward the east, the relict channel shoaled to 4 to 5 m and a third 4-m deep channel formed between the new breach channel and the relict channel. The ebb tidal delta of the former main channel eroded between the 1880's and 1930's (List et al., 1994), signaling a decrease in ebb current velocity in the former main channel. During that period waves reworked the ebb tidal delta sediment in a westward (downdrift) direction. The small portion of Timbalier Island that was located between the relict channel and the breach became a sand shoal, named Timbalier Shoal. Timbalier Shoal has remained ephemeral to date, becoming subaerially exposed during extended periods of calm weather and reworked to a subtidal shoal during tropical cyclone events. During the 1930's Little Pass Timbalier was characterized by a wide inlet with multiple channels separated by shoals. There were no prominent flood or ebb tidal delta deposits during this time period. Whereas the channel did migrate laterally during the period from 1880 to 1930 due to the avulsion and lateral spit migration, landward migration was approximately 1 km. Inlet throat cross sectional area increased from 3,177 m^2 in the 1800's to 8,677 m^2 in the 1930's.

1980's

Between the 1930's and the 1980's, the main channel migrated 1.25 km landward and 0.85 km laterally to the west. During the 1980's and subsequent timeframes, the inlet consisted of two ebb channels (the relict and new breach) separated by Timbalier Shoal (Fig. 4). Marginal flood tidal channels existed along the flanks East Timbalier and Timbalier islands, as well as along the flanks of Timbalier shoal. The inlet width at the throat was 7 km for the 1980's, a reduction of 1.6 km since the 1930's. During this period, Timbalier Shoal was subaerially exposed having an arcuate-shaped form built by an amalgamation of swash bars. During extensive periods of calm weather, swash bars migrate landward across the ebb tidal delta and eventually weld onto Timbalier Shoal. This phenomenon results in the vertical aggradation and subaerial exposure of Timbalier Shoal (Miner et al., 2005).

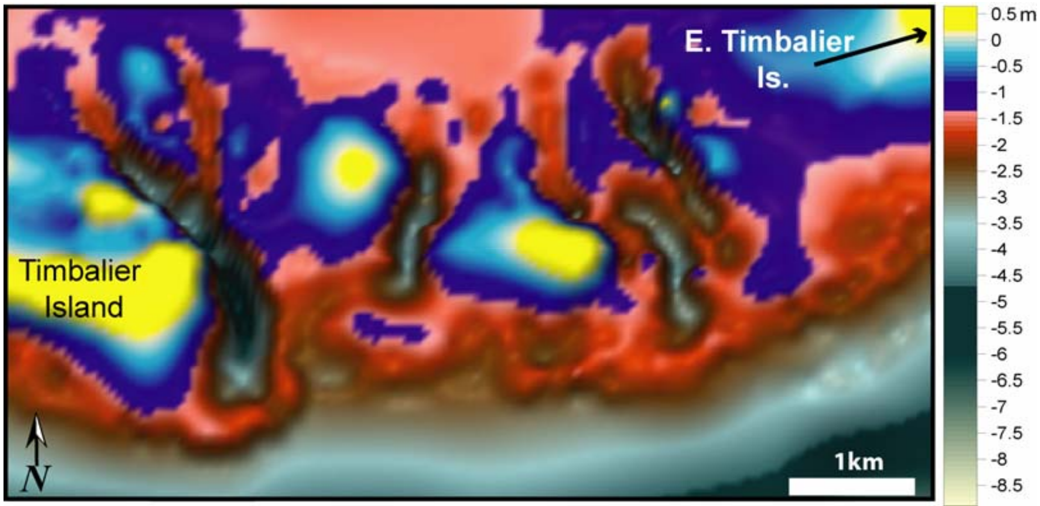

Figure 3. DEM of Little Pass Timbalier for the 1930's. Note the increased throat width (from 1.5 km to 8.6 km) compared to the 1880's data (Fig. 2) and the multiple channels separated by shoals. The easternmost channel is the relict main channel from the 1880's DEM and the deepest and westernmost channel was the result of a breaching event on Timbalier Island prior to 1925. Note that most of the inlet related sediment bodies are contained within the throat and the lack of pronounced ebb and flood tidal deltas. Bathymetric data from List et al. (1994).

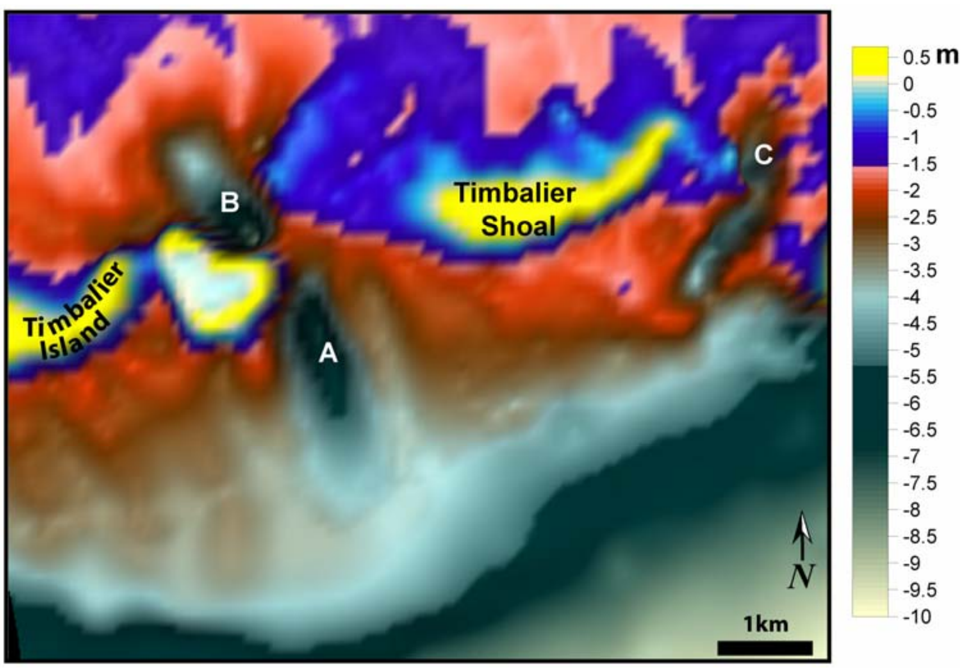

Figure 4. DEM of Little Pass Timbalier for the 1980's. Note that there are two ebb channels (A and C) that remained open since the 1930's DEM (Fig. 3). A scour hole (B) landward of the main channel is formed by tidal scour where backbarrier tidal channels converge. The secondary ebb channel (C) deepened slightly by 1980, indicated by a comparison of the 1880's DEM, but is still shallower than the 1880's DEM (Fig. 2) when it was the only ebb channel for the inlet. This 1980's data additionally indicates that the ebb tidal delta enlarged and prograded onto the shelf since the 1930's. Bathymetric data from List et al. (1994).

In the 1980's the two ebb channels of Little Pass Timbalier consist of differing morphologies. The deepest and westernmost channel was 7 to 8 m deep, whereas the eastern channel was 4 m deep (List et al., 1994). At the western channel site a large ebb tidal delta had become prominent since the 1930's due to increasing tidal prism (Fig. 4). The ebb tidal delta volume for the 1980's was estimated to contain 53 x 10^6 m^3 of sediment, an increase of 45 x 10^6 m^3 since the 1880's. The deepest point of the main channel did not exist at the throat during this time, but rather a large scour hole was present landward of the throat, having a depth of 8 to 9 m (List et al., 1994). Scour holes landward of the throat are typical of MRDP tidal inlets during certain periods of their evolution and are found landward of tidal inlet channels on the Atlantic coast as well. Kjerfve et al. (1979) hypothesize that their formation coincided with the junction of tidal creeks and resulted from tidal scour associated with high turbulence. Presently, there is a deep scour hole landward of the throat at Barataria Pass occurring at the confluence of multiple backbarrier tidal creeks. The main channel of Barataria Pass migrated into this scour hole resulting in an extraordinarily deep (~50 m) inlet channel (Shamban, 1985; FitzGerald et al., 2004). According to the 1980's DEM, the easternmost channel of Little Pass Timbalier for the 1980's displayed no ebb or flood tidal delta features. The inlet throat cross sectional area increased from 8,677 m^2 in the 1930's to 9,129 m^2 in the 1980's.

2005

The morphology of Little Pass Timbalier reflected in the 2005 DEM is similar to that of the 1980's DEM exhibiting two ebb channels separated by Timbalier Shoal and marginal flood channels flanking the spits. However, the backbarrier scour hole disappeared and the deepest part of the main ebb channel is located at the inlet throat (Fig. 5). Dredging for the Louisiana Department of Natural Resources (LDNR) Project TE-40 Timbalier Island Dune/Marsh Restoration, resulted in the removal of approximately 3.5 x 10^6 m^3 of sediment from distal portions of the channel margin linear bar and central ebb tidal delta. This sediment was placed along the downdrift shoreline of Timbalier Island in 2004 (Personal communication, Beau Tate LDNR; Shaw Coastal, 2005). Of note is that between the 1980's and 2005 the ebb tidal delta ceased its progradation onto the inner shelf. The terminal lobe has since begun to retreat landward and the ebb tidal delta has broadened in a downdrift direction. Between the 1980's dataset (List et al., 1994) and the 2005 survey the inlet throat of the main channel migrated 2 km in a landward direction and 1.1 km alongshore to the west, and throat width widened from 8.1 km to 9.8 km. The main ebb channel increased in depth from 7 to 8 m deep in the 1980's to 9 to 10 m deep in 2005. The inlet throat cross sectional area increased from 9,129 m^2 in the 1980's to 17,510 m^2 in 2005.

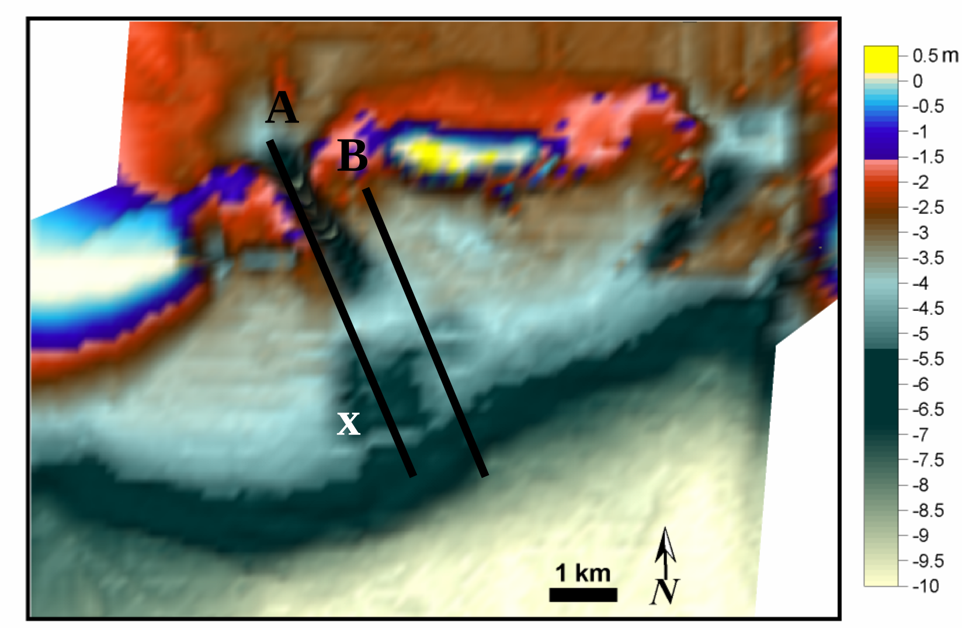

Figure 5. DEM of Little Pass Timbalier for 2005. Note that the overall morphology is similar to that of the 1980's DEM (Fig. 4), however there is no scour hole landward of the inlet throat. Also note the dredge borrow pit (x), which was excavated in 2004 as a sand source for nourishment of the downdrift Timbalier Island shoreline. Both ebb channels have increased in depth and width relative to the 1980's and 1930's (Fig. 3) inlet morphology; a response to increased tidal prism volumes associated with bay margin/interior wetland loss. In addition, the ebb tidal delta has retreated landward since the 1980's, a shift from the seaward advance observed from the 1930's to 1980's. See Figure 1 for single-beam survey coverage. Lines A and B are locations of profiles shown in Figure 9.

MORPHOLOGIC EVOLUTION

The morphological evolution of Little Pass Timbalier is complex and encompasses: 1) landward and lateral migration of its main channel (44 m/yr and 28 m/yr, respectively for the 1930 – 2005 time frame), 2) changes in inlet throat geometry, and 3) formation of a new stable ebb channel through the combined processes of channel avulsion and breaching of the adjacent shoreline (Fig. 6, Table 1).

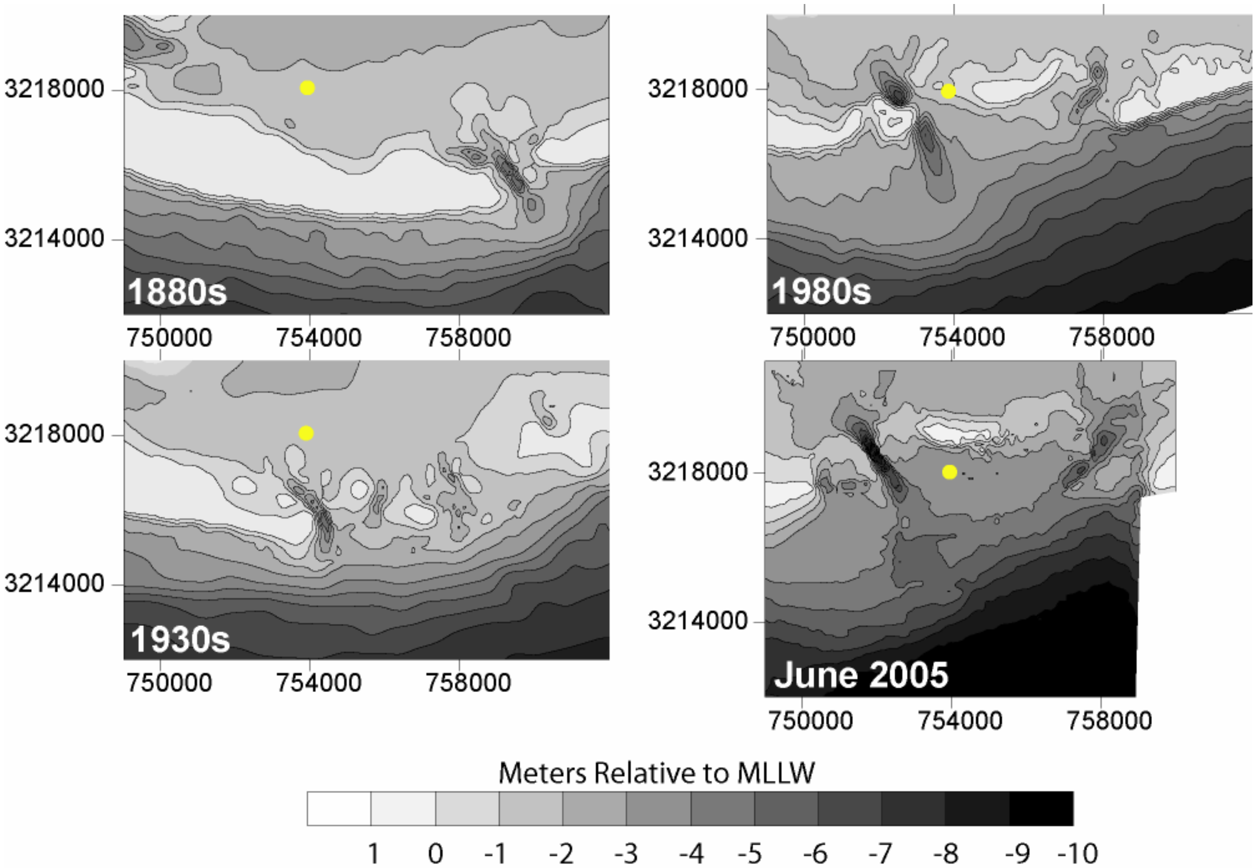

Figure 6. Morphological evolutionary model of Little Pass Timbalier for the period from the 1880's to 2005. The yellow dot on each map identifies a fixed geographical position. Important aspects of the inlet's evolution are the morphological responses to increasing tidal prism volumes and rapid relative sea-level rise. These responses include landward migration of the inlet throat, widening and deepening of the throat, formation of additional stable channels within the same inlet system, enlargement and precursory seaward progradation of the ebb tidal delta, and subsequent retreat of the ebb tidal delta and associated increased sediment transport along the downdrift lower shoreface. Note the westward lateral shift in inlet position that resulted from a channel avulsion to a breach on Timbalier Island (TI) between 1880 and 1930. During the subsequent time frame (1980 to 2005), both ebb channels remained open and continued to deepen in response to increasing tidal prism volumes. Between 1980 and 2005lateral migration of Timbalier Island and deterioration of East Timbalier Island (ETI) resulted in lateral migration of each channel in an opposite direction leading to inlet widening. The channels are separated by Timbalier Shoal (TS), which is submerged after tropical storm impacts but becomes subaerially exposed as swash bars migrate landward across the ebb delta and amalgamate during extended periods of calm weather. Seaward progradation of the ebb tidal delta occurred as the barrier/inlet system migrated landward between 1930 and 1980. This precursory progradation was followed by retreat and submergence of the ebb delta terminal lobe driven by shoreface erosion. The inlet system evolves from a balanced flood/ebb dominance with flood and ebb tidal deltas in the 1880's to an inlet morphology displaying no prominent ebb or flood deltas and sediment bodies separating multiple channels within the throat in the 1930's and later became morphologically stable as a two-channel inlet with a large ebb delta and insignificant flood tidal delta. Contours are in meters relative to Mean Lower Low Water and grid coordinates are in meters UTM Zone 15. 1880's, 1930's, and 1980's bathymetric data from List et al. (1994).

Time Period	Number of Ebb Channels	Throat Width, km	Throat Depth, m	Throat Cross-sectional Area, m^2	Ebb Delta Volume, m^3	Landward Migration, km	Lateral Migration, km
1880’s	1	1.5	7	3,177	8×10^6	-	-
1930’s	3	8.6	7	8,677	-	0.9	4.7*
1980’s	2	8.1	9	9,129	53×10^6	1.9	0.9
2005	2	9.8	10	17,510	-	2.1	1.1

Table 1. Summary of morphological evolution for Little Pass Timbalier. * Denotes lateral migration that occurred due to a storm breaching event and formation of a new main ebb channel.

Inlet channel migration and widening

Inlet throat migration is controlled by barrier landward migration in response to relative sea level rise, changes in tidal prism volume, the erodablity of the substrate (antecedent geology), longshore versus cross-shore transport processes, sediment supply, and frequency of storm impacts.

The morphologic evolution of Timbalier and East Timbalier Islands is closely associated with channel migration and constant inlet widening at Little Pass Timbalier (Fig. 7). The lateral migration observed for the 115 year period is mostly driven by inlet widening and a tendency for the inlet channel to hug the downdrift shoreline as Timbalier Island migrates laterally and degrades (Fig. 8). Downdrift lateral spit migration from East Timbalier Island is not a dominant control on lateral inlet migration at Little Pass Timbalier. A regime of rapid barrier degradation driven by breaching events dominates East Timbalier Island, making it the most rapidly eroding shoreline in North America (McBride et al., 1992). This process, which has been amplified by failed attempts to stabilize the island with hard structures since the 1950’s (McBride et al., 1992), has led to the development of multiple ephemeral inlets along the East Timbalier Island shoreline and hinders lateral migration. In turn, lateral migration processes dominate at Timbalier Island, which is rapidly migrating to the west at a rate of 35 m/yr as the island length and total area slowly decrease (McBride et al., 1992; Penland et al., 2005). The disparity in shoreline movement trends between the two islands has resulted in the gradual widening of Little Pass Timbalier from 1.5 km in 1880 to 9.8 km in 2005 (Figs. 6 – 8).

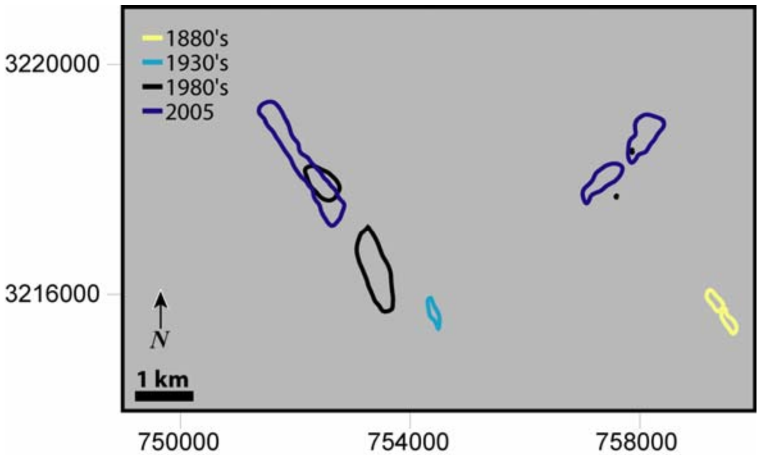

Figure 7. Position of the Little Pass Timbalier inlet channel thalweg based on the –5 m bathymetric contour for each period covered in the study. The rapid lateral migration between 1880's and 1930's is due to a breaching and inlet avulsion event that occurred prior to 1925. For the time period from 1930 –2005, the main ebb channel has migrated landward at a rate of 44 m/yr as the Timbalier Barrier shoreline retreats landward in response to rapid relative sea level rise rates in excess of 1 cm/yr. Also, note the increasing aerial extent of the – 5m bathymetric contour as the inlet increases in cross-sectional area in order to accommodate the increasing tidal prism volumes. Grid coordinates are in meters UTM Zone 15. 1880's, 1930's, and 1980's bathymetric data from List et al (1994).

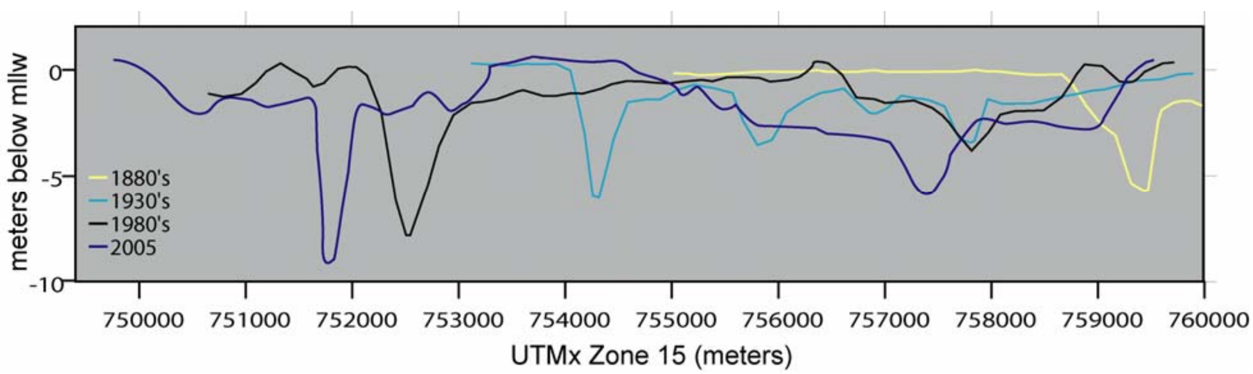

Figure 8. Shore-parallel bathymetric profiles across the Little Pass Timbalier tidal inlet throat for the years covered in this study. Profiles traverse the minimum inlet throat cross section for each period, but are fixed relative to UTM X (longitudinally). Note the increasing throat cross-sectional area, and westward lateral migration for the inlet system with time. 1880's, 1930's, and 1980's bathymetric data from List et al (1994).

It has been established by previous tidal inlet studies along the Gulf of Mexico, Pacific, and Atlantic coasts of North America that inlet cross sectional area and bay tidal prism volume have a direct relationship (O'Brien, 1939; 1967; 1969; Jarrett, 1976), changes in the tidal prism volume will result in changes in inlet cross sectional area (O'Brien, 1969; FitzGerald et al., 1984a), and increasing tidal prism driven by wetland loss in Louisiana has resulted in increased tidal inlet cross sectional areas for the

Louisiana coastal zone (FitzGerald et al., 2003; FitzGerald et al., 2004; Miner et al., 2005). At Little Pass Timbalier, increasing bay tidal prism volumes driven by backbarrier and interior land loss rates in the Timbalier/Terrebonne basin of 26.4 km^2/yr for a period from 1956 to 1990 (Barras et al., 1994) has forced this inlet widening process. Little Pass Timbalier has also increased in depth from 7 m in 1880 to 10 m in 2005 to accommodate the larger tidal prism volume.

A breaching event sometime between 1880 and 1925 resulted in the formation of a second ebb channel down drift of the former inlet location. This second inlet channel has become the main ebb channel for Little Pass Timbalier and remains stable to date as part of a two-channel inlet system separated by an ephemeral shoal. Breaches and ephemeral inlets along the adjacent East Timbalier Island shoreline will eventually become stable tidal inlets in order to accommodate increasing tidal prism volume. The formation of additional tidal inlets along the Barataria shoreline in response to Barataria basin land loss has occurred during the past century as well (FitzGerald et al., 2004).

In the abandoned deltaic coastal setting, abrupt lateral facies changes of the antecedent geology have the potential to control inlet migration pathways. It has been proposed by previous workers studying tidal inlets in coastal Louisiana that inlet location is controlled by former distributary channel locations because the abandoned distributary channel fill is more erodable than the prodelta and delta front clays in which it incises (Levin, 1995; Kulp et al., 2004). For Little Pass Timbalier it is probable that the modern ebb channel formed during the breaching event occurred at the site of a former distributary channel based on the stratigraphic data in Chapter 5 (vibracore 05LPT04). However, it is also likely that the landward migration pathway is controlled by relict tidal inlet and ebb tidal delta retreat paths based on the alignment of inlets along the Timbalier Shoreline with the relict Terrebonne transgressive shoreline inlets located landward of Little Pass Timbalier and stratigraphic data presented in Chapter 5 (cross section A – A').

Ebb tidal delta expansion, precursory progradation, and retreat

Another consequence of the increasing tidal prism is the attendant increased volume of sediment sequestered in ebb tidal deltas (cf. Walton and Adams, 1976). As the tidal prism of the Terrebonne/Timbalier basin increased between the 1880's and 1980's, the ebb tidal delta of Little Pass Timbalier enlarged by 45 x 10^6 m^3 and prograded onto the shelf as the barrier shoreline translated landward. This phenomenon of ebb tidal delta enlargement and seaward progradation in an overall transgressive regime has been noted by previous workers on the Louisiana coast (List et al., 1991; 1994; FitzGerald et al., 2003; FitzGerald et al., 2004). The volume increase in the ebb tidal delta occurs at the expense of the barrier islands, not only due to erosion of the tips of the barriers associated with inlet widening, but also because sand that builds the ebb tidal deltas would otherwise bypass the tidal inlet (FitzGerald et al., 2003).

During the period between 1980 and 2005 the ebb tidal delta began undergoing retreat after an initial stage of progradation (Fig 9). This process is due to a progressive increase in the effective area of the ebb-tidal delta as it aggrades and progrades until its seaward extent is balanced by wave and shoreface erosional processes. Also, the continual landward and westward (lateral) migration of the inlet throat, where tidal current velocities are greatest, results in decreased ebb tidal current velocities along the updrift ebb tidal delta terminal lobe. The terminal lobe became starved of sediment and dominated by shoreface ravinement; forcing it to erode similarly to shoreface retreat, resulting in the transfer of sand to a downdrift lower shoreface depocenter. This proposed mechanism for ebb delta retreat and downdrift expansion after a period of seaward progradation is similar to that observed in flume experiments and stratigraphic investigations of a delta front conversion from the progradation stage to continuous retreat under constant relative sea-level rise and sediment supply as described by Muto and Steel (1992; 1997; 2001; 2002) and Muto (2001). The results are erosional processes dominating updrift portions of the ebb delta, and distribution of these sediments to downdrift flanking portions of the ebb delta, and along the adjacent downdrift shoreface.

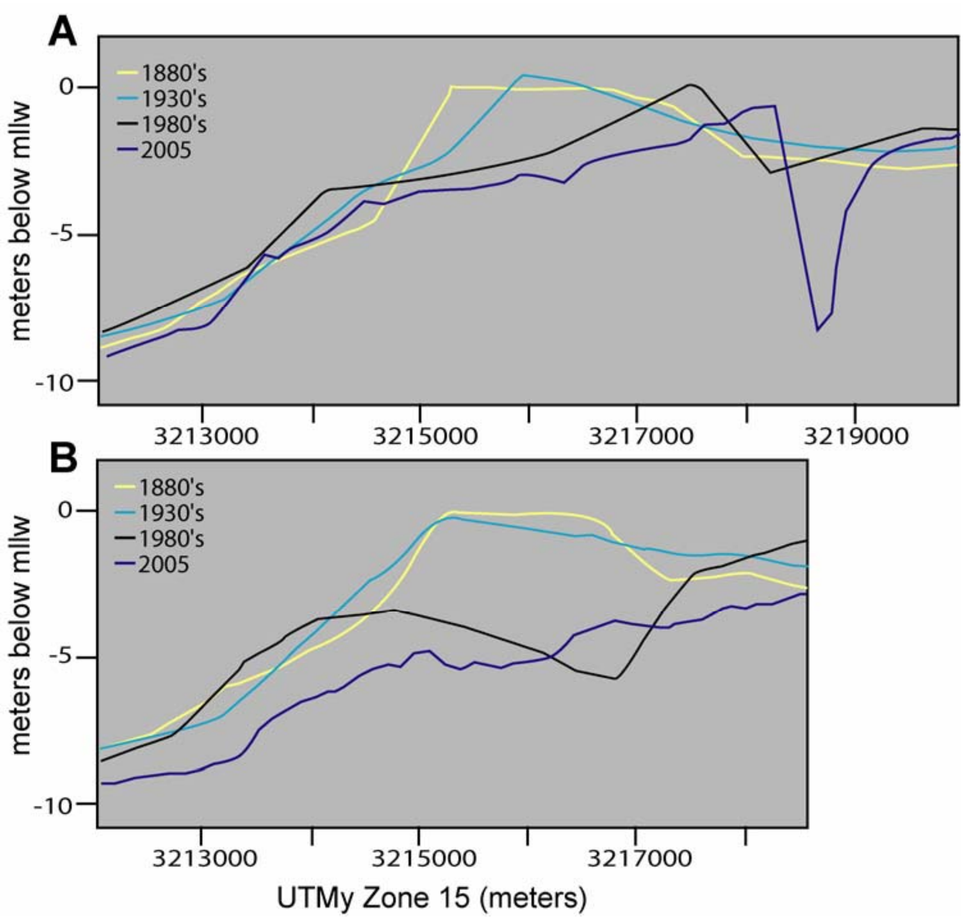

Figure 9. Shore-normal profiles extending from the inlet throat location for 2005 (A) and 1980's (B) beyond the terminal lobe of the ebb tidal delta. Note the change from aggradation and progradation of the ebb tidal delta through the 1980's followed by retreat and erosion in both profiles for the 2005 data. Location of transects shown in Figure 5.

MODEL APPLICATION

Transgressive Tidal Inlet Migration

The results of this study describe the morphological evolution of a transgressive tidal inlet that is dominated by throat and landward channel migration. Because tidal inlet channels and inlet channel fill sequences have relatively high preservation potential during a transgression, the presence of inlet fills on the shelf have been used to document locations of relict barrier shorelines (Shideler et al., 1972; Sheridan et al., 1974; Stahl et al., 1974; Field, 1980; Niedoroda et al., 1985; Rieu et al., 2005). These interpretations are based on inlet fill models developed at modern inlets where lateral migration is the dominant control on inlet fill stratal geometry and sedimentary character. As shown here, the inlet migration pattern of a transgressive tidal inlet (shore perpendicular) is quite different than the laterally migrating inlet (shore parallel), and results in a distinctly different set of stratal architecture and facies successions (see Chapter 5 for details).

Shelf Sand Ridges

Lobate, shore oblique areas of accretion located offshore Timbalier Island have been identified by previous workers (List et al., 1994; Jaffe et al., 1997) (Fig. 10). However, the study conducted by Jaffe et al. (1997) did not identify a sediment source large enough to account for the accretion. A possible source for this sediment is the Little Pass Timbalier ebb tidal delta and suspended sediment transported out of the backbarrier through Little Pass Timbalier during ebbing tides. Sediment along distal portions of the ebb tidal delta is reworked by storm wave processes and deposited along the lower shoreface of Timbalier Island as shore oblique, lobate accumulations of sediment. Similar shore oblique, sediment transport trends and attendant bedforms along the middle and lower shoreface and shoreface-connected sand ridges have also been observed along the Atlantic coast (Swift, 1975; Ludwick, 1978; Swift et al., 1978; Swift et al., 1985) and have been attributed to transgressive shoreface-shelf dispersal systems (Figure 8 in Swift et al., 2003, Tillman and Martinsen, 1984), deposition as a lowstand shoreface during a forced regression (Posamentier et al., 1992), and sourced from abandoned ebb tidal deltas during a transgression (McBride and Moslow, 1991; Snedden et al., 1994; 1999). The Atlantic examples are hydraulically maintained, and believed to be closed systems due to transport pathways that circulate the sediment (Swift 1975). Movement of the sediment within the Atlantic ridges occurs during peak storm flow and downwelling (Wright et al., 1986; Swift et al., 1986; 2003).

Long-term landward migration of Timbalier Island combined with the enlargement and progradation of the Little Pass Timbalier ebb tidal delta resulted in the decoupling of the sediment transport pathway to the shoal from the upper shoreface and littoral systems. It has been proposed that, unlike the Atlantic lobes, the sediment transported downdrift along the lower shoreface of Timbalier Island is not lost to offshore sinks, but eventually becomes reintroduced to longshore processes downdrift at the Isles Dernieres (Jaffe et al., 1997). This notion is supported by the relative lack of subsurface sand apparently present in the Isles Dernieres headland (Petro, 2005). By the 1980's, the lateral accretion of lobes had been transported past the downdrift inlet Cat Island Pass and became a source of sediment that nourished the eastern Isles Dernieres barrier shoreline, where shoreline erosion rates are now about half of pre-bypassing rates (Jaffe et al., 1997) (Fig. 10).

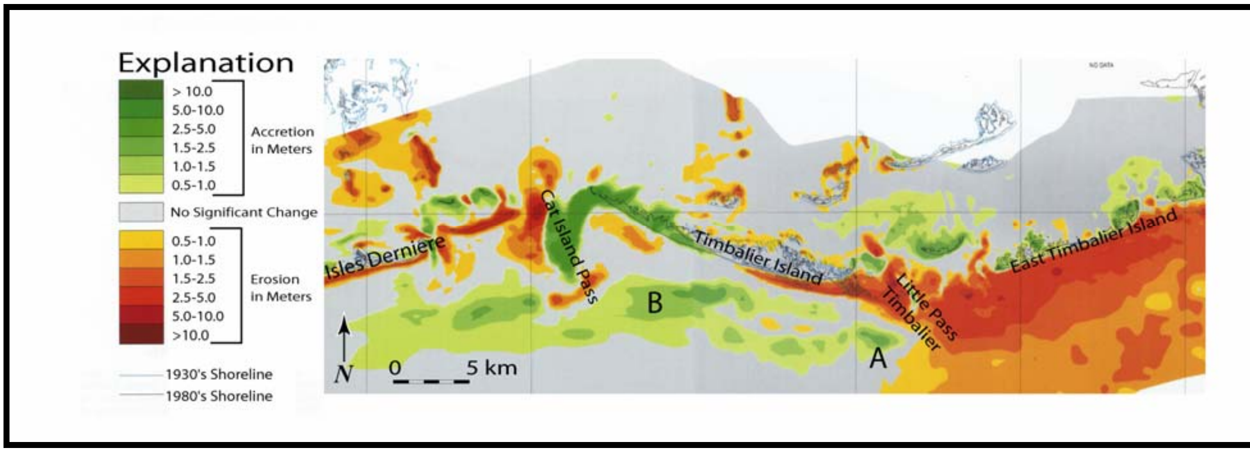

Figure 10. Sea-floor change 1930's to 1980's (map from List et al., 1994). Note the area of accretion seaward of Little Pass Timbalier (A) resulting from ebb tidal delta progradation during this time period. Also note the lobate-shaped accretionary zone along the lower shoreface down-drift of the Little Pass Timbalier ebb tidal delta (trends between A and B). A possible source of this sediment is the erosion of the updrift portion of the ebb tidal delta and shoreface erosion at the ebb tidal delta terminal lobe. This sediment transport pathway allows for lower shoreface bypassing of down-drift Cat Island Pass tidal inlet and delivery of sediment to the eastern Isles Derniere shoreline, where erosion rates are half of the pre-bypassing rates (Jaffe et al., 1997).

During the period from the 1880's to 1980's, ebb tidal delta volume increased at Little Pass Timbalier from 8 x 10^6 m^3 to 53 x 10^6 m^3, resulting in its seaward progradation while at the same time the barrier and inlet channel system migrated landward. This morphological development is a response to increasing tidal prism. Since the 1980's, the ebb tidal delta of Little Pass Timbalier has shifted from seaward prograding to downdrift migrating. This shift results in shore-parallel downdrift growth of the ebb tidal delta and sediment transport and deposition along the downdrift lower shoreface of Timbalier Island.

A model for the formation and evolution of shoreface attached and detached sand ridges that develop from ebb tidal delta abandonment due to inlet migration or overstepping by transgression was proposed by McBride and Moslow (1991). One paradigm based on correlation between the location and orientation of existing sand ridges and the presence of relict or active tidal inlets along the modern shoreline, is that abandoned ebb tidal deltas act as an initial sand source for the generation of sand ridges (McBride and Moslow, 1991). Radiocarbon age-dated vibracore and high resolution shallow seismic data collected on the New Jersey Atlantic shelf provide chronostratrigraphic evidence to support the correspondence between inlets and shelf sand ridges, however, the exact genetic process is still unknown (Snedden et al., 1994; 1999). The modern processes of transgressive tidal inlet morphodynamics at Little Pass Timbalier in which ebb tidal deltas expand and prograde seaward as the inlet channel and barrier migrate landward and their possible relationship to the formation of lobate accretionary zones along the downdrift lower shoreface along Timbalier Island have implications for the genesis of sand ridges and transgressive sand-sheets on the Holocene Atlantic (Swift et al., 2003) and northern Gulf of Mexico continental shelves (McBride et al., 2004), as well as sand sheets identified within the subsurface of the Holocene MRDP (Penland et al., 1988b; Penland, 1990). A coast-wide bathymetric survey of Louisiana is currently in progress as a cooperative study between the UNO Pontchartrain Institute for Environmental Sciences, U. S. Geological Survey, and Louisiana Department of Natural Resources. The results of this study will provide insight as to the recent depositional and erosional trends along the lower shoreface of Timbalier Island and evolution of the shore-oblique accretionary features.

CONCLUSIONS

1) Shoreface retreat along the barrier islands, driven by relative rise rates greater than 1 cm/yr, causes the Little Pass Timbalier tidal inlet system to migrating landward at an averaged rate of 44

m/yr. Westward lateral migration of the main ebb channel is also occurring at an averaged rate of 28 m/yr, resulting in a widening of the inlet. Widening results because East Timbalier Island can not accrete westward and is drowning in place due to its rip-rap lined shoreline.

2) The dominant control on the morphological evolution of Little Pass Timbalier since the 1880’s has been increasing tidal prism driven by interior wetland loss. This has resulted in changes in inlet throat geometry (widening and deepening) and relocation of a new stable ebb channel to a site along the adjacent barrier that was breached during major storm. Increasing tidal prism has also resulted in increased volumes of sediment sequestered in the ebb tidal delta. In response to storm events and tidal prism changes, Little Pass Timbalier has evolved from an inlet having ebb and flood deltas in the 1880’s to an inlet morphology with no prominent flood or ebb tidal delta but rather a system with multiple ebb channels separated by intra-inlet shoals by the 1930’s. Most recently (1980’s to 2005), the distribution of tidal channels and sand bodies reflects ebb dominance with a large ebb tidal delta and negligible flood tidal deltas.

3) The seaward growth of the ebb tidal delta ceased between the 1980’s and 2005 and coincided with a downdrift growth of the ebb tidal delta. This downdrift dispersal of sediment explains the genesis of an accretionary zone along the Timbalier Island lower shoreface. This accretionary zone appears to be attached to the Little Pass Timbalier ebb tidal delta. The relationship between transgressive ebb tidal delta morphology and evolution and lower shoreface accretionary zones may help explain shelf sand ridge formation and transgressive sand sheet development.

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CHAPTER 4

SHORT TERM MORPHOLOGIC CHANGES WITHIN A TRANSGRESSIVE TIDAL INLET: THE ROLE OF 2005 HURRICANES AT LITTLE PASS TIMBALIER, LOUISIANA

INTRODUCTION

Barrier island shorelines of the Mississippi River delta plain (MRDP) are rapidly degrading due to an increase in tidal inlet cross sectional area (widening and deepening of inlet throats and/or formation of additional, stable inlet channels) across the coastal zone. This increase in inlet cross-sectional area is driven by increasing backbarrier tidal prism volumes (Levin, 1993; FitzGerald et al., 2004) associated with backbarrier and interior wetland loss. Land loss rates of as much as 26.4 km^2/yr have been documented in the Timbalier/Terrebonne basin for a period extending from 1956 to 1990 (Barras et al., 1994). Whereas ongoing subsidence, increasing tidal prism volumes, and antecedent morphology are suggested as the dominant factors controlling long-term tidal inlet morphological evolution within the barrier islands fringing the MRDP (Levin 1993; 1995; Kulp et al., 2004; FitzGerald et al., 2004), tropical cyclone impacts are major forcing factors that can rapidly alter the morphology and rate of tidal inlet and barrier shoreline evolution (Penland et al., 2003).

The passage of tropical cyclones brings about rapid, large-scale morphological and spatial changes to inlet systems and adjacent barrier shorelines. The largest and least predictable of these changes occurs at tidal inlets due to the complex wave and current climate that are the result of the interaction between the beach, ebb tidal delta, and tidal channels (FitzGerald, 1988; Morton et al., 1995). Impacts may vary greatly due to storm characteristics and are dependent upon storm path, shelf and shoreline morphology at the landfall location, and storm intensity (Nummedal et al., 1980). For the Louisiana coastal zone the rapid changes brought about by many large cyclones are not followed by gradual recovery, such as those reported for Atlantic coast inlets (Sexton, 1995; Zhang et al., 2002). Contrastingly, along the MRDP major storms produce an enduring signature on the long-term morphological evolution of the inlet/barrier system (Penland et al., 2003).

During the past two decades, much effort on the local, state, and federal levels has attempted to understand the mode of Louisiana barrier island deterioration as well as implement methods to mitigate barrier land loss. Previous studies using aerial photographic analysis concluded that most of the changes along barrier shorelines are event-driven (storm impact) and occur at tidal inlets (e.g. Penland et al, 2003). Identifying the forcing mechanisms that control shoreline morphological evolution across short- and long-term time spans is a crucial to managing transgressive shorelines. The active 2005 Gulf/Atlantic hurricane season resulted in the landfall of three hurricanes along the Louisiana coast and provided an opportunity to document and understand the effects that storms have on a transgressive tidal inlet system. This study uses pre- and post-hurricane season bathymetric data at Little Pass Timbalier inlet to determine erosion versus accretion patterns and sediment volumetric changes as a result of the active 2005 season of hurricanes

HURRICANES IMPACTING THE LOUISIANA COASTAL ZONE IN 2005

Three major tropical cyclones, strong enough to be classified as Hurricanes with winds greater than 119 km/hr, made landfall within 320 km of Little Pass Timbalier during the 2005 Gulf/Atlantic Hurricane Season (Fig. 1). The first of these storms to make landfall was Hurricane Cindy on July 6, 2005, 14 km east of the study area (Stewart, 2006). With a pressure of 991 mb and sustained winds of 120 km/hr at the time of landfall, Cindy produced storm surges 1.5 m above normal tide at Port Fourchon (Stewart, 2006).

Hurricane Katrina made landfall near Buras, Louisiana, 85 km east of Little Pass Timbalier as a strong Category 3 hurricane with estimated maximum sustained winds of 204 km/hr and a pressure of 920 mb on August 29, 2005 (Knabb et al., 2006a). Maximum surge levels recorded at NOAA tide station at Port Fourchon were 3 m above normal tide.

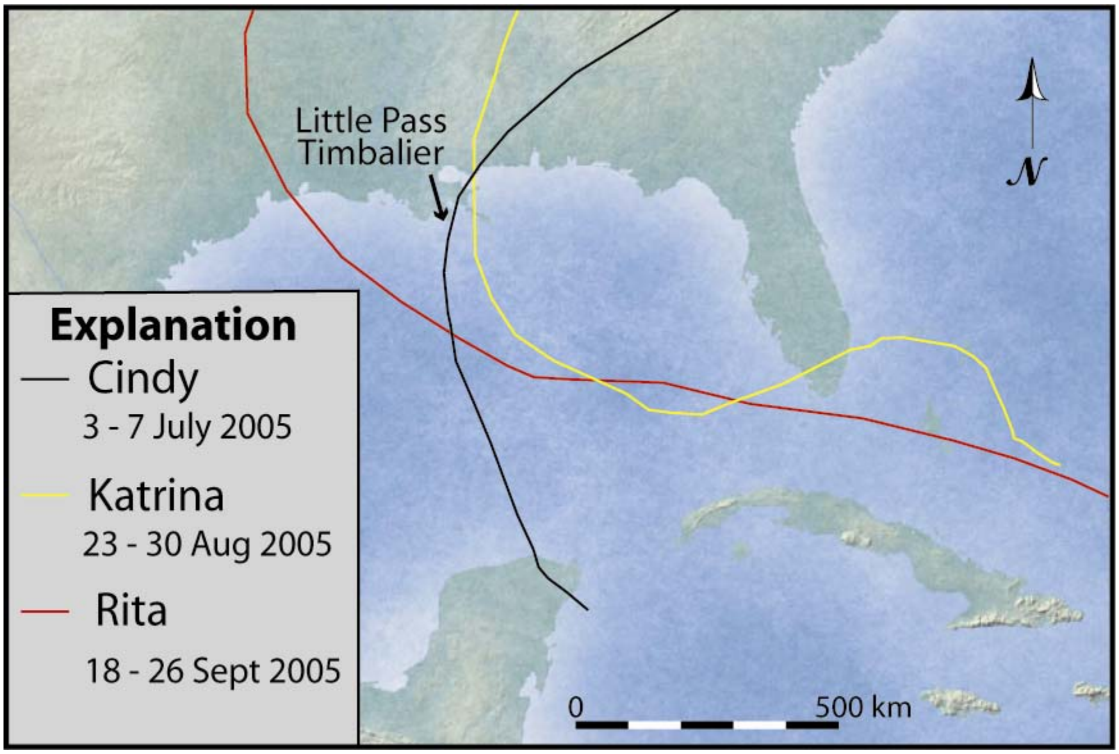

Figure 1. Hurricanes impacting Little Pass Timbalier during the 2005 Gulf of Mexico hurricane season. Note that Hurricanes Cindy and Katrina passed closest and to the east of Little Pass Timbalier resulting in the long duration maximum velocity winds blowing from the north, increasing wave attack from the bay along the Timbalier shoreline. Hurricane tracks from Stewart (2006), Knabb et al. (2006a), and Knabb et al. (2006b).

Hurricane Rita made landfall in southwestern Louisiana on September 24, 2005 as a category 3 hurricane with maximum sustained winds of 185 km/hr and a pressure of 937 mb (Knabb et al., 2006b). Rita's track brought the strong winds and high surge levels associated with the eastern portion of the storm within the study area where water level measurements at Port Fourchon were 2 m above normal tide (Knabb et al., 2006b).

METHODOLOGY

In June 2005, prior to the passage of the 2005 Hurricanes, a high-resolution bathymetric survey was conducted across the study area as part of a long-term tidal inlet morphological evolution study. The proximate storm tracks and landfall of the three hurricanes within a 3 month period provided an opportunity to acquire post-storm bathymetry within the study area and document the impact of these storms at Little Pass Timbalier Inlet. The second survey was completed in November 2005 after the passage of Hurricanes Cindy, Katrina, and Rita near the study area (Fig. 2).

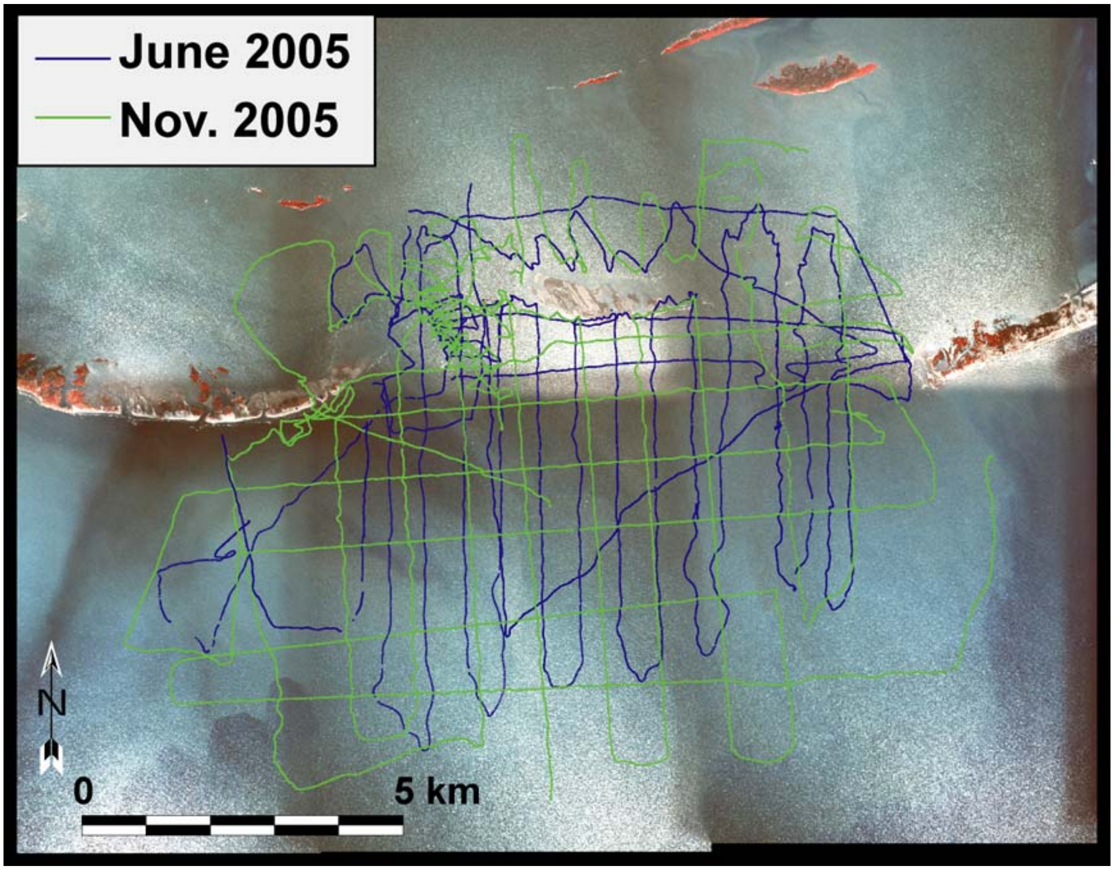

Figure 2. Map showing data coverage for the two single-beam bathymetric surveys conducted at Little Pass Timbalier in June 2005 and November 2005.

The bathymetric data for the area were gathered using the University of New Orleans Coastal Research Laboratory single-beam bathymetric rig mounted aboard the 21-foot *R/V Mudlump*. This bathymetric survey rig consists of an *Odom Hydrographics Hydrotrac* system with a factory specified vertical resolution of 1.0 cm. Depth soundings are collected through a side-mounted *Odom Hydrographics* 200 kHz transducer with a beam width of 3°. The fathometer is equipped with a *Starlink Invicta 210L* differential global positioning system (DGPS) for navigation. Heave, pitch, and roll of the transducer and DGPS antenna, arising from vessel motion, are recorded using a *VT TSS Dynamic Motion Sensor Series-25* that is mounted vertically in-line with the DGPS antenna and the transducer. The bathymetric, motion correction, and navigation data are simultaneously recorded digitally and integrated using *Coastal Oceanographics Hypack Max* hydrographic survey software run on an *Amrel Rocky Unlimited* field notebook computer.

Survey lines in the study area were programmed using *Hypack* and had an approximate 800-m line spacing along shore perpendicular transects. During the actual survey, this spacing was not always followed in areas where shallow depths (-0.4 m) due to limited survey vessel accessibility or where shoal and island shorelines interfered with the completion of a planned line. When shallow depths along a shoal or island shoreline were encountered, the perimeter was mapped at the minimum depth accessible by the survey vessel (approximately -0.4 m). Synthetic data points with a Z value of 0.5 m were digitized in for the islands and subaerial portions of the shoals based on aerial photography taken within a month of the bathymetric survey. A tightly-spaced zigzag survey trajectory along the axis of the inlet channel throat was used to clearly define the bathymetric changes in that area. Hence, the distribution of data points acquired during the survey does not reflect the planned line spacing, and therefore the data set consists of a somewhat random distribution of data points based on an understanding of the geomorphology of the tidal inlet system. In addition, because of bathymetric changes between the June and November surveys, the position of survey transects were altered in the field due to vessel draft limitations.

The bathymetric data were processed using *Hypack Single Beam Editor* module. Tidal elevation corrections were integrated using 6-minute interval data from a NOAA tide gauge station (# 8762075) located at Port Fourchon. The water level elevation from the tide gauge was measured relative to mean lower low water (MLLW), a tidal datum based on the National Tidal Datum Epoch 1983 –2001.

After processing, the bathymetric data were used to make a series of grids, which became the basis for the construction of digital elevation models (DEMs) for each survey. The grids and DEMs were constructed using *Golden Software Sufer 8* contouring software. A kriging geostatistical algorithm was used to create the grids. Kriging is a distance weighting, moving average method that takes into account naturally occurring regional variables that are continuous from place to place (such as a linear bar or inlet channel), and assigns optimal weights on the basis of the geographic arrangement of data point Z values taken from a variogram (Davis, 1986; Krajewski and Gibbs, 2003). Kriging was determined to be the most appropriate contouring method because it takes into account spatial characteristics of the local geomorphology and provides the best linear estimate that can be obtained from an irregular arrangement of data samples. The grids created by the kriging method became the basis for contouring bathymetry and subsequent grid comparisons.

Grid math calculations were carried out between the two survey datasets (pre and post storms) to determine the difference between the November and June Z values at each grid node (eg. November Z – June Z = net bathymetric change). This resulted in the creation of a new grid that showed areas of accretion and erosion through positive and negative values, respectively. A new DEM was contoured from these differential Z values in order to show changes (erosion, deposition, or dynamic equilibrium) that occurred during the 5 month time frame between the two surveys. Volume calculations of the bathymetric change grid were computed in *Surfer 8* in order to determine positive volume (accretion) and negative volume (erosion).

QUANTIFICATION OF UNCERTAINTY WITH BATHYMETRIC DATA AND CHANGE ANALYSIS

An error analysis was performed on the digital elevation models in order to document the accuracy of the bathymetry for Little Pass Timbalier and consequently the accuracy of the volume change calculations between the two periods. Sources of uncertainty in the bathymetric change analysis include sounding measurements, tidal corrections, and data interpolation for the grid surface. Much of the uncertainty that might be brought about by human error during surveys is difficult to isolate and quantify, however, quality control measures such as comparison of soundings at line crossings and careful documentation of potential errors (e.g. bar-check calibration of echosounder and transducer) during surveys helped to identify these types of errors. Tidal correction inaccuracies arise from indeterminate tidal elevation differences between the tide gauge at Port Fourchon and the study area. An approximation of water level differences between Little Pass Timbalier and Port Fourchon was calculated based on the NOAA predicted water levels at each location during each survey. It was determined that the average time lapse for maximum and minimum water levels from Port Fourchon to Little Pass Timbalier was 25 minutes, and given a mean annual tide range of 0.30 meters, the average difference in water level between the two locations is estimated to be 0.005 m. This value is considered to be an order of magnitude less than the values determined by the error analysis described below, and is therefore assumed to have little or no measurable effect on the outcome of the bathymetric change and volume calculations.

Survey line crossings are important to help identify potential equipment and human errors during the survey as well as post-processing tidal corrections used to arrive at the measured Z value. In order to determine the accuracy of the tide-corrected measured depths, 10 survey line crossings from each temporal data set were examined for differences in Z value at the point where the lines intersect. The crossings for the June data had an average difference in elevation of 0.05 m (+/- 0.025 m uncertainty) and 0.08 m (+/- 0.04 m uncertainty) for the November data. In order to determine the magnitude of the deviation the root mean square value for the two data sets was calculated and determined to be +/- 0.05 m. The line crossing uncertainty is not calculated as error and was only used to identify any large disparity at the crossings. The minor disparity observed at line crossings might be attributable to actual bathymetric changes because the surveys were carried out over multiple days, and the November survey was interrupted by the passage of a cold front.

A major source of uncertainty results from part of the gridding procedure involving synthetic data when z-values are interpolated for areas where no empirical bathymetric measurement was taken. In order to determine uncertainty with interpolated Z values, a grid calibration line was surveyed along an approximate 45° angle to the North-South trending planned survey lines. The grid calibration lines were chosen as transects that cross irregular bathymetry such as the ebb channel, channel margin bars, and ebb tidal delta. Before creating the entire study area grid, the data along the grid calibration line was removed from each data set. Grids were then created with the data points along these lines omitted. Bathymetric profiles through each of these modified grids, along the transect of the calibration line, were produced.

The actual measured depth along the calibration line was then plotted against the profile from the modified grids to determine differences in cross sectional area between the grid surface profile and the measured data profile. The absolute value of the difference in the cross sectional area between the two lines was divided by the line distance to determine the average elevation difference between the two lines. The resulting value is the estimated range in uncertainty for the grid interpolations in areas where no data were acquired. For the June 2005 data, the cross sectional area of the grid profile was 3901.80 m^2 and 4111.07 m^2 for the data profile, a difference of 209.27 m^2. By dividing the difference in cross sectional area by the line distance of 4000 m it was determined that there was an average elevation difference range of 0.052 m, or ± 0.026 m. For the November 2005 survey data the cross-sectional area of the grid profile was 5311.29 m^2 and 4970.91 m^2 for the data profile, a difference of 340.38 m^2. The difference in cross sectional areas divided by the length of the profile line of 4500 m results in an average elevation difference range of 0.076 m or ± 0.038 m.

In order to determine the accuracy of the grid surface Z values relative to the measured soundings, the residuals (deviations of the grid surface Z value from the measured Z values) were computed using *Surfer 8*. For every measured Z value (over 1.5 x 10^6 data points), a Z value for the grid surface is given. The mean difference between the data and the grid was 0.0072 m with a standard deviation of 0.23 for the June 2005 data and a mean difference of 0.0010 m with a standard deviation of 0.21 for the November 2005 data. Because these values are an order of magnitude smaller than the errors estimated by the grid calibration analysis, they are not included in the error uncertainty.

In order to determine the uncertainty in seafloor change and make sediment budget calculations, the root mean square (RMS) of the uncertainty values determined for each grid surface based on the grid calibration survey was calculated by:

$$RMS = \sqrt{\sigma^2_{nov} + \sigma^2_{june}}$$

Where σ_{nov} is the Z value uncertainty estimate for the November grid and σ_{june} is the Z value uncertainty estimate for the June grid as determined by the grid error analysis. The RMS value for the two grid sets is ± 0.05 m. This value was used as the uncertainty for the bathymetric change analysis and sediment volume change calculations. The uncertainty for the volume change calculations was determined by using the ± 0.05 m uncertainty Z value and multiplying it by the area in which the bathymetric change analysis study was conducted (3.6×10^7 m^2). Using this procedure, it was calculated that the maximum amount of error in the volume analysis was ± 3.6×10^6 m^3.

BATHYMETRIC CHANGE ANALYSIS RESULTS

DEMs were created from the June 2005 and November 2005 grids using *Surfer 8* in order to analyze the morphological variance (Fig. 3). The bathymetric change analysis was used to determine the distribution and magnitude of erosion and accretion across the study area. These analyses indicate an overall pattern of destruction of shoals and bars, erosion of the ebb tidal delta terminal lobe, and erosion in the backbarrier area that is landward of Timbalier Shoal. Some of the eroded sediments were deposited broadly across the proximal ebb tidal delta seaward of Timbalier Shoal, in the seaward portion of the ebb channel floors, in marginal flood channels, and in the recently excavated dredge borrow pit (Fig. 4). Volume calculations from the bathymetric change analysis indicate that for the study area covering 36.0×10^6 m^2, a net decrease in sediment volume of 10.7×10^6 $\pm 3.6 \times 10^6$ m^3 took place between June and November 2005.

Ebb-Tidal Delta

The magnitude of shoaling across the proximal ebb tidal delta, landward of the 4 m isobath ranged from 0 to 0.75 m. Thickest accumulations occurred where new swash bars have formed (during the post storm recovery period) and migrated towards Timbalier Shoal. The distal portion of the ebb tidal delta, including the terminal lobe between the 4 m and 8 m isobaths, underwent extensive erosion, with only small areas (generally < 10 m^2), where the bottom remained unchanged. On the basis of patterns of erosion and accretion, storm bars appear to have formed along the terminal lobe of the ebb tidal delta. The area on the ebb tidal delta that underwent the most erosion (1.0 – 1.5 m) was located seaward of a dredge borrow area along the axis of the inlet channel (Figs. 3 and 4).

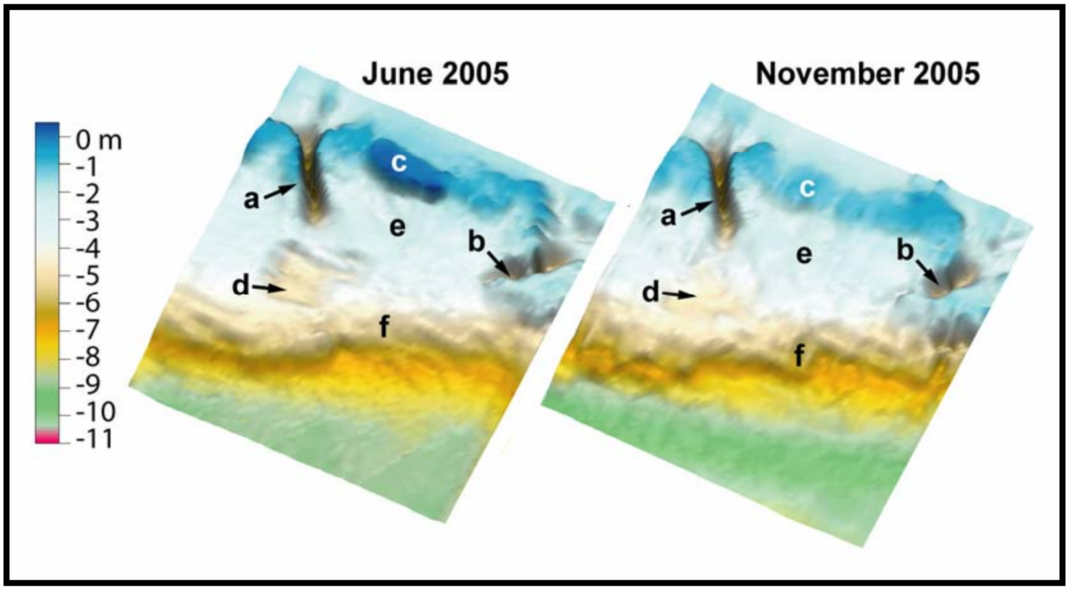

Figure 3. Digital elevation models of Little Pass Timbalier constructed from the June 2005 and November 2005 grids. Zones of bathymetric change discussed in text include the main ebb channel (a), secondary ebb channel (b), Timbalier Shoal (c), dredge borrow area (d), proximal ebb tidal delta (e), and ebb tidal delta terminal lobe (f). Bathymetry is in meters relative to mean lower low water (MLLW) and scale varies due to perspective view.

Main Ebb Channel

Between June and November 2005, the axis of the main ebb channel shoaled in the seaward most portions and eroded in the landward most part (Fig. 4). The most substantial shoaling along the channel axis took place across the seaward-most portion of the ebb channel on its eastern flank where 0.75 – 1.0 m of sediment appears to have been deposited. An erosional zone along both flanks of the channel is present in an area confined to the throat. Prior to storm impact this region had been constricted due to sand transported by flood tidal currents along the channel margin bar. The post-storm bathymetric soundings indicate that 1.5 – 2.0 m of erosion took place in this area, resulting in a widening of the thalweg at the channel throat. Overall, the seaward infilling and landward scour contributed toward a landward channel migration pattern that is similar to that observed for the long-term morphological evolution (Chapter 3).

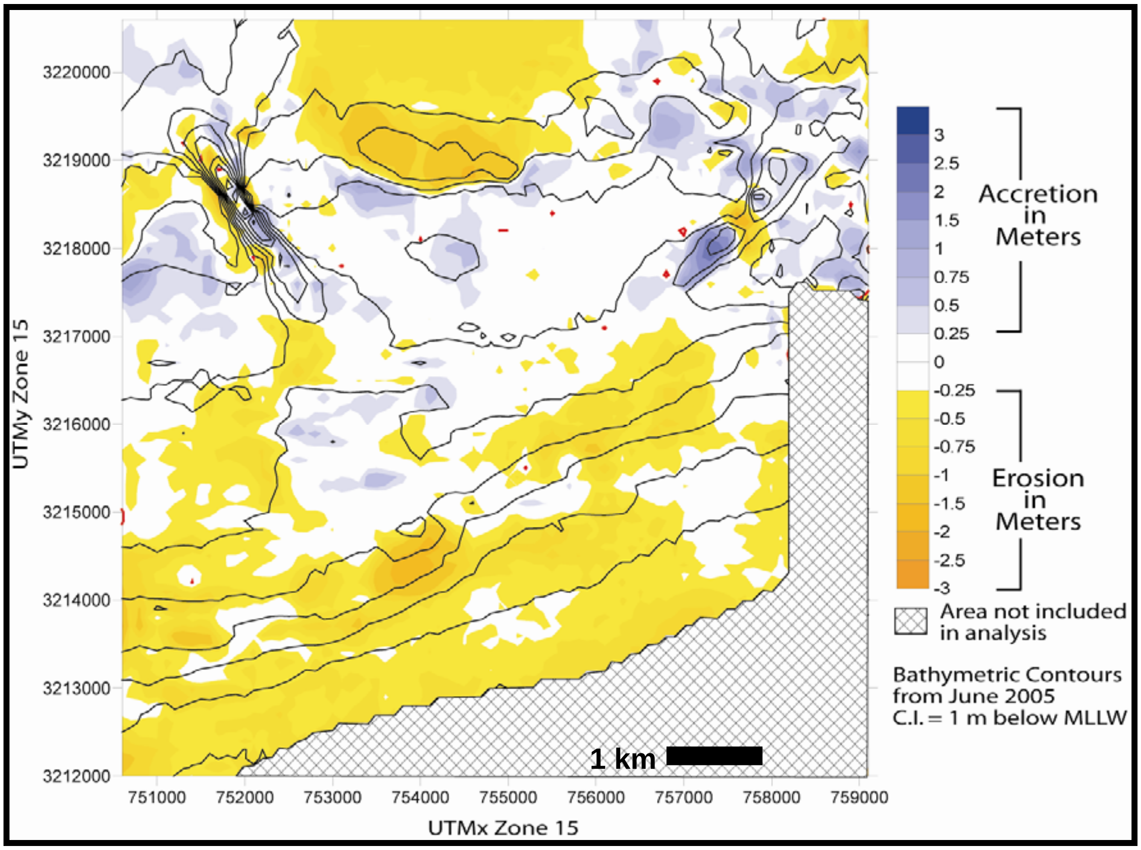

Figure 4. Bathymetric change map for the period from June 2005 to November 2005. Map was derived by creating a grid of the difference between pre-storm and post-storm Z values. Erosion is represented by negative Z and accretion is represented by positive Z. Note the erosion of Timbalier Shoal and widespread erosion along the ebb tidal delta terminal lobe. Areas where accretion occurred include the proximal ebb delta, marginal flood channels, and dredge pit. Both ebb channels widened at the throats, shoaled in the seaward portions, and eroded in landward portions.

Secondary Ebb Channel

The secondary (easternmost) ebb channel underwent similar erosional and depositional patterns as those observed for the main ebb channel. Shoaling at the seaward portion of the channel was 1.5 – 2.0 m, and erosion landward of the throat was 1.0 – 1.5 m. The flanks of the channel at the throat also eroded resulting in increased throat cross-sectional area.

Timbalier Shoal

Timbalier Shoal was exposed subaerially and supported a small, vegetated dune field prior to the 2005 storm impacts. However, as a result of the 2005 storms the shoal was destroyed and the shoal sand was dispersed throughout the tidal inlet system. By November 2005, at the time of the post-storm survey, a small portion of the shoal was only exposed during low tide. This shoal underwent 0.5 to 1.5 m of total 2005 erosion, which suggests that it is the source for much of the increased volume of sediment deposited along the ebb tidal delta and within the main ebb channel. The backbarrier area landward of Timbalier Shoal also experienced 0.25 to 0.75 m of erosion. The complete remobilization of sediment comprising the shoal during extreme weather events has implications for sediment dispersal patterns for Little Pass Timbalier that will be discussed in the following section.

Marginal Flood Channel and Timbalier Island Recurved Spit

The westernmost marginal flood channel that abuts the eastern recurved spit of Timbalier Island migrated to the west, destroying much of the recurved spit. This effectively widened the inlet throat from 8.5 km in 2004 to over 9.5 km in November 2005 (Fig. 4).

Dredge Borrow Pit

A dredge pit that was excavated in late 2004 as a sand resource for The Louisiana Department of Natural Resources, Timbalier Island Dune/Marsh Creation Project TE-40, underwent shoaling. The borrow pit, located on the ebb delta seaward of the inlet throat shoaled as much as 0.75 m in some places, however the ebb delta seaward of this pit eroded 0.75 to 1.5 m (Fig. 4).

DISCUSSION

Short Term Inlet Migration

The pattern of rapid inlet migration indicated by the bathymetric change analysis in this study is consistent with the overall long-term (1930's to 2004) migration pattern determined by a previous study on the morphological evolution of Little Pass Timbalier (Miner et al., in press). Miner et al. (in press) concluded that the inlet migrated in a landward direction at a rate of 44 m/yr during the 75-year period.

The short-term inlet channel landward migration distance for the 5-month period from June 2005 and November 2005 was 160 m. During a period covering 11 months from July 2004 to June 2005 the inlet migrated only 30 m (Fig. 5) (Table 1). The disparity in inlet migration rates for the two time periods is explained by the active 2005 hurricane season relative to 2004. During 2004 only one weak tropical cyclone, Tropical Storm Matthew, made landfall proximal to Little Pass Timbalier (Avila, 2004).

Time Period	Distance
1930 – 2004	3250 m
July 2004 – June 2005	30 m
June 2005 – Nov. 2005	160 m

Table 1. Inlet landward migration distance for Little Pass Timbalier in relation to active tropical cyclone activity.

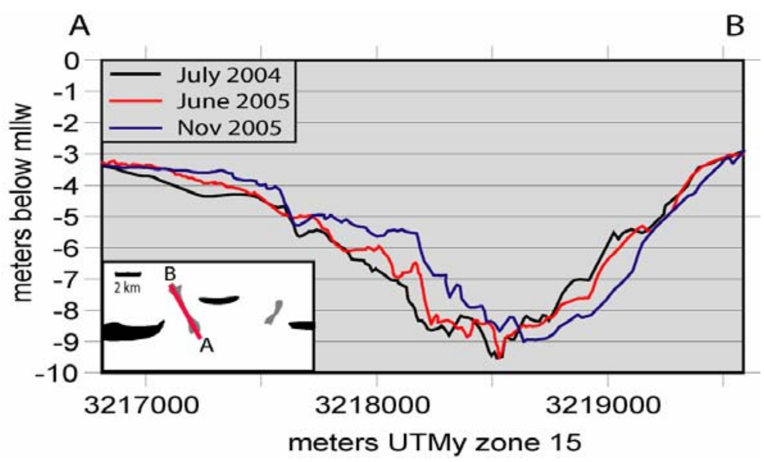

Figure 5. Profiles along the axis of the main ebb channel at Little Pass Timbalier for July 2004, June 2005, and November 2005. Note the rapid change during the 5-month period between June 2005 and November 2005 relative to the 11-month period covering July 2004 to June 2005. Also, note the process in which the ebb channel migrates landward by shoaling at the seaward portions of the channel and eroding in the landward portions.

High rates of rapid relative sea-level rise in the MRDP result in landward migrating barrier systems; this controls the landward migration of the inlet channels. While the barriers migrate by means of overwash processes followed by post-storm recovery and development of the shoreline landward of the pre-storm position, the inlets go through a similar cycle of landward migration and recovery period. The paucity of sand-sized material along the Louisiana coast, does not allow for the infilling of the seaward portion of the inlet channel during calm weather periods. Intense sediment mobilization events such as tropical cyclones induce bottom shears, which result in erosion of the landward portions of the channel. This scouring provides a source of sediment that infills the seaward portion of the channel, drastically increasing the rate of inlet channel landward migration.

Sediment Dispersal and Inlet Sediment Bypassing

The results of the volumetric change analysis showed that $10.7 \times 10^6 \pm 3.6 \times 10^6$ m^3 of sediment was removed from the study area. The patterns of erosion and accretion determined from the bathymetric change analysis indicate that bathymetric highs (bars, shoals, and recurved spits) are the sources for sediment that was mobilized and redeposited within preexisting bathymetric lows (tidal inlet channels and dredge pit) and on the proximal ebb tidal delta. Within the inlet, Timbalier Shoal was destroyed and the area landward of the shoal was dominated by erosion, whereas the proximal ebb tidal delta just seaward of the shoal was a zone of accretion. This bathymetric change pattern suggests that the sand formerly comprising Timbalier Shoal was redistributed seaward of the shoal across the ebb tidal delta. On the basis of available storm surge elevation data, direction and velocity of the wind, the bathymetric change analysis, and aerial photography, it appears that much of the sediment comprising Timbalier Shoal was transported seaward. The mechanism for this seaward movement of sediment is believed to be the strong return flow, which accompanied the passage of Hurricane Cindy and Katrina when surge waters were directed seaward by strong northerly winds.

During calm weather, sand deposited along the updrift side of the main ebb channel on the ebb tidal delta are exposed to wave action forming swash bars that are evident in the bathymetric data and aerial images. These swash bars migrate landward and weld to Timbalier Shoal (Fig. 6). Sand that is deposited on the west (downdrift) side of the channel on the ebb delta forms swash bars and the channel margin linear bar. These bars migrate landward where they are reworked by flooding tidal currents and deposited along the Timbalier Island recurved spit and spit platform resulting in inlet sediment bypassing. The sand comprising the swash bars and channel margin bars also has the potential to be reworked and deposited as part of the inlet channel backfill.

Longshore transport at Little Pass Timbalier is primarily to the west; however, inlet sediment bypassing is inefficient during normal wave conditions because the distal ebb tidal delta is submerged below normal wave base. The waves can propagate up the inlet channel and into the bay without breaking (Georgiou et al., 2005) or break on the proximal ebb delta where the swash bars are confined to during calm weather conditions. The armored shoreline of updrift East Timbalier Island also inhibits longshore sediment supply to Little Pass Timbalier.

As storms approach Little Pass Timbalier from the Gulf, storm wave attack erodes the ebb tidal delta terminal lobe and transports sand downdrift and across the swash platform (Fig. 7). As the storm surge increases water levels and wave height continues to increase, spit breaching and overwash processes dominate the innertidal and supratidal zones within the inlet system. The net movement of sand during the flooding surge and storm wave attack is in a landward and downdrift direction.

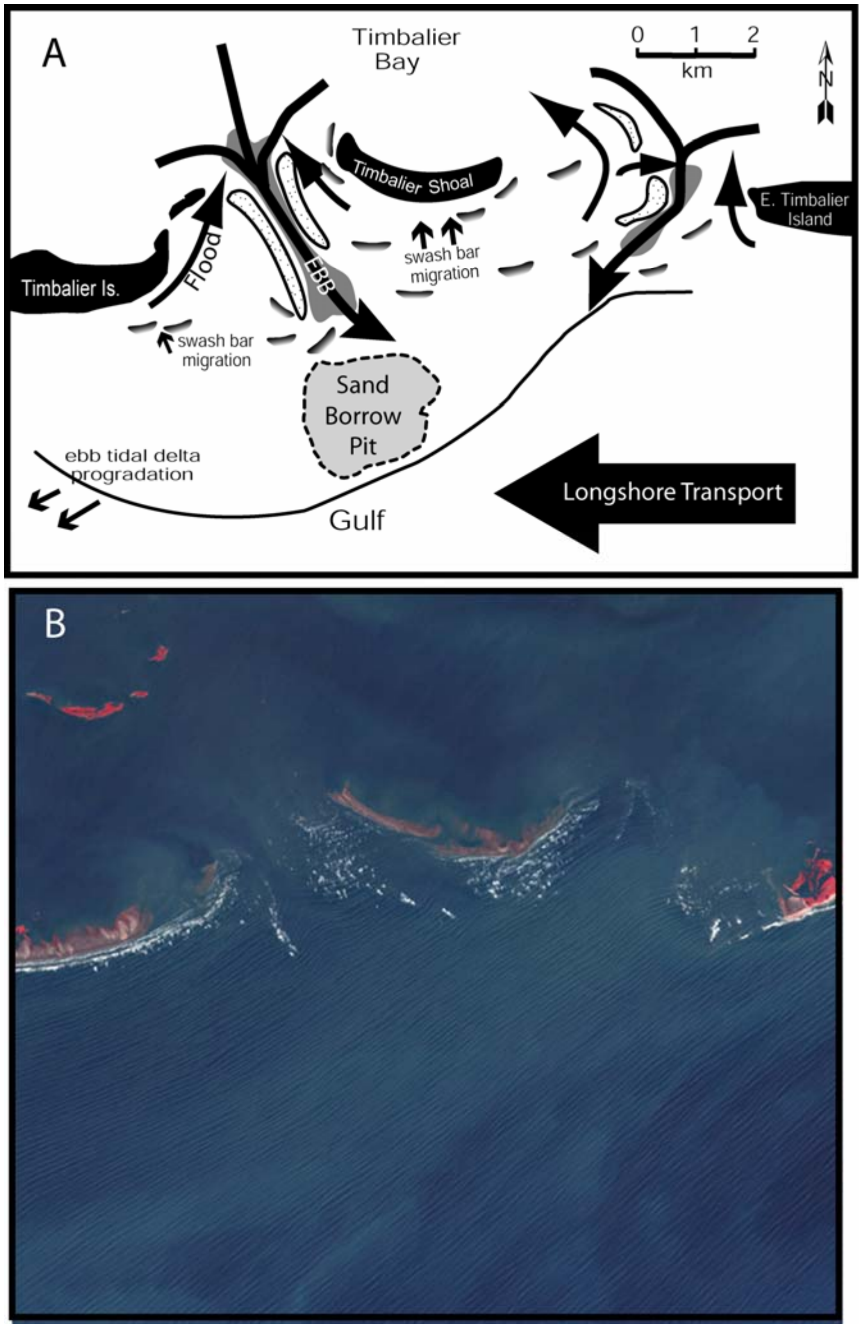

Figure 6. (A) Little Pass Timbalier sediment dispersal model during normal weather conditions. Longshore sediment transport is to the west, swash bars form on the ebb delta and migrate landward. Increasing backbarrier tidal prism results in seaward and downdrift progradation of the ebb tidal delta. (B) Satellite image of Little Pass Timbalier from 2001 after a period of minimal storm activity. Note the relatively robust and exposed Timbalier Shoal and waves breaking on swash bars and channel margin bars across the ebb tidal delta.

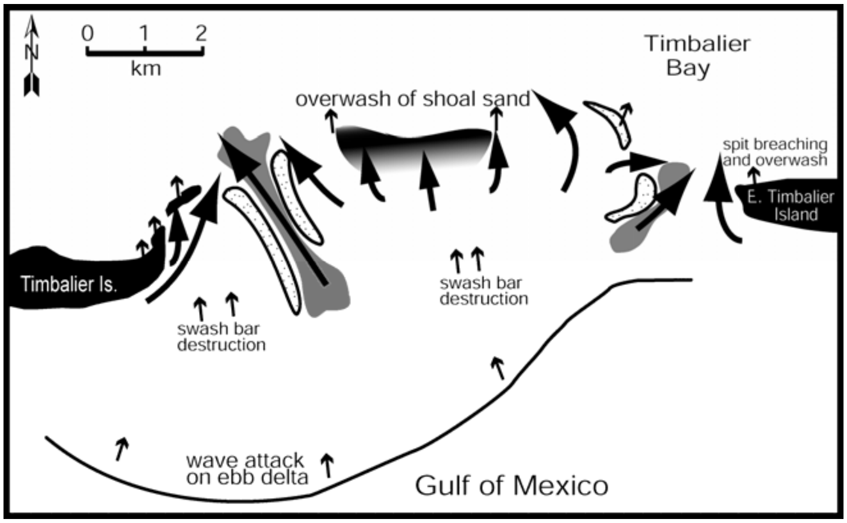

Figure 7. Sediment dispersal model for Little Pass Timbalier during the approach of a tropical cyclone with flooding storm surge and storm wave attack on the ebb tidal delta terminal lobe.

During this study Hurricanes Cindy and Katrina made landfall within 85 km east of Little Pass Timbalier. Storms passing east of the inlet system produce lower surge levels than those that track to the west. However as the storm passes, winds shift to a northerly direction and maintain high wind velocities for long durations. This results in storm wave attack on the bay shoreline of the inlet, and surge ebbing or return flow moving through the inlets, causing the following:

1. Scouring of the landward portions of the inlet channel,
2. Throat widening,
3. Gulf-directed overwash,
4. Development of return flow channels on spits and shoals (Fig. 8).

These processes provide a mechanism for a net seaward movement of sediment, onto the proximal ebb delta, along the shoreface, and nearshore. Storm impacts disperse sediment previously comprising Timbalier Shoal leading to submergence through its reduction by erosion.

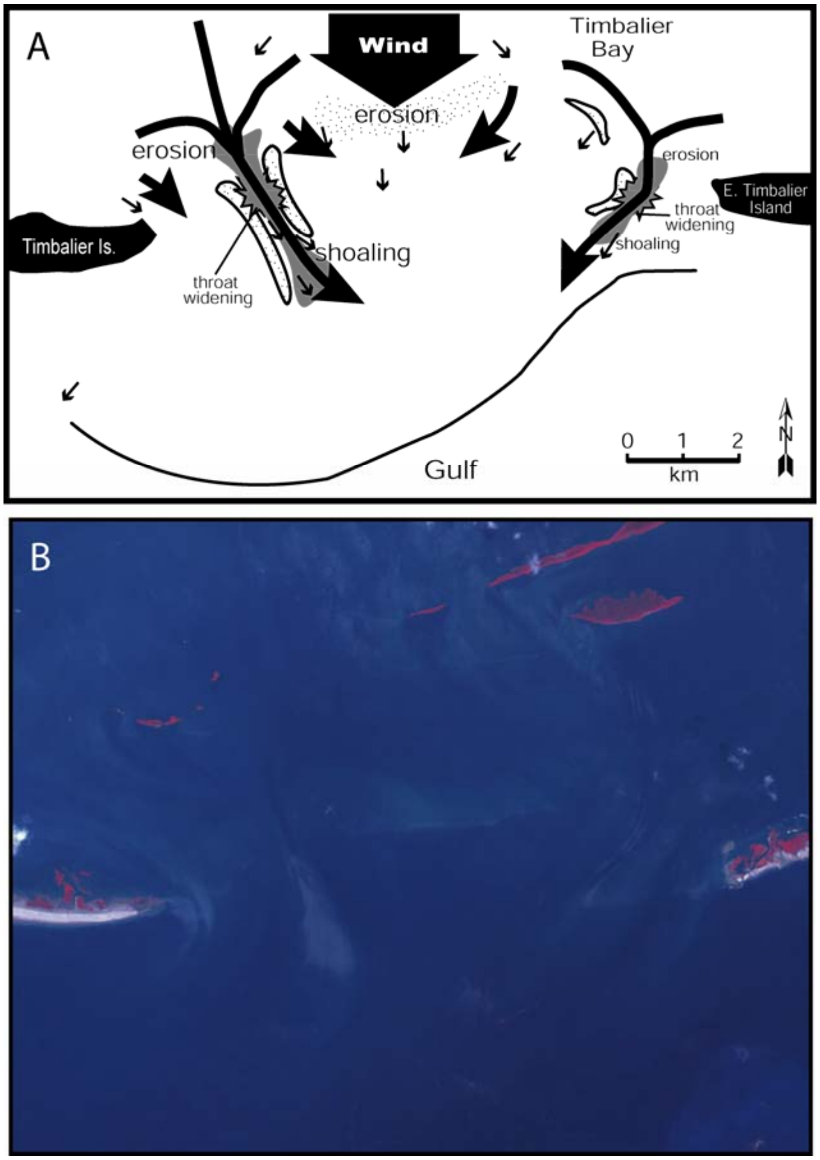

Figure 8. (A) Sediment dispersal model for Little Pass Timbalier during storm surge ebb as storm passes and winds shift to blow for long durations from a northerly direction. This process increases current velocities at the throat causing throat widening and landward channel scour, increases bay wave attack, and results in a net seaward movement of sediment. (B) Satellite photo taken on 13 September 2005, two weeks after Hurricane Katrina. Note that Timbalier Shoal is submerged and that the inlet widened from 8.5 km to more than 9.5 km. Also note the seaward directed return flow channel that formed on Timbalier Island recurved spit.

Subsequent to the passage of tropical cyclones, the sediment transported in a landward direction and deposited across the proximal the ebb tidal delta forms new swash bars and begins to migrate landward and weld onto the Timbailer Island and Shoal shorelines (Fig. 9). This results in the gradual reemergence of Timbalier Shoal. The landward movement of sediment during the recovery period also migrates into the extreme seaward portions of the main ebb channel as the throat migrates landward.

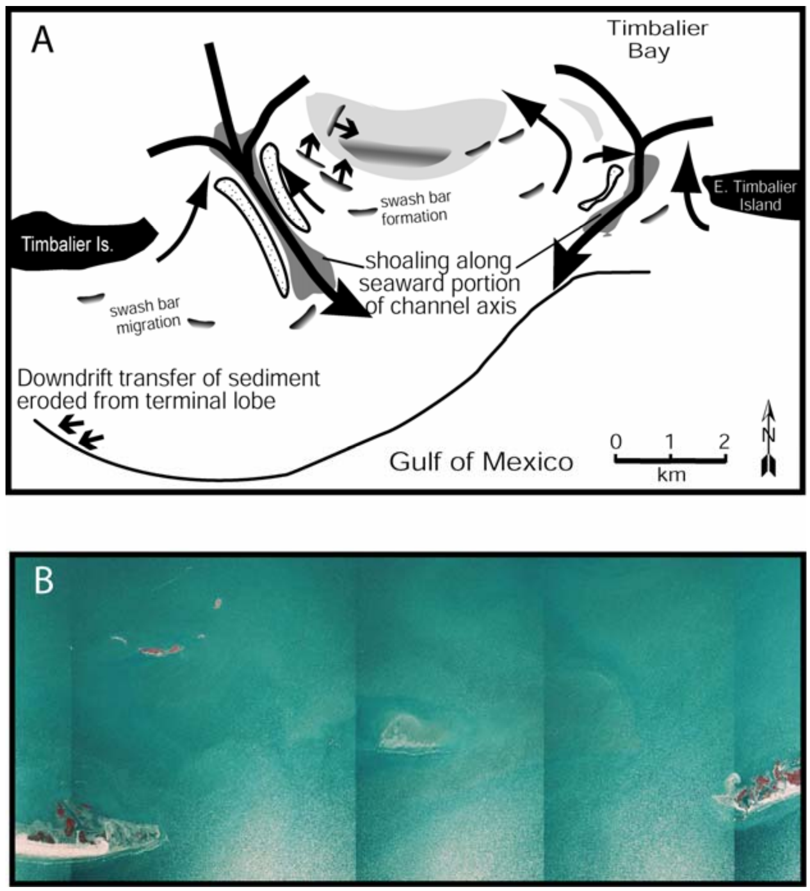

Figure 9. (A) Sediment dispersal model for the early post-storm recovery period at Little Pass Timbalier. Note the formation of swash bars, bar migration and welding onto the shoreline. These bars are composed of sediment that was redistributed in a seaward direction as a result of storm processes. The process of seaward sediment movement and deposition on the ebb tidal delta and subsequent formation of swash bars along the downdrift of the inlet that weld onto the Timbalier Island shoreline is an example whereby sediment bypasses Little Pass Timbalier,. Alteration of the ebb tidal delta morphology and sediment volume have the potential to interrupt this episodic sediment bypassing process. (B) Aerial photograph taken in November 2005 close to the time of the post-storm bathymetric survey. Note the reemergence of Timbalier Shoal, bar welding at Timbalier Shoal and extension of the Timbalier Island recurved spit.

Previous models of the Timbalier shoreline have purported that sediment bypassing at Little Pass Timbalier is minimal due to the armoring of East Timbalier Island (Georgiou et al., 2005). Georgiou et al. (2005) explain the lack of an efficient continuous sand bypassing process at Little Pass Timbalier and estimate that maximum longshore transport rates are 50,000 m^3/yr.

The 3-order of magnitude disparity between modeled transport rates and the sediment volume change determined in this study, points to a more episodic, storm-driven mechanism for sand bypassing at Little Pass Timbalier. Similar conclusions were derived in a study conducted by Morton et al. (1995) at San Luis Pass along the Texas Gulf Coast where bypassing was determined to be episodic, event driven and inefficient during typical calm weather conditions. At San Luis Pass waves and flood tidal currents transfer sand landward of the ebb tidal delta where sand is stored as shoals that are periodically reworked by storm events making the sand stored in them available for bypassing (Morton et al., 1995). A similar process, but on a much larger scale, occurs at Little Pass Timbalier with Timbalier Shoal. This episodic process allows for the introduction of relatively large quantities of sand, previously stored in the backbarrier and within the intra inlet shoal, into the ebb channel, ebb delta, and ultimately the littoral system. The storm impact provides a temporary increase of sediment available on the ebb tidal delta for normal inlet bypassing processes to occur (*sensu* FitzGerald, 1984; 1988). A comparison of pre and post hurricane aerial photographs at Little Pass Timbalier show a relatively robust Timbalier Shoal during extended periods of calm weather, and the destruction and submergence of Timbalier Shoal in response to storm impacts (Figs. 6B, 8B, and 9B). The emergence of the shoal as an ephemeral barrier island during calm weather serves to protect interior marshes from the direct impact of offshore waves that would otherwise propagate into the backbarrier through the inlet channel.

Possible Redeposition Location to Account for Net Sediment Loss from Inlet System

As storms approach, storm wave attack results in erosion of the ebb tidal delta terminal lobe. This area underwent widespread erosion. A probable location for the redeposition of this sediment is along the lower shoreface of downdrift Timbalier Island. This location has been a site of accretion and formation of a muddy sand lobe that trends obliquely to the shoreline based on a bathymetric change analysis covering 1880 – 1980 (List et al., 1994; Jaffe et al., 1997). The accretion along this lobe might be attributable to erosion of the shoreface and ebb deltas along the Timbalier and Isle Dernieres shorelines and downwelling after storm events. Similar storm-associated offshore depositional episodes have been reported for the Texas nearshore (Hayes, 1967; Snedden et al., 1988) and Atlantic shelf (Wright et al., 1986; Swift et al., 1986; 2003).

Long-Term Effects of Storm Impact and Implications for Barrier Shoreline Management

The Timbalier Islands are migrating landward in response to rapid relative sea level rise in a system that has a large sediment deficit. As the islands migrate landward, so does the inlet throat. This process involves sediment deposition in the seaward-most reaches of the channel as the ebb-jet widens and velocity slows. Large storms accelerate this process as indicated by the shoaling of the seaward portions of the inlet channel and erosion of the landward portion. The relatively thin barrier sand deposits of the Mississippi River Delta Plain are thickest at tidal inlets, and as transgression ensues, shoreface ravinement destroys all but the basal portion of the tidal inlet fill.

The inlet fill and ebb tidal delta deposits at Little Pass Timbalier have been used as a source for nourishment projects on adjacent barrier islands. A site of laterally widespread and deep (1.5 m) erosion developed landward of the main TE-40 dredge pit on the ebb tidal delta (Fig. 4). While the latest nourishment project (TE-40) at Timbalier Island helped to maintain barrier integrity throughout the active 2005 Hurricane season, the dredge borrow pit is located within the zone of swash bar formation and could have potentially interrupted the episodic inlet sediment bypassing process at Little Pass Timbalier. Also, in response to the excavation of sediment contained within the ebb tidal delta, surrounding areas of the ebb delta eroded in order to attain an equilibrium elevation across the shoal (Figs 4 and 10.). The adjustment to a new equilibrium ebb tidal delta surface elevation after the removal of sediment results in increased water depths across the ebb tidal delta, necessitating larger wave heights for sediment transport to occur.

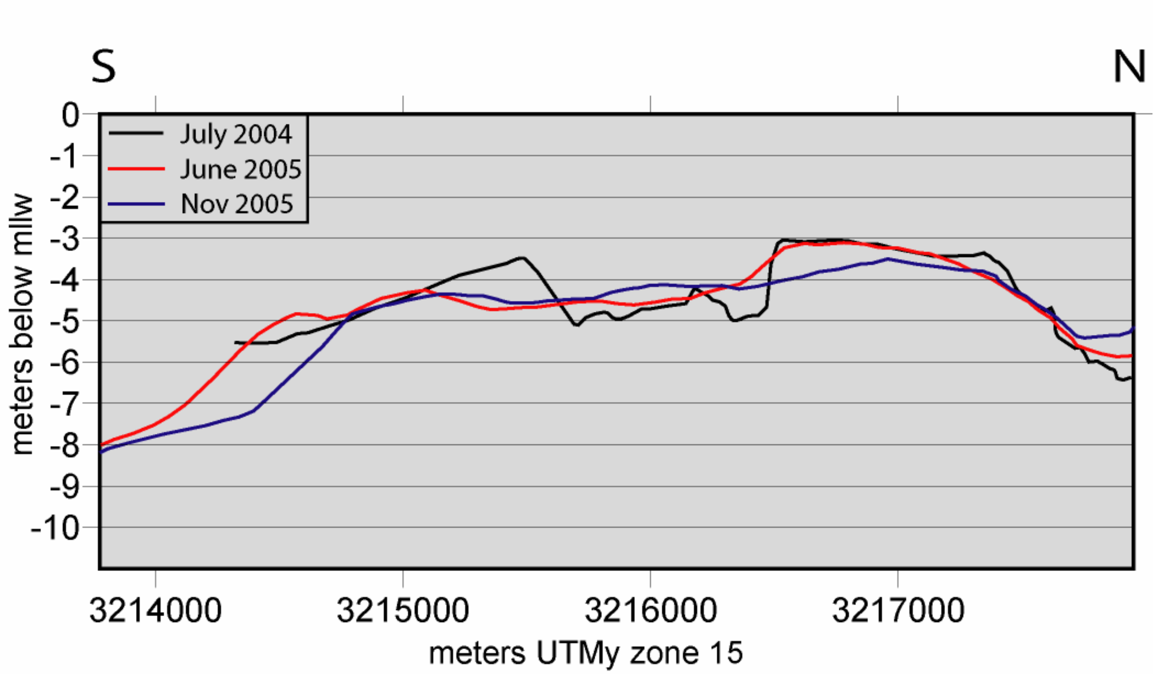

Figure 10. Bathymetric profile trending north – south across the ebb tidal delta. The July 2004 survey was conducted during dredging operations for the LADNR TE-40 Timbalier Island Dune/Marsh Restoration Project. Ultimately 3.5 x 106 m3 of sediment were removed by the end of 2004 and placed along the downdrift Timbalier Island shoreline. Note the erosion seaward of the dredge pit (see Figure 4 for aerial extent of erosion associated with the dredge pit) and the overall loss of elevation across the ebb-tidal delta.

Tidal inlets of the south central Louisiana coastal zone undergo rapid and large-scale changes in morphology due to the impacts of tropical cyclones. The transgressive barrier shorelines of the Mississippi River delta plain are undergoing rapid degradation due to inlet widening and formation of new inlets, a process that is driven by increasing backbarrier tidal prism volume. Increasing tidal prism volume also results in an increased amount of sediment that can be sequestered in ebb tidal deltas (Walton and Adams, 1976). Along the Louisiana coast, the expansion of some ebb deltas results in progradation onto the shelf as the islands migrate landward (FitzGerald et al., 2004; Miner et al., 2005). Throughout the historical morphological evolution of Little Pass Timbalier, storm events have led to inlet widening, breaches that form new stable ebb channels, and landward inlet migration. The impact of storms also results in a redistribution of sediment and drives sediment bypassing at Little Pass Timbalier. The deficiency of sediment available for recovery, coupled with the effects of subsidence and increasing tidal prism results in the rapid changes that occur during storms to have an irreversible and lasting effect on the inlet system. An understanding of the continual and event-driven sediment transport processes such as those described here at Little Pass Timbalier is crucial for effective barrier/inlet management. This is important for the long-term sustainability of barrier nourishment projects, as well identification of suitable sand borrow sites.

CONCLUSIONS

1. The bathymetric change analysis of pre and post-Hurricane season bathymetry for Little Pass Timbalier show that shoaling occurred across the proximal ebb tidal delta, within the ebb channel, and in marginal flood channels. Most of the erosion took place at island spits, shoals, and along the terminal lobe of the ebb tidal delta. A net decrease in sediment volume of $10.7 \times 10^6 \pm 3.6 \times 10^6\ m^3$ occurred at the study area between June 2005 and November 2005. A possible redeposition site is downdrift of Little Pass Timbalier along the lower shoreface of Timbalier Island. This was an area of accretion from 1880 to 1980 (List et al., 1994; Jaffe et al., 1997).

2. The main ebb channel accreted on its eastern flank and eroded on its western flank. Along the axis of the main channel, shoaling occurred in the seaward portion and erosion occurred in the landward portion. This pattern of landward scour and seaward shoaling results in migration of the inlet throat in a northeasterly direction and is consistent with the long-term pattern of inlet migration for the period from 1930 to 2005, but at a dramatically increased rate. During the period from 1930 to 2005 the inlet migrated 3250 m. Data in this study show that during the 11-month period between July 2004 and June 2005 the inlet migrated 30 m. However, during 5 month period from June 2005 to November 2005 when three major tropical cyclones impacted the area, the inlet migrated 160 m. Documentation of inlet channel migration and backfilling processes in a regime of rising sea level and shoreline recession is important in recognizing tidal inlet fill deposits within transgressive shoreface stratigraphic packages.

3. During prolonged periods of calm weather, sediment bypassing at Little Pass Timbalier is minimal due to a paucity of longshore-derived sand as well as a relatively deep ebb tidal delta that does not reduce wave energy in the nearshore. Rather, waves are easily propagated across the ebb tidal delta platform and up the inlet throat before breaking in the backbarrier area. A large volume of sand that is stored as in intra-inlet shoal during calm weather is dispersed during storm events. The destruction of the intra-inlet shoal and dispersal of sediment throughout the inlet system makes sediment available on the ebb tidal delta for bar formation and episodic bypassing at Little Pass Timbalier.

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CHAPTER 5

STRATIGRAPHIC ARCHITECTURE OF A LANDWARD-MIGRATING TIDAL INLET IN RESPONSE TO RAPID RELATIVE SEA-LEVEL RISE AND INCREASING TIDAL PRISM

INTRODUCTION

The Mississippi River delta plain (MRDP) coastal zone is currently undergoing an erosional transgression (*sensu* Curray, 1964; Swift, 1968) driven by high rates of relative sea-level rise (RSLR) in excess of 1 cm/yr (Penland and Ramsey, 1990; Tornqvist, 2006). These high rates of RSLR result in shoreface retreat and a landward migration of the shoreline at rates of more than 3 km per century. Shoreface retreat rate is the dominant control on barrier and tidal inlet lithosome development and preservation potential for MRDP barrier, inlet, estuarine, and lower delta plain deposits.

The stratigraphic architecture that develops during a transgression is dependent upon the rate of RSLR, sediment availability, wave climate, tidal range, and antecedent geology (Belknap and Kraft, 1981; Demarest and Kraft, 1987). In a continuously retreating shoreline system such as the abandoned Lafourche deltaic headland of the MRDP, the basal strata of tidal inlet systems have the highest preservation potential (Kumar and Sanders, 1974; Demarest and Kraft, 1987). This is a consequence of the relatively deeper incision that characterizes tidal inlets because of tidal scour into underlying sediments. As the shoreline and active tidal inlet throat migrate landward, accommodation space created by the tidal scour is subsequently backfilled and ebb tidal delta deposits overlay the filled inlet channel. If the depth of tidal ravinement is deeper than that of shoreface ravinement, the inlet fill strata will be preserved. The high preservation potential, relative to penecontemporaneous barrier deposits, of transgressive tidal inlet fills and associated bounding surfaces are important for identifying barrier associated deposits of transgressive systems tracts and improving the understanding of former sea level positions.

RSLR rates and associated shoreline retreat rates for the MRDP are so high that historical nautical charts capture the geomorphic evolution, thus enabling a detailed stratigraphic framework to be directly linked to processes and the resulting geomorphology. This makes the MRDP coastal zone an ideal study area for the investigation of transgressive processes and resulting stratal architecture. The tidal inlet retreat path for Little Pass Timbalier was determined based on a morphological evolutionary model constructed from recently acquired bathymetric data and an 1880's to 1980's historical bathymetric change analysis conducted by List et al. (1994). High resolution subbottom profiles and vibracores were sampled along the locations of the inlet retreat path determined from the morphological evolutionary model and these data were used to interpret facies relationships and stratal geometry of the transgressive tidal inlet system. In this way, the morphology and processes influencing inlet evolution are related to the resulting stratigraphy. The goal of this study is to gain an understanding of the stratal geometry, facies, and preservation potential of the inlet fill in a regime of rapid RSLR and coastal retreat, and ultimately to construct a process-response stratigraphic model for transgressive tidal inlet systems.

BACKGROUND

Stratigraphy of Tidal Inlet Channels

Tidal inlet deposits represent a significant portion of the sedimentary facies preserved within barrier island systems, both modern (Hoyt and Henry, 1965; Kumar and Sanders, 1974; Berelson and Heron, 1985; Moslow and Tye, 1985) and ancient (Barwis and Makurath, 1978; Reinson et al., 1988; Uhlir et al., 1988; Cheel and Leckie, 1990). This is due to the depth to which the tidal inlet channels scour and their ability to migrate laterally along the shoreline, reworking previously deposited sediments. This high preservation potential leads to inlet fill constituting as much as 50% of the subsurface of many modern barrier islands (Hoyt and Henry, 1967; Heron et al., 1984; Moslow, 2004). There are numerous Holocene inlet-fill stratigraphic models that have been presented (Hoyt and Henry, 1965; 1967; Ingram, 1968; Kumar, 1973; Kumar and Sanders, 1974; Oomkens, 1974; Greer, 1975; Hayes and Kana, 1976; Hubbard and Barwis, 1976; Moslow and Heron, 1978; Hubbard et al., 1979; Susman and Heron, 1979; Hayes, 1980; Hine and Snyder, 1985; Moslow and Tye, 1985; Demarest and Kraft, 1987; Nummedal and Swift, 1987; Siringan and Anderson, 1993). However, most of these are heavily based on one or two factors therefore tend to become site-specific examples. Much of the literature for inlet channel migration and channel fill stratigraphy applies to coarse (relative to the very fine-grained MRDP) clastic shorelines where the inlet is filled by lateral spit migration (e.g. Hoyt and Henry, 1965; 1967; FitzGerald, 1976). There is a lack of literature that focuses directly on transgressive tidal inlet stratigraphy using subsurface data. A few authors have touched on the subject when addressing regional transgressive stratigraphy (Allen and Posamentier, 1994; Lericolais et al., 2001) or inlet fill that develops from localized changes in inlet geometry (Imperato et al., 1988).

Despite a large number of tidal inlet studies, most of which are theoretical in nature and lack stratigraphic data, the existing inlet-stratigraphy models do not readily apply to the transgressive tidal inlets of Louisiana because of: 1) the dominantly fine-grained nature of the MRDP, 2) the high rates and depths of shoreface retreat, and 3) the lateral stability of many of the inlets. Exceptions to the laterally (alongshore) stable inlets of the MRDP exist at leading edges of laterally migrating, flanking barrier islands such as is the case with Cat Island Pass and Timbalier Island (Suter and Penland, 1987; Peyronnin, 1962). This location along the leading edge of a laterally migrating flanking barrier island has a relatively abundant sand supply derived from longshore transport and therefore, lateral inlet migration is the result of lateral spit accretion and infilling of the channel.

The stratigraphy of tidal inlet systems is complex because a variety of interacting processes that control styles of deposition (accretion) and influence preservation potential (erosion). This is especially true for tidal inlets of transgressive coasts because shoreface erosion may truncate much of the barrier ~~system~~ stratigraphy; even the uppermost portion of a transgressed channel fill is rarely preserved (Kumar and Sanders, 1974; Demarest and Kraft, 1987; Dalrymple et al., 1992). Shoreface erosion has been closely correlated to the rate of RSLR, and high rates result in a greater preservation potential (Belknap and Kraft, 1981). The bounding surfaces formed during the transgression of an inlet result from tidal scour (tidal ravinement surface) and wave-bottom interaction (wave or shoreface ravinement surface) (Nummedal and Swift, 1987; Cattaneo and Steel, 2003). The tidal ravinement surface is a scour surface that marks the base of the tidal inlet channel environment and is the stratigraphic boundary that separates the underlying and adjacent fluvial, estuarine, or deltaic facies from the tidal inlet fill. The shoreface ravinement surface is a scour surface that represents storm wave base. The relationship between the tidal ravinement and shoreface ravinement leads to a fundamental concept with regard to preservation potential of an inlet stratigraphic package: for preservation to occur, the depth of tidal ravinement must be greater than that of shoreface ravinement.

Besides having the highest preservation potential of barrier deposits, transgressive inlet channel fills are also important to understand because of the modifications that occur to antecedent deposits by tidal scour during transgression. Tidal inlets may coincide with the mouth of an estuary if it occurs along a barrier coast and the size of the opening is governed by the tidal prism. During a transgression, the inlet migrates landward up the estuary axis and may modify the antecedent incised fluvial valley fill as well as truncate erosional surfaces produced by fluvial systems previously active within the valley (Foyle and Oertel, 1997). The tidal ravinement surface that originates at the thalweg of the landward-migrating tidal inlet progressively extends updip along with transgression (Allen and Posamentier, 1993). If an inlet is migrating laterally (alongshore) as it migrates landward the tidal ravinement surface may be widespread regionally. The presence of multiple inlets along a transgressive shoreline may contribute significantly toward a geographically extensive erosional surface. As the inlet migrates laterally along the barrier island, previous barrier deposits are scoured and inlet fills develop above a sharp erosional basal contact and subjacent to the wave or shoreface ravinement surface, which is capped by lower shoreface sand and mud (Demarest and Kraft, 1987).

In order to fully understand tidal inlet stratigraphy for transgressive systems it is essential to construct a comprehensive model that considers a range of barrier/inlet system depositional environments and processes, morphologic evolution, and facies architectures. Comprehensive models have been proposed (e.g., Hubbard et al., 1979), however they are hypothetical and assume a transgression with 100% preservation of the inlet and barrier systems. Since many previously published studies assume lateral migration as the forcing mechanism of inlet fill sedimentation, these models apply to shorelines for which longshore processes dominate over shore-perpendicular process, indicating a relatively stable sea level.

This study of tidal inlets along the transgressive south-central Louisiana coast provides an opportunity to determine the stratigraphic signature and geometry for channel fill within inlet retreat paths. Because of the relatively high preservation potential of tidal inlet fills in transgressive systems tracts, an understanding of the stratigraphic signature of inlet channel fill provides a basis for interpreting the initiation, duration, and rate of sea level fluctuations in transgressive deposits.

Inlet Channel Fill and the Holocene Transgression

Inlet fill sediments have been the focus of many studies because of their preservation potential and utility in identifying the former locations of barrier islands that were beveled by shoreface erosion (e.g. Sanders and Kumar, 1975; Panageotou and Leatherman, 1986). The basic model for the development of inlet fill sedimentary packages is derived from the study of modern inlet fills produced by the lateral migration of an inlet along a stable barrier shoreline (Hoyt and Henry, 1965; 1967; Kumar and Sanders, 1974; Moslow and Heron, 1978). However, these lateral accretion models may not be applicable to transgressive barriers in which inlets do not migrate great distances parallel to the barrier but instead migrate landward in a shore normal direction. During a transgression, the backfilling of inlet scars may contribute toward a markedly different sedimentary package and seismic signature than those that characterize, or are predicted by, existing models. Multiple studies of the U.S. Atlantic inner continental shelf have attempted to identify inlet channel fill lithosomes in order to determine the presence of mid-

Holocene transgressive barrier shorelines (Hine et al 1979; Hine and Snyder, 1985; Panageotou and Leatherman, 1986). However no convincing evidence has identified transgressive inlet channel fill preserved on the Atlantic shelf. This study of Little Pass Timbalier tidal inlet will provide a better understanding of tidal inlet fill geometry characteristic of a landward migrating inlet/barrier complex.

DATA BASE AND METHODS

In order to determine the location of inlet fill sediments along the inlet retreat path, digital elevation models were constructed from historical bathymetric maps (1880’s to 1980’s) and newly acquired bathymetric data (Chapter 2). Overlays of the DEMs from various time periods were used to determine preservation potential of inlet fill by assessing the depth of modern wave ravinement verses the depth of tidal inlet ravinement from the historical data (Fig. 1). In areas where tidal inlet ravinement was deeper than the depth of wave ravinement it was assumed that the inlet fill sedimentary package would be preserved along the retreat paths. Subbottom profile transects and core locations were picked to capture the inlet fills on the basis of the morphological evolutionary model, with the intent of correlating geomorphic response to stratigraphic architecture (Fig. 2). This approach provided an opportunity to link process and resulting stratigraphic form.

In order to define the character of the inlet fill lithologic units, cores were sampled along the modern inlet throat and areas flanking the channel. The primary objective was to identify the stratigraphic and sedimentologic character of the modern sediments comprising the inlet system. Deciphering the stratigraphic response to shoreline/inlet evolution was plausible because of the detailed historical shoreline and bathymetric records. Coupled with stratigraphic information these data provide an advantage to relating stratigraphy to process. With this in mind, vibracores were sampled perpendicular to the relict channel axis at three different sites, each of which represented the former location of the inlet throat for the 1880’s, 1930’s, and 1980’s.

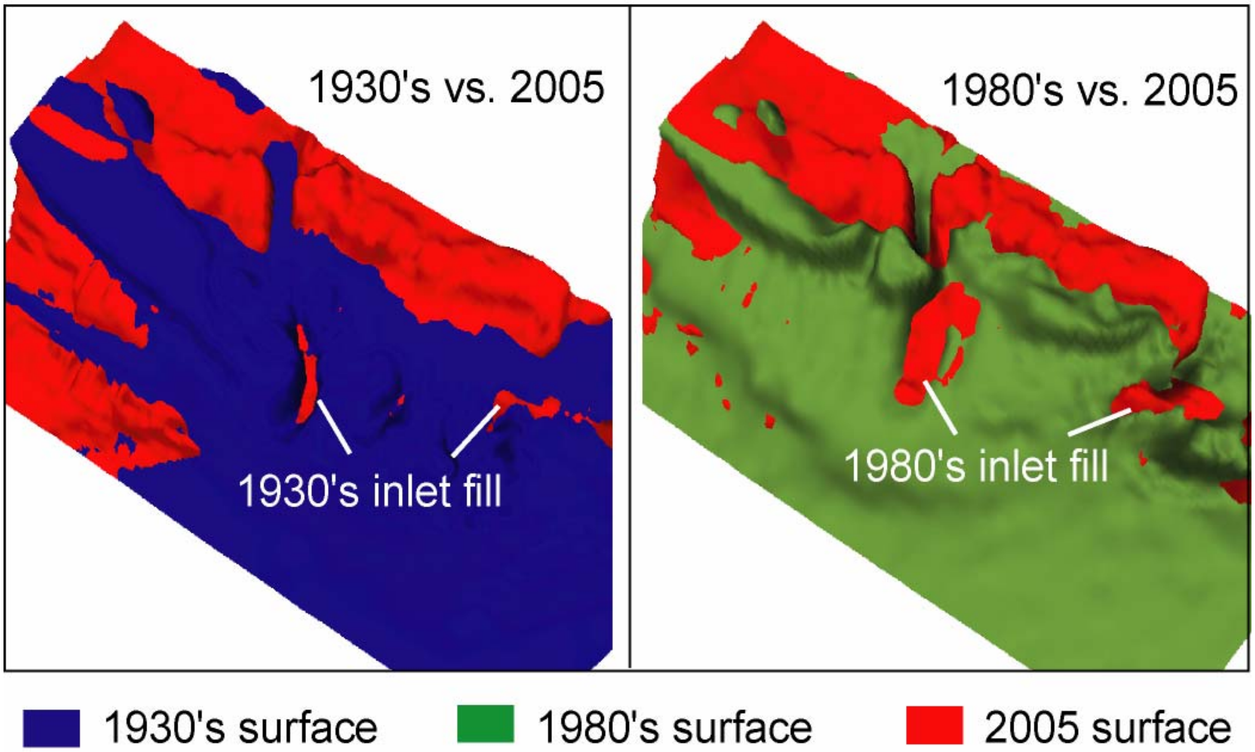


Figure 1. Results from an overlay analysis that was conducted in order to determine preservation of inlet fill along the Little Pass Timbalier landward migration path. Digital elevation models (DEM) were created for several time periods and the surfaces from historical data were merged with the 2005 surface in order to visualize the locations of areas that had undergone shoaling along the inlet retreat path. Areas in red show where deposition has occurred since the time of the earlier surface (1930's or 1980's). Subbottom profiler transects and vibracore locations that targeted the inlet fill along the retreat path were picked based on this analysis. Note that the 1880's surface is not shown because the small amount of inlet fill remaining on the shelf was not resolvable on a DEM. The 1930's and 1980's bathymetric data is from List et al. (1994).

Geophysical Data

A team of U.S. Geological Survey (USGS) and University of New Orleans (UNO) coastal scientists collected 875 line km's of high-resolution single-channel seismic reflection (HRSP) and CHIRP sonar reflection profiles during 2001, 2004, and 2005 summer cruises aboard the USGS *R/V G. K. Gilbert*. Of the 875 line-km, 55 line-km were obtained specifically for this stratigraphic investigation of Little Pass Timbalier. The high-resolution, single channel seismic and sonar reflection profiles were collected using BOOMER and CHIRP systems, respectively. The BOOMER system uses an acoustic source with a range from 2.0 to 6.0 kHz and a resolution of approximately 1.0 m (Kulp et al., 2002). The

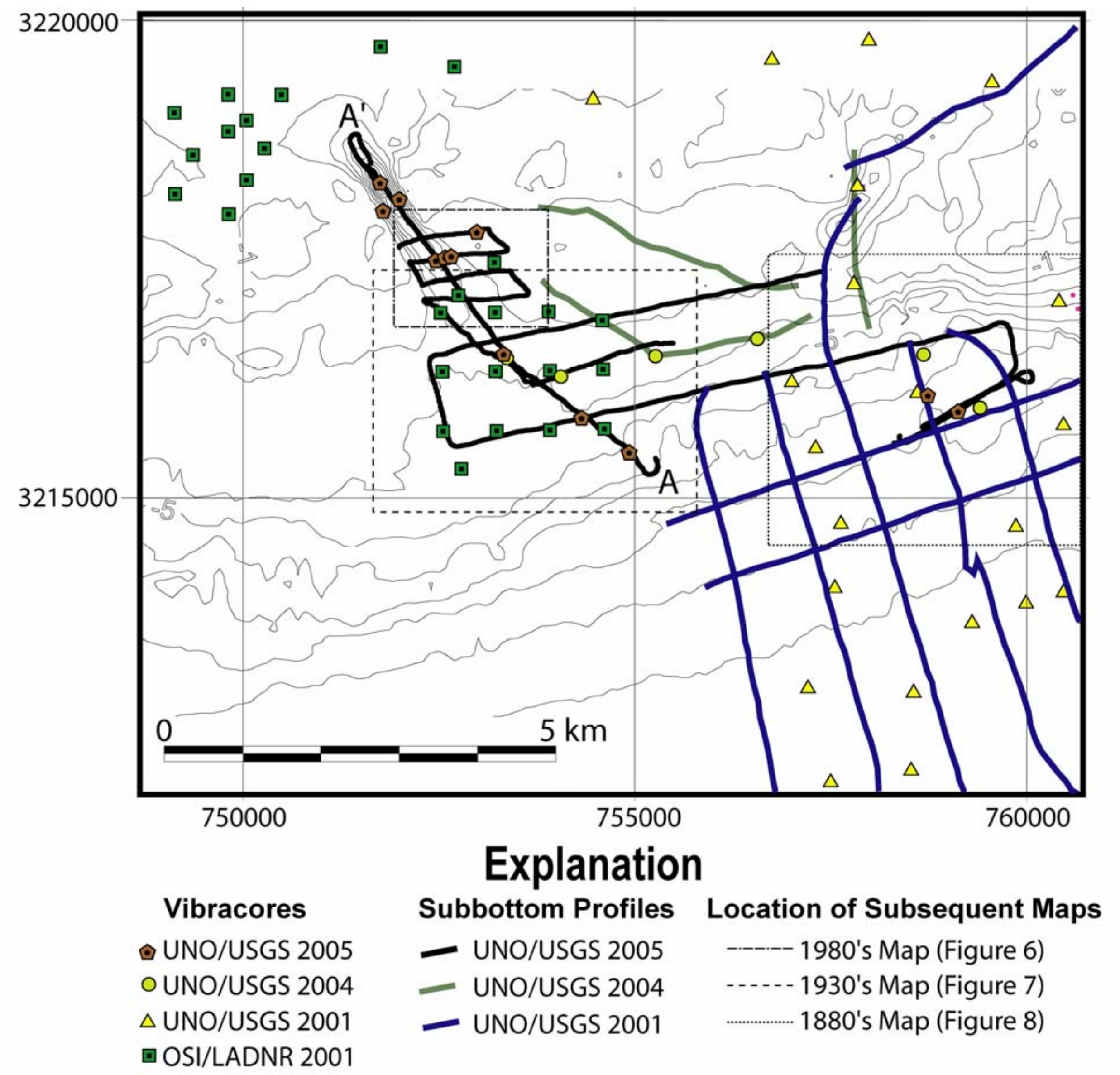


Figure 2. Vibracore and subbottom profile coverage for the Little Pass Timbalier study area. Bathymetry is from November 2005 relative to mean lower low water (MLLW) and the contour interval is 1 meter. Grid coordinates are in meters for Universal Transverse Mercator (UTM) Zone 15. The dashed rectangles indicate the location of maps covered in subsequent figures.

CHIRP system is an FM sonar source with a range from 4.0 to 24.0 kHz and a resolution of approximately 0.2 to 0.6 m (Kulp et al., 2002). Raw acoustic data was collected in the field and post-processed at the USGS Center for Coastal and Regional Marine Studies in St. Petersburg, Florida. HSRP and CHIRP profile lines for this study were picked to traverse former inlet channel locations along the inlet's migration path, a known trajectory on the basis of the historical bathymetric data sets from List et al. (1994). The morphological evolutionary model for Little Pass Timbalier that was presented in Chapter 3 additionally provided a means to pick core locations. The profiles were then interpreted and used to determine locations for vibracore sampling for identification of seismic facies, defining stratal geometry and relationships, and seismic analysis verification.

Vibracore Data

Two recently conducted sand resource studies, Kulp et al. (2002) and Ocean Surveys, Inc. (2002) contained sediment vibracore samples from within the study area. These data points were compiled into a database that contained 161 locations. Eighteen additional vibracores were sampled specifically for this study during the 2004 and 2005 summer cruises aboard the USGS *R/V G. K. Gilbert*, with their locations chosen on the basis of historical bathymetric datasets, a morphological evolutionary model for Little Pass Timbalier, and high-resolution single-channel seismic reflection profiles.

The vibracoring system aboard the *R/V G. K. Gilbert* consists of a 208 volt electric powered *Rossfelder P-3* underwater vibracore head mounted to a 7 m-long rigid frame. This system is capable of sampling at depths of as much as 650 m. The system uses core barrels are 6.1 m-long and 7.6 cm-diameter aluminum irrigation tubes with brass core catchers riveted to the interior of one end. Core penetration rate and depth below the seafloor are measured real time using an electric wire-line penetrometer. The vibracore rig is deployed, positioned, and recovered using a *Hiab* hydraulic crane mounted on the deck of the *R/V G. K. Gilbert*. Positioning and depth of coring locations were determined using a *CSI* wireless differential global positioning system (DGPS) with wide area augmentation system (WAAS) output and an *Innerspace* dual 200 kHz transducer single-beam echosounder, respectively.

Vibracores were split in half lengthwise and described in detail to identify sedimentary texture and structures, percent sand, physical characteristics, stratification type, sample type, fauna, and overall stratal relationships. Vibracores were then cut down to 1 m intervals and photographed. After complete documentation the cores were wrapped in vinyl sleeves and archived in the UNO Department of Earth and Environmental Sciences core warehouse. Vibracore descriptions for all cores sampled for this study are included in Appendix A.

RESULTS

Lithofacies

Lithofacies interpreted in the study area represent depositional environments of both the regressive and transgressive components of the delta cycle. Facies classifications were made using, texture, sedimentary structures, faunal assemblages, facies associations, and stratigraphic relationships. This study relates previously deposited sediments to the modern environment of the same system (e.g. inlet fill and the modern inlet channel) and therefore the documented depositional environments provide the opportunity to identify each sedimentary facies.

For this research the regressive environments and sedimentary facies nomenclature are derived from Coleman (1981), a scheme that was developed for the modern Mississippi River deltaic sedimentary environments and stratigraphy and has gained widespread acceptance in deltaic literature. Regressive facies in the study area include prodelta, delta front, distributary, and bayfill deposits. Overall, these genetically-related environments coarsen upward, display unidirectional paleo-current-directions, and contain relatively low marine fauna content.

Transgressive environments include bay, ebb tidal delta, ebb channel, marginal flood channel, barrier/spit platform, and shoreface. Deposits of these environments are characterized by wave- and tide-generated sedimentary structures, extensive bioturbation, and high concentrations of marine mollusks. Transgressive tidal inlet facies nomenclature is derived and modified from Kumar and Sanders (1974), Hayes and Kana (1976), FitzGerald (1984), Penland et al. (1988), Suter et al. (1991), and Levin (1995). Seismic facies descriptions follow the terminology of Mitchum et al. (1977) and Berryhill et al. (1986).

Prodelta Facies

The prodelta environment represents the basal and seaward most portion of a prograding delta lobe. Numerous previous workers (e.g. Coleman, 1981) have shown that it consists of massive to horizontally laminated clays with rare silt lenses. The relatively high rates of deposition common to prodelta environments precludes most organisms and thus burrows and shell material are rare within these facies. Seismic characteristics of prodelta deposits include laterally continuous, horizontal to low-angle parallel reflectors that are locally interrupted by channel cut and fill features.

Delta Front

The delta front environment overlies the prodelta or bay-fill deposits and is the seaward sloping margin of the advancing delta lobe (Coleman, 1981). A proximity to the prograding distributary results in a relatively coarse grain size within delta front deposits compared to prodelta deposits. The delta front is recognized by the presence of silt and clay laminations with thin sand lamina or lenses. The delta front is represented by an overall coarsening upward unit consisting of smaller (~10-cm thick) fining upward units. Sedimentary structures include silt lenses, scour and fill, current ripples, and erosional truncations that separate fining upward sequences. Burrows and shell material are rare to nonexistent.

Bay-fill

Bayfill deposits are commonly represented stratigraphically by cyclic units indicating progradation and abandonment as crevasses or subdeltas form and prograde across an interdistributary bay. As accommodation space within the bay decreases, fluvial deposition ceases and marine forces and subsidence dominate. As subsidence continues, accommodation space increases and another bay-fill sequence is deposited. A typical bay-fill deposit consists of a basal interdistributary bay deposit overlain by prodelta clays that coarsen upward into delta front clays and silts usually underlying distributary mouth bar deposits, and capped by rooted marsh deposits. Bay-fill deposits commonly occur in the

MRDP as multiple, stacked coarsening upward units representing the cyclical relationship between accommodation space created by subsidence and reoccupation of that space by fluvial deposition. In the study area, however, no complete cycle was encountered; a likely result of removal by more recent tidal and wave processes.

Distributary

The distributary facies is representative of environments that are associated with distributary channel progradation and abandonment. In the study area distributary environments are represented by fine sands contained in lower channel fill or distributary mouth bar deposits. The presence of rafted organics and fining-upward intervals from silty sands to sandy silts represent the upper distributary channel fill. A complete distributary channel fill interval begins above a basal scour surface with overlying poorly-sorted sands and silts that contain organic material concentrated along bedding planes, fining upward into bioturbated silts and clays with occasional plant debris, which is capped by fine-grained organic debris and peats (Coleman, 1981).

The distributary mouth bar consists of cross-bedded sands and horizontally laminated sandy silts that are deposited under fluvial flow and high sedimentation rates. Thick beds of rafted woody organic material or "coffee grounds" commonly exist within the distributary mouth bar facies. Due to the proximity of the distributary mouth bar at the seaward terminus of the distributary mouth, depositional rates are higher here than in any other deltaic environment (Coleman, 1981). The deposits of the distributary mouth bar are the coarsest clastics in the Mississippi River system, and form an important coarse-grained component of the deltaic sediments that are ultimately are reworked and winnowed during transgression to form barrier islands.

Interdistributary Bay/Lagoon

The interdistributary bays are large expanses of open water separating major distributaries; examples include Timbalier and Terrebonne Bays. Sediments of the bay environments typically consist of sandy silts and clays with abundant bioturbation and a brackish water faunal assemblage. In rare examples where bioturbation is limited and primary sedimentary structures are preserved, lenticular-bedded fine sands and silts are contained within a silty clay matrix. In the study area, *Mulinia lateralis* and *Crassostrea virginica* dominate the bay deposits. Bay deposits are often conformably overlain by prodelta deposits in the study area. Locally however the bay deposits are commonly truncated by regional wave ravinement surfaces that are marked by a coarsening-upward gradational contact with a greater abundance of shells relative to other bay deposits.

Inlet Fill

Inlet Channel Lower –

The basal facies of the inlet fill represents the deepest portion of the inlet channel floor depositional environment. This facies includes the basal scour surface, representing the maximum depth of tidal ravinement, that is marked by shell hash and large oyster and gastropod fragments in a fine sandy clay to fine sand matrix (Fig. 3). Shells are abraded and the faunal assemblage consists of *Mulinia lateralis, Crastostrea virginica*, and marine gastropod fragments. Overlying the basal scour is a 10 to 50-cm thick, massive-bedded fine sand with abundant bedded organics and shell material. Clay drapes, flaser beds, and clay rip-up clasts are common within this unit. Some cores contain inclined bedding in this interval with bedding surfaces that are marked by shell hash or coffee ground organics. Shell content and organic content decrease upward and burrows are rare. The unit fines upward and is gradational into the overlying *inlet channel upper* facies. In some cores, several of these fining upward packages were present.

Inlet Channel Upper –

The lithology of the *inlet channel upper* facies varies substantially from core to core, which is likely a result of their proximity to sediment sources and depositional episodes produced by tropical cyclones and winter frontal systems. The *inlet channel lower* facies fines upward into the *inlet channel upper* facies with a contact that is sharp to gradational. The *inlet channel upper* facies consists of dusky

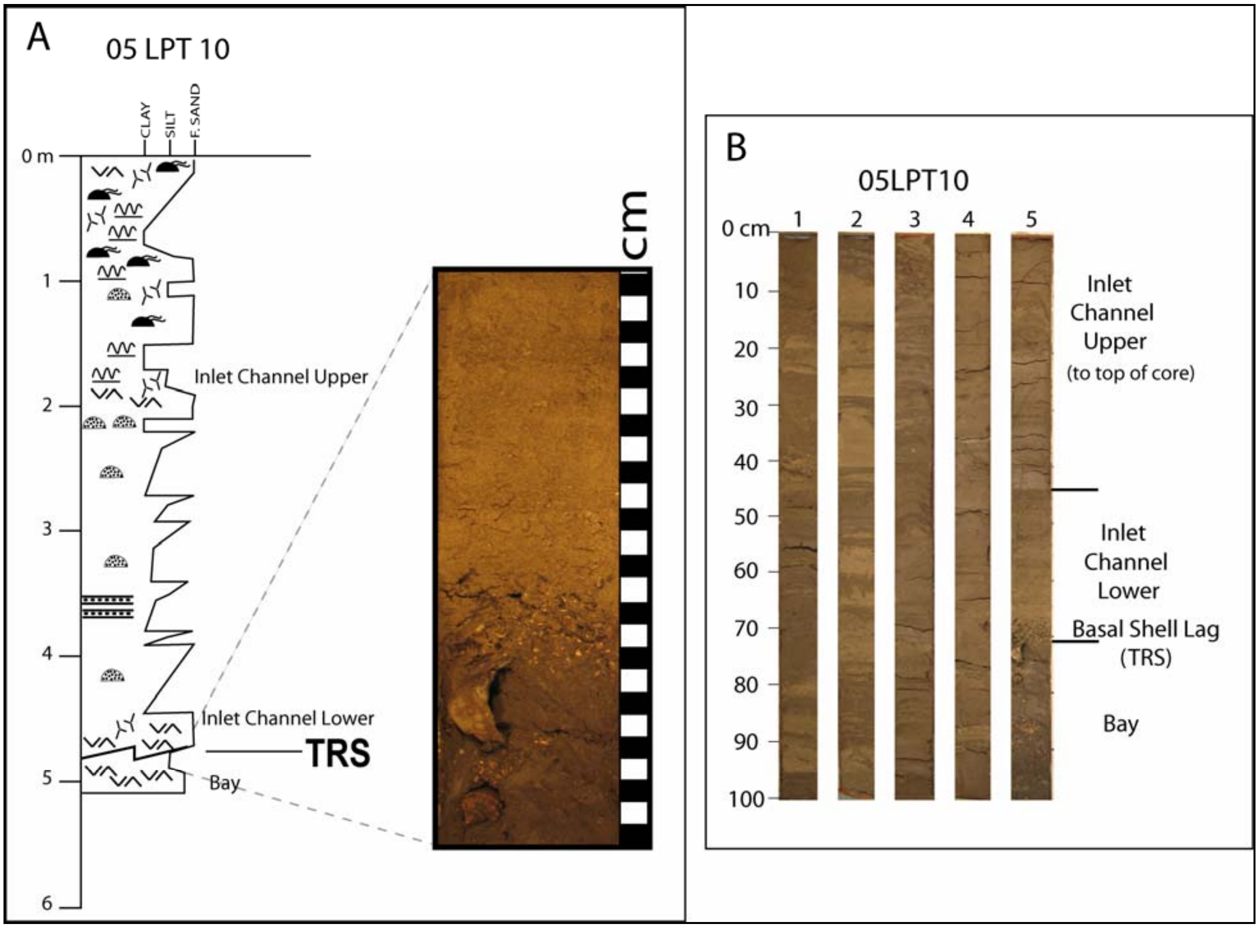


Figure 3. (A) Description and interpretation of vibracore 05LPT10 that sampled the thickest inlet fill interval. Note the photograph of the basal shell lag, which marks the tidal ravinement surface (TRS) and the base of the overlying *inlet channel lower* facies. See Figure 5 for vibracore symbol explanation. (B) Whole core photo of 05LPT10. Note the thickness of the inlet fill unit (4.74 m) and the lack of any overlying ebb delta deposits. Also note the abundance of mud (darker brown) as inlet fill relative to sand (tan) within the inlet fill. Location of core is proximal to the position of the inlet channel throat in the 1980's (see Figure 6 for core location and 1980's bathymetry).

yellowish-green to grayish-black, fine sand that is interbedded with dark, greenish gray-clays. The sedimentary structures within the facies of the *inlet channel upper* range from flaser, to wavy, to lenticular beds with some horizontal laminae of clay and some burrows. Millimeter-thick horizontal laminae of organics and *Mulinia lateralis* concentrations are present within the unit, with rare fragments and whole (disarticulated) valves randomly distributed throughout the sandier intervals. The *inlet channel upper* facies is an overall coarsening upward interval because of increased influence of ebb tidal delta depositional processes in the shallow parts of the channel. In some cores this facies contains multiple, fining upward sequences of approximately 10-cm thickness, consisting of bedded fine sand to flaser to wavy bedded clays separated by sharp erosional contacts. Additionally, some cores include multiple, stacked intervals that contain 10 to 20-cm thick clays that coarsen upward into 1-cm thick silt lenses and ultimately 1 to 4-cm thick fine sands that are capped with coffee ground bedded organics and highly abraded shell material. In cores located in the seaward most portions of the channel, the uppermost unit of the inlet fill is a coarsening upward interval that is gradational into overlying ebb tidal delta deposits. This contact can often be identified by a vertical increase in shell and organic material and a decrease in clay. This uppermost inlet fill interval consists of heavily bioturbated, massively bedded, dusky yellowish-green clayey fine sands with rare 1-cm thick dark greenish-gray clay interbeds. Of the total shell content approximately 0.5% is *Mulinia lateralis* fragments, whole (disarticulated) valves, and rare articulated specimens. Clay clasts are common and sometimes heavily saturated with water giving them an aqueous consistency.

Channel Margin Linear Bar

Cores 05LPT07 and 05LPT07A, which sampled along the margin of the inlet channel in approximately 2 m water depth and core 05LPT06 in 5 m of water flanking the inlet throat, were used to define the inlet channel margin facies. This facies consists of massive and burrowed fine sand as much as 2-m thick with occasional flaser beds of clay, bedded “coffee ground” organics and abraded shell material, and randomly dispersed whole (disarticulated) valves and articulated *Mulinia lateralis*. This massive bedded sand represents channel margin linear bar deposition as migrating swash bars intersect the ebb channel (c.f. FitzGerald, 1976). Some clay clasts and clay-filled burrows are present in the sand. Underlying and interfingering the massive sand are 10 to 30-cm thick intervals of flaser beds containing mm-thick beds of organic debris and shell hash. It is suggested that these units represent ebb channel flank or marginal flood channel deposits.

Marginal Flood Channel

The marginal flood channel fill facies consists of flaser, to wavy, to lenticular bedded grayish brown to dark gray clays and fine sand. The unit coarsens upward except for the top of the unit, which is marked by an abrupt increase in clay, abundant fine-grained organics, and shell material. This upper fine-grained and organic-rich bed represents the abandonment of the marginal flood channel where fines were deposited in the trough of migrating swash bars before ebb tidal delta deposition became dominant. Shell content decreases downward. Sand and shell-filled burrows are present in the more clay-rich intervals. The base of the unit is marked by rafted wood fragments and shell fragments. Shell content includes fauna typical of bay (*Mulinia lateralis* and *Crassoctrea virginica*), inlet (*Astrangia astreiformis*), and shoreface and surf zone (*Perticola pholadiformis*) environments (Parker, 1960).

Ebb Tidal Delta/Swash Platform

The ebb tidal delta facies overlies inlet fill, deltaic, and bay deposits in the study area with a basal contact that varies from sharp to gradational with underlying units. The lithology consists of coarsening upward, massive-bedded pale yellowish-brown to grayish-brown fine sand with abundant *Mulinia lateralis* and oyster shell fragments (Fig. 4). Also present are “coffee ground” organics within distinct mm-thick beds and randomly distributed throughout the unit. Burrows are common throughout the ebb tidal delta facies and some zones are bioturbated to the extent that they possess a mottled appearance. Rare clay beds are present toward the base of the ebb tidal delta unit.

Seismic reflection characteristics of the ebb tidal delta package locally include a distinct basal reflector in some places, however the hard-packed sand that comprises the ebb delta can inhibit acoustic penetration and imaging. Consequently, much of the underlying geometry was not resolvable in areas with thick ebb tidal delta deposits as overburden. A regional stratigraphic study of the Barataria coastline, adjacent to the study area, determined that much of the seismic data was obscured at the surface where ebb tidal delta deposits are present (Flocks et al., 2006).

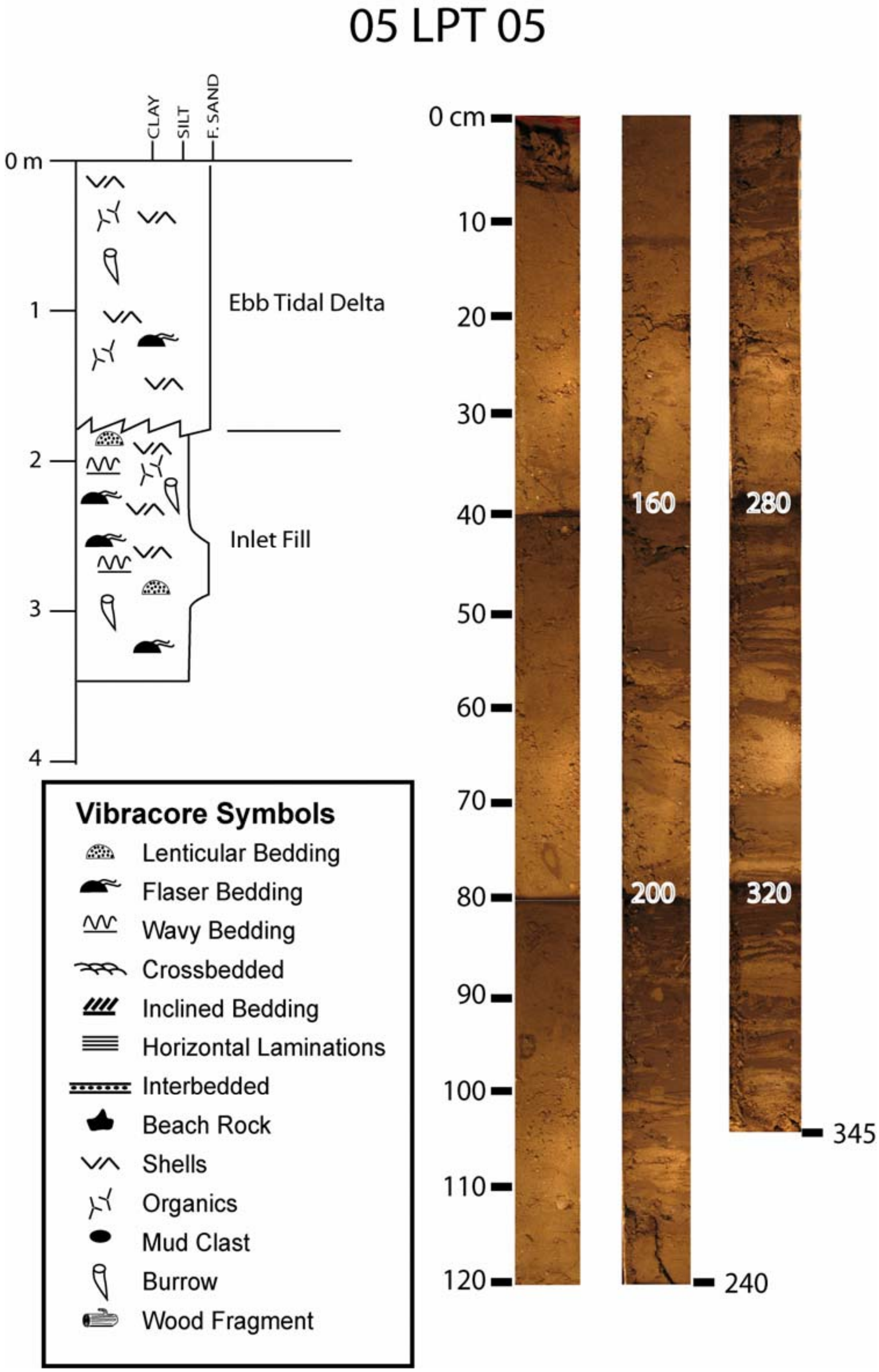


Figure 4. Vibracore 05LPT05 showing ebb tidal delta deposits overlying inlet channel upper facies inlet fill deposits. Note the burrowed, massive sands with sparse shell material that is characteristic of the ebb tidal delta facies (above 180 cm). The upper inlet fill consists of flaser to wavy to lenticular bedded sand and mud with shell and organic material. Location of vibracore on Figure 6.

DISCUSSION

Transgressive Inlet Fill Stratigraphic Architecture

Inlet fill vertical sedimentary intervals were identified within the Little Pass Timbalier landward retreat path along three separate inlet-channel perpendicular transects, which were derived from the available historical data (1880's, 1930's, and 1980's) of the inlet location (Figs. 5-7). The inlet fill thickness and facies relationships are variable along the inlet retreat path and thin seaward as ebb tidal delta deposits thicken. This change in facies and thickness is closely linked to increasing exposure to wave processes (Figs. 8 and 9). The youngest stratigraphic section (1980's) shows a more complete inlet fill interval than the 1930's or 1880's with little or no overlying ebb tidal delta deposits (Figs. 10 and 11). The 1930's vertical section shows an inlet fill interval overlain by relatively thick (2 m) ebb tidal delta deposits (Fig. 12). The 1880's section has a thin lower inlet fill and a thin veneer of ebb tidal delta sands that are preserved within the channel fill on the shelf (Figs. 13 and 14). The inlet fill facies is the result of sediment accumulation above the inlet basal scour diastem that marks the transgressive tidal ravinement surface. Inlet filling is the result of depositional processes within the inlet channel and eventually the infilling by ebb tidal delta sands as transgression proceeds.

A dip-line seismic profile oriented along the inlet retreat path shows a scalloped seismic facies that is interpreted, on the basis of the geometry of reflectors and vibracores, as inlet channel cut and fill and the transgressive tidal ravinement surface (Fig. 8). Reflectors comprising the fill are chaotic above the scalloped basal reflectors. In a strike-oriented section that cuts across the position of the 1980's inlet throat, a strong reflector interpreted to represent the basal scour surface coincides with the location of the shell lag in core 05LPT10 (Fig. 3). Also in the strike section are sets of tangential oblique clinoforms that represent lateral accretion surfaces along the inlet channel margin. These reflectors correlate with textural variations in core 05LPT12. Offshore East Timbalier Island, at the relict 1880's position of Little Pass Timbalier, a Boomer seismic profile shows a complex channel fill reflection configuration that truncates underlying and laterally adjacent reflectors (Fig. 11). A CHIRP profile along the same transect shows a channel fill that truncates the adjacent and underlying reflectors with a fill characterized by complex, chaotic, and reflection free fill. Cores in the area show a lower inlet channel fill facies overlying and adjacent to prodelta and distributary deposits (Fig. 12).

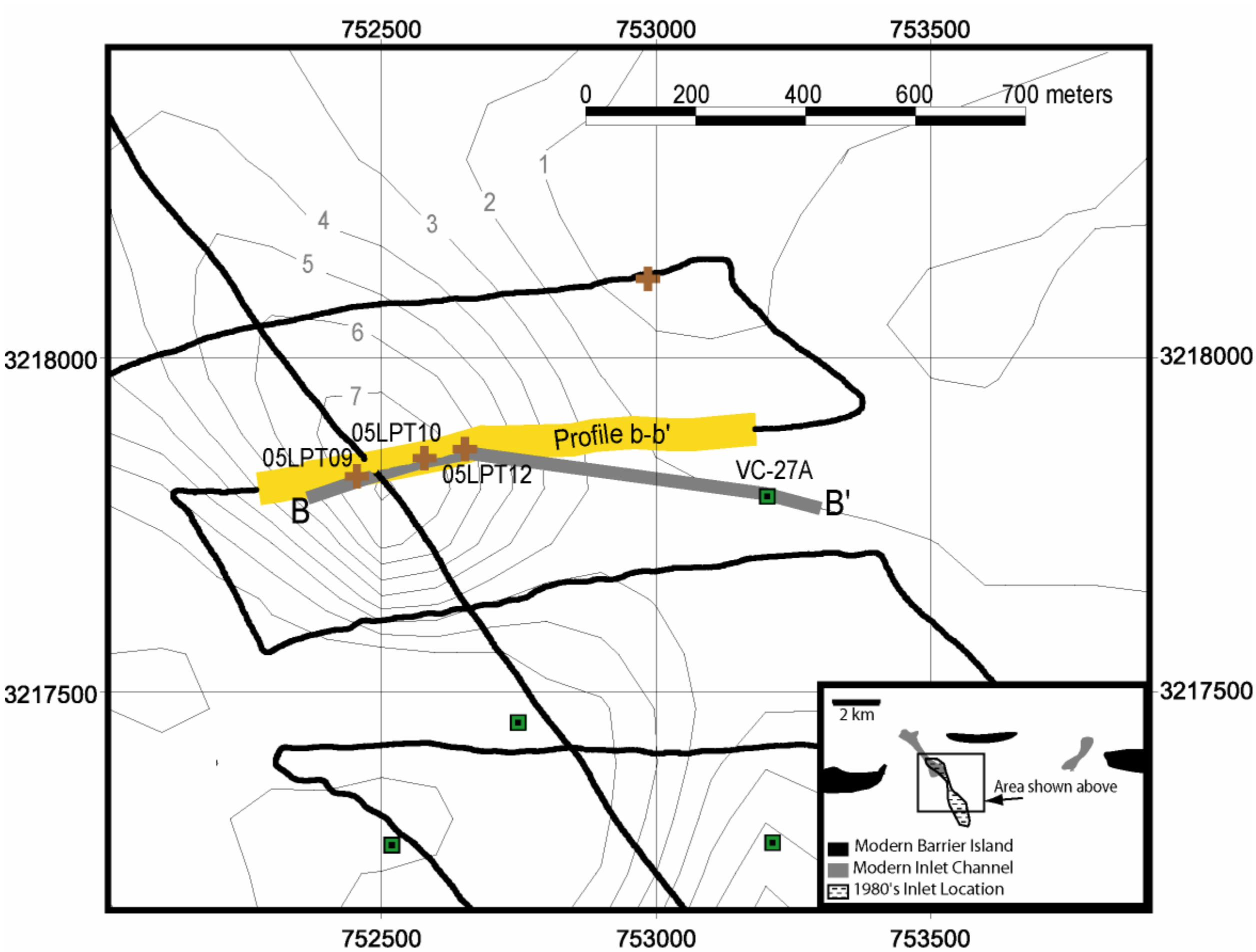


Figure 5. Map showing 1980's 1 m bathymetry for the Little Pass Timbalier inlet throat and location of vibracores for stratigraphic cross section B-B' and the transect for subbottom profile b-b' (Fig. 9). Location of map within the Little Pass Timbalier inlet system can be found in Figure 2. Bathymetric data from List et al. (1994).

Inlet Fill Facies Relationships

The facies descriptions presented in this study are representative of the lithologic variability present in the sediment cores along the inlet retreat path. Many factors control the resulting lithology of the inlet fill along the retreat path including tropical cyclones, frontal systems, variations in longshore sediment transport, substrate in which the inlet is scouring, tidal prism changes, and high discharge events of the Mississippi River (prior to artificial containment in the 1920's).

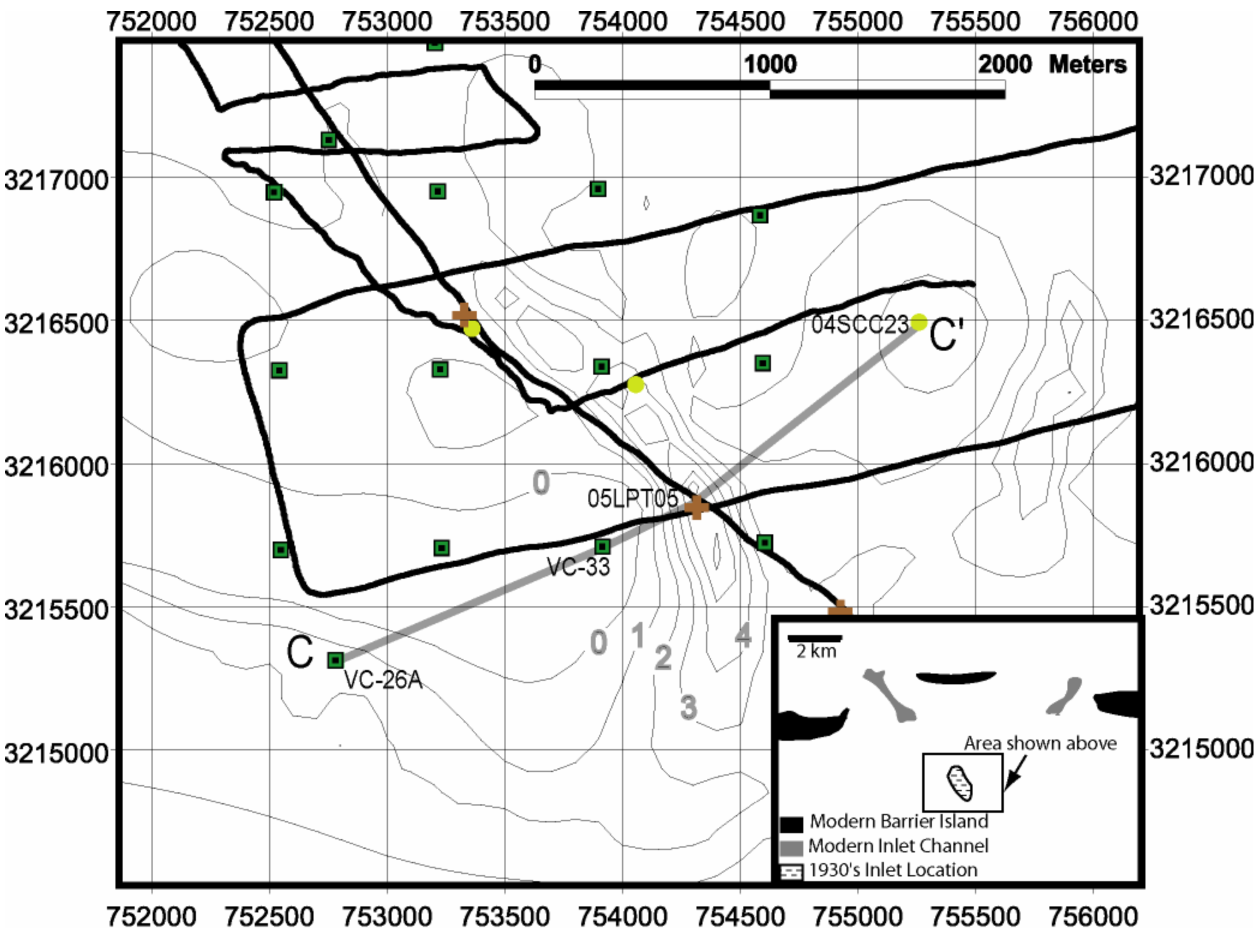


Figure 6. Map showing Little Pass Timbalier 1 m bathymetry for the 1930's inlet throat location. Vibracore and subbottom profile locations used for the stratigraphic analysis are shown and the line of section for the stratigraphic cross section C-C' (Fig. 10) is indicated by the bold gray line. Location of map within the Little Pass Timbalier inlet system can be found on Figure 2. Bathymetric data from List et al. (1994).

Little Pass Timbalier tidal inlet migrated landward at an average rate of 44 m/yr between 1930 and 2005 (List et al., 1994, Chapter 3). The inlet fill at Little Pass Timbalier is the result of backfilling as the channel migrates landward and wave processes deposit swash bar sand into the channel, deposition of fine-grained material during times of high suspended load concentrations, deposition of coarse-grained material along the channel axis, and lateral accretion due to spit growth. The lower channel facies is the result of deposition within the active channel throat which is dominated by relatively coarse-grained bedload (fine sand and shells) and suspended load fines. The upper channel facies consists of mud that is commonly deposited during times of increased suspended sediment concentrations driven by the passage of winter frontal systems when waves suspend muds in the backbarrier and transport them seaward during north winds or by weak ebb tidal currents. Rapid, event-driven deposition of sand within seaward portions of the ebb channel, results from the passage of tropical cyclones as explained in Chapter 4.

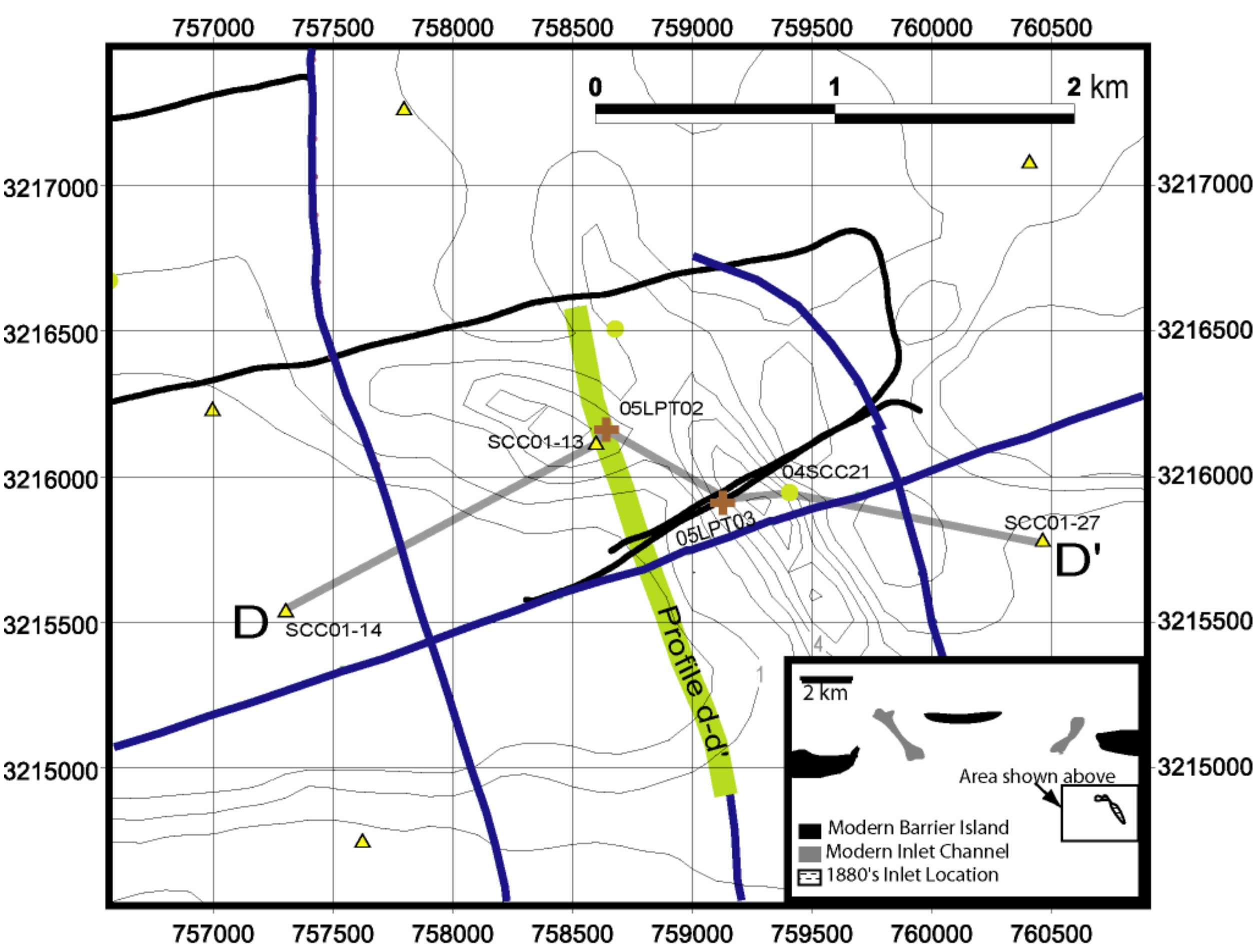


Figure 7. Little Pass Timbalier inlet throat 1 m-contour bathymetry map for the 1880's. Vibracores used for the stratigraphic analysis and the correlation of stratigraphic cross section D-D' (Fig. 12), and subbottom profile d-d' (Fig. 11) are labeled. Location of map within the modern Little Pass Timbalier inlet system can be found on Figure 2. Bathymetric data from List et al. (1994).

Figure 8. (following page) Subbottom profile (CHIRP) and interpreted stratigraphic cross section (A-A') constructed from vibracores trending north along the axis of the Little Pass Timbalier main ebb channel. Location of the seismic profile is shown in Figure 2. Note that the subbottom profile does not trend directly along the retreat path, and the stratigraphic section contains an additional vibracore (VC-28) that is offset to the east from the subbottom profile transect and penetrates a deeper inlet fill interval. The relict ebb tidal delta interpreted from the seismic and vibracore data is attributed to an earlier Lafourche Delta Complex delta lobe progradation and subsequent transgressive shoreline that is associated with a relict barrier trend located seaward of the Timbalier Islands.

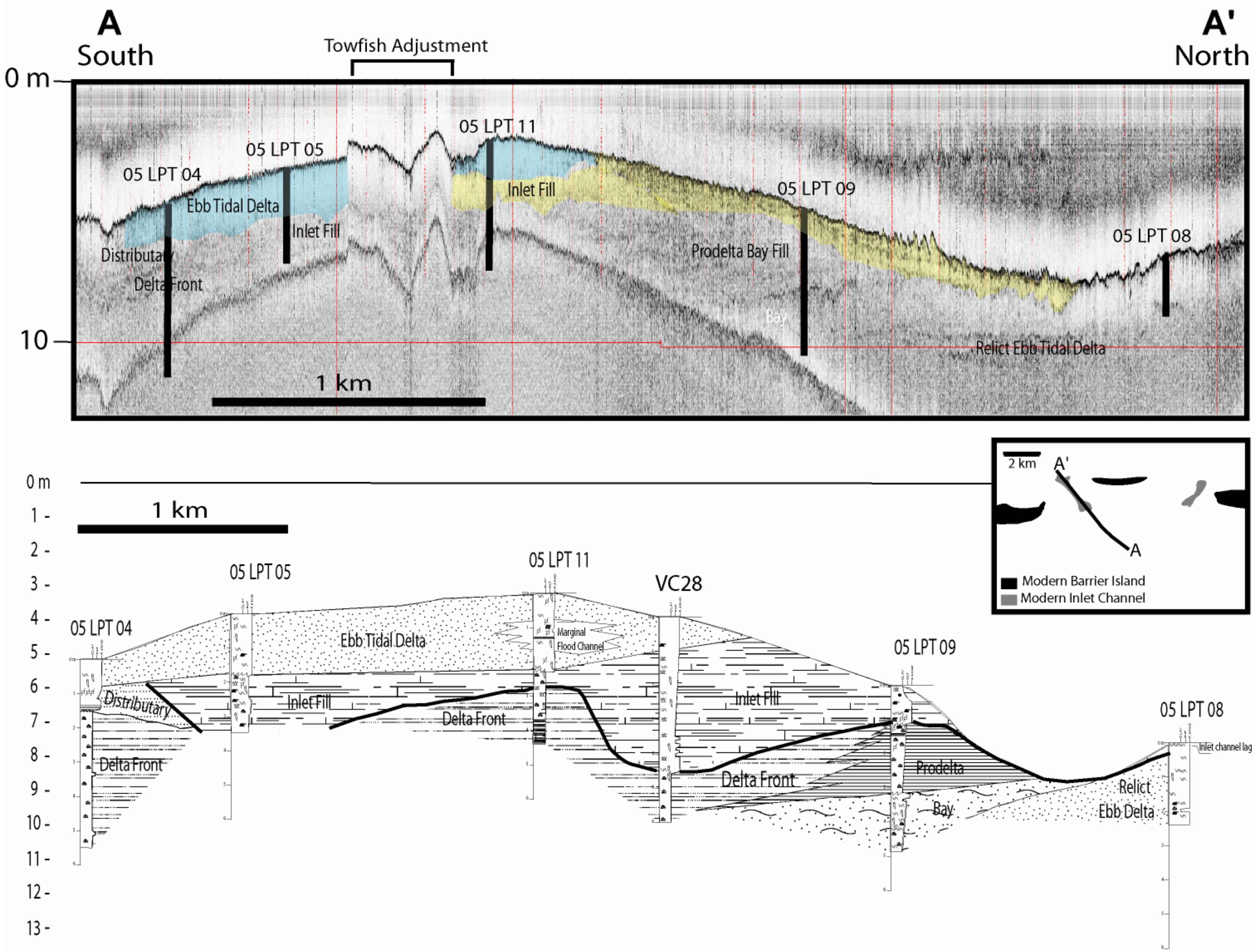
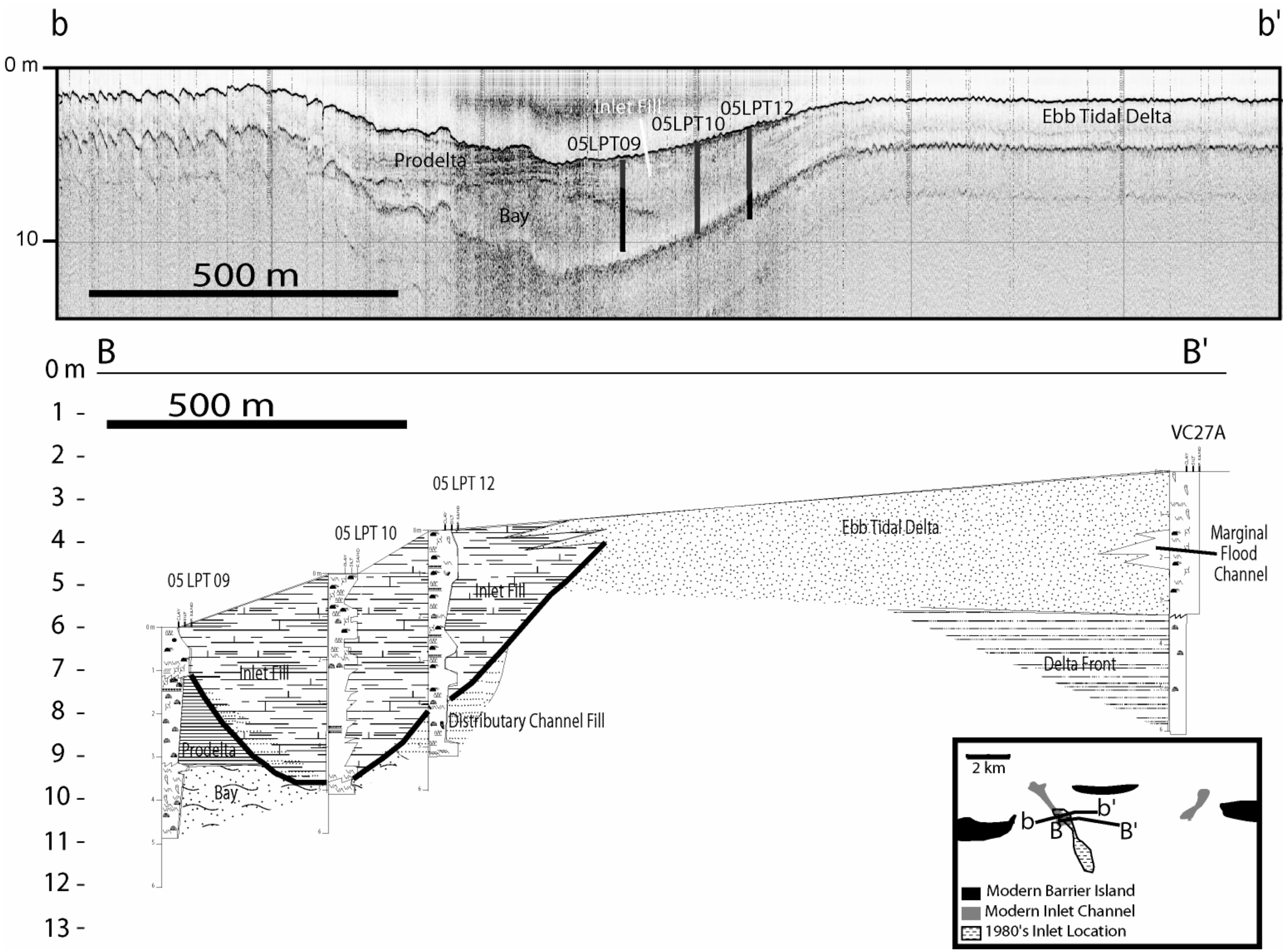

A
South
A'
North
Towfish Adjustment
0 m
10
05 LPT 04
05 LPT 05
05 LPT 11
05 LPT 09
05 LPT 08
Ebb Tidal Delta
Inlet Fill
Inlet Fill
Distributary
Delta Front
Prodelta Bay Fill
Bay
Relict Ebb Tidal Delta
1 km
0 m
1 -
2 -
3 -
4 -
5 -
6 -
7 -
8 -
9 -
10 -
11 -
12 -
13 -
1 km
05 LPT 04
05 LPT 05
05 LPT 11
VC28
05 LPT 09
05 LPT 08
Ebb Tidal Delta
Marginal Flood Channel
Distributary
Inlet Fill
Delta Front
Inlet Fill
Delta Front
Delta Front
Prodelta
Bay
Relict Ebb Delta
Inlet channel lag
2 km
A'
A
Modern Barrier Island
Modern Inlet Channel

Figure 9. (Following page). Subbottom profile (CHIRP) b-b' and stratigraphic cross section B-B' interpreted from vibracore and subbottom profile data. Section trends perpendicular to the seaward portion of the modern ebb channel axis and transects the location of the 1980's inlet throat. Note that there are no ebb tidal delta deposits capping the inlet fill interval unlike the more seaward section (Figure 10) in which ebb tidal delta deposition has begun to override the inlet fill. Location of cross section and subbottom profile transect can be found in Figure 5. Also, note the correlation to the 1980's morphology depicted by the bathymetry in Figure 5 and the bounding surfaces (tidal ravinement surface) in the stratigraphic cross section and subbottom profile.



b
b'
0 m
10
500 m
Inlet Fill
05LPT12
05LPT10
05LPT09
Ebb Tidal Delta
Prodelta
Bay
B
B'
0 m
1
2
3
4
5
6
7
8
9
10
11
12
13
500 m
VC27A
05 LPT 12
05 LPT 10
05 LPT 09
Ebb Tidal Delta
Marginal Flood Channel
Inlet Fill
Inlet Fill
Delta Front
Distributary Channel Fill
Prodelta
Bay
2 km
b
b'
B
B'
Modern Barrier Island
Modern Inlet Channel
1980's Inlet Location

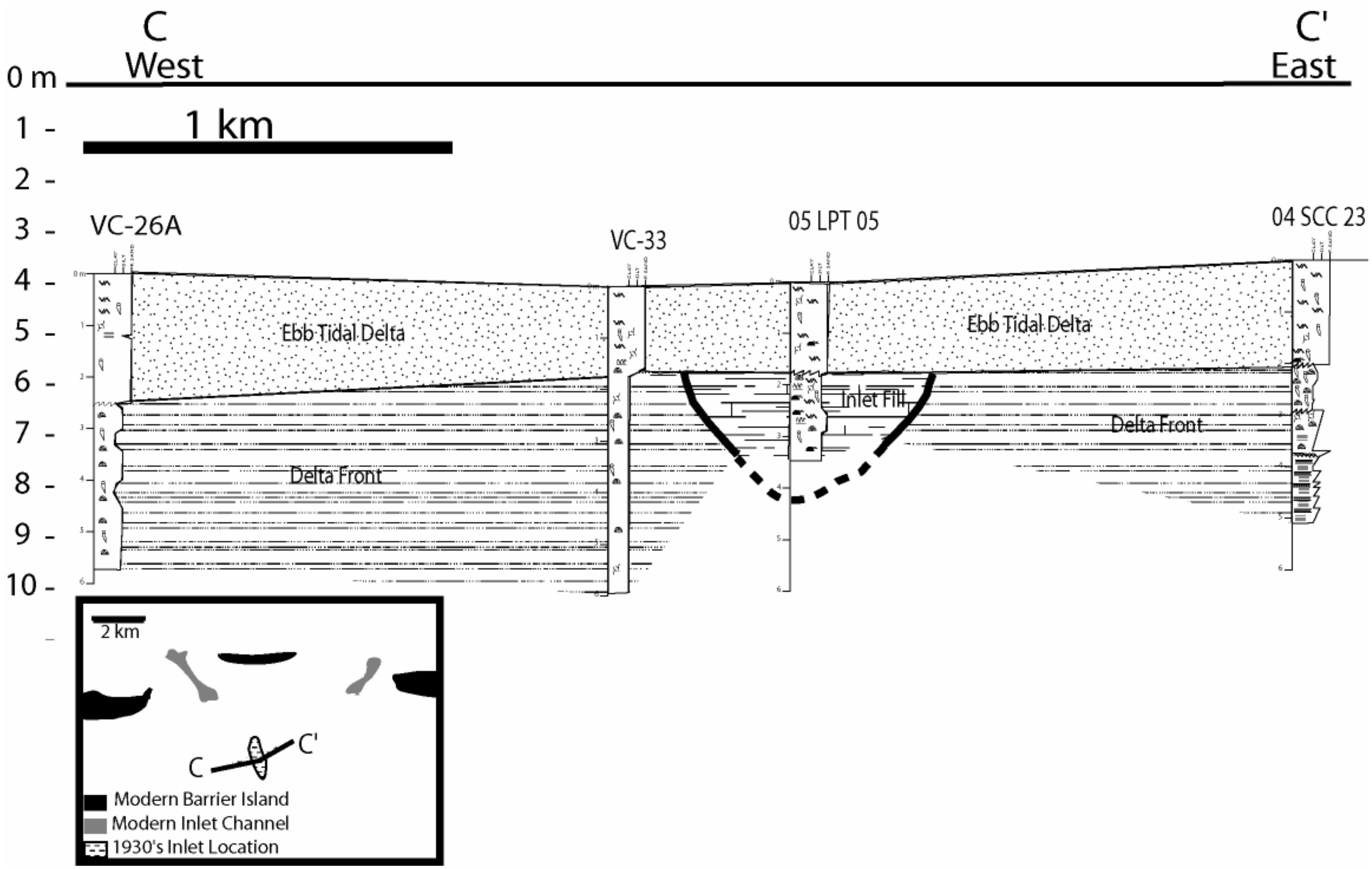


Figure 10. Stratigraphic cross section C-C' that trends perpendicular to the Little Pass Timbalier main ebb channel and is located on the modern ebb tidal delta. Note the inlet fill in vibracore 05LPT05 (did not penetrate entire section) that is overlain by ebb tidal delta deposits. Figure 6 shows the line of section for this cross section. Note the correlation between the basal scour surface of the inlet fill and the 1930's inlet morphology depicted by the bathymetry in Figure 6.

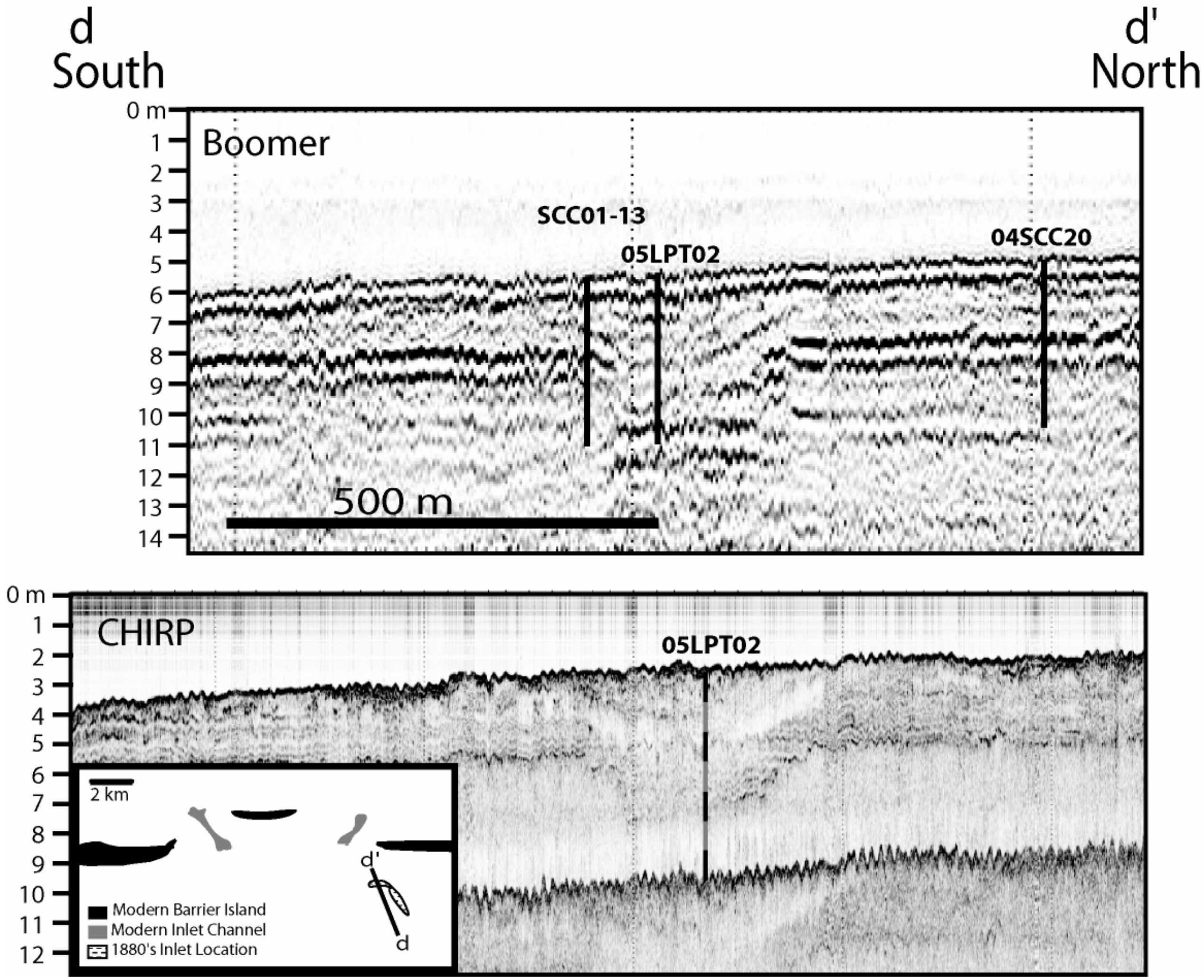


Figure 11. Boomer and CHIRP subbottom profiles that are located offshore the Little Pass Timbalier secondary ebb channel and transect the 1880's ebb channel position. Note the inlet fill seismic facies that is characterized by channel in channel and chaotic clinoforms patterns and also reflection free channel fill in the CHIRP profile. Profile transect is shown in Figure 8 and a stratigraphic cross section for the 1880's inlet channel is shown in Figure 12. Note that subbottom profiles do not trend along the same profile as the stratigraphic cross section in Figure 12.

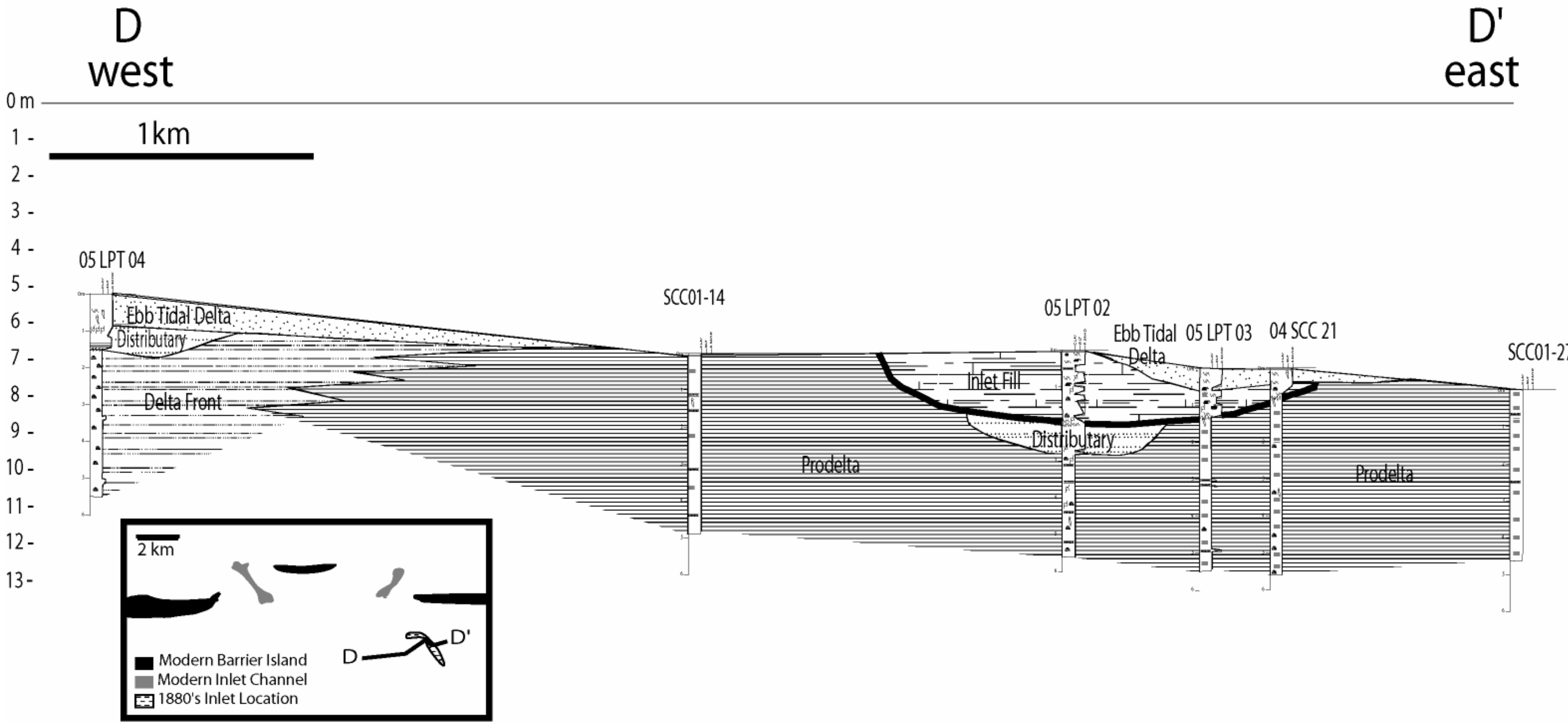


Figure 12. Stratigraphic cross section located offshore the eastern (secondary) ebb channel of Little Pass Timbalier that transects the 1880's main ebb channel. Note that the channel fill in cores 05LPT02, 05LPT03, and 04SCC21 is isolated on the shelf from any recent (1930's to present) inlet deposits and is surrounded by prodelta deposits into which the inlet channel incised while active at this location. The seafloor at this location is above the depth of modern wave ravinement (10 to 12 m) and therefore, if transgression continues at the present rate this section has a low preservation potential. The basal portion of the 1880's inlet channel is preserved on the shelf and is capped by a thin veneer of ebb delta deposits in some cores. Note that these are relict ebb delta deposits that were preserved in the bathymetric low formed at the distal ebb channel during the 1880's and are not part of the active Little Pass Timbalier ebb tidal delta that is shown to the west in vibracore 05LPT04.

As the inlet throat migrates landward the channel flanks are eroded and the former throat location widens. At this stage the channel shoals seaward of the throat and deposition is increasingly influenced by wave processes. Swash bars and channel margin linear bars migrate into the seaward terminus of the inlet channel (c.f. FitzGerald, 1976) and much of the muddy primary inlet fill becomes reworked, resulting in a relative increase of sand content vertically and a coarsening upward of the inlet fill deposit. The 1880's relict inlet channel locations, which are offshore and cut-off from modern inlet processes and ebb tidal deposition contain a small amount of ebb tidal delta sand locally that is confined along the inlet retreat path, adjacent to and overlying prodelta clays. Shoreface ravinement destroys almost the entire barrier lithosome and much of the inlet fill sequence.

The lower inlet fill facies represents deposition during active inlet channel processes that take place in the inlet throat at the deepest part of the channel. The rapid rate of transgression, as well as the continual infilling at the seaward portion of the channel, results in a situation in which there is high preservation potential for active channel deposits. This basal unit has the highest overall preservation potential of the entire barrier system.

The relative abundance of sand versus clay content in the *inlet channel upper* facies seems to be dependant upon location within the relict channel (i.e. proximal to the source of sand along the edges of the channel). In core 05LPT10 there are multiple coarsening-upward units. This core was located in the central portion of the 1980's relict throat location and a mud-dominated but coarsening-upward *inlet channel upper* interval is 4.5 m thick, extending to the top of the core with no overlying facies (Fig. 3). Core 05LPT12, located approximately 75 m east of 05LPT10, and closer to the edges of the relict channel contains a higher sand content, and overall thicker sand beds. Cores sampled along the flanks of the modern channel throat showed similar lithologies.

The abundance of fine-grained sediments contained within tidal inlet fill of the south central Mississippi River delta plain is not surprising considering the overall fine-grained character of the delta plain. This is demonstrated by the mud-dominated expansive backbarrier bay and inner shelf environments compared to the paucity of sand contained within the barriers. Sedimentologic and stratigraphic investigations of the Bolivar Roads Tidal Inlet along the Texas Gulf Coast identified an inlet fill facies that ranges between clayey, silty sand and silty sand (Sirigan and Anderson, 1993), and an inlet bottom surface sediment distribution consisting of sand in the deepest portion and mud at intermediate depths along the inlet channel (Morton and McGowen, 1980). Sirigan and Anderson (1993) speculated that the presence of mud in tidal inlet channels reflects the dominance of tidal processes over wave processes and the fact that abundant fine-grained sediment is transported to the inlet. The work of Hoyt and Henry (1967) along the Georgia coast at Doboy Sound Inlet, concluded that a tidal inlet fill facies deposited by a laterally migrating tidal inlet contained layers of silt and clay in the troughs of large ripples. They suggested that the mud is deposited during times of weaker currents, and is subsequently buried as the large ripples migrate over the fine-grained material (Hoyt and Henry, 1967). Moslow and Tye (1985) described a mud-dominant inlet fill for tide-dominated inlets along the South Carolina coast, however the infilling of those inlets is driven by shore-parallel migration of the inlet. Inlet channels are abandoned as swash bars migrate and act to close the inlet mouth, resulting in a waning of tidal flow in the channel and promoting deposition of silt, clay and organics in the abandoned channel (FitzGerald, 1984; Moslow and Tye, 1985). None of the previously published models for inlet fill are applicable to Little Pass Timbalier because the dominant forcing mechanisms for inlet fill development are not longshore processes and shore-parallel inlet migration.

In Louisiana, the high percentage of fine-grained sediment comprising the inlet fill is related to estuarine flocculation rates and suspended sediment concentrations in the backbarrier bays and marshes during the passage of 20 to 30 winter cold fronts each year (Roberts et al., 1987; Georgiou et al., 2005). Prefrontal conditions produce strong southerly winds that impound water in the backbarrier, increasing water levels in the bays and marshes. As the front passes, winds shift quickly to northerly and the impounded bay waters are driven out the inlets. Northerly winds also produce moderate wave action along the back sides of the barriers. Wave action in the backbarrier coupled with the storm-induced currents suspends fine-grained sediment in bays, tidal creeks, and marshes, and transports it toward the inlets.

In an experiment conducted by Murray et al. (1993) in northern Terrebonne Bay during November 1991, instruments were deployed in a tidal creek to measure suspended sediment transport during a three-week period. Results showed that the marsh exported 3.8 x 10^6 kg of sediment during a three week period, and most of the flux took place during the first major northerly wind event of the season (Murray et al., 1993). Measurements made in the same area during periods of calm weather showed negligible sediment flux between the bays and marshes. Measurements made the previous December, when weaker northerly winds prevailed compared to the November 1991 event, recorded a net sediment flux *into* the marsh of 3.6 x 10^6 kg (Murray et al., 1993). Suspended sediment concentration is high in MRDP estuaries during periods of long-duration, increased wind velocities that result from cold front passage. Maximum settling velocities of fine-grained particles take place during periods of maximum suspended load concentrations (Prejup, 1991). Such conditions are produced during strong wind events such as frontal passages (Prejup, 1991). Flocculation increases exponentially with suspended load concentration producing larger flocs with relatively higher settling velocities (Metha, 1989; Pejrup, 1986; 1991). Also, sediment concentration decreases linearly with an increase in water depth because the flocs must have time to be deposited (Pejrup, 1991). This is a possible explanation for the dominance of clay at intermediate inlet channel depths, and sand dominance in the deepest section of the channel. Preexisting mud-rich deltaic deposits into which the inlet channel is scouring are also a source of fine-grained sediments, readily available within the channel for redeposition.

Stratigraphic Evolutionary Model and Preservation Potential

For transgressive tidal inlet systems, inlet fill sequences form narrow, elongated muddy sand bodies that are oriented mostly perpendicular to the strike of the shoreline. Stratigraphically, the deposits are erosionally bounded and the channel fill thins seaward and pinches out either at the location of inlet formation (e.g. storm breach) or at the shoreface ravinement surface if the depth of wave ravinement is greater than the depth of tidal ravinement. Transgressive tidal inlet fill accumulation is dominated by backfilling processes, and of lesser importance are lateral spit-accretion processes. The transgressive inlet fill facies is characterized by a basal erosional surface (tidal ravinement surface) overlain by abraded shell material and fine sands that are stratigraphically overlain by a fining upward interval of lower inlet channel sands. In the shallow portion of the inlet fill, the strata consist of flaser to wavy to lenticular bedded. The inlet fill facies grades upward into the ebb tidal delta facies that is characterized by massive bedded fine sand containing abundant shell fragments. The flanks of the inlet fill are marked by marginal flood channel and channel margin linear bar deposits that coarsen upward and interfinger with adjacent and overlying ebb tidal delta deposits. This inlet fill stratigraphic architecture is different from the sand-rich inlet fills produced by lateral inlet migration and spit accretion on sandier and more stable coastlines such as the Texas and Florida Gulf and U. S. Atlantic coasts (Fig. 13). The inlet fill geometry for laterally migrating inlets consists of erosionally bounded sets of shore-normal, lateral accretion surfaces that resemble fluvial point bars in cross-section. The rate of lateral inlet migration and the depth of the inlet determine the volume of inlet fill produced, but unlike the transgressive inlet channel fill, these deposits are shore-parallel and extend along the axis of the barrier. Laterally migrating inlet in regressive, stable, or aggradational barrier environments are characterized by an inlet sequence consisting of a basal erosional surface marked by coarse shell material, sand and gravel, that fines upward into muddy sands and is capped by spit platform and ultimately spit and eolian dune deposits (Kumar and Sanders, 1974).

Inlet fill preservation potential is dominantly controlled by the rate of RSLR; higher RSLR rates increase inlet fill potential. Also, in transgressive barrier systems, the dominance of shore-perpedicular procecess (overwash and tidal flushing) over shore parallel processes (longshore transport) results in more laterally stable tidal inlets. This results in different inlet fill stratigraphic architectures for transgressive versus stable or regressive barrier systems. This contrast in geometry should be taken into account when interpreting ancient transgressive deposits, as well as when using inlet fill preserved on the shelf to interpret late Holocene sea level and barrier island genesis and migration histories.

A study conducted along the inner continental shelf offshore Bogue Banks, North Carolina determined that all of the transgressive coastal lithosomes, including tidal inlet channel, had been removed by shoreface erosion (Hine and Snyder, 1985). A shoreface profile extended landward at Bogue

Banks shows that all but the deepest tidal channels would be removed with only 1–2 m of the deepest portions of those channels would be preserved, which is probably below the resolution of a regional seismic study (Hine and Snyder, 1985).

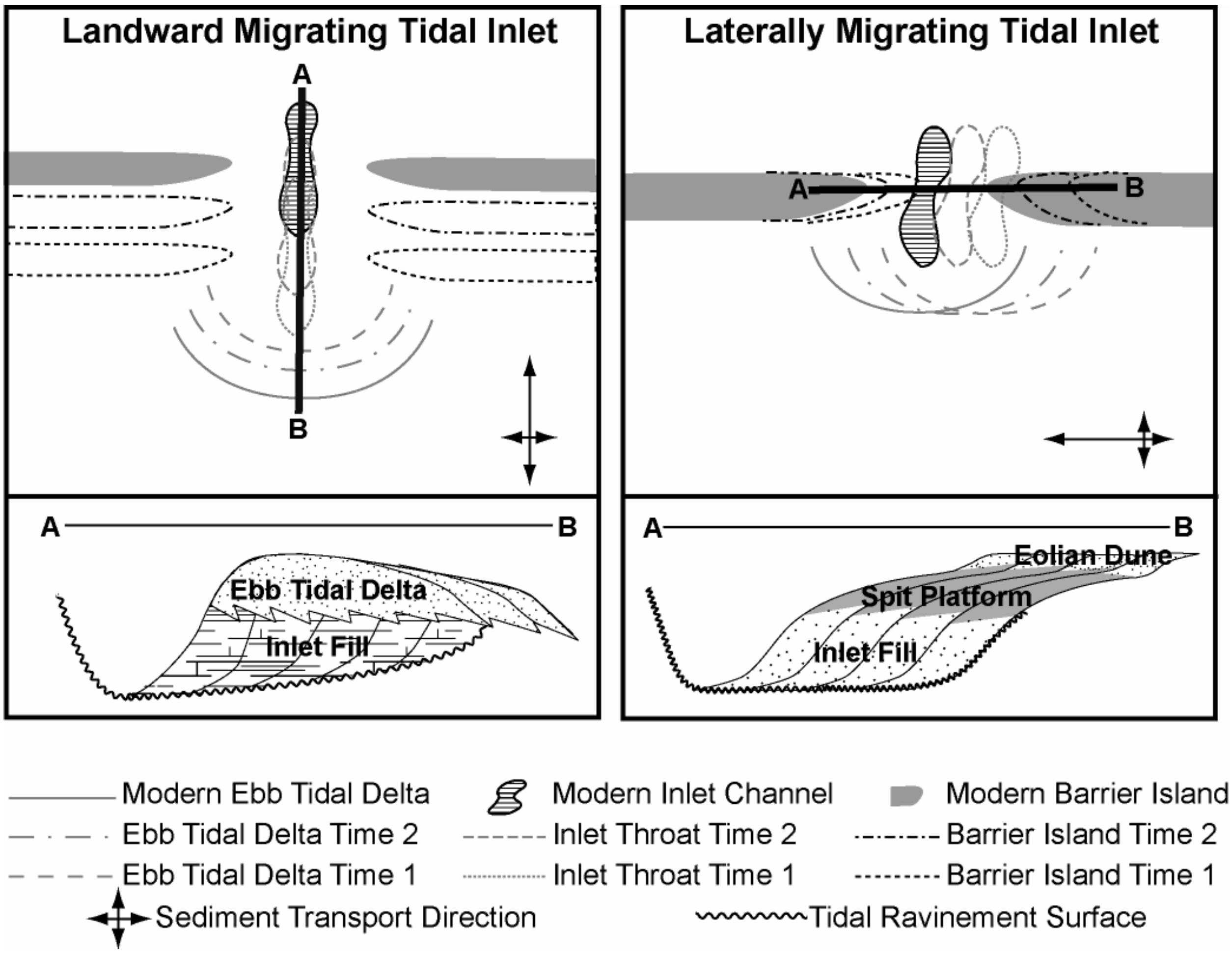


Figure 13. Conceptual models for stratigraphic architecture of landward and laterally migrating tidal inlets. Note that the landward migration produces an erosionally bounded dip-elongate stratigraphic package and the lateral migration produces an erosionally bounded strike-elongate stratigraphic package. The infilling of a landward migrating inlet is dominated by migration of swash bars into the channel, deposition of suspended sediment and bedload in the channel, and of lesser influence is lateral accretion from spit growth. The dominant process in the development of inlet fill at laterally migrating inlets is spit accretion. Note the different vertical sections that result from the two differing migration processes. For landward migrating inlets the inlet fill is muddy sand underlying ebb tidal delta sands. At laterally migrating inlets the sandy inlet fill is overlain by spit platform sands capped by eolian or barrier island sands.

The backfilling of the inlet channel is the result of three distinct modes of deposition that include; 1) lateral accretion, 2) wave influenced shore processes at the seaward terminus of the channel (e.g. migration of swash bars into channel), and 3) deposition of bed load and suspended load during periods of low velocity currents or increased suspended load concentration. The result of this tidal scour, landward inlet migration, and subsequent backfilling is a tidal inlet fill unit that is located seaward of the modern inlet system. The unit is laterally and subjacently bounded by a sharp contact (tidal ravinement surface) with deltaic sediments and capped by a second sharp contact (shoreface or wave ravinement surface) and overlying ebb tidal delta deposits. During and subsequent to the transgression, this inlet backfill has the highest preservation potential of the entire barrier lithosome, and for the Timbalier Islands, is the only part of the barrier system to be preserved on the shelf below the depth of wave ravinement.

The morphological evolutionary model described in Chapter 3 shows that the Little Pass Timbalier ebb tidal delta has been prograding seaward since at least the 1930's. The prograding ebb delta at Little Pass Timbalier protects and stabilizes its deep ebb channel, which allows backfilling of the channel to take place before complete excavation that will result from shoreface retreat. The subsidence-driven RSLR coupled with ebb-tidal delta progradation and increasing tidal prism volumes, increases the potential of tidal inlet fill preservation because the distance between the tidal ravinement and shoreface ravinement surfaces is continually increasing with time (Fig. 14).

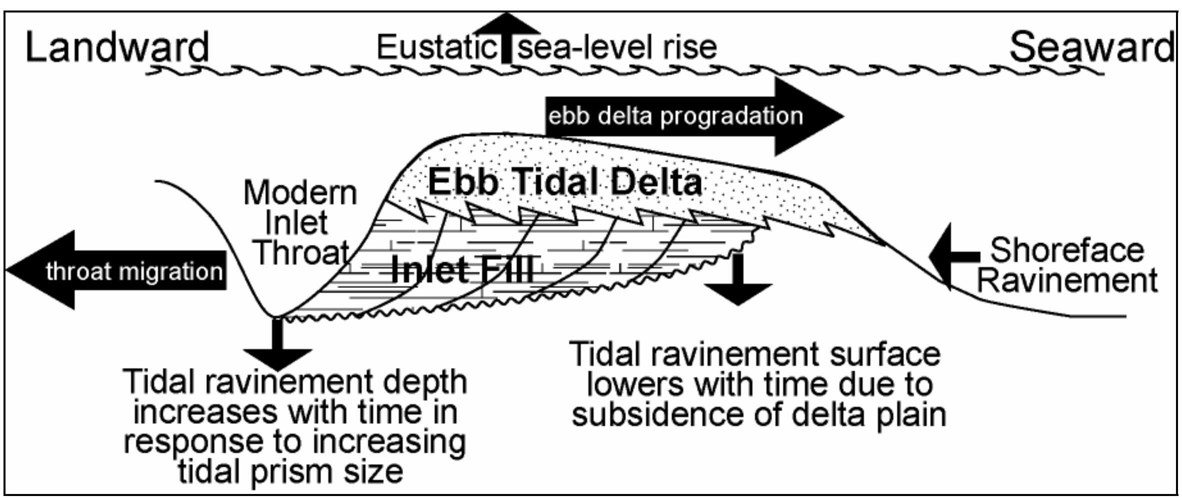


Figure 14. Conceptual model that illustrates the temporal component to controls on tidal ravinement preservation potential in a regime of rapid RSLR and a prograding ebb tidal delta.

CONCLUSIONS

1. The inlet fill stratal geometry at Little Pass Timbalier consists of a dip-elongate, erosionally bounded asymmetrical channel fill that thins seaward and pinches out at the location of inlet formation. This location is proximal to the position of the inlet in the 1930's as indicated by historical bathymetric maps. The inlet fill can be separated into two separate facies, the *inlet channel lower* and *the inlet channel upper*. The *inlet channel lower* is bounded at the base by the tidal ravinement scour surface and is marked by a sharp basal contact with high shell content, underlying massive fine sand with rare flaser beds and organic material. The *inlet channel lower* has a gradational to sharp contact with the overlying *inlet channel upper* facies, which consists of flaser to wavy to lenticular bedded mud and fine sands with shell material and scour reactivation surfaces. The *inlet channel upper* is an overall coarsening-upward facies that has a gradational to sharp contact with the overlying ebb tidal delta deposits. The *inlet channel lower* facies is the result of ebb channel depositional processes such as bedload and suspended sediment deposition. In the more shallow part of the inlet fill, waves and weather events such as the passage of frontal systems and tropical cyclones become the dominant processes that effect inlet fill deposition.

2. The inlet fill at Little Pass Timbalier is distinctly different from inlet fills developed from lateral spit accretion, which are the basis for most inlet fill models and are applied to all inlet deposits. The lateral accretion inlet fill is not a likely scenario in a transgressive system because cross-shore processes are dominant over longshore processes and inlets tend to be laterally stable as the channel migrates landward. Instead of developing tangential clinoforms that dip into the channel, by a process similar to fluvial point bar deposition, the transgressive inlet backfills as the channels and adjacent barriers migrate landward. This results in a complex channel fill reflection configurations that truncate the subjacent and adjacent reflection patterns in seismic profiles. The resulting inlet fill

lithology has the potential to be highly varied and is dependent upon factors such as tropical storm impact, frontal passages, tidal prism size, and sediment supply.

3. Because tidal inlets scour to depths below the base of the penecontemporaneous adjacent barrier deposits, they have the highest preservation potential during a transgression. At Little Pass Timbalier the tidal ravinement depth is approximately 10 m, somewhat shallower than the depth of shoreface ravinement along the adjacent barriers. However, the expanding ebb tidal delta and increasing depth of the inlet channel through time, result of increasing tidal prism size, help to prolong the exposure of inlet fill deposits and tidal ravinement surface to the effects of shoreface erosion, increasing the preservation potential. The inlet channel throat from the 1880's bathymetric data is preserved on the inner shelf approximately 4000 m seaward of the modern throat, however only the basal portion of the inlet channel remains.

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CHAPTER 6

CONCLUSIONS

The rapid relative sea-level rise (RSLR) occurring throughout the Mississippi River delta plain (MRDP) results in landward migrating and eroding barrier shoreline systems that are some of the most dynamic on Earth. Despite this rapid coastal degradation and retreat threatening the people and ecological sustainability of the region, as well as the national economy, the process provides an opportunity to understand this dynamic environment and to better protect and manage the Mississippi River delta plain and northern Gulf of Mexico coastal zone. Additionally this accelerated geologic change allows us to better understand modern and ancient transgressive deposits and barrier island/tidal inlet systems worldwide. The latter is especially relevant as predicted global sea-level rise will increasingly affect coastal regions.

The rapid morphological changes of the MRDP barrier islands and tidal inlet systems provide a unique opportunity to study the morphological evolution and relate the historical morphology and forcing mechanisms to the resultant stratigraphy. This study was centered on the transgressive tidal inlets of the MRDP and focused on their historical morphologic evolution, short-term morphological changes brought on by storm events, and the stratigraphic architecture that developed as a result of these long and short-term morphologic changes. The rapid RSLR, primarily driven by delta plain compactional subsidence, controls the morphology, position, and preservation potential of the barrier/inlet systems because it results in: (1) landward barrier/inlet retreat and (2) interior wetland loss that in turn increases tidal prism size resulting in larger inlet cross-sectional areas and enlarged ebb tidal deltas. Transgressive retreat of the barriers is characterized by a net landward movement of sediment which, for the most part, results in laterally stable, landward-migrating tidal inlet channels. The enlarging tidal prism size is the primary control on barrier island degradation in the MRDP. Increasing cross sectional area of inlet channels, formation of new inlets, and the expansion of the ebb tidal deltas all occur at the expense of the barriers.

This study resulted in the development of conceptual models that depict the long-term morphologic evolution, short-term morphologic changes, and stratigraphic evolution of a transgressive tidal inlet in response to RSLR, increasing tidal prism size, and tropical cyclone impacts.

In Chapter 3, a morphological evolutionary model for Little Pass Timbalier was constructed. The model was created on the basis of historical bathymetric data sets compiled by List et al. (1994) for bathymetry of the 1880's, 1930's and 1980's. A single-beam bathymetric survey at Little Pass Timbalier was conducted in June 2005. Digital elevation models (DEMs) were produced from these data in order to interpret the geomorphology of the inlet and identify the changes that took place between each time period. Based on the resulting model, it was determined that Little Pass Timbalier has undergone a complex morphological evolution that includes widening and deepening of the ebb channels and formation of additional channels in response to increasing tidal prism, expansion of the ebb tidal delta due to tidal prism increase, and landward and lateral migration of the main ebb channel (44 m/yr and 28 m/yr, respectively for the 1930 – 2005 time frame) in response to RSLR.

Chapter 4 focused on the short term morphological changes that occurred at Little Pass Timbalier in response to the active 2005 season of hurricanes. Subsequent to the single-beam bathymetric survey conducted in July 2005 for the long-term morphological evolution study, 3 tropical cyclones, Hurricanes Cindy, Katrina, and Rita, impacted the Louisiana coastal zone. In November 2005 a post-hurricane season survey was conducted at Little Pass Timbalier with the intention of identifying changes that occurred at the inlet due to active tropical cyclone activity. A bathymetric change analysis and sediment volume change calculations were preformed by comparing the pre and post-storm data. It was determined that a net loss of $10.7 \times 10^6 \pm 3.6 \times 10^6$ m^3 of sediment occurred within the study area between the two surveys, three orders of magnitude larger than the annual sediment budget determined from wave modeling studies. Timbalier Shoal, an ephemeral barrier island situated within Little Pass Timbalier, was completely destroyed and became submerged. Erosion occurred landward of Timbalier Shoal, in landward portions of the ebb channels, along the ebb channel flanks, and along the ebb tidal delta terminal lobe. Accretion occurred along the seaward portion of the ebb channels, across the proximal ebb delta, in marginal flood channels, and in a dredge borrow pit located on the ebb tidal delta. The shoaling in seaward portions and erosion in landward portions of the main ebb channel resulted over 160 m of landward channel migration between June 2005 and November 2005. On the basis of bathymetric changes, net loss of sediment volume, and aerial photographic analysis, conceptual models for the sediment dispersal at Little Pass Timbalier were developed. The models show a net seaward and downdrift movement of sand attributable to strong, long duration north winds associated with the passage of Hurricanes Cindy and Katrina to the east of the study area and storm wave attack on the ebb tidal delta terminal lobe. While it has been previously determined that inlet sediment bypassing at Little Pass Timbalier is minimal during normal weather conditions, the results of this study show that sediment transported landward as a result of storm impact has the potential to bypass the inlet and nourish downdrift shorelines.

Chapter 5 provided a sedimentologic and stratigraphic analysis of the Little Pass Timbalier tidal inlet with an emphasis on the stratigraphic architecture, lithology, and preservation potential of the inlet fill that is deposited in the seaward portions of the channel as the inlet system migrates landward. The morphological evolutionary model developed in Chapter 3 was used to identify the former position of the main ebb channel and determine the preservation of inlet fill based on overlay analyses comparing each historical bathymetric data set to the 2005 data. Once the inlet retreat path was identified, subbottom profiles and vibracores were taken along transects that trend perpendicular to the inlet throat location for each historical time period. In this way, the historical morphology and processes are related to the stratigraphy. The inlet fill lithology consists of a basal shell and muddy sand lag deposit that marks the tidal ravinement surface. Overlying the lag is massive, shelly fine sand with occasional clay flasers and mud rip-up clasts that was deposited in the deepest portions of the inlet channel. The lower inlet facies fines upward into the upper inlet fill that consists of lenticular to wavy to flaser bedded shelly clay and sand with bedded organics and scour reactivation surfaces. The inlet fill is approximately 5 m thick at the throat location of the 1980’s channel and is dominated by muddy sediments. The inlet fill coarsens at the top and is usually gradational with overlying ebb tidal delta deposits. The ebb tidal delta consists of massive and burrowed fine sand with rare organic material. The inlet fill geometry is in the form of a dip-elongate, erosionally bounded asymmetrical channel fill that thins seaward and pinches out at the location of inlet formation (storm breach location). The preservation potential of inlet fill is controlled by the relationship between the shoreface ravinement surface and tidal ravinement surface. Presently, 1880's inlet fill is still preserved on the inner shelf, however it is in a zone of active shoreface erosion. The channel fill that developed since the 1930's underlies ebb tidal delta deposits that have prograded seaward. The subsidence-driven RSLR coupled with ebb-tidal delta progradation increases the potential of tidal inlet fill preservation because the distance between the tidal ravinement and shoreface ravinement surfaces is continually increasing with time. The stratigraphic model displays an inlet fill geometry and lithology for transgressive tidal inlets that is quite different from hypothetical transgressive inlet fill models. Existing models are based on studies conducted on inlets located along laterally migrating barriers in which the inlet fill develops by lateral spit accretion, producing a strike-elongate, sand-rich inlet fill. Transgressive inlets are more likely to be laterally stable due to the dominance of cross-shore processes over longshore processes. Transgressive inlet fills are produced by deposition of suspended sediment and bed load, migration of swash bars into the channel, storm deposits, and of lesser importance are lateral migration processes. The transgressive fills are dominated by mud instead of sand and display a dip-elongate geometry instead of the strike-elongate geometry developed by a laterally migrating inlet. This study on the stratigraphic and morphologic evolution of Little Pass Timbalier, a transgressive tidal inlet along the Mississippi River delta plain coastal zone, resulted in the development of morphologic and stratigraphic evolutionary models for transgressive tidal inlet systems. Also, a process-response model for short term change and sediment dispersal was developed. The dominant controls on inlet morphology and stratal architecture in the MRDP are increasing tidal prism size, rapid RSLR, and storm impacts. While the barriers migrate landward as a result of RSLR, their degradation is primarily due to the increased tidal prism volumes that result from interior wetland loss. This is because, as the tidal prism grows, so do the inlet cross sectional area and ebb tidal delta volume, both of which happen at the expense of the barrier. While the results of this study have broad implications for better understanding tidal inlet fill and barrier lithosomes deposited during transgressions, the case of increasing tidal prism volume during a transgression has direct implications for the sustainability of the barrier islands along the MRDP. These models will be useful in the present effort to manage barrier systems of coastal Louisiana by providing a better understanding of how inlets develop through time, identifying controls on evolution, defining the role of inlet evolution in barrier island degradation, and refining sediment transport models and sediment budgets.

FUTURE RESEARCH

The development of the models in this study and the improved understanding of transgressive tidal inlet processes in the MRDP make it apparent that numerous unanswered questions regarding the hydrodynamic, sediment transport, stratigraphic, and morphologic aspects of transgressive tidal inlets exist. Moreover, in order to fully test and further develop the conceptual models presented in this study, the results should be applied to tidal inlets across the MRDP coastal zone. The following is a summary of proposed future directions that might expand on the findings of this study:

1. Continual monitoring of the morphology of Little Pass Timbalier in order to determine effectiveness and impacts of the dredging and removal of sediment from the ebb tidal delta for placement on downdrift shoreline, better constrain long-term versus short-term evolutionary trends, and document the post-storm recovery. This could also be used to formulate sediment budgets and test the possibility of using the expanding ebb tidal deltas as a renewable sediment source for barrier restoration projects.
2. Hydrodynamic and sediment transport study of tidal inlets using acoustic doppler current profiler (ADCP) instrumentation both deployed in tidal inlets for extended time periods and mounted to survey vessels. The findings would help constrain daily discharge values at tidal inlets, estimate tidal prism volumes, understand the effects of meteorological events such as frontal passages that amplify astronomical tides and increase wave activity, determine variation in suspended load

associated with tidal currents and wind events, and provide a better understanding of the processes that control tidal inlet morphological evolution and sedimentation.

3. Integrate a shallow stratigraphic study with the short-term bathymetric monitoring and hydrodynamic study by taking short cores along the axis of the inlet channel, then repeat the sampling at each core location after a given time period to determine the stratal response to hydrodynamic, storm, and sediment transport processes.
4. Apply conceptual models produced in this study to refine existing and develop new quantitative models of tidal inlet processes. This could be used to better predict future trends of barrier island and inlet evolution as it relates to changing tidal prism size, ebb tidal delta sediment volumes, RSLR, and development of shoreface sand ridges and transgressive sand sheets.
5. Application of conceptual models developed at Little Pass Timbalier to other MRDP tidal inlets in order to better determine interrelationship of the number of tidal inlets, increased cross-sectional areas, increase in sediment stored in ebb deltas, and barrier degradation to the changes in tidal prism volumes on a interdistributary basin scale.
6. Incorporate the newly acquired Louisiana Department of Natural Resources/University of New Orleans/U.S. Geological Survey Barrier Island Comprehensive Monitoring Program bathymetric data, currently in the processing phase, to better understand the sediment budget and transport along the lower shoreface of downdrift Timbalier Island that possibly results from the erosion of the Little Pass Timbalier ebb tidal delta. This could lead to the development of a model that better explains the origin and evolution of Atlantic shelf, northern Gulf of Mexico shelf, and MRDP subsurface sand sheets and sand ridges associated with transgression.
7. Application of stratigraphic model for transgressive tidal inlets to ancient transgressive deposits; most of the previous interpretations relied on tidal inlet fill models based on inlet fills developed from laterally migrating instead of landward-migrating tidal inlets.

8. Relate the inlet retreat pathways to antecedent geological controlling factors including previous inlet locations from former transgressive shorelines and fluvial distributary locations, both as subsurface controls due to erodable substrate and surface controls on backbarrier hydrodynamics.

APPENDIX A

VIBRACORE DESCRIPTION SHEETS

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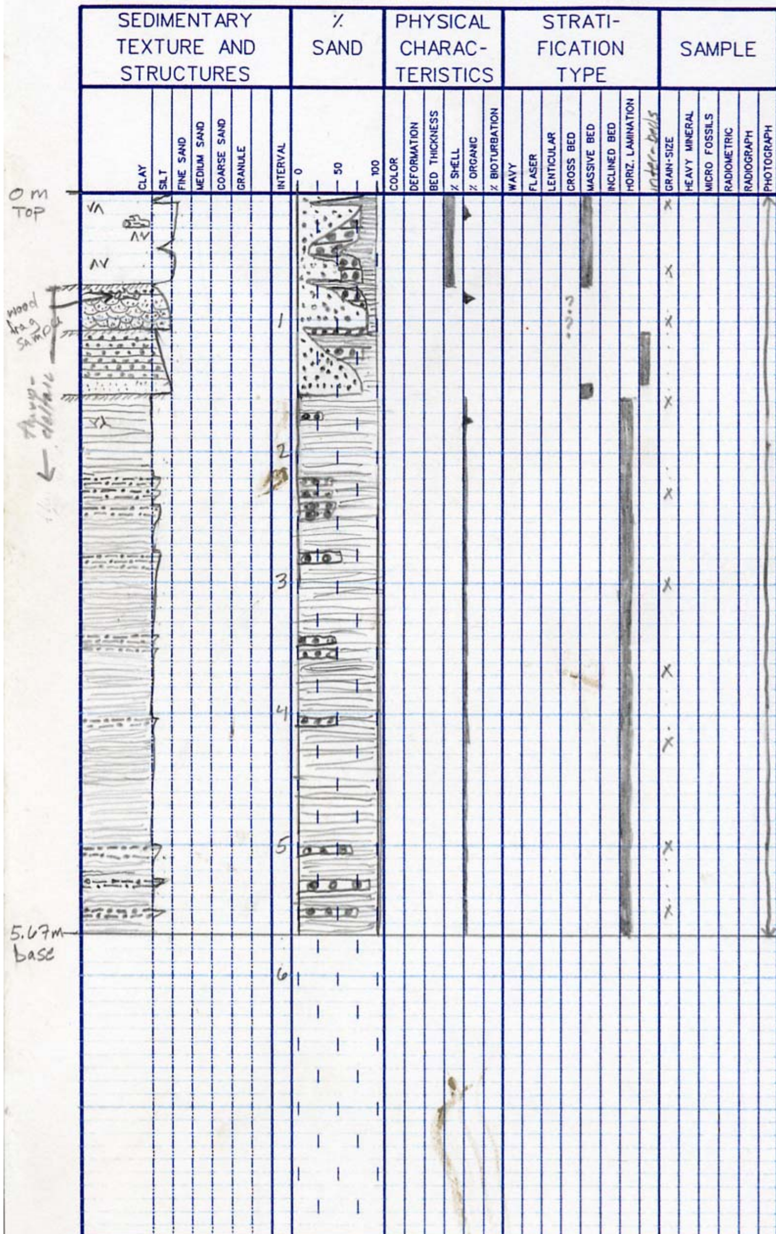
DEPARTMENT OF GEOLOGY AND GEOPHYSICS

VIBRACORE DESCRIPTION SHEET

CORE ID: 04SCC20
DATE: 10/18/2004
DESCRIBED BY: Mike Miner
ELEVATION: WD = 6.09 m
LOCATION: Little Pass Timbalier (eastern)
CORE LENGTH: 5.67 m
LAT/LONG: utmx: 758676 utmy: 3216616
TOTAL DEPTH:
COMPACTION:



PHYSICAL DESCRIPTION

0–0.73 m: dusky yellow grn (5GY 5/2) to brnish gry (5YR 4/1) clayey to silty fine sand. 0.08 m → 0.10 m has dk gry (N3) clay bed w sand at top. Shell frags (*M. lateralis* & oyster throughout interval ~3% abundant). Wood frag @ 0.28 m. Bryozoan & *Astrangia astreiformis* encrusted beachrock @ 0.53 m

0.73 m – 1.07 m: laminated brnish gry (5YR 4/1) to dk gry (N3) fine sands. Possible X-beds ??. Fining upward into brnish gry silty sands up into mod. red (5R 5/4) to pale brn (5YR 5/2) clays & silty clays w/sharp contact w/ overlying interval. Shell material absent.

1.07–1.53 m: massive pale brn sand @ base fining up to silty sands up to pale brn to grayish brn (5YR 3/2) interbedded silt & clay. Sharp contacts at top & base of interval

1.53–5.67 m: horizontally laminated greyish brn (5YR 3/2) clays w/ gryish brn silt to silty v. fine sand beds & lenses. Traces of black organic material present. Shell material absent.
~5 cm thick silty very fine sand layers @ 5.26 & 5.47 m.

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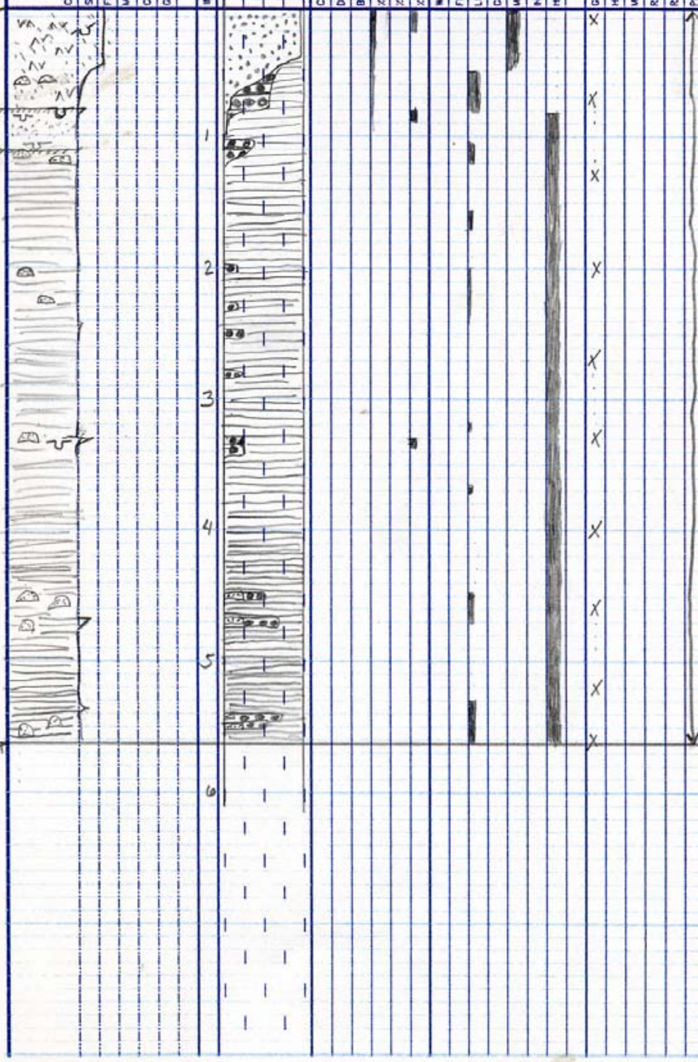
VIBRACORE DESCRIPTION SHEET

CORE ID: 04SCC21
DATE: 10/17/2004
DESCRIBED BY: Mike Miner
ELEVATION: WD= 6.7 m
LOCATION: Little Pass Timbalier
CORE LENGTH: 5.62 m
LAT/LONG: utmx: 759403 utmy: 3215933
TOTAL DEPTH:
COMPACTION:

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARACTERISTICS	STRATIFICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION
CLAY, SILT, FINE SAND, MEDIUM SAND, COARSE SAND, GRANULE, INTERVAL (m)	0, 50, 100	COLOR, DEFORMATION, BED THICKNESS, % SHELL, % ORGANIC, % BIOTURBATION	WAVY, FLASER, LENTICULAR, CROSS BED, MASSIVE BED, INCLINED BED, HORIZ. LAMINATION	GRAIN-SIZE, HEAVY MINERAL, MICRO FOSSILS, RADIOMETRIC, RADIOGRAPH, PHOTOGRAPH	

0m Top

diastem



5.62m base

0-0.81m: coarsening upward brnish gry (5YR 4/1) silty clays @ base w/ sharp contact below, grades up into lenticular bedded brnish gry to med dk gry (N4) silty fine sand in brnish gry silty clay, grading up through organic/heavy mineral zone ~ 2 cm thick, grading up into massive bedded, mottled dusky yellow (5Y 6/4) to gryish blk (N2) fine sand w/ M. Lateralis frags.
0.81-1.06m: Lt olive gry (5Y 5/2) clay grading into 2 cm thick dk gry sandy silt w/ organics & heavy min. & has sharp contact w/ overlying interval. Burrows present just below contact filled w/ silty sands & shell frags. Sharp contact w/ underlying unit
1.06-5.35m: horiz. laminated pale brn (5YR 5/2) to mod. yellowish brn (10YR 4/2) clays with gryish brn (5YR 3/2) fine sandy silt - to silty clay lenses.
Occasional blk organics
silty sand-filled burrows @ 3.33-3.50m
shell material absent except for one frag @ 2.20 w/ thin wall shell so probably freshwater species
5.35-5.62m: multiple coarsening upward sequences ~ 7cm thick each consisting of brnish gry (5YR 4/1) clay grading up into pale yellowish brn (10YR 6/2) silt beds ~ 2-4cm thick. Top of each CUS has sharp contact w/ overlying

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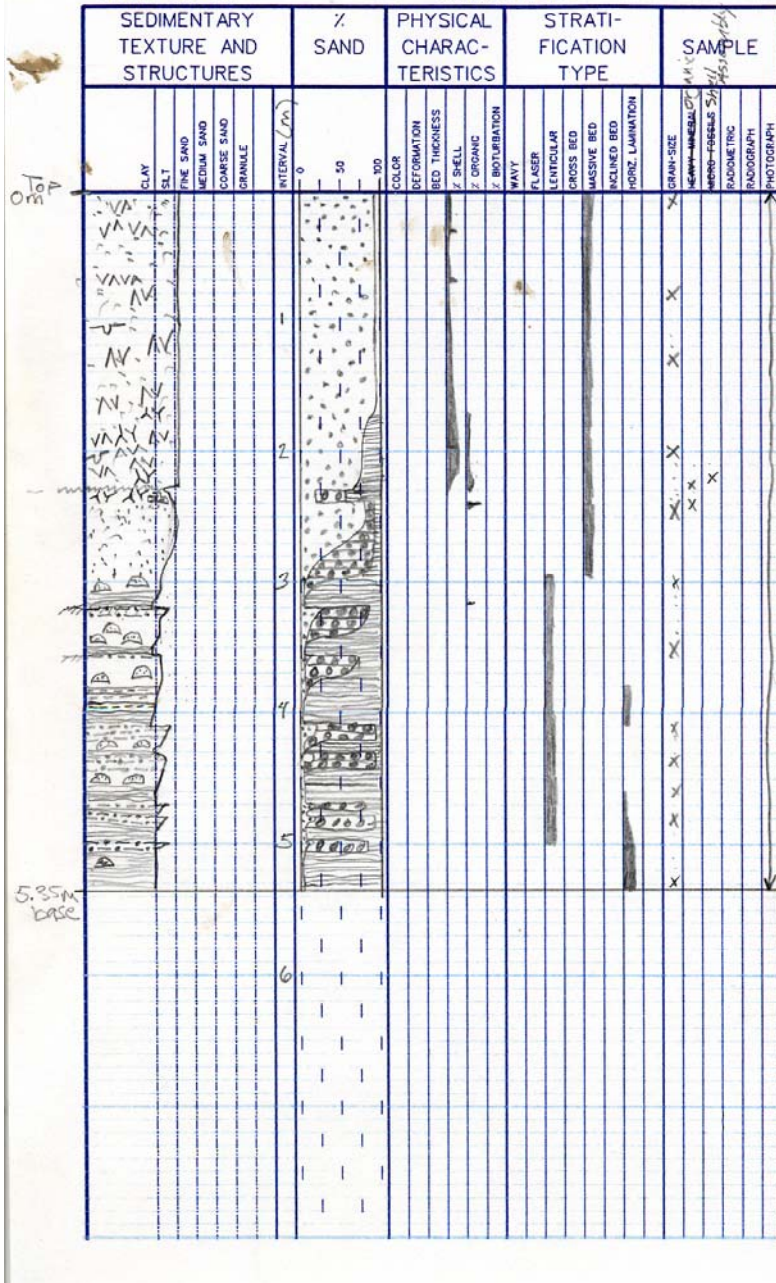
VIBRACORE DESCRIPTION SHEET

CORE ID: 04SCL22
ELEVATION: WD = 3.50m
CORE LENGTH: 5.35m
TOTAL DEPTH:

DATE: 10/22/04
LOCATION: Little Pass Timbalier (on seismic line 04SCC15a)
LAT/LONG: utmx: 756563 utmy: 3216818
COMPACTION:

DESCRIBED BY: Mike Miner



PHYSICAL DESCRIPTION

0-2.30m: massive-bedded pale brn (5YR 5/2) to brnish gry (5YR 4/1) fine sand with Mulinia Lateralis & Marine gastropod shell frags throughout. Shell material increasing towards base of interval from 1.80-2.30m. Increased organic & clay content b/t 1.80-2.30m.

Organic layer. ~ 0.5cm thick @ 1.84m.

High concentration of shell material @ 2.07-2.25m (shell material is samples Freshwater & ML)

2.30-2.41m: Transitional zone of organics (wood) in pale brn clays to clayey silt. No shell material below this zone.

2.41-3.21m: coarsening upward interval w/ pale brn to brnish gry (5YR 4/1) horiz. laminated clays w/ silt interbeds & lenses from 2.93-3.21 w silt increasing upward, grades up into pale brn silty fine sand w/ silt decreasing upward & bedding is more massive. Gradational w/ overlying interval & sharp contact @ base of interval @ 3.21m

3.21-4.16m: coarsening upward interval of laminated pale brn clay w/ silt beds (~1cm) @ base silt increasing upward & lenses of sandy silt occur b/t 3.30-3.50m. uppermost portion of interval fine sandy silt w/ sharp contact above.

4.16-5.35m: multiple coarsening up intervals of 10-40 cm thick consisting of laminated clays w/ trace organics becoming silty upwards w/ silt lenses up into pale brn silt beds w/ sharp contact @ top of each. Silt portion dominates the upper cus intervals & clay dominates lower. Contacts of each are @ 4.16, 4.30, 4.70, 4.80, 4.99

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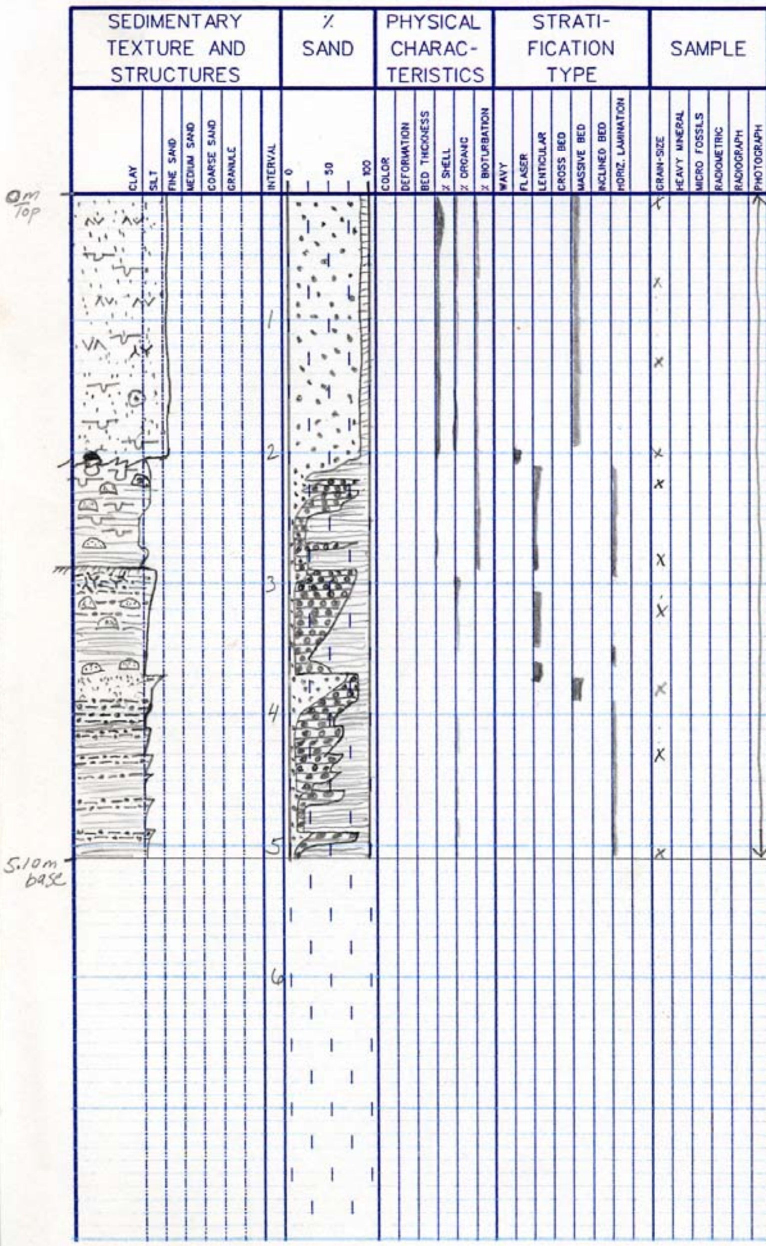
DEPARTMENT OF GEOLOGY AND GEOPHYSICS

VIBRACORE DESCRIPTION SHEET

CORE ID: 04SCL23
ELEVATION: WD=3.41 m
CORE LENGTH: 5.10 m
TOTAL DEPTH:

DATE: 10/22/04
LOCATION: Little Pass Timbalier (on seismic line 04SCL15a)
LAT/LONG: utmx: 755257 utmy: 3216598
COMPACTION:

DESCRIBED BY: Mike Miner



PHYSICAL DESCRIPTION

0-2.05m: massive-bedded pale yellowish brn (10YR 6/2) fine sand w/ Marine gast. & bivalve frags. Also oyster frags & M. Lateralis. Burrowing present.
2.05-2.86m: dark yellowish brn (10YR 4/2) clays that coarsen upward into clayey silts w/ pale yellowish brn sand filled burrows. Grades in to overlying sandy unit through a transitional CUS zone of lenticular bedded silty sands in clays, up into flaser bedded clays in sand. Lenticular silt beds occur throughout that contain trace organics. Horiz. Laminations in clay appear to be textural (depositional) & not diagenetic. Only shell material is in burrows.
2.86-3.66m: Lenticular bedded silts in dk yellowish brn clays up into organic sandy silty w/ faint X-beds b/t 2.86-3.01 m. Contact w/ overlying clayey unit is sharp
3.66-5.10m: interbedded dk yellowish brn clays & light brn (5YR 6/4) silts @ base w/ silts becoming lenticular bedded in horiz laminated clays w/ rare organics in silts. Unit coarsens upward into dk yellowish brn silty sand that is massively bedded & grades into overlying unit. Shell material absent

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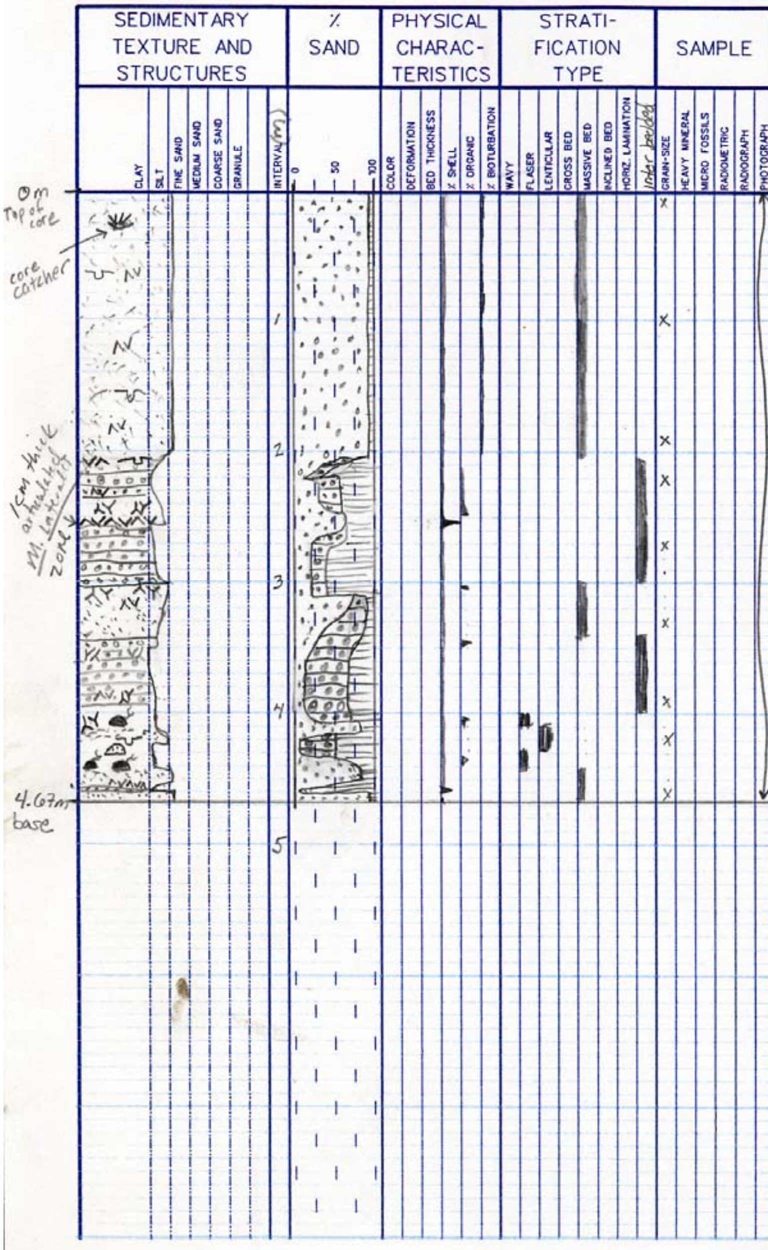
VIBRACORE DESCRIPTION SHEET

CORE ID: 04SCC24
ELEVATION: WD = 3.29 m
CORE LENGTH: 4.67 m
TOTAL DEPTH:

DATE: 10/18/2004
LOCATION: Little pass timbalier
LAT/LONG: utmx: 754053 utmy: 3216333
COMPACTION:

DESCRIBED BY: Mike Miner



notes: core catcher @ 0.25m

PHYSICAL DESCRIPTION

0-2.06 m: massive-bedded mottled dusky yellow grn (5GY 5/2) to dk gry (N3) fine sand. M. Lateralis & other small shell frags present. Burrows.
2.06-2.55m: coarsening up intervals from greyish gry (5G 5/2) clays up into Lt olive gry (5Y 5/2) clayey silts up into Lt olive gry silty fine sands. w/ organics & M. Lateralis frags.
2.55-2.56m: 1cm thick layer of M. Lateralis. Some are articulated & most shells whole. All ~ 0.5cm dia.
2.56-2.65m: Fining upward sequence from sandy silt up to silt w organics up to clays. Capped by M Lateralis zone discussed above.
2.65-3.10m: multiple coarsening up sequences clay → silty clay → sandy silt w/ organics & rare shell hash CUS's are ~ 2-8cm thick. Clay dominant at top of interval w/ silt & sand becoming dominant towards base.
3.10-3.74 m: coarsening upward from dk gry clays w/ interbedded silt up to silty clays & concentrated organics @ 3.56m, up into silty sands. which become massively bedded 3.10-3.40m
3.74-4.16m: lt olive gry (5Y 5/2) sands @ base w/ flaser beds of dk gry clays becoming interbedded upward where clay dominates w/ lenses of sand. Rare M Lateralis in sands.
4.16-4.28m: dk gry cly w/ lenses of sand and sandy silt
4.28-4.56m: Conc. M Lateralis @ base w/ massive lt olive gry sands above, Flaser clay beds increase upward into overlying interval.
4.56-4.60: dk gry clay grading into above w/ sharp contact below
4.60-4.67: lt olive gry sand w/ sharp contact w/ above. rare M. Lateralis

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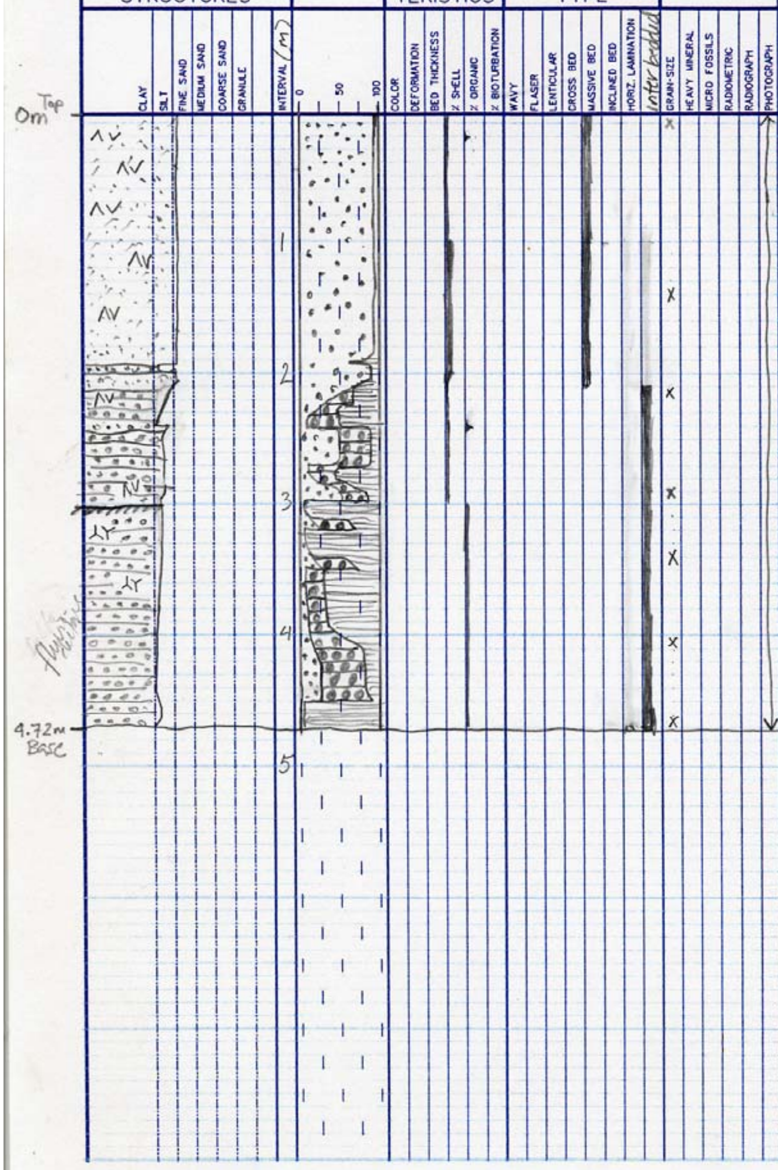
VIBRACORE DESCRIPTION SHEET

CORE ID: 04SCC25
DATE: 10/18/2004
DESCRIBED BY: Mike Miner
ELEVATION: WD= 3.26 m
LOCATION: Little pass Timbalier
CORE LENGTH: 4.72m
LAT/LONG: utm x: 753358 utm y: 3216572
TOTAL DEPTH:
COMPACTION:

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARACTERISTICS	STRATIFICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION



PHYSICAL DESCRIPTION

0-2.10 m: dusky yellowish grn (5GY 5/2) to gryish blk (N2) massive bedded fine sands w/shell frags some M lateralis, marine bivalve & gastropods.

2.10-2.98 m: multiple fining upward sequences from thin (0.5cm) silty fine sands w/heavy min & shell frag up into dk gry cly w/ interbeds of silt & silty sand. FUS's are ~2-10 cm thick.

2.98-4.72 m: Multiple FUS from pale brn (5YR 5/2) sandy silt ↑ into pale brn to gryish brn (5YR 3/2) clays. FUS are graded. Rare organics, Shells absent

FUS's b/t <1cm to 10 cm thick

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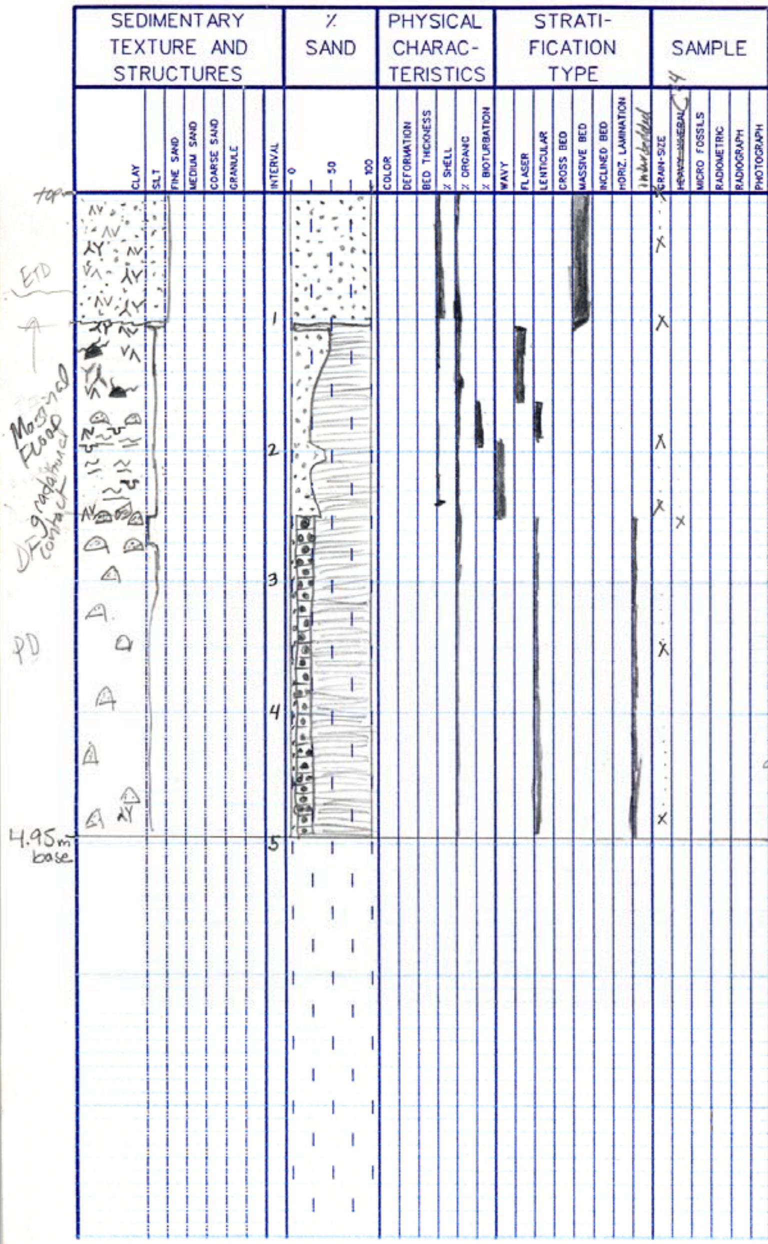
VIBRACORE DESCRIPTION SHEET

CORE ID: 05LPT01
ELEVATION: WD = 2.7 m
CORE LENGTH: 4.95 m
TOTAL DEPTH:

DATE: 8/23/2005
LOCATION: Little Pass Timbalier (~ 500 m east of active channel)
LAT/LONG: 752983.6 / 3,218,182.7 (UTM zone 16)
COMPACTION:

DESCRIBED BY: Mike Miner



PHYSICAL DESCRIPTION

0 - 1.05 m

massive-bedded greyish brn fine sand w/ *M. Lateralis* shell material & organics increasing in abundance & decreasing in grain size (of organics & shell) towards base of unit. Sharp contact w/ underlying clay @ base of interval

1.05 - 2.50 m

flaser to wavy to lenticular bedded gry brn to dk gry clays & fine sand. Abundant fine grained organics & shell material @ top of interval. 1.05 - 1.60 m is flaser bedded w/ fine grain organics & shell. 1.60 - 2.50 m is wavy to lenticular bedded and shell content decreasing towards base. Bioturbation & sand/shell filled burrows 1.50 - 1.95 Base of unit is marked by wood frag, small (1 cm) "angel wing" shell, & oyster frag w bryozoans & *Astrangia astreiformis* colony. Contact w/ underlying unit is gradational into underlying clay. Sand lenses & interbeds contain sand-sized organic grains & heavy minerals.

2.50 - 4.95 (base)

brownish gry to olive gry clay w/ silt & v. fine sand interbeds & lenses. Occasional carbonized root traces. No shell material & no organics w/in sand.

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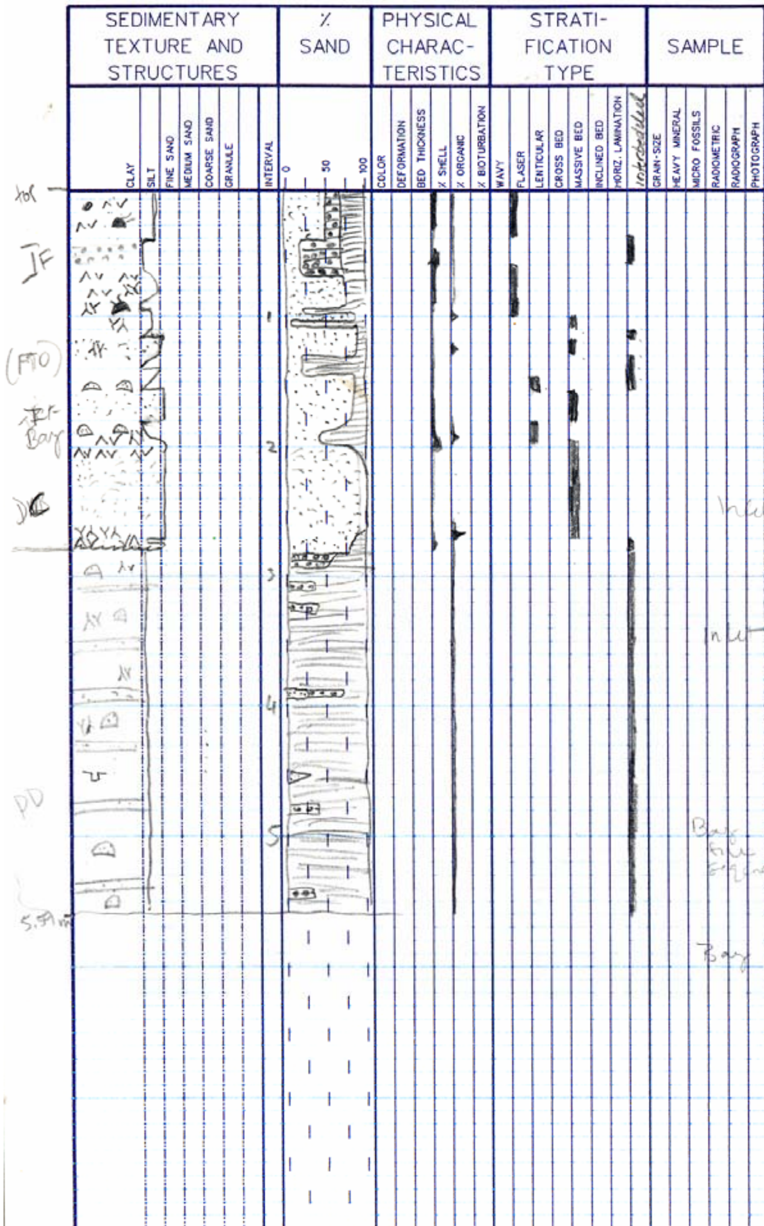
VIBRACORE DESCRIPTION SHEET

CORE ID: OSLPT02
~~ELEVATION:~~ WD = 6.7 m
CORE LENGTH: 5.59 m
TOTAL DEPTH:

DATE: 1/16/2006
LOCATION: offshore Little Pass Timbalier (1890's channel)
~~LAT/LONG~~ UTM: 758637.5 3,216,196.2
COMPACTION:

DESCRIBED BY: Mike Miner



PHYSICAL DESCRIPTION

0 – 0.40 m
dk greenish gry silty fine sand w clay clasts, flaser beds of olive gry clay. Organics, & M. Lateralis shell frags throughout.

0.40 – 0.65 m
dk greenish gry clay w dk greenish gry silty sand interbeds. som M. Lateralis

0.65 – 0.90 m
dk greenish gry silty fine sand w/ abundant (~5%) M. Lateralis shell frags & clay flaser beds. Organics throughout

0.90 – 1.15 m
dk grn gry clay @ base of unit CUS into massive dk grn gry sand that is massive-bedded becoming flaser to wavy bedded @ top of unit. Base of unit has sharp contact w/ underlying unit

1.15 – 1.83 m
multiple coarsening upward sequences that are 5.0 – 20.0 cm thick. Sequences consist of sharp contact @ base of each w/ dk grnish gry clay that grade up into silty sands up into massive bedded sands. 1.56 – 1.83 m is massive sand w/ sharp contact @ 1.83 m

1.83 – 1.95 m
silty sand lenticular beds in dk grn gry cly, organics & shell frags.

1.95 – 2.76 m
above unit grades into this one as sand & shell content increase. Consists of massive-bedded olive gry fine sand, Abundant shell content in upper 5 cm (oyster & M. Lateralis) Bedded organics 1 cm thick @ 2.66 m clay interbed, organics & shell hash @ base. Sharp contact w/ underlying unit.

2.76 – Base
dusky yellowish grn clay w/ sandy silt interbeds & lenses. some organics. Sand-filled burrow @ 4.5 m

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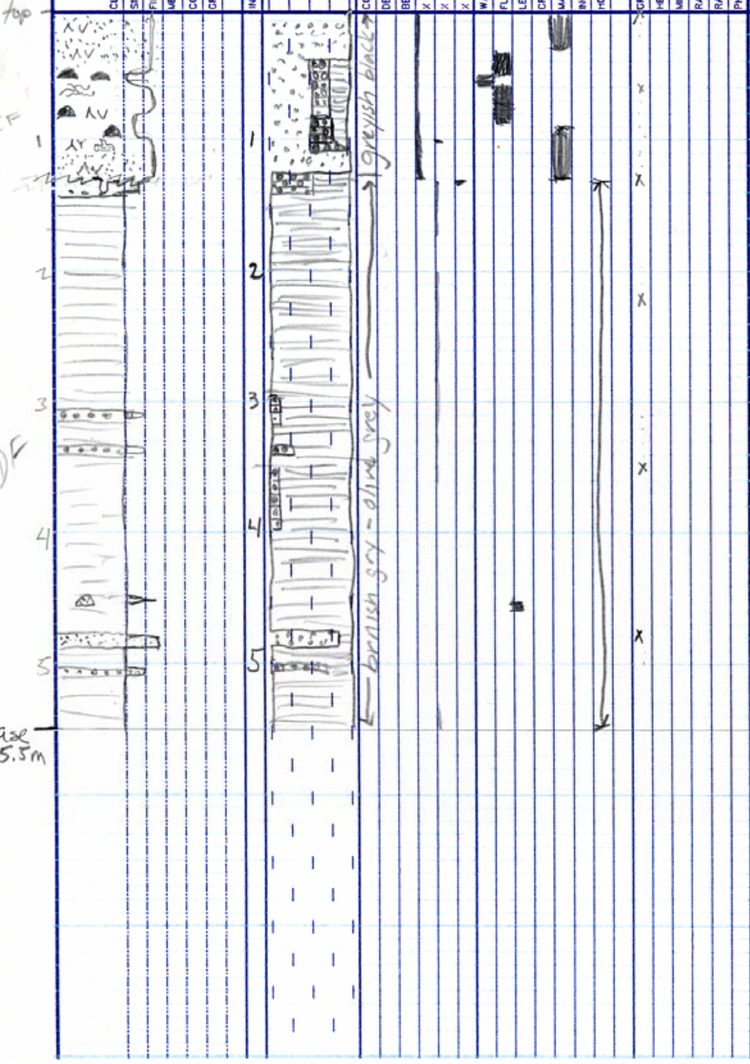
VIBRACORE DESCRIPTION SHEET

CORE ID: 05LPT03
ELEVATION: WD = 7.2 m
CORE LENGTH: 5.5 m
TOTAL DEPTH:

DATE: 8/22/05
LOCATION: Little Pass Timbalier (1820's channel)
UTM X/Y ~~LAT/LONG~~: 759123.7 3215889.7 (UTM zone 16)
COMPACTION:

DESCRIBED BY: Mike Miner

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARAC-TERISTICS	STRATI-FICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION
CLAY, SILT, FINE SAND, MEDIUM SAND, COARSE SAND, GRANULE, INTERVAL (m)	0, 50, 100	COLOR, DEFORMATION, BED THICKNESS, X SHELL, X ORGANIC, X BIOTURBATION	WAVY, FLASER, LENTICULAR, CROSS BED, MASSIVE BED, INCLINED BED, HORIZ. LAMINATION	GRAIN-SIZE, HEAVY MINERAL, MICRO FOSSILS, RADIOMETRIC, RADIOGRAPH, PHOTOGRAPH	



0-1.27 m

Top 0.4 m is greyish black fine sand w/ ~10% shell hash (*Mulinia Lateralis*)
0.4 - 0.94 m: greyish black fine sand w flaser bedded olive grey clay. Clay beds ~ 1cm thick. Decrease in shell material in zones of flaser bedding. Wavy bedding @ 0.60 - 0.65 m
0.96 - 1.10 m: greyish black v. fine sandy silt. Shell material absent. Wood fragment @ 1.8m is draped by 1cm thick clay lens above.
1.10 - 1.27: above subunit grades into this one. Greyish black to olive gray fine sand. Mottled appearance w/ rare shell material increasing towards base. Some shell hash @ base consisting of *M. lateralis* & *Crassostrea virginica* frags ~ 1-2 cm. Sharp contact w underlying unit w/ burrow filled w sand & shell material.

1.27 - 5.50 m (base)

brownish grey to olive grey clay w brownish grey silt beds throughout. Lenticular bedded sand @ 4.5 m ~ 0.75 cm thick. 8.0 cm thick dusky yellow green sand @ 4.81 - 4.89 m. Shell material absent through entire interval except at 5.17 m where a single valve of a small (1 cm) brown bivalve shell occurs in clay matrix. Some organic specks within clay.

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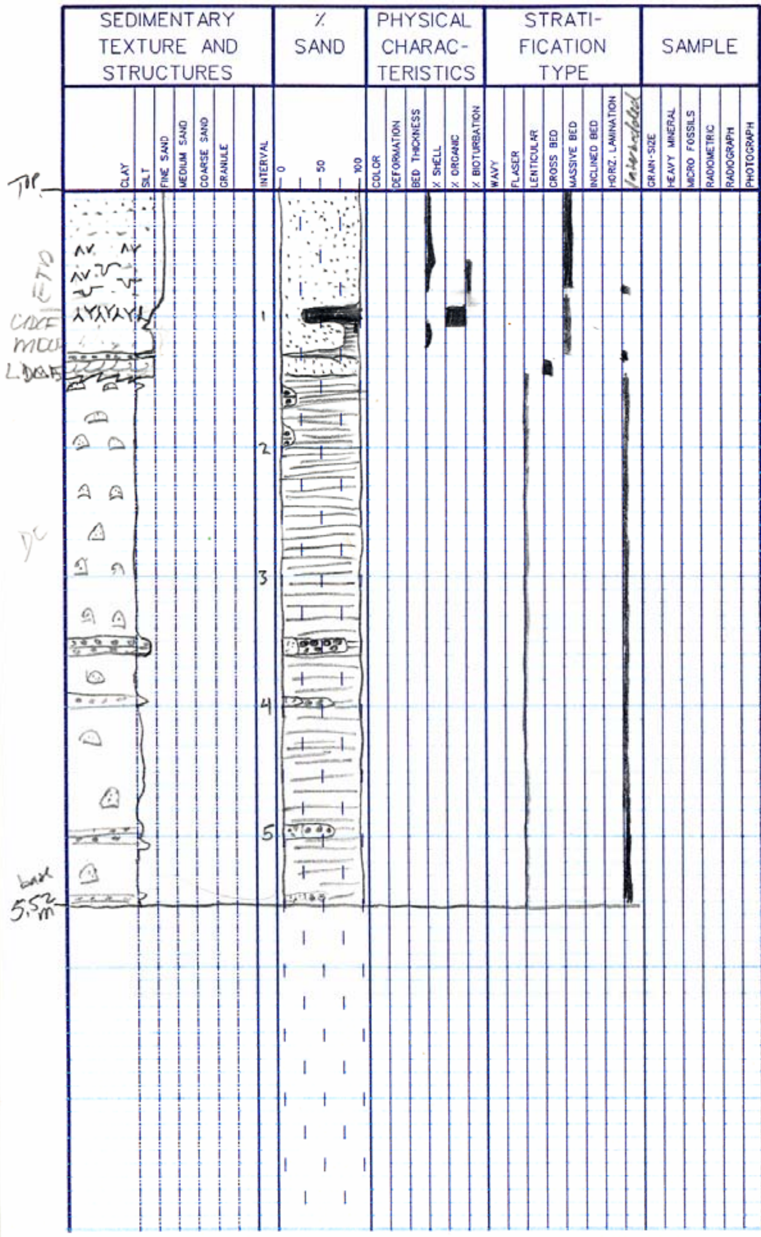
VIBRACORE DESCRIPTION SHEET

CORE ID: 05 LPT 04
DATE: 1/18/2006
DESCRIBED BY: Mike Miner
ELEVATION: WD = 5.2 m
LOCATION: offshore Little Pass Timbalier, LA
CORE LENGTH: 5.52 m
LAT/LONG: UTM: 754,923.02 3,215,367.7
TOTAL DEPTH:
COMPACTION:



PHYSICAL DESCRIPTION

0 – 0.93 m: massive-bedded dk grnish gry v. fine sand with (2-5%) shell hash of M. Lateralis & oyster. Burrows from 0.58 – 0.90 m. 0.82 m – 0.93 m has increased clay + silt content w/ decrease in shell material.

0.93 – 1.09 m: bedded coffee ground organics & wood frags @ base becoming sandy towards base.

1.09 – 1.45 m: top of unit is gradational w/ overlying organics. massive to cross-bedded dk grnish gry silty v. fine sand w/ clay interbeds no shell material.

1.45 – 5.52 m
Lenticular bedded silty v. fine sand and silt in dusky yellowish gray clays

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VIBRACORE DESCRIPTION SHEET

CORE ID: 05 LPT 05
DATE: 8/26/2005
DESCRIBED BY: Mike Miner

ELEVATION: WD = 3.8m
LOCATION: Little Pass Timbalier

CORE LENGTH: 3.45 m
LAT/LONG: 754,312.9 / 3215,811.4 (utm zone 16)

TOTAL DEPTH:
COMPACTION:

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARAC-TERISTICS	STRATI-FICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION
CLAY, SILT, FINE SAND, MEDIUM SAND, COARSE SAND, GRANULE, INTERVAL	0, 50, 100	COLOR, DEFORMATION, BED THICKNESS, % SHELL, % ORGANIC, % BIOTURBATION	WAVY, FLASER, LENTICULAR, CROSS BED, MASSIVE BED, INCLINED BED, HORIZ. LAMINATION, interbedded	GRAIN-SIZE, HEAVY MINERAL, MICRO FOSSILS, RADIOMETRIC, RADIOGRAPH, PHOTOGRAPH	

TOP

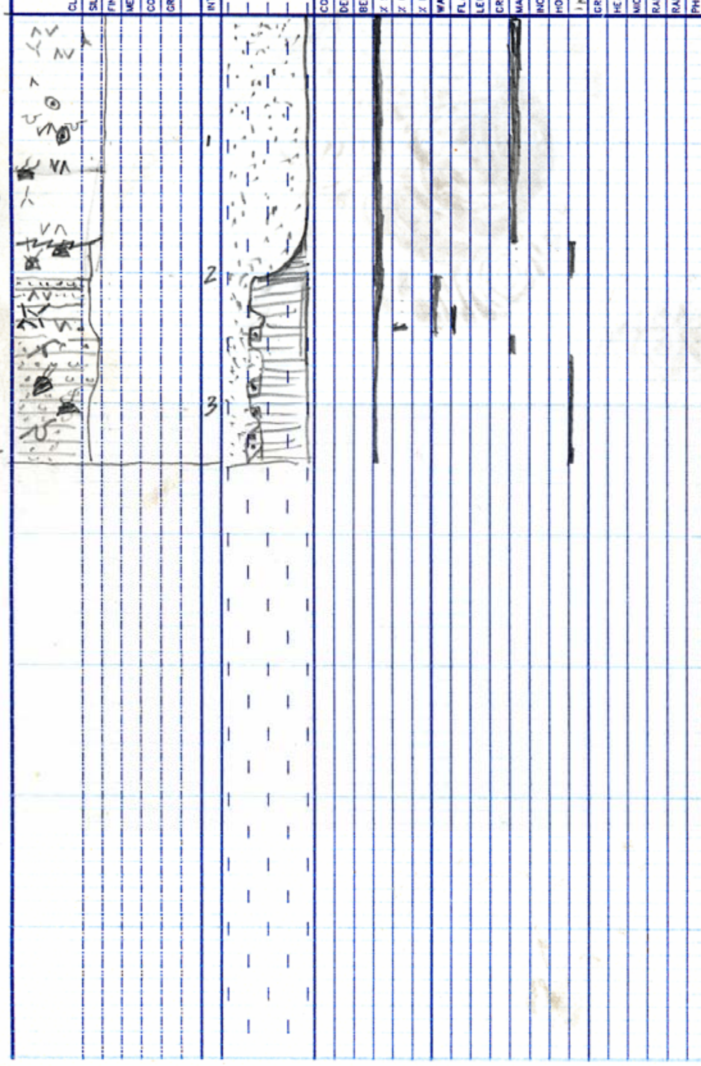
DETD

ID

DETD

IF

3.45



0 - 1.75 M
massive-bedded dusky yellow grn fine sand. Burrows (donut) @ 0.35, 0.75, 0.95. Shell material throughout, consits of whole shell, frags, & articulated M. Lateralis & rare oyster frags. DK greenish gry clay bed @ 1.33 m is ~1.5cm thick. Below this organics increase slightly & M Lateralis has increased preservation. Contact w underlying unit is sharp

1.75M - 3.45 m
interbedded dusky yel grn f. sand w/ dk grn gry clays. Some horiz beds of clay btw 0.5 & 70 cm thick. Also flaser beds, wavy & lenticular based on clay/sand dominance. M Lateralis abundant at top of interval becoming rare to absent @ base. Burrows common in clays that are sand-filled. Sands @ base are somewhat lighter in color, silt content increases (apparently) probably due to better sorting than massive-bedded intervals

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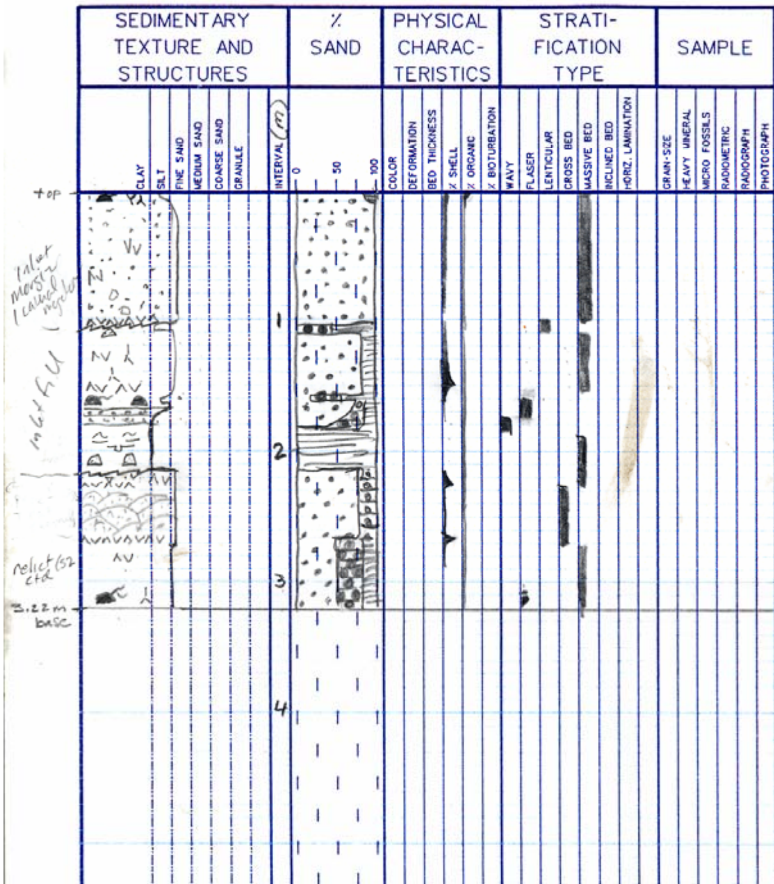
VIBRACORE DESCRIPTION SHEET

CORE ID: O5LPTO6
DATE: 8/24/2005
DESCRIBED BY: Mike Miner

ELEVATION: WD: 5.00 m
LOCATION: Little Pass Timbalier (eastern flank of channel at throat)

CORE LENGTH: 3.22 m
~~LAT/LONG~~: 751,990.9 3,218,604.0 (UTM zone 16)

TOTAL DEPTH:
COMPACTION:



PHYSICAL DESCRIPTION

0-0.10 m
brnish blk clay clast in dark greenish gry fine sand w/ organics & some shell hash. (clay clast may be filled burrow?)

0.10 m - 1.05m
massive-bedded olive gry fine sand w/ rare (>1%) shell material. Clay clast @ 0.83, 0.94 m. & 1.03m. Base of unit is marked by increase in shell material (~30%) w avg grain size of 2 mm. Underlying shelly zone is a sharp contact w/clay.

1.05-1.57m
fining upward unit w/ gryish blk clays at top containing fine sandy silt lenses. Clay interval is 3-4 cm thick. 1.09-1.58 m is dk greenish gry silty fine sand w/ shell hash that increases towards base. organics (fine grained) throughout w/ mud clast at 1.26 m

1.57-1.65 & 1.65-1.68m
a thinner fining upward units as described above (coffee grounds bedded @ 1.60 m 14C)

1.68-2.17m
coarsening upward unit that is gradational with fining upward unit described above (1.65-1.68)
flaser bedding 1.68-1.72 w organics & shell hash
wavy bedding 1.72-1.83, shell content is decreasing
1.83-2.17m
massive clay with rare silty sand lenses & sand filled burrows
contact w/underlying unit is sharp

2.17-2.26 - fine sand w/ shell material concentrated @ 2.25-2.26 w oyster frags ~2cm

2.26-2.71 silty fine sand w/ ~1% shell material faint x-bedding present. base of unit marked by increase in shell & identical to 2.25-2.26 in appearance

2.71-base: dk gry silty sand w/ clay flaser & rare shells (rangia?)

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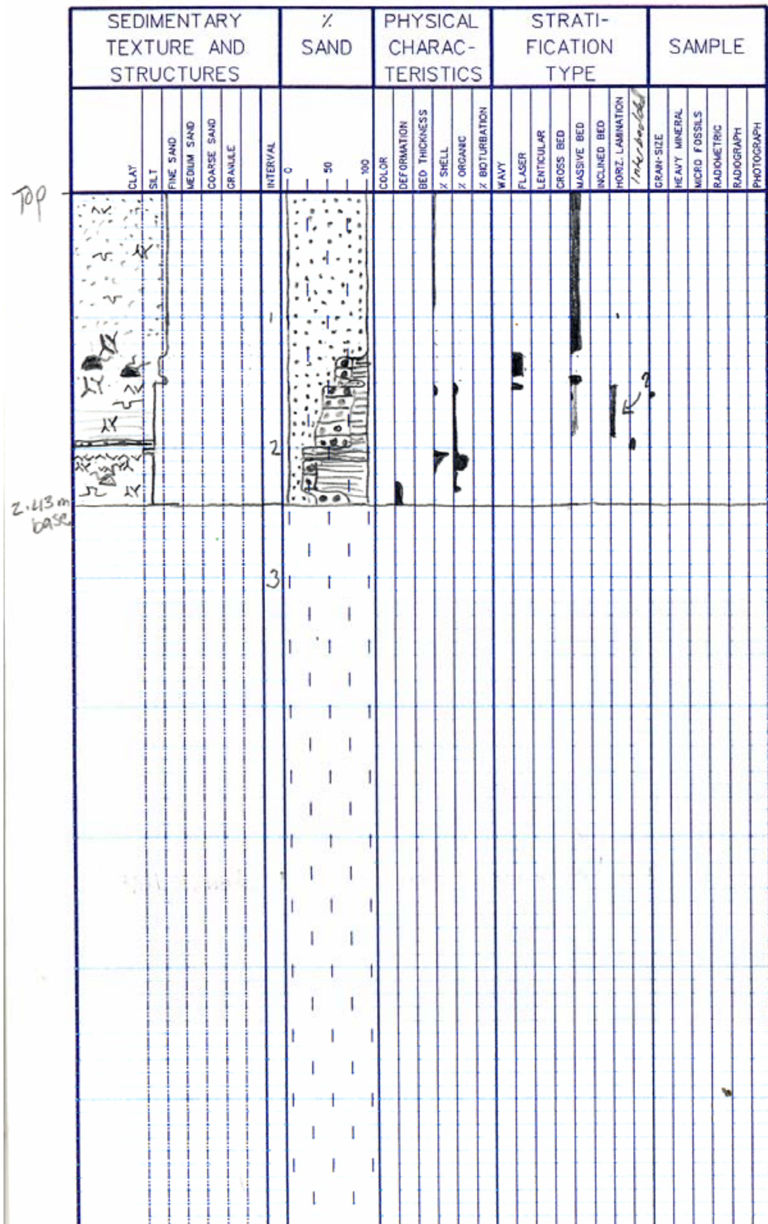
VIBRACORE DESCRIPTION SHEET

CORE ID: 05LPT07
ELEVATION: WD = 1.8 m
CORE LENGTH: 2.43 m
TOTAL DEPTH:

DATE: 1/19/2006
LOCATION: Little Pass Timbalier (west flank of channel @ throat)
~~LAT/LONG~~: UTM: 751,783.9 3,218,453.2
COMPACTION:

DESCRIBED BY: Mike Miner



PHYSICAL DESCRIPTION

<u>0-1.50 m:</u> massive-bedded dusky yel grn f. sand. Sandy clay-filled burrows @ 0.49, 0.85, 1.10 m. Concentration of sand-sized grain. organics @ 0.46, 0.94 and smaller concentrations occur throughout interval. 1 cm thick bedded organics w fine grained shell frags @ 1.23 m. 1.28 to 1.43 consists of dk grnish gry clays flaser bedded & interbedded w/ sand. Thin bedded layers of organics occur throughout the flaser zone. 1.43 to 1.50 (base of unit) is massive sand

<u>1.50-2.07 m:</u> dk grnish gry clay interbed ~1 cm thick caps this unit interval consists of olive gry silty fine sand w/ horizontal bedded organics. Some clay flases or clay clasts. Sand-filled burrows @ 1.62 m. Gastropod frag @ 1.56 m. 3 cm thick clay bed @ 2.00-2.03 m. Base of unit marked by concentrated zone of <u>M. lateralis</u> shells & frags.

<u>2.07-2.14 m:</u> Zone of concentrated coffee ground & finer grained organics in clayey silt matrix. Concentrations of <u>M. Lateralis</u> shell frags @ top & base of unit

<u>2.14 - base</u>
grnish gry silty clay w/ silty vf sand lenticular beds @ top of unit. becoming dominantly vf sand @ base w horiz laminations that show deformation in vibracore. Shell material & organics fill burrow @ 2.32 m.

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VIBRACORE DESCRIPTION SHEET

CORE ID: DSLPT07A
DATE: 8/25/05
DESCRIBED BY: Mike Miner
ELEVATION: WD = 1.8 m
LOCATION: Little Pass Timbalier (western flank of channel at throat)
CORE LENGTH: 2.75m
~~LAT/LONG~~: 751,781.9 3,218,453.2 (utm zone 16)
TOTAL DEPTH:
COMPACTION:

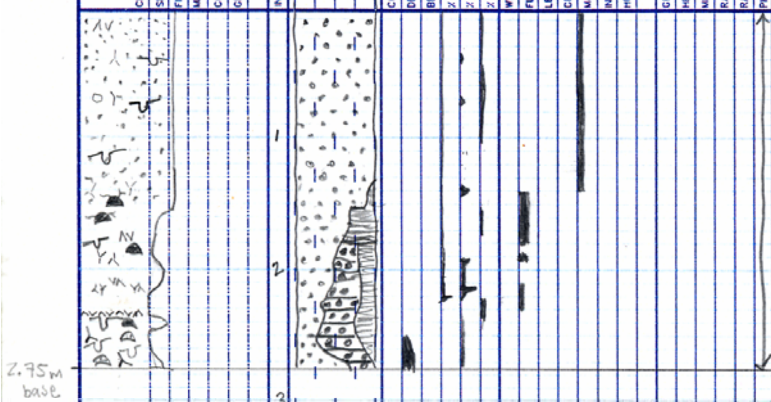
SEDIMENTARY TEXTURE AND STRUCTURES: CLAY, SILT, FINE SAND, MEDIUM SAND, COARSE SAND, GRANULE, INTERVAL (m)

% SAND: 0, 50, 100

PHYSICAL CHARACTERISTICS: COLOR, DEFORMATION, BED THICKNESS, % SHELL, % ORGANIC, % BIOTURBATION

STRATIFICATION TYPE: WAVY, FLASER, LENTICULAR, CROSS BED, MASSIVE BED, INCLINED BED, HORIZ. LAMINATION

SAMPLE: GRAIN-SIZE, HEAVY MINERAL, MICRO FOSSILS, RADIOMETRIC, RADIOGRAPH, PHOTOGRAPH



PHYSICAL DESCRIPTION

0-1.55m
massive-bedded dusky yellow green fine sand. bedded fine-grained organics @ 0.34-0.44m, 0.73m, 0.92m, & 1.36-1.42 Burrows filled w/clay, organics & sand occur throughout interval. Flaser bed @ 1.47m. contact w/ underlying unit is gradational

1.55-1.81m
flaser-bedded & burrowed dusky yellow green fine sand w/ dk greenish gry clay lenses & burrow fill. Base is gradational w/ underlying unit & marked by organic rich horizon

1.81-2.31m
Olive gry silty fine sand w/ fine grain bedded organics, some coffee grounds & wood frags. Shell frag of gastropod @ 2.10m. Abundant coffee ground organics @ 1.15m. flaser beds of brnish gry clay from 2.24-2.31m. Base of unit is marked by abundant M. Lateralis horizon in clays & silty fine sand w/ some organics. Most valves are intact.

2.31-base
brnish gry clays, silt & fine sand. Silts & sands are lenticular beds in clay w/ increase in sand @ base. Sand & silt filled burrows also in clay. Notable absence of shell material except in burrows near top. Deformation due to sampling evident @ base. Some fine grain organics

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VIBRACORE DESCRIPTION SHEET

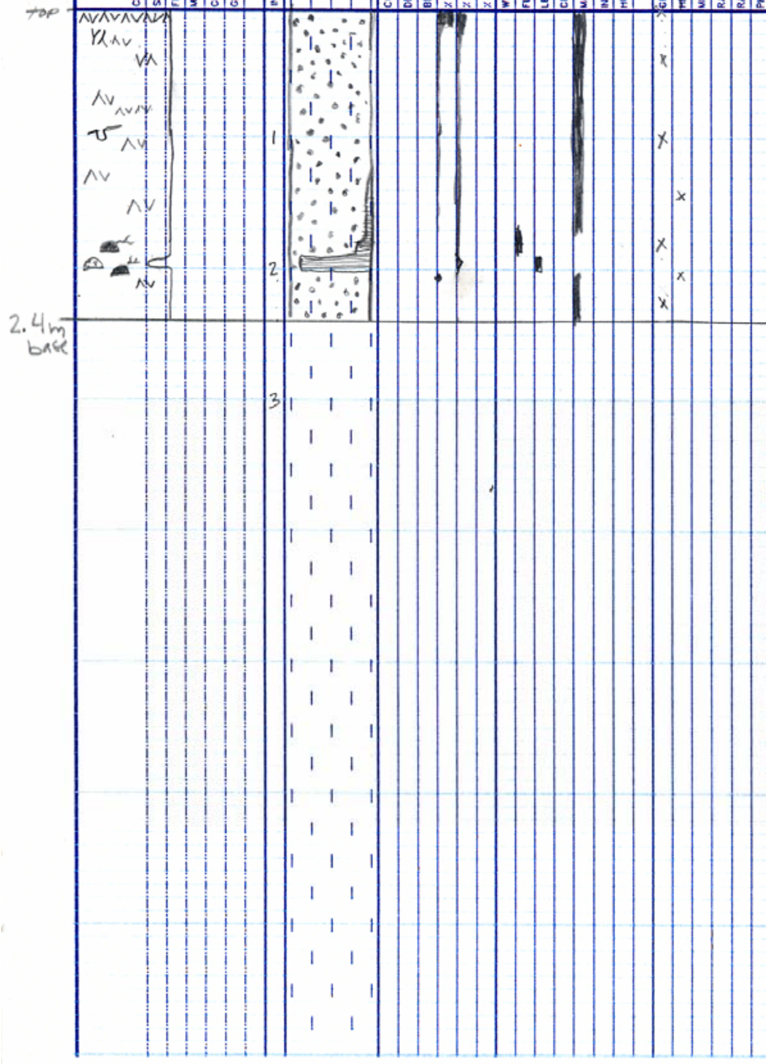
CORE ID: 05LPT08 DATE: 8/23/2005 DESCRIBED BY: Mike Miner

ELEVATION: WD = 7.5 m LOCATION: Little Pass Timbalier (in modern channel landward of throat)

CORE LENGTH: 2.4 m ~~LAT/LONG~~: 751,744.3 / 3,218,815.9 (UTM zone 16)

TOTAL DEPTH: COMPACTION:

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARACTERISTICS	STRATIFICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION
CLAY, SILT, FINE SAND, MEDIUM SAND, COARSE SAND, GRANULE, INTERVAL (m)	0, 50, 100	COLOR, DEFORMATION, BED THICKNESS, % SHELL, % ORGANIC, % BIOTURBATION	WAVY, FLASER, LENTICULAR, CROSS BED, MASSIVE BED, INCLINED BED, HORIZ. LAMINATION	GRAIN-SIZE, ~~HEAVY MINERAL~~, MICRO FOSSILS, RADIOMETRIC, RADIOGRAPH, PHOTOGRAPH	



PHYSICAL DESCRIPTION

0 – 0.14 m
shell hash in sand matrix >50% shell material ranging from <1mm to 2cm dia. Consisting of frags of *Crassostrea virginica*, *M. lateralis* & other marine bivalves.
Note: at time of sampling when core was capped off at top, there was abundent "coffee grounds" (organics)

0.14 – 1.80 m
Massive-bedded olive gray fine sand w/ rare (<1%) shell frags. large (5cm) oyster frag @ 0.47 m. concentration of organics & small shell material @ 0.85 m. Articulated bivalve @ 1.43 m sampled for ^{14}C (unable to ID but is size of *Mulinia lateralis*) ~~[illegible]~~

1.80 – 2.40 m (base)
1.60 – 1.90 m flaser beds of brnish gry clay in med gry sand. Some organics in clay.
1.90 – 2.01 m: brnish gry clay w organics & med. gry. sand lenses.
2.01 – base: Med gry clean sand small bivalves @ 2.06 m sampled for ^{14}C dating. (valves in tact but not articulated) Brown bivalves 0.5 cm in diam besides these bivalves there is a lack of shell material in this lower unit.

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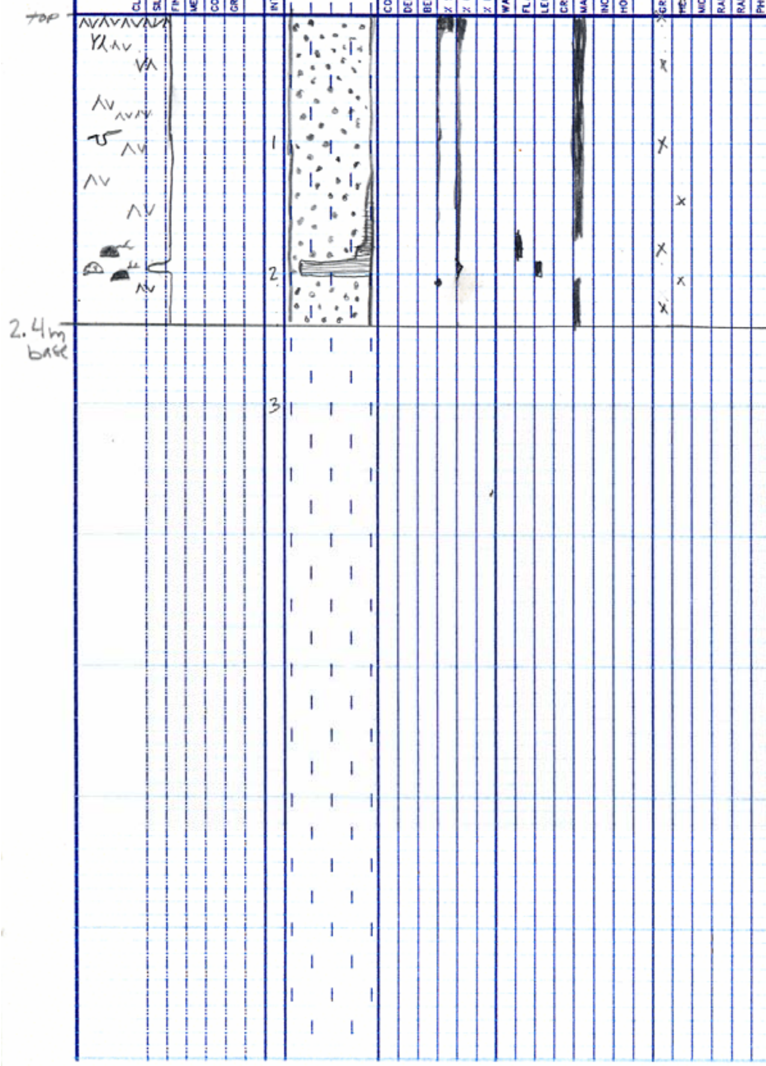
VIBRACORE DESCRIPTION SHEET

CORE ID: 05LPT08
DATE: 8/23/2005
DESCRIBED BY: Mike Miner
ELEVATION: WD = 7.5 m
LOCATION: Little Pass Timbalier (in modern channel landward of throat)
CORE LENGTH: 2.4 m
~~LAT/LONG~~: 751,744.3 / 3,218,815.9 (UTM zone 16)
TOTAL DEPTH:
COMPACTION:

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARACTERISTICS	STRATIFICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION
CLAY, SILT, FINE SAND, MEDIUM SAND, COARSE SAND, GRANULE, INTERVAL (m)	0, 50, 100	COLOR, DEFORMATION, BED THICKNESS, % SHELL, % ORGANIC, % BIOTURBATION	WAVY, FLASER, LENTICULAR, CROSS BED, MASSIVE BED, INCLINED BED, HORIZ. LAMINATION	GRAIN-SIZE, ~~HEAVY MINERAL~~, MICRO FOSSILS, RADIOMETRIC, RADIOGRAPH, PHOTOGRAPH	



0 – 0.14 m
shell hash in sand matrix >50% shell material ranging from <1mm to 2cm dia. Consisting of frags of Crassostrea virginica, M. lateralis, & other marine bivalves.
Note: at time of sampling when core was capped off at top, there was abundant "coffee grounds" (organics)

0.14 – 1.80 m
Massive-bedded olive gray fine sand w/ rare (<1%) shell frags.
large (5cm) oyster frag @ 0.47 m.
concentration of organics & small shell material @ 0.85 m.
Articulated bivalve @ 1.43 m sampled for ^{14}C (unable to ID but is size of mulinia lateralis) ~~[illegible]~~

1.80 – 2.40 m (base)
1.60 – 1.90 m flaser beds of brnish gry clay in med gry sand. Some organics in clay.
1.90 – 2.01 m: brnish gry clay w organics & med. gry. sand lenses,
2.01 – base: Med gry clean sand small bivalves @ 2.06 m sampled for ^{14}C dating. (valves in tact but not articulated) Brown bivalves 0.5cm in diam besides these bivalves there is a lack of shell material in this lower unit.

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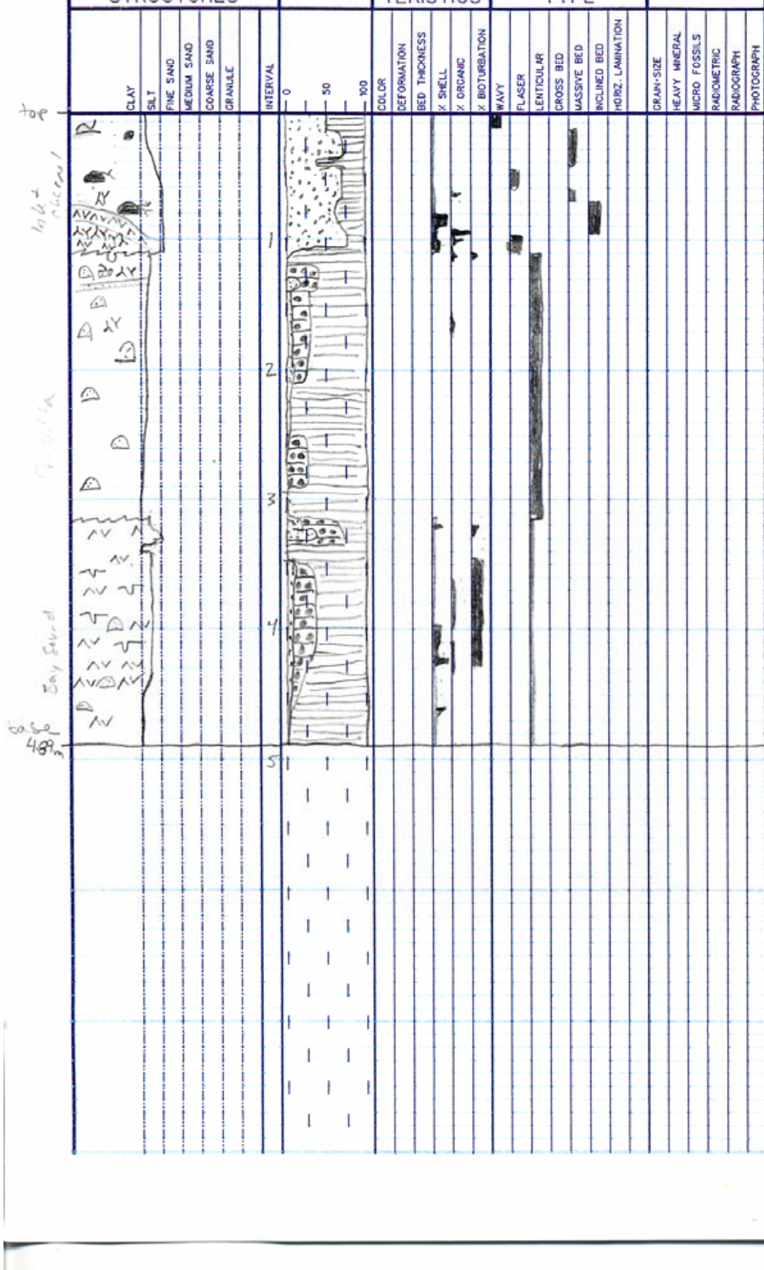
VIBRACORE DESCRIPTION SHEET

CORE ID: 05LPT09
DATE: 1/20/06
DESCRIBED BY: Mike Miner
ELEVATION: UD= 5.9 m
LOCATION: offshore Little Pass Timbalier, LA (1980's channel)
CORE LENGTH: 4.89 m
~~LAT/LONG~~: UTM: 752,454.7 3,217,823.0
TOTAL DEPTH:
COMPACTION:

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARACTERISTICS	STRATIFICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION



PHYSICAL DESCRIPTION

0-1.10 m: gryish olive grn f. sands, & 0-0.15 m is wavy bedded with gryish olive grn clays. 0.15-0.70 is massive sand w clay clasts. Clays in interval 0-0.70 are aqueous. 0.70-1.00 m consists of inclined beds of organics, clay flasers & clasts and zones of shell hash (M. lateralis) Base of unit is marked by sharp contact w/ burrows extending into underlying unit

1.10-3.16m: dk gry clays w/ dk gry silty v. fine sand lenses. Unit coarsens upward and lenses become increasingly spaced & thinner towards base. Some organic specks in clays and rare wood fragments. No Shells

3.16-base: dusky yellowish green clays with dusky yellowish grn silty fine sand lenses. Abundant (~5%) shell frags of oysters & M. lateralis. Contact w/ above unit is sharp. Much of the zone from 3.40 to 4.45 is heavily bioturbated Zones of organics occur in sandier interval from 3.68 to 4.45. Bioturbation and shell content decrease toward base except for Shelly zone @ 4.66m.

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VIBRACORE DESCRIPTION SHEET

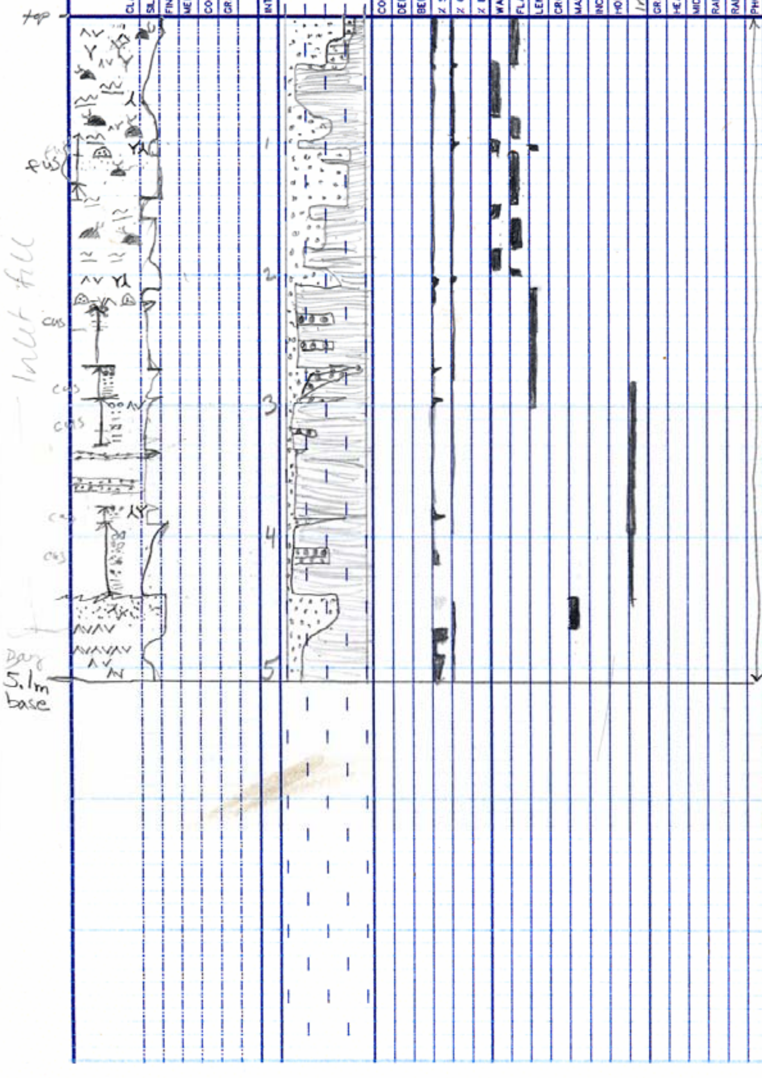
CORE ID: 05LPT10 DATE: 8/22/2005 DESCRIBED BY: Mike Miner

~~ELEVATION~~: WD= 4.6 m LOCATION: Little Pass Timbalier (1980's throat)

CORE LENGTH: 5.10 m ~~LAT/LONG~~ XY: 752578.0 3217855.7 (UTM zone 16)

TOTAL DEPTH: COMPACTION:

SEDIMENTARY TEXTURE AND STRUCTURES	% SAND	PHYSICAL CHARAC-TERISTICS	STRATI-FICATION TYPE	SAMPLE	PHYSICAL DESCRIPTION
CLAY, SILT, FINE SAND, MEDIUM SAND, COARSE SAND, GRANULE, INTERVAL (m)	0, 50, 100	COLOR, DEFORMATION, BED THICKNESS, % SHELL, % ORGANIC, % BIOTURBATION	WAVY, FLASER, LENTICULAR, CROSS BED, MASSIVE BED, INCLINED BED, HORIZ. LAMINATION, interbed	GRAIN-SIZE, HEAVY MINERAL, MICRO FOSSILS, RADIOMETRIC, RADIOGRAPH, PHOTOGRAPH	



0 - 1.08 m:

interbedded dark yellowish green to grayish blk f. sand, silt, & clay w fine-grained organics & fine-grained shell material

0 - 0.45 m: flaser to wavy-bedded clays & sand. organics & shell material concentrated @ 0.42 m

0.45 m - 0.83 m: increased mud from overlying interval. Wavy-bedded to lenticular, or

0.83 - 0.96 m: increase in sand, mud is flaser bedded

0.96 - 1.08 m: wavy to lenticular bedded w/ concentration of organics in ~1 cm thick layer @ 1.05 m

1.08 - 1.41 m

fining upward fine sand to flaser to wavy bedded clays sharp contact b/t clay & sand @ 1.16, 1.29, 1.41 m

1.41 - 2.16 m

f. sand w/ clay interbeds. Some flaser & zones of wavy to lenticular bedding @ 1.41-1.54, 1.80 - 1.92.

2.02 - 2.10: mixed sand & mud w abundant fine grained organics & shell material (M. Lateralis?)

2.16 - 4.44 m

coarsening upward intervals w/ sharp contacts. thick (~10-20 cm) clay intervals grade upward into silt lenses & ultimately f. sand w/ fine organics & shell.

4.44 - 5.10 (base)

4.44 - 4.68: massive bedded f. sand w/ organics & shell material

shell hash w/ oyster frags, M. lateralis, & gastropods @ 4.68 - 4.73 in sandy cly matrix

Abundant M. lateralis @ 4.85 - 4.90 + shell hash in cly matrix 4.73 - base

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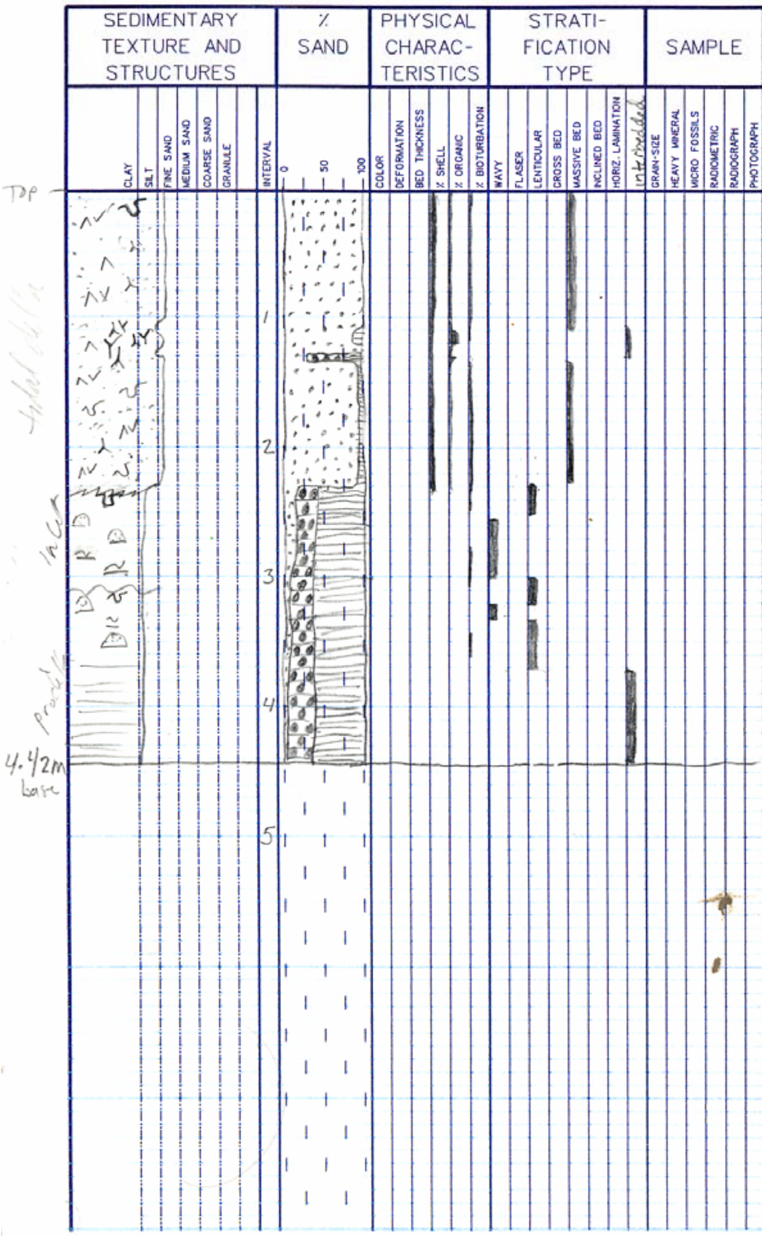
VIBRACORE DESCRIPTION SHEET

CORE ID: DS LPT 11
ELEVATION: WD= 3.3 m
CORE LENGTH: 4.42 m
TOTAL DEPTH:

DATE: 1/19/2006
LOCATION: Little Pass Timbalier, LA
~~LAT/LONG~~: UTM: 753,324.9 3,216,628.0
COMPACTION:

DESCRIBED BY: Mike Miner



PHYSICAL DESCRIPTION

0-2.28 m: massive bedded dusky yel grn f. sand, Burrowed & ~0.5% M Lateralis frags & whole valves scattered randomly throughout unit. Zone of bedded organics & heavy minerals from 1.10 to 1.20 m. Beds are ~1cm thick in sandy matrix. Brunish gry clayey sand bed from 1.28 - 1.33 m. Below this bed massive bedded sand continues but has increased clay content and is brownish gry. Contact @ base of unit is sharp w/ burrows extending into underlying unit

2.28 - base

Dk gry clays with dusky yel grn f. sand lenticular beds from 2.28 to 2.5 m. Becoming wavy beds w/ increase in silt from 2.5 to 3.00 m. Below 3.00 m lenses are dominated by dk gry silty v. fine sand. Some burrows are silt-filled in ~~sd~~ clay matrix. Below 3.70 clay is massive with occasional silt & silty v.f. sand interbeds & lenses, 2cm thick tan vf. sand interbed @ 4.13 m. Some rare organics & wood frags toward base. Entire unit void of shell material except that which is filling burrows towards the top of unit

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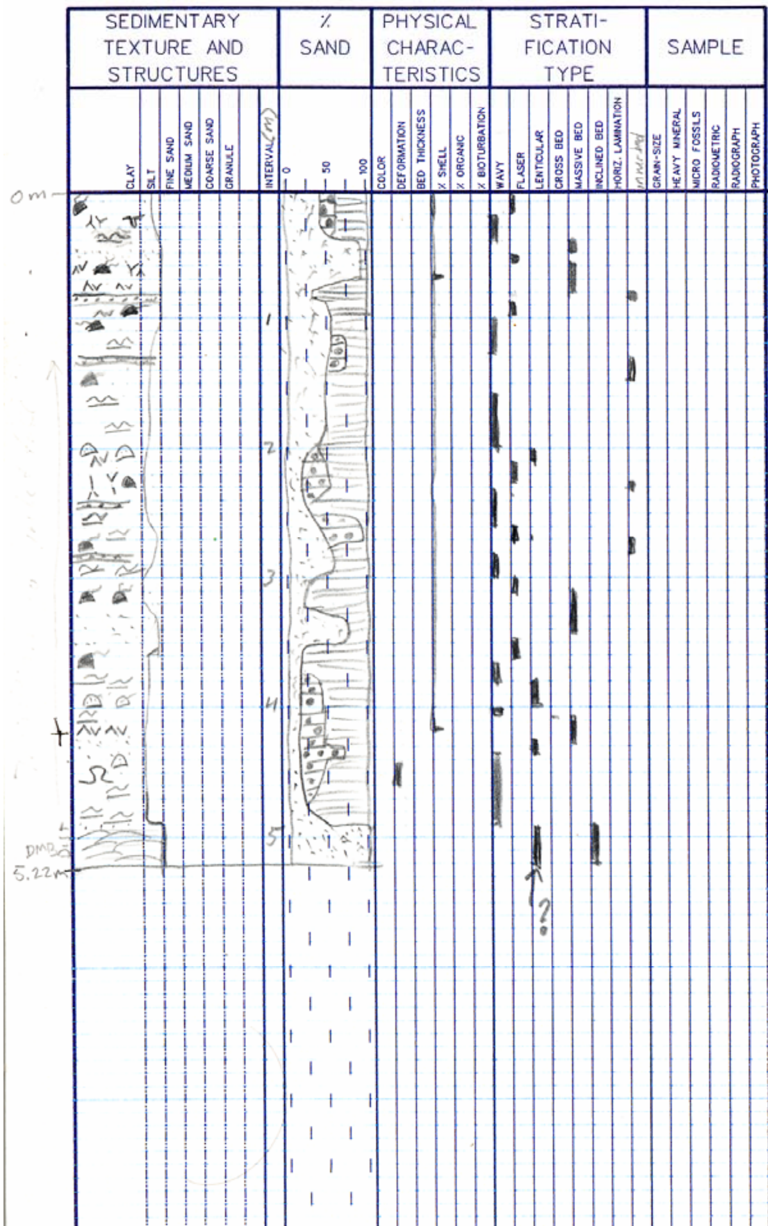
VIBRACORE DESCRIPTION SHEET

CORE ID: 05LPT12
DATE: 01/13/2006
DESCRIBED BY: Mike Miner
ELEVATION: WD: 3.6 m
LOCATION:
CORE LENGTH: 5.22 m
LAT/LONG: Utm: 752,651.96 3,217,871.5
TOTAL DEPTH:
COMPACTION:



PHYSICAL DESCRIPTION

0 - 5.22 m (base)
entire core consists of dusky yel grn fine sand innerbedded w/ dk greenish gry clays in varied proportions ranging from flaser to wavy to lenticular sometimes horizontal beds of clay.
- Organics (heavy concentrations @ 0.25, 0.78, 0.90 - 0.94, 1.02, 3.19 as ~1mm thick laminations.
- M. Lateralis concentrations @ 0.76 & 4.17. Rare M. Lateralis frags throughout but none below the 4.17 zone.
- 4.17 - Base
zone contains thinner laminations of clays, increase in silt & decrease in shell. 4.95 - base is horiz laminated v. fine well-sorted sand (could be x-bedded) contact @ 4.95 is sharp.
Deformation @ 4.47 - 4.59.

VITA

Mike Miner was born in New Orleans, Louisiana on March 4, 1975. He graduated from high school at Metairie Park Country Day School in 1994. Mike received a Bachelor of Science in Geology from The University of Mississippi in 1999 and a Master of Science in Geology from The University of Mississippi in 2003. In 2003, he returned to New Orleans and began work on his doctorate in Geology at the University of New Orleans, which he completed in May 2007. Dr. Miner is currently employed as a Post-Doctoral Research Associate with the Pontchartrain Institute for Environmental Sciences at the University of New Orleans.