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REPRESENTATIVE PUBLICATIONS
FROM THE
LOUISIANA BARRIER ISLAND EROSION STUDY

Compiled by

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Introduction

The Louisiana Barrier Island Erosion Study was a cooperative investigation conducted by the U.S. Geological Survey (USGS) and the Louisiana Geological Survey (LGS) over a 5-year period (1986-1990). Encompassing the coastal deltaic plain region of south-central Louisiana, the study focussed primarily on the geologic framework and evolution of the coast and inner continental shelf, the critical coastal and nearshore processes, and the transfer and application of the scientific results to a broad audience. As one of nine studies of the USGS National Coastal Geology Research Program, the results of this study are becoming the foundation on which other studies in the Gulf of Mexico region are building.

The publications included in this report represent a sampling of interim and final results of research investigations conducted not only by the USGS and the LGS but also by the Louisiana State University and other universities as well.

The USGS National Coastal Geology Research Program is headquartered in St. Petersburg, Florida, with additional personnel based in Reston, Virginia; Woods Hole, Massachusetts; and Menlo Park, California. The Louisiana Geological Survey is located on the campus of Louisiana State University, Baton Rouge, Louisiana.

Coastal Erosion and Wetlands Loss in Louisiana: Status of U.S. Geological Survey Coastal Research Activities

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Introduction

More than one-half of the population of the United States currently live within 50 miles of one of the Nation's ocean or Great Lakes coasts, and the density of population and development in the coastal zone is predicted to increase into the 21st century. At present, developed coastal areas face potential loss of life and billions of dollars in property damage because of long-term coastal erosion and storm effects. In addition, valuable coastal wetlands and estuarine habitats are being altered rapidly as a result of natural and man-induced factors. All 30 States bordering a coast are experiencing erosion and wetlands deterioration, and 26 of these States suffer from an overall net erosion of their shorelines. The National Academy of Sciences forecasts an increase in sea-level rise; this would accelerate coastal erosion and wetlands degradation.

The physical processes causing wetlands loss and barrier island erosion are complex and varied, and many are not well understood. In addition, the technical and academic community debate about which of the many contributing processes, both natural and human-induced, are most significant. Controversy also surrounds some of the measures that are being proposed to mitigate erosion and reduce wetlands loss. Much of the debate is focused on the reliability of predicted results of a given management, restoration, or erosion mitigation technique. With better understanding of the physical processes causing erosion and wetlands loss, such predictions will become more accurate, and a clearer consensus should appear on which solutions will be most effective.

Role Of The U.S. Geological Survey In Coastal Erosion And Wetlands Loss Research

As the primary Federal agency for conducting research and information gathering on all earth-science topics, the U.S. Geological Survey (USGS) is engaged in studies focused on improving scientific understanding of the physical processes affecting coastal environments. In 1992, the USGS's National Coastal Geology Program supported ten major regional studies, with five addressing erosion, three addressing wetlands deterioration, and two addressing pollution; they are: (1) Louisiana Barrier Island Erosion, (2) Louisiana Wetlands Loss, (3) Southern Lake Michigan Coastal Erosion, (4) Alabama/Mississippi Coastal Erosion and Pollution, (5) Western Louisiana-East Texas Erosion, (6) Lake Erie (Ohio) Erosion, (7) Massachusetts Bay Pollution,

(8) Great Lakes and Florida Wetlands Loss, (9) South Carolina Erosion, and (10) Great Lakes Regional Mapping. Each study is being done in close cooperation with other Federal agencies (e.g., U.S. Fish and Wildlife Service (USFWS), U.S. Army Corps of Engineers, National Oceanic and Atmospheric Administration, Environmental Protection Agency) and State geological surveys as well as academic researchers. The two Louisiana studies are described below.

Louisiana Barrier Island Erosion Study

Much of the territory bordering the Gulf of Mexico is undergoing shoreline erosion. Louisiana, however, has the greatest rate of erosion compared with other Gulf region States, and also with other coastal States. Much of this erosion occurs along the barrier islands, which act as buffers, protecting landward wetlands and estuaries from the effects of storms, ocean waves, and currents.

In 1986, the USGS and the Louisiana Geological Survey (LGS) began a 5-year study that focused on the processes causing barrier island erosion. The study areas extended from the Isles Dernieres to Sandy Point and to the Chandeleur Islands east of the Mississippi River Delta. Because long-term erosion of Louisiana's barrier islands is due to both sea-level rise, relative to the land, and diminishing sand supply, the primary objectives of this study were to quantify processes related to sea-level rise and sand supply and to present the results in a form that can be applied to practical problems such as predicting future changes. The study was divided into three main parts:

- Investigations of the geologic framework of the Mississippi River deltaic plain where the barrier islands formed and migrated landward. This involved using sediment cores and geophysical profiles to provide a broad regional understanding of the historical development of the barrier islands and a conceptual view of the processes of barrier island erosion. Comparisons of archival maps and photographs of the coast (from the past 135 years) yielded accurate measurements of the geomorphic changes taking place.

- Development of a better quantitative understanding of the processes responsible for erosion. The focus was on only a few of the many physical processes, including relative sea-level rise, overwash, net offshore sediment transport, and gradients of sediment transport. Careful analyses of tide gauge records showed a progressive rise in relative sea level over the entire region, with local rates exceeding 1 cm/yr. Most of the rise is due to compaction and subsidence of the recent deltaic sediments. A series of field experiments and modeling efforts were undertaken (e.g., direct measurements of overwash of the Isles Dernieres barrier islands during winter storms and hurricanes).

- Compilation of the research results as digital data sets, atlases, and technical reports for use by coastal scientists, planners and engineers.

Applications of the study results include developing better techniques for determining the rate at which artificially nourished beaches should be replenished and predicting future shoreline erosion so coastal planners can plan construction at a safe distance landward from the eroding shoreline.

This study was concluded in September 1990, and final products are being completed.

Louisiana Wetlands Loss Study

Of the 48 conterminous States, Louisiana has 25 percent of the vegetated wetlands and 40 percent of the tidal wetlands. These coastal wetlands, including the associated bay and estuary environments, support renewable natural resources valued at approximately $1 billion per year. However, an estimated 80 percent of the Nation's tidal wetlands area loss has occurred in Louisiana. The areas of greatest loss are in the modern Mississippi River Delta and the Barataria and Terrebonne basins to the west. Map comparisons by several scientists have been used to show that wetlands loss has steadily increased during the 20th century to an estimated 100 km^2/yr by 1978, the latest year for which detailed measurements are available. If this rate of wetlands loss continues, the USACE estimates that in the next 50 years, nearly 1 million acres of Louisiana wetlands will be converted to open water.

Conceived as a natural extension of the Barrier Island Erosion Study, this USGS study began in late 1988 in cooperation with the USFWS and Louisiana State agencies. Emphasis is on understanding the critical physical processes that cause the extreme rate of wetlands loss in coastal Louisiana and identifying the best management practices to address those losses.

This USGS and USFWS wetlands study includes four parts: (1) baseline data is being compiled and put into a computer-based Geographic Information System; (2) research is being conducted on a basin scale to understand some of the critical processes causing wetlands loss; (3) at specific sites, research is being conducted on the effects and utility of various wetlands management activities on the processes; and (4) the information and results from these studies are being passed to the user community by means of reports, maps, and workshops.

The wetlands study elements dealing with research on some of the critical physical processes are being undertaken by USGS scientists as well as scientists at LGS and Louisiana State University under contract with the USGS. Field studies are underway in two separate hydrologic basins, one sediment-rich and the other sediment-poor, in order to compare and contrast the dominant processes in each. Investigations are nearly complete in the sediment-poor Terrebonne Basin-Timbalier Bay and parts of the Barataria Basin; field studies in the sediment-rich Atchafalaya basin started in 1991. Research elements under investigation for each basin include meteorological forcing events, fine-grained sediment dispersal, saltwater and freshwater dispersal, physical

processes of marsh deterioration, wetlands soil development, and subsidence-soil compaction. In addition, a study contracted to Coastal Environments, Inc., has examined and reported on the effects of small-scale freshwater diversions from the Mississippi River on brackish marshes adjacent to the levees. The duration of the USGS-USFWS Wetlands Study is anticipated to be six years.

Summary

In addition to the ten studies currently underway in USGS's National Coastal Geology Program, other activities have been undertaken. Congress directed the USGS to formulate a plan to extend and expand regional coastal studies into a research program of national scope, an effort which included obtaining recommendations from other Federal agencies as well as the appropriate agencies in each of the 30 coastal States. The plan, prepared and submitted to Congress in May 1990, addresses research needs for coastal issues - erosion, wetlands loss, polluted sediments, and marine hard-mineral resources - and provides for two complementary types of research: *fundamental studies* focusing on critical processes, which can be applied nationally, and *regional studies* to improve understanding of natural and man-induced processes within specific regions. While not fully funded by Congress, incremental funding for some regional studies has been provided as a result. In addition, Congress directed the USGS to prepare a plan for a potential new regional study in Hawaii and U.S. possessions in the Pacific.

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Louisiana Barrier Island Erosion Study

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Abstract

During 1986, the U.S. Geological Survey and the Louisiana Geological Survey began a five-year cooperative study focused on the processes which cause erosion of barrier islands. These processes must be understood in order to predict future erosion and to better manage our coastal resources. The study area includes the Louisiana barrier islands which serve to protect 41% of the nation's wetlands. These islands are eroding faster than any other barrier islands in the United States, in places greater than 20 m/yr. The study is divided into three parts: geological development of barrier islands, quantitative processes of barrier island erosion and applications of results. The study focuses on barrier islands in Louisiana although many of the results are applicable nationwide.

Introduction

Coastal erosion and wetland loss are serious national problems with long-term economic and social consequences. Developed areas face billions of dollars in property damage and potential loss of life as a result of long-term erosion and storm impacts, and valuable wetlands are being altered at rapid rates. Of the 30 states bordering an ocean or Great Lake, 26 presently experience a net erosion of their shores (May and others, 1983). Erosion will likely accelerate in the future in view of the National Academy of Sciences and the Environmental Protection Agency forecasts of increasing rate of sea level rise (Hoffman and others, 1983).

Louisiana has the highest rates of coastal erosion and wetland loss of any of the United States. In the Mississippi River delta plain, rates of wetland loss exceed 102 square kilometers per year (Gagliano and others, 1981). Louisiana's barrier islands, which serve to protect wetlands, are eroding in places up to 20 m/yr (Penland and Boyd, 1981). These barriers are not simply migrating landward while maintaining a constant length and

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width. Rather, the islands are decreasing in area as they migrate landward. For example, between 1890 and 1979, Louisiana barriers decreased in area by 37%, from 92 to 58 square kilometers (Penland and Boyd, 1981; 1982). If this rate of land loss continues, the barrier islands will disappear, which in turn will accelerate the destruction of valuable wetlands. Louisiana contains 41% of the nation's wetlands which support a one billion dollar a year fishery. The magnitude of barrier island erosion and wetland loss in Louisiana is a problem of national significance.

Many of the processes contributing to barrier island erosion are poorly understood and are not quantifiable with any degree of confidence. These processes must be better understood in order to predict the future shoreline response and, thus, allow better management of our coastal resources. In 1986, the U.S. Geological Survey (USGS) and Louisiana Geological Survey (LGS) began a 5-year study focused on the processes causing barrier island erosion. In this paper, we discuss the objectives of the ongoing study, present the approach that we are taking, and outline some results from our initial efforts.

Study Overview

Long-term erosion of Louisiana's barrier islands is due both to sea level rise relative to the land and diminishing sand supply. The primary objectives of the study are to better quantify processes related to sea level rise and sand supply, and to present the results in a form so that they can be applied to practical problems, such as prediction of future changes. The study is divided into three overlapping parts: geologic development of barrier islands, quantitative processes of barrier island erosion, and applications of results. Each part of the study will be discussed in subsequent sections.

Basic data required by each part of the study include historical measures of volumetric changes in sediment on the islands and offshore. Previous studies have documented shoreline changes and wetland loss in Louisiana (e.g. Morgan and Larrimore, 1957; Penland and Boyd, 1981; and Gagliano and others, 1981). Since the most recent bathymetric survey of coastal Louisiana was prepared in the 1930's, there have been few studies which compared historical charts for volumetric changes. Our initial work included resurveying bathymetry in the vicinity of Isles Dernieres, a barrier island arc that extends for 35 km along the central Louisiana coast (Figs. 1, 2, and 3). These barriers are eroding faster than any of the other barrier islands in Louisiana. In 1887, Isles Dernieres was nearly a continuous island, whereas by 1985 the barrier was cut into a series of smaller islands separated by wide inlets (Fig. 4). During this same period, the Gulf front shoreline retreated more than a kilometer (Figs. 4

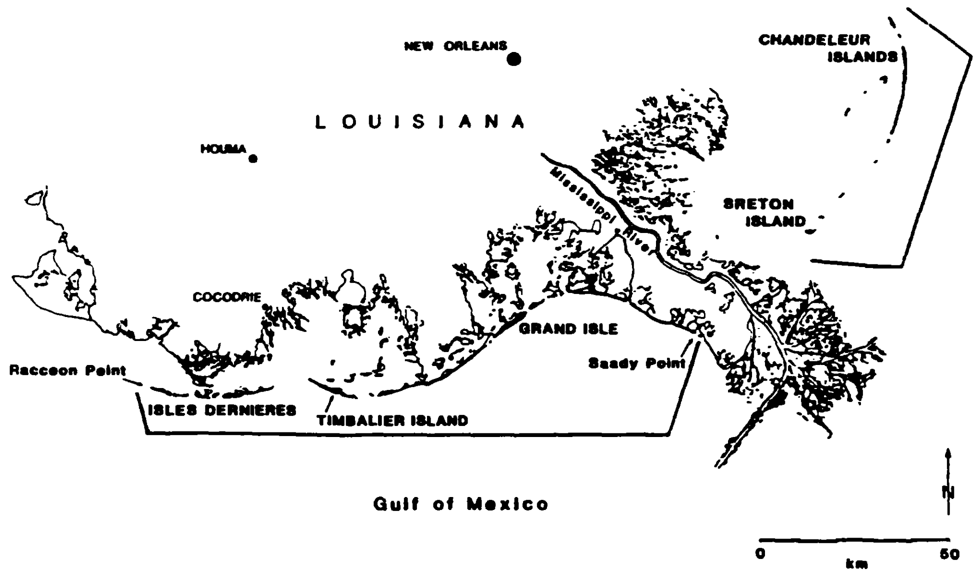

Figure 1. Location of the USGS/LGS Barrier Island Erosion Study.

Figure 2. Aerial photograph of part of the Isles Dernieres.

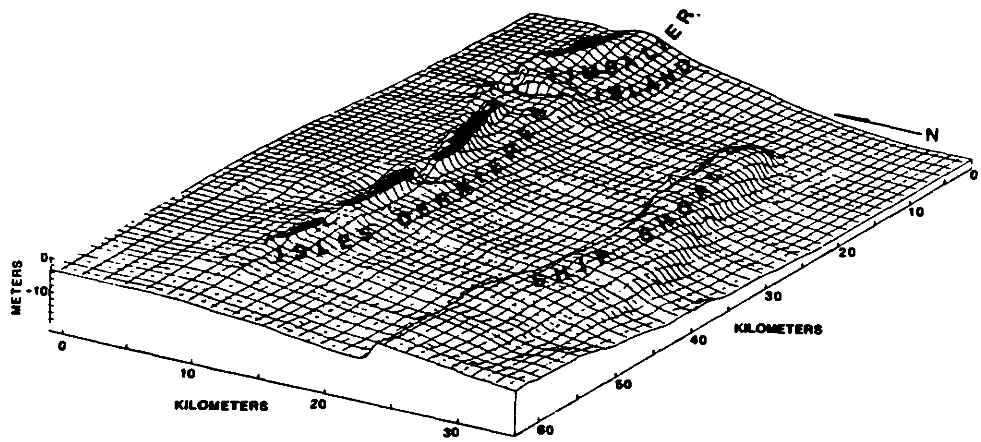

Figure 3. Mesh perspective plot of bathymetry in the vicinity of the barrier islands known as Isles Dernieres. Bathymetry from a new survey conducted by the USGS/LGS study during May-June 1986.

and 5). Over a 92 year period, the Isles Dernieres have decreased in area 63%, from 48 to 18 square kilometers, a rate of 0.33 square kilometers per year (Penland and Boyd, 1981). Projecting this rate into the future, the Isles Dernieres will disappear by the year 2034.

I. Geological Development of Barrier Islands

A first step in evaluating causes of barrier island erosion is to establish the geologic framework within which the barriers formed and migrated landward. These studies, which involve both stratigraphy and geomorpholgy, are providing a broad regional understanding of the historical development of the islands and are contributing to a conceptual understanding of the processes involved.

Regional Stratigraphy

The formation of the Louisiana barrier islands is closely related to the development and subsequent erosion of abandoned Mississippi River deltas (Kolb and Van Lopik, 1958; Fisk, 1944; Frazier, 1967; and Penland and Boyd, 1981). The changing course of the Mississippi River over the past six thousand years has lead to the development of at least four delta complexes which overlap and create complicated sedimentary facies relationships (Coleman and Gagliano, 1964; Frazier, 1967). Our objective is to map the stratigraphy and facies relationships between each transgressive barrier shoreline and its associated delta, both onshore and offshore. The three-dimensional geometry and sediment texture of facies are being defined by analyzing high resolution geophysical profiles and vibracores, supplemented by surface sampling and drilling.

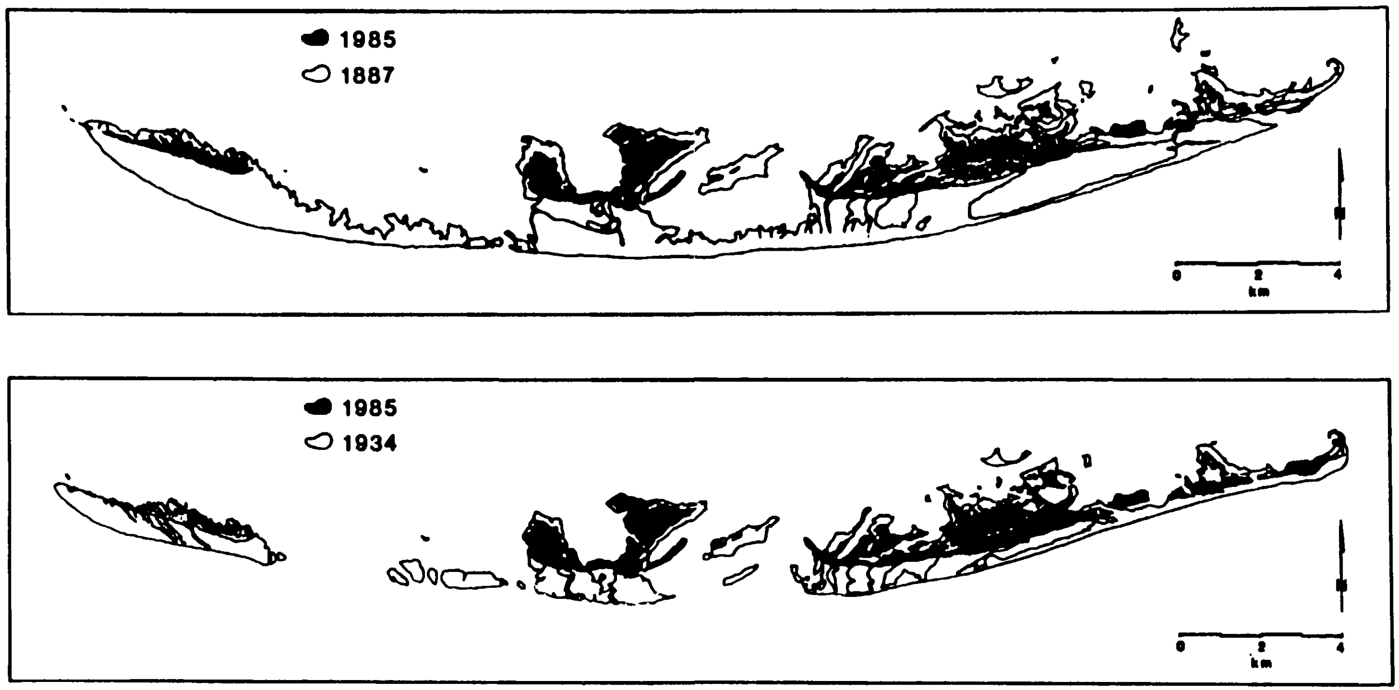

Figure 4. Shoreline of the Isles Dernieres from surveys of 1887, 1934, and 1985. The 1887 and 1935 shorelines were digitized from historical maps of the NOAA National Ocean Survey. The 1985 shoreline was digitized from USGS/LGS vertical photography that had been corrected for distortion and printed in map format.

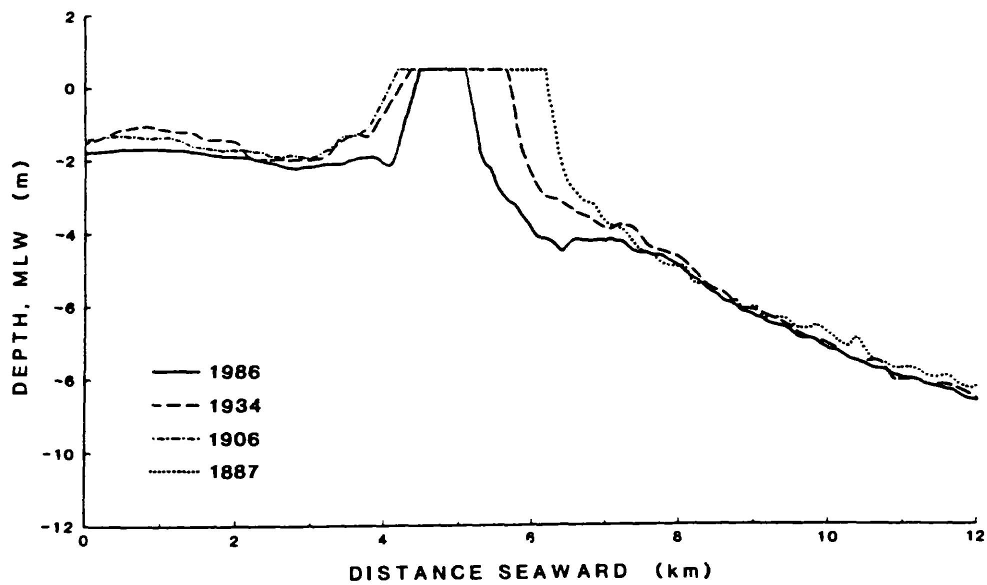

Figure 5. Example of historical shoreface erosion from the Isles Dernieres. Profile location is 12 km west of eastern end of Isles Dernieres. The 1887 and 1935 bathymetry have been digitized from historical surveys of the National Ocean Survey, and the 1986 bathymetry is from the May-June survey funded by this study. The vertical datum is mean low water at the time of the survey and has not been adjusted for historical changes associated with relative sea level rise.

Age relationships and sea-level history are being determined through geochronological techniques. These studies are supplying data needed by the quantitative process investigations, such as the distribution of sands both surficially and in the subsurface.

Between 1982 to 1985, the USGS and LGS have collaborated to collect more than 10,000 line-km of high-resolution seismic-reflection profiles in coastal Louisiana. These profiles are part of a regional data base used to provide information on the shallow geologic framework of the Louisiana inner shelf and to locate nearshore sand resources (Penland and Suter, 1983; Penland and others, 1985). In 1986, as part of the study discussed here, an additional 1200-line km of geophysical data were surveyed off the Isles Dernieres and 148, 40 foot-long vibracores were obtained (Fig. 6).

Geomorphology

Hurricanes, tropical storms, and cold fronts all contribute to erosion of Louisiana's barrier islands. The effects of these storms on the geomorphology of the

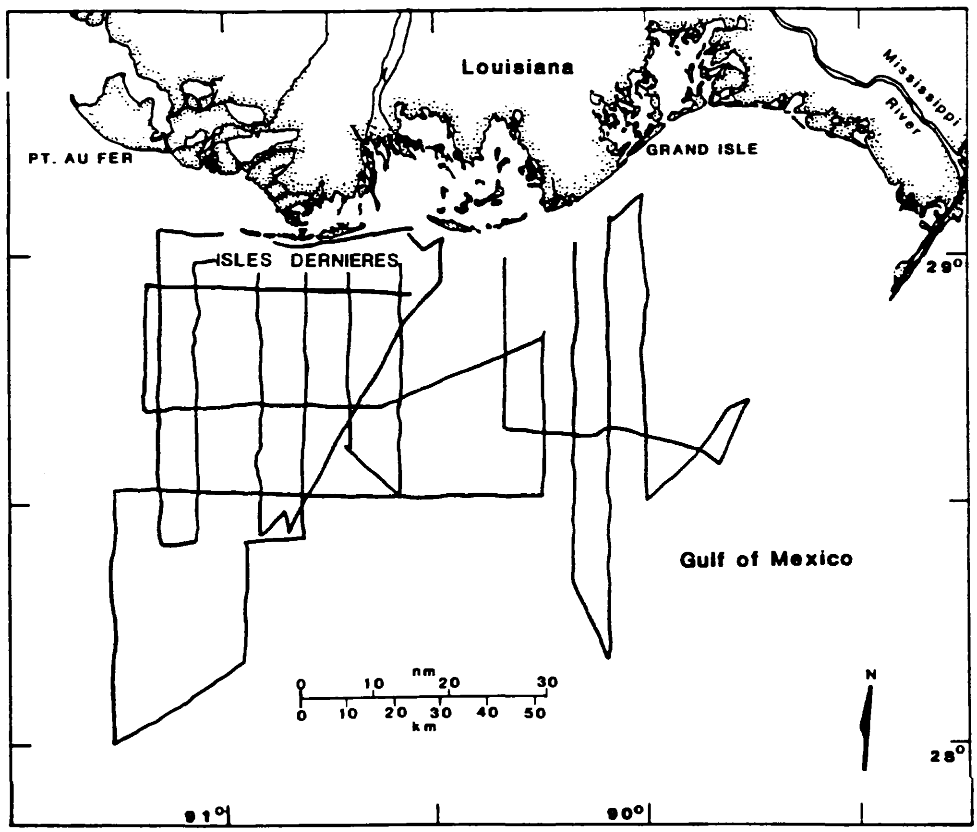

Figure 6. Track lines of the 1986 geophysical cruise. Seismic systems used in the 1986 cruise include an ORE Subbottom Profiler and an ORE Geopulse.

islands are being investigated using pre- and post-storm aerial videotapes, mapping photography, and beach profiles. Offshore, the response of the shoreface to storms are being examined through repetitive bathymetric profiles and sediment sampling. Processes are being qualitatively assessed through examining water levels, offshore wave conditions, and meteorological data. These studies are providing regional scale information on the variability of erosion and the different processes at work, and are contributing to determining relative roles of infrequent but severe hurricanes to the more frequent but less severe cold fronts. The results of these studies are identifying processes to be addressed by the quantitative studies.

Since 1984, the LGS has conducted annual videotape surveys of the Louisiana coastline. As we prepared for our study in the summer and fall of 1985, three hurricanes impacted the Gulf Coast between Louisiana and Florida. Pre- and post-storm aerial videotape surveys showed that barrier shorelines underwent repeated intense overwash, and beach and dune erosion exceeding 30 m (Penland, Suter, and Nakashima, 1986). The effects of Hurricane Danny on the barrier islands west of the Mississippi River are summarized in Figure 7.

II. Quantitative Processes of Barrier Island Erosion

Many processes contributing to barrier island erosion can not be accurately quantified. In some cases, it is even difficult to assess whether one process is more important in causing erosion than another. In this study, we focus our efforts and resources on several processes that are not well understood, but are approachable experimentally.

Sea Level Rise

In coastal Louisiana, relative sea level is rising rapidly as a result of land subsidence and world-wide sea level (eustatic) rise. Erosion due to sea level rise is not entirely due to inundation, but includes a readjustment of the nearshore profile (e.g. Bruun, 1962) that is not well understood. Critical processes controlling erosion due to sea level rise, such as the distances offshore and onshore to which sand is exchanged with the beach during the storm/recovery cycle, are being determined. Models which predict erosion due to sea level

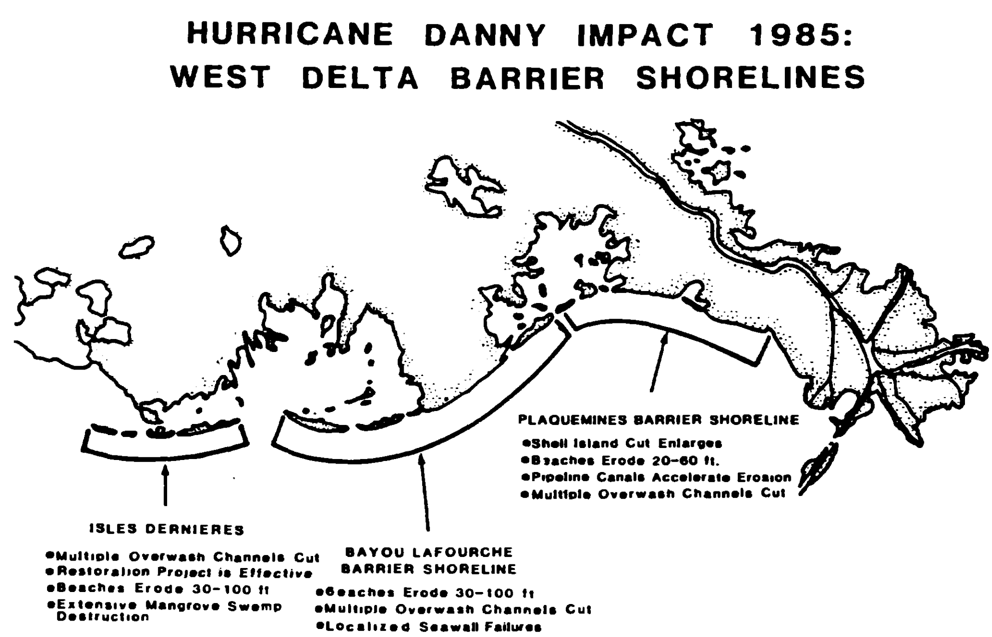

Figure 7. Summary of shoreline effects of Hurricane Danny which occurred in 1985 (adapted from Penland and others, 1986).

rise (e.g. Everts, 1985) are being tested against historical measures of erosion.

Our first step was to determine as accurately as possible the magnitude of relative sea level (RSL) rise (Fig. 8). At tide stations in both Houma and Grand Isle, linear regression of the entire record indicates RSL rise of 1.3 cm/yr. This is significantly greater than the eustatic rise, or world wide sea level rise, of about 0.01 cm/yr (Gornitz and others, 1982). Interestingly, there appears to be a recent acceleration in RSL rise that also occurs around the U.S. coast of the Gulf of Mexico, although at different magnitudes (Penland and others, in press).

Overwash Processes

It is well known that overwash during storms contributes to the net landward transport of sediment and the landward migration of Louisiana's barrier islands (Ritchie and Penland, 1985). However, the magnitude of the contribution of overwash to shoreline erosion is not

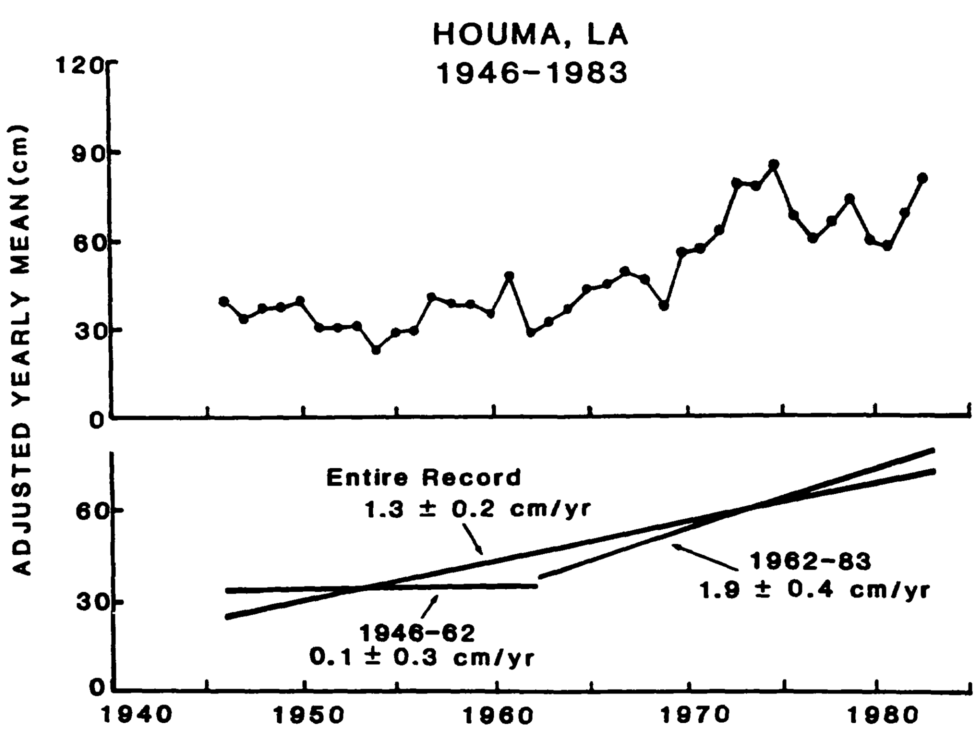

Figure 8. Water level time series for the U.S. Army Corps of Engineers tide gauge station at Houma (Intracoastal Waterway, #25). For location, see Figure 1. Note that there appears to be a recent acceleration in sea level rise. (Plot adapted from Penland and others, in press).

well known. Our objectives are to better quantify processes forcing overwash and to quantify landward sediment transport during overwash events. The plan includes monitoring overwash events with a variety of sensors, including wave and current meters, mounted on a barrier island. Additional assessments of sediment transport include measurements of morphological changes and tracer studies.

During the initial phase of the study, we have begun overwash experiments on the Isles Dernieres (Fig. 9). The experiment area is of very low relief with a berm about 1 to 1.5 m above MSL. Minor dunes occur in scattered locations, but overwash generally flows like a sheet over the barrier compared to channelized overwash that occurs when foredune ridges are well developed and breached (Ritchie and Penland, 1985). Figure 10 shows some of the instruments that have been deployed. The acoustic altimeter measures the distance, in air, between the altimeter and the sand surface. This provides measures of erosion and accretion immediately after storms, once the storm surge recedes. During overwash events, the altimeter measures the distance between the altimeter and the sea surface providing water depth and wave height data. Should the storm surge become too deep for the

Figure 9. Oblique aerial photograph of the Isles Dernieres showing the transect across the island that is the location of overwash experiments.

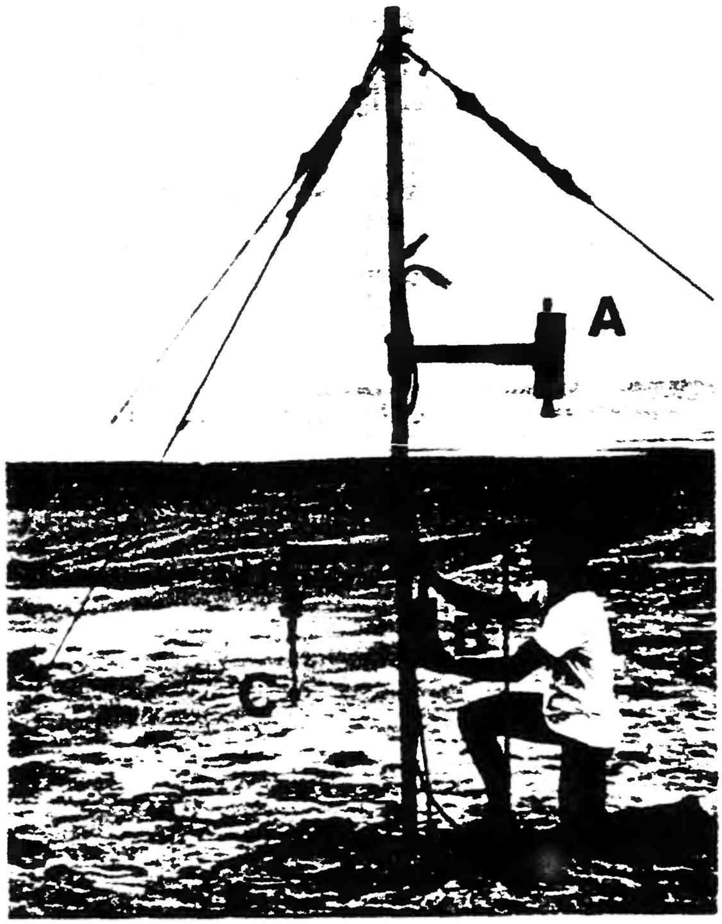

Figure 10. Examples of the instruments deployed as part of the overwash experiments. Shown are an experimental acoustic altimeter (A), a pressure sensor (B), and an electromagnetic current meter (C).

altimeter to function, a pressure senor (B) will measure sea surface elevations. All instruments are hardwired to a tower where the data, along with additional meteorological data, are digitized and transmitted to the Louisiana Universities Marine Consortium (LUMCON) in Cocodrie, LA, 32 km away.

Net Offshore Loss of Sediment

During storms, as a result of a variety of different processes, sediment can be transported across the surf zone to the inner shelf. For example, during a hurricane Murray (1970) measured very strong offshore mean flows that could contribute to transporting sand offshore. In the Gulf coast environment, where high-energy swell is generally absent, the potential for sand movement onshore following a storm is not as high as coasts where swell prevails under nonstorm conditions. The sand may be spread in thin sheets across the inner shelf and the buildup over time may be difficult to detect with traditional measures of bathymetry. Objectives are to better understand processes which might force strong offshore flows seaward of the surf zone during storms, and to assess sediment transport using a variety of independent means, such as direct measurement of suspended sediment, calculations, and measurements of bottom changes. Work on this task is planned to begin during the second year (1987) of the study.

Longshore Sediment Transport

The most commonly used models for predicting longshore sediment transport are integrated across the surf zone and the assumption is made that sand extends across the surf zone (e.g. Komar and Inman, 1970). In Louisiana, this assumption is commonly not valid. During a major storm, the surf zone can be extremely wide yet the sand may only be concentrated at the shoreline and perhaps in the form of nearshore bars. Our major objective here is to develop a better means for assessing longshore sediment transport in a sand/mud environment so that the role of gradients in longshore transport in causing erosion can be better determined. Work on this task is planned to begin during the third year of the study.

III. Applications of Results

Our ultimate objective is to present the results on the processes of barrier island erosion in a form so that they can be applied to practical problems. The types of applications include developing better techniques for determining the rate at which artificially nourished beaches should be renourished, finding potential sources of sand offshore for beach nourishment, and predicting future shoreline erosion so that coastal planners can properly locate new construction a safe distance landward from the eroding shoreline. This part of the study is being approached by working with coastal engineers and coastal planners.

Summary

In 1986, the U.S. Geological Survey and Louisiana Geological Survey began a new cooperative study on the processes causing barrier islands to erode. The study includes investigations of the geologic development of barrier islands, experiments on quantifying critical processes of erosion, and integration of results such that they can be applied to practical problems. The study is located in Louisiana, however, many of the results will be applicable nationwide.

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DELTA PLAIN DEVELOPMENT AND SEA LEVEL HISTORY IN THE TERREBONNE COASTAL REGION, LOUISIANA

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ABSTRACT

The Terrebonne coastal region is located on the south central portion of the Mississippi River delta plain. The depositional history of this area was investigated using vibracores, seismic profiles, radiometric dating techniques and tide gauge record analysis. A new chronostratigraphic model depicting Lafourche and Teche delta complex development is presented. Eustatic-enhanced and isostatic sea level changes were delineated based on the correlation of regressive and transgressive delta-plain sequences with regional and localized ravinement surfaces. Tide gauge analysis indicates the Terrebonne coastal region is faced with potentially catastrophic land loss conditions over the next century if current relative sea level rise acceleration rates of 1.03-1.28 cm/yr continue.

INTRODUCTION

The development and stability of coastal depositional systems are controlled by a balance between changes in relative sea level and sediment supply (Curray, 1964). In the Terrebonne coastal region, a combination of rapid relative sea level rise and a lack of sediment supply is responsible for generating the most severe wetland loss and barrier island erosion conditions in the United States. The Terrebonne coastal region is located on the Mississippi River delta plain in southeast Louisiana stretching between Point Au Fer and Grand Isle, extending north to Thibodaux, and offshore to Ship Shoal (Figure 1). Current predictions indicate the Terrebonne coastal region will be converted to open water in 135 years based on a land loss rate of 4162 hectares per year (Gagliano et al. 1981). The magnitude of land loss taking place and the documented acceleration in relative sea level rise evidence the need to understand the relationship between delta plain development and sea level history in order to forecast the future coastal conditions Louisiana may face.

The objective of this paper is to explain the pattern of delta plain development in the Terrebonne coastal region as it relates to the history of relative sea level changes over the last 7000 years. The analysis of vibracore, seismic, radiometric, and tide gauge data

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provides the information necessary to delineate the depositional history of this coastal region.

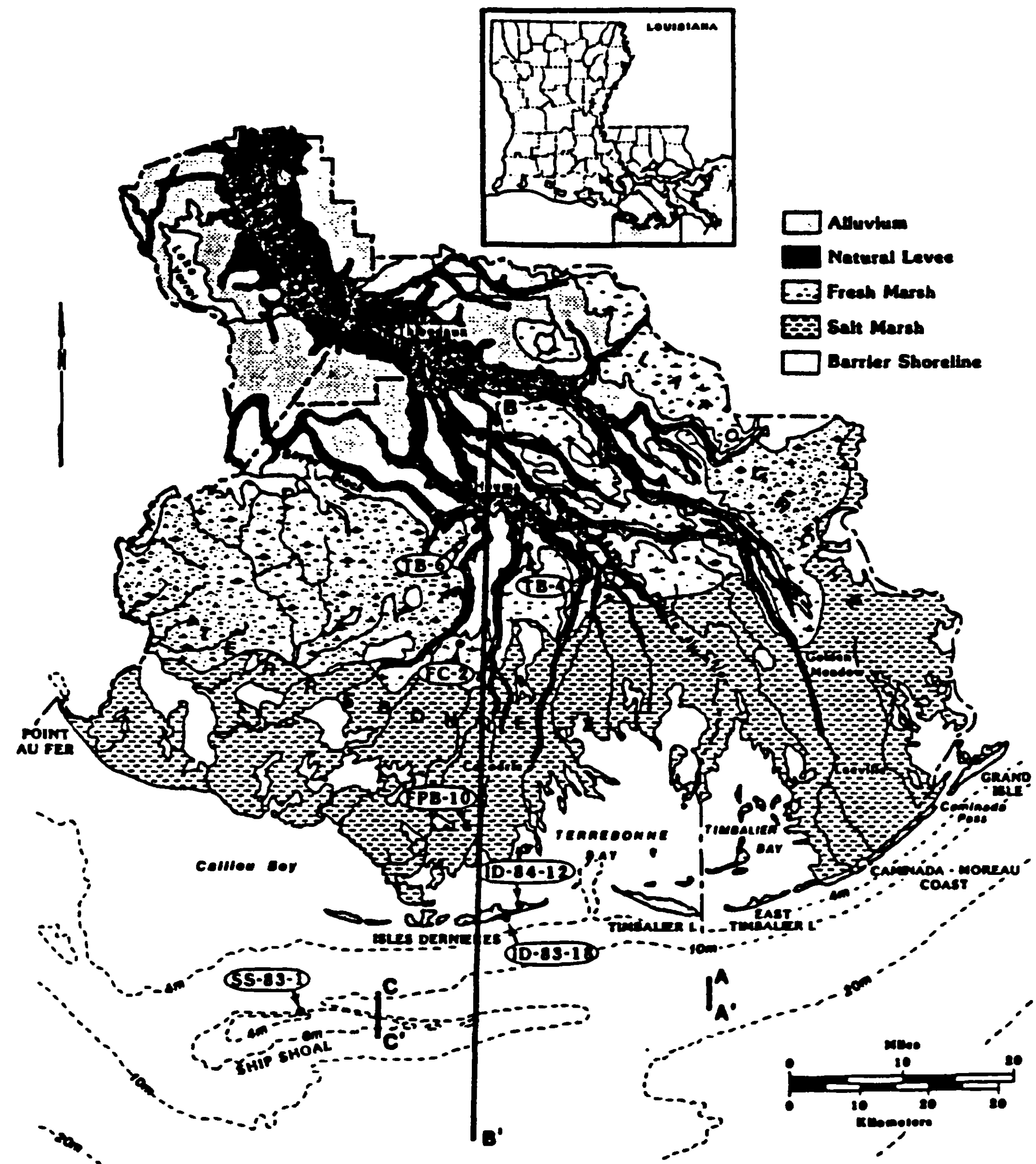

Figure 1. Geological map of the Terrebonne coastal region with the location of vibracore and seismic data presented in text (Louisiana Geological Survey 1984).

GEOMORPHIC SETTING

The Terrebonne coastal landscape is dominated by the abandoned distributaries of the Teche delta complex that radiate southeastward from Bayou Teche at Morgan City and extend into the northwestern half of the region (Figure 1). In the southeastern half of the region, distributary ridgelands of the Lafourche delta complex dominate the landscape and radiate southwestward before sinking below the marsh surface. Since the end of the Holocene transgression, the Mississippi River delta plain has been built by a process of sequential episodes of delta building followed by abandonment and barrier shoreline generation collectively known as the "delta cycle" (Fisk 1944; Kolb and Van Lopik 1958; Scruton 1960; Coleman and Gagliano 1964; Frazier 1967; Penland et al. 1981). Through this process the Mississippi River built a delta plain 26,000 km^2 in area. Chronostratigraphic models describing delta plain development have been presented by Fisk (1944), Kolb and Van Lopik (1958), and Frazier (1967). The most recent model (Frazier 1967) depicts a single Holocene delta plain consisting of five delta complexes composed of 16 individual deltas (Figure 2).

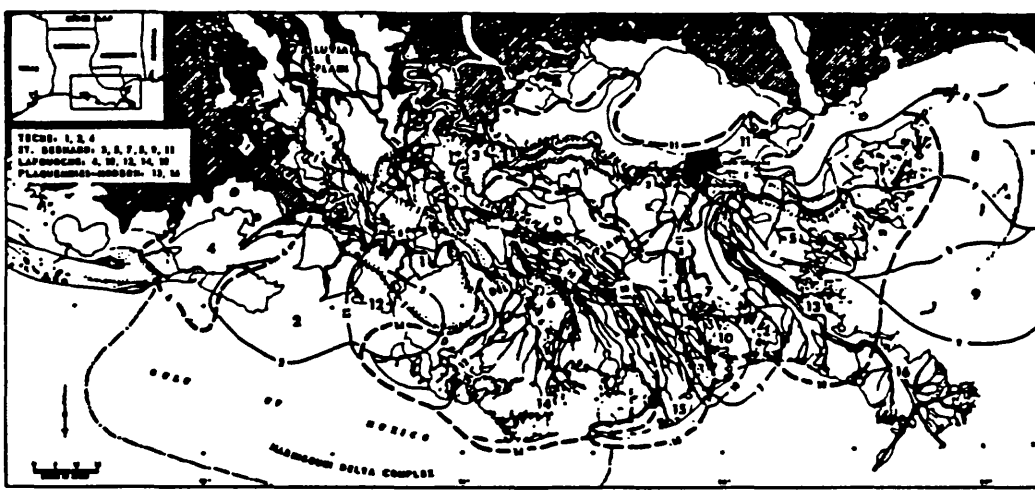

Figure 2. Frazier's (1967) chronostratigraphic model depicting a single delta plain composed of five delta complexes consisting of 16 individual deltas.

DELTA PLAIN STRATIGRAPHY AND DEVELOPMENT

Methods

The regional stratigraphy and development of the Teche and Lafourche delta complexes are described based on the analysis of delta-plain geomorphology, vibracores, radiocarbon-dated samples and high resolution seismic profiles (Figure 1). Between 1981 and 1986, the Louisiana Geological Survey (LGS) collected a data set of 368 vibracores, 5000 line km of high resolution seismic profiles, and 158 new radiocarbon dates in the study area. In addition, records from 29 tide gauge stations in the Terrebonne coastal region and elsewhere in Louisiana and the Gulf of Mexico were analyzed. The term delta plain is used to describe a set of delta complexes deposited during a sea level still-stand. Delta complexes are composed of smaller deltas, which are made up of individual distributaries. Each of the delta plain systems has a set of deposits separated by erosional unconformities (ravinement surfaces) caused by shoreface erosion upon transgression (Swift, 1975). Each delta plain sequence consists of a regressive suite of environments overlain by a transgressive suite of environments truncated by a ravinement surface. The ages of these deltaic systems were delineated by the radiocarbon dating of in-situ peat and shell deposits.

Teche Delta Complex

The Teche delta complex in the northwest portion of Terrebonne Parish is separated from the younger Lafourche complex of the southeast by a relict transgressive shoreline (Figure 3). The strike of the relict shoreline, as delineated by McIntire (1958), is west to east along a line extending from the mouth of Creole Bayou, to the western shore of Lake Penchant, to southeast of Houma, where it is buried beneath the

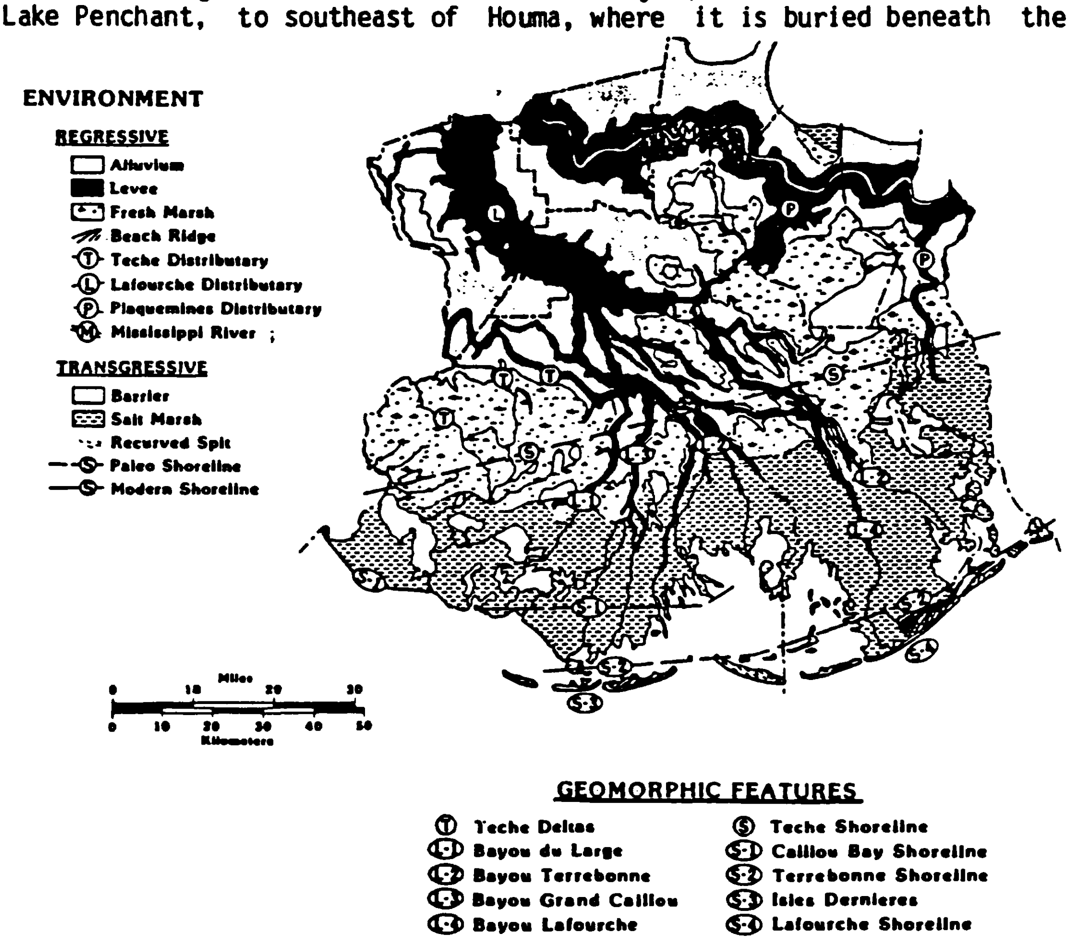

Figure 3. A new chronostratigraphic model illustrating the distribution of individual deltas and associated shorelines in the Terrebonne coastal region.

Bayou du Large, Bayou Terrebonne, and Bayou Grand Caillou deltas of the younger Lafourche delta complex. The term **Teche shoreline** is used to describe this transgressive relict shoreline, which is a continuation of the Atchafalaya Bay shoreline farther to the west.

The principal deltas of the Teche delta complex in the Terrebonne coastal region are Bayous Black, Cocodrie, Penchant, and Big Horn. These deltas extend in a radial pattern from Bayou Teche in the Morgan City area southeast to their truncation by the Teche shoreline. The average thickness of the regressive component of the abandoned Teche delta complex sequence is 10-12 m with greater thicknesses found associated with distributary channelling. The regressive component consists of fresh marsh swamp, overbank, bay fill, levee, distributary, delta front, and prodelta environments. The distributary environments describe sands deposited in or near the active channel in crevasse splays and distributary mouth bars. The active progradation of the Teche delta complex took place between 3340 and 6682 years B.P. The top of the abandoned Teche delta complex is subaerially exposed north of the relict Teche shoreline. Here a 3-5 m thick sequence of salt marsh and bay deposits is found, representing the transgressive component of the abandoned Teche delta complex (Figure 4). Basal marsh peats date 3340-4680 years before present (B.P.). The thickness of this transgressive sequence reflects sustained surface aggradation landward of the once-retreating Teche shoreline under the conditions of relative sea level rise.

South of the Teche shoreline, the **Teche ravinement**, a relict erosional shoreface and ravinement surface, can be traced in the subsurface at the base of the Lafourche delta complex and at the top of the Teche delta complex. Downdip, the ravinement surface lies 8-9 m below msl beneath the Isles Dernieres and at -10 m msl beneath Ship Shoal (Figure 5). Below this surface lies a thin 1-2 m sequence of salt marsh and lagoonal deposits which corresponds to the thick salt marsh and lagoonal deposits found up-dip and landward of the Teche Shoreline. In-situ organics from this thin sequence are dated 5930-6682 years B.P. The base of the Teche delta complex lies on a second ravinement surface, located in the subsurface at -22 m below mean sea level (msl) under Ship Shoal (Figure 6). This surface gradually rises updip to -18 m msl beneath Dulac in Terrebonne Parish. The ravinement was generated by shoreface erosion during the transgression of an earlier delta plain associated with a sea level stillstand about 16 m below current sea level, as identified by Fisk (1944).

Offshore, Ship Shoal lies on the Teche ravinement surface which merges updip with the Teche shoreline (Figures 4, 5, and 7). The shoal sand body represents a marine sand body that was generated by the transgression and submergence of a barrier shoreline associated with the reworking of the Teche delta complex (Penland et al. 1986a). Today this shoal is migrating landward onto the Teche ravinement surface at rates of 5-10 m/yr (Figure 8). The stratigraphic relationship between the base of the Ship Shoal sand body, the Teche ravinement surface (A), the ravinement surface (B), the Teche shoreline, and the thick Teche marsh deposits suggest a sea level stillstand about 6 m below present between 3340 and 6682 years B.P. during the active progradation for this delta

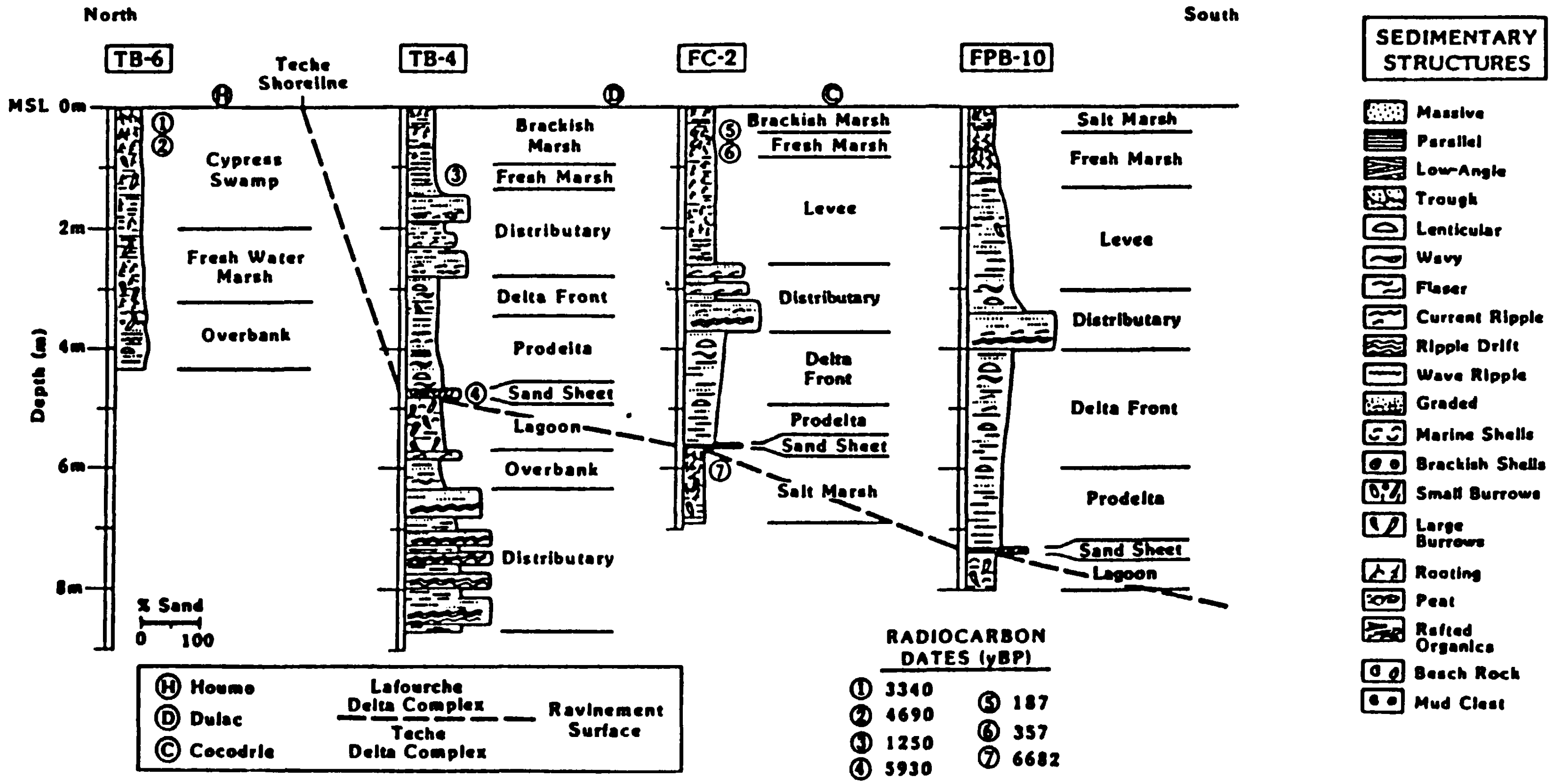

Figure 4. A series of four vibracores illustrating the stratigraphic relationship between the Teche delta complex, the Teche shoreline, and the Lafourche delta complex (see figure 1 for location).

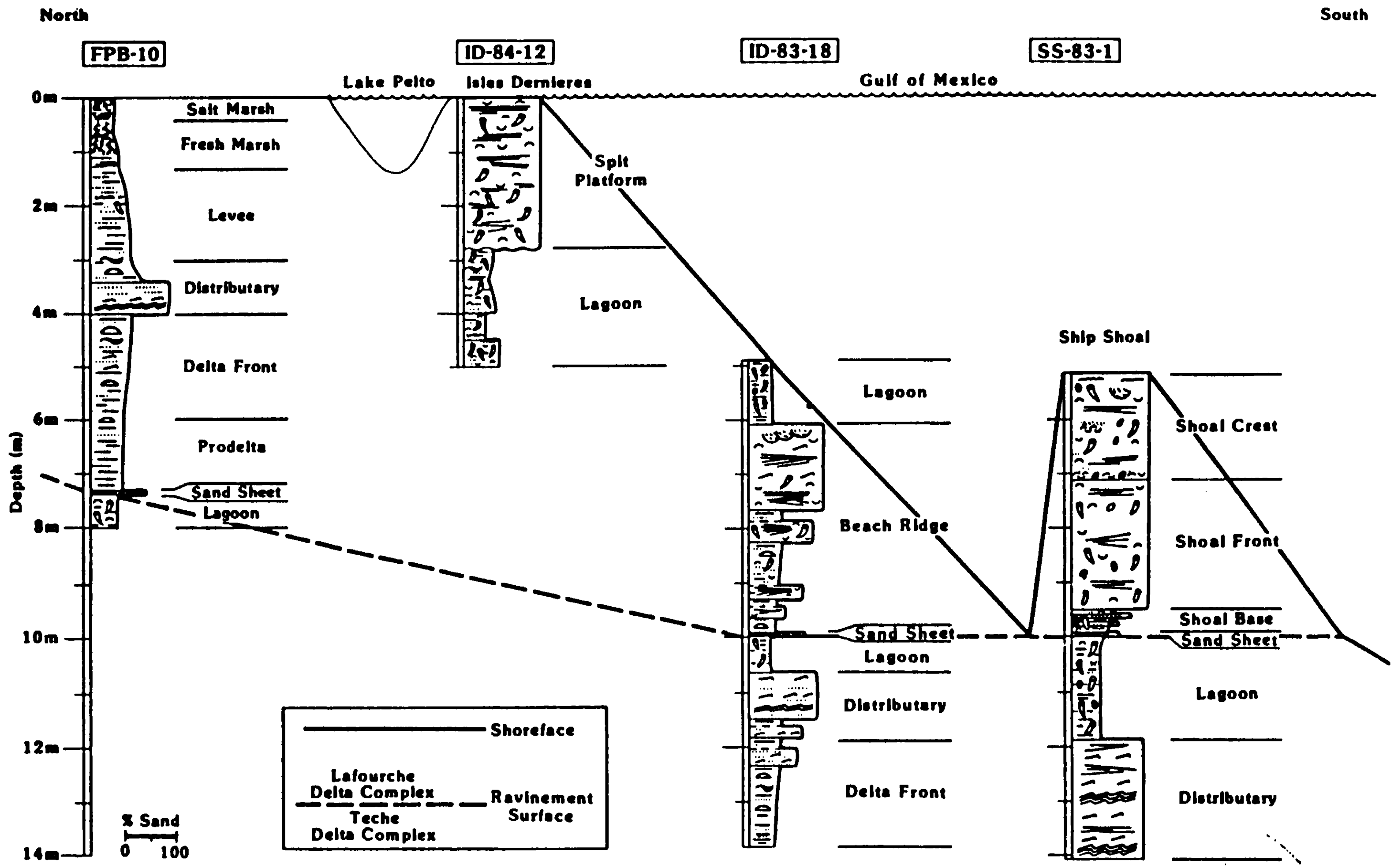

Figure 5. A series of four vibracores illustrating the stratigraphic relationship between the seaward margin of the Lafourche delta complex and Ship Shoal of the Teche delta complex (see figure 1 for location).

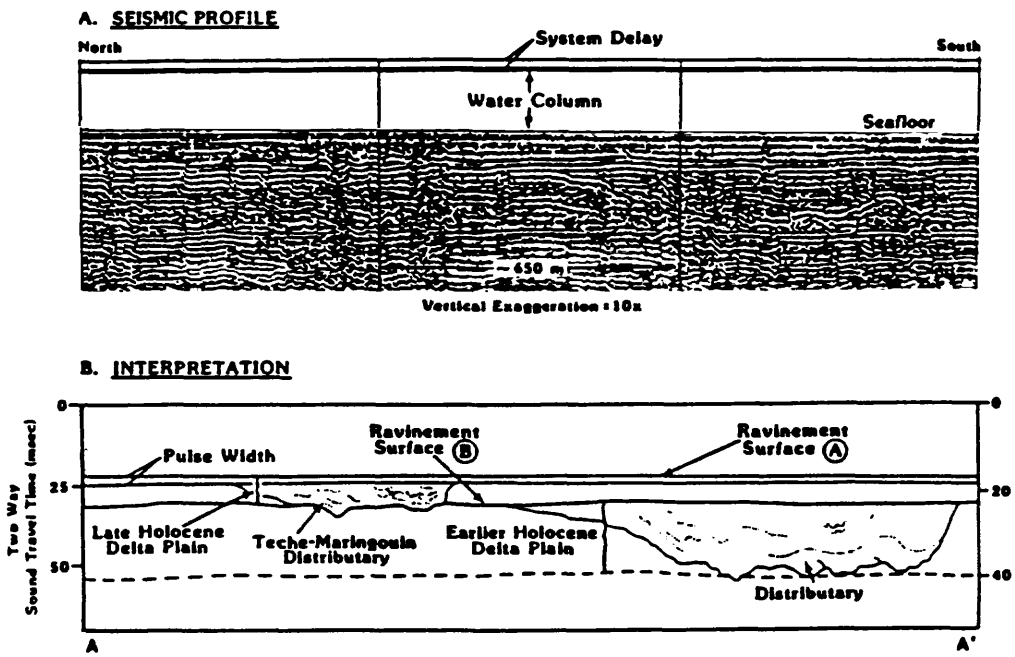

Figure 6. A high resolution seismic profile (ORE Geopulse) illustrating two ravinement surfaces bounding the Teche delta complex of the late Holocene delta plain (see figure 1 A-A' for location).

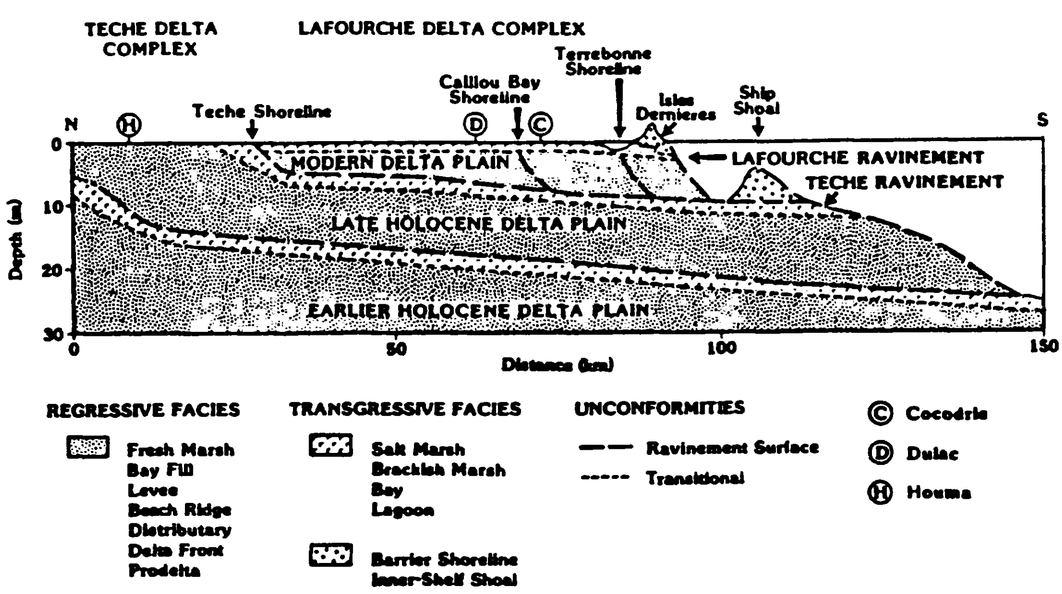

Figure 7. Generalized dip-oriented cross-section, B-B', illustrating the stratigraphic relationship between the Lafourche and Teche delta complex (see figure 1 for location).

complex. There is no stratigraphic evidence of a third separate Maringouin delta complex as mapped by Frazier (1967).

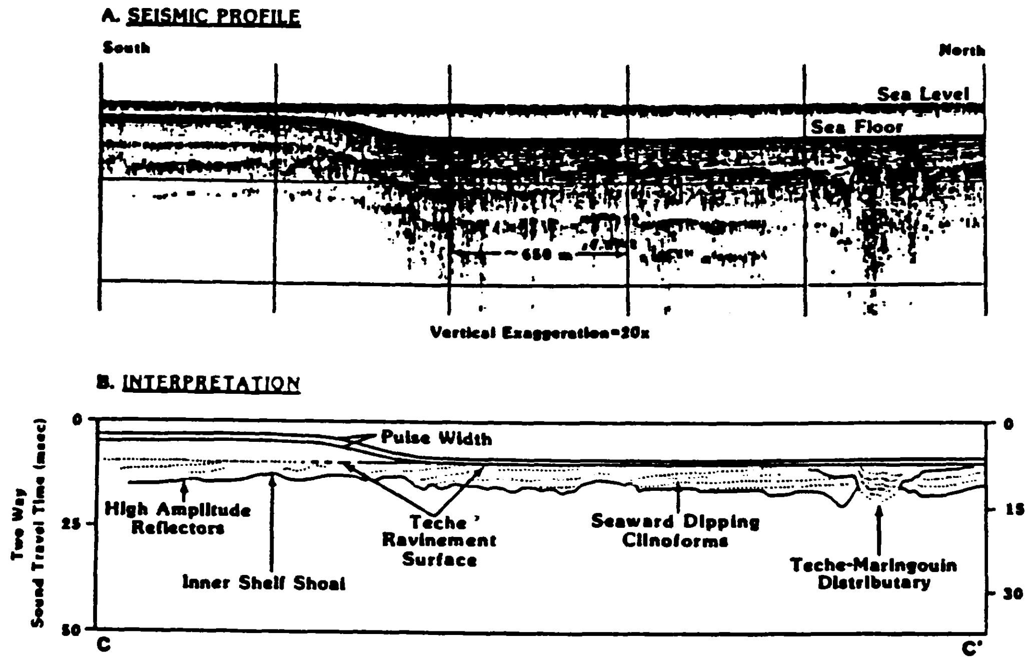

Figure 8. A high resolution seismic profile C-C' illustrates the Teche ravinement surface upon which Ship Shoal is migrating (see figure 1 for location).

Lafourche Delta Complex

The Lafourche delta complex began prograding over the abandoned Teche-Maringouin delta complex about 2490 years B.P. During this period sea level was relatively stable. Landward of the Teche shoreline the Lafourche delta complex built across the salt marshes and lagoons of the submerged Teche delta complex infilling these areas with new sediment. Eventually Bayou Lafourche built over 50 km seaward of the Teche shoreline onto the previously eroding shoreface, reversing the trend of shoreline retreat, which had been taking place over the preceding 800-900 years B.P. The active building of individual deltas within the larger Lafourche delta complex continued until about 300 years B.P.

The regressive component of the Lafourche delta complex generally averages 7-8 m thick, increasing to as much as 20 m in areas of distributary channelling. The larger Lafourche delta complex is made up of four individual deltas which, in order of increasing age, are Bayou du Large, Bayou Terrebonne, Bayou Grand Caillou, and Bayou Lafourche. The transgressive component is 1-2 m thick except where barrier shoreline sand bodies reach thicknesses of 5-10 m. The relative thinness of these salt marsh deposits reflects the initial effects of submergence over the last several hundred years in contrast to the older, much thicker marshes found landward of the Teche shoreline.

The first delta of the Lafourche delta complex is the Bayou du Large delta, which extends southwest from Houma to the coast between Bay Junop and Bayou Grand Caillou Pass (Figure 3). Bounded on the west by the Teche shoreline, this distributary network built out perpendicularly across Bayou Black of the Teche delta complex. Bayou Black was temporarily occupied by the Bayou du Large distributaries before Bayou Mauvais Bois and several other small distributaries bifurcated and built toward the southwest (Smith et al. 1986). The seaward extension of Bayou du Large correlates with the shallow protuberance defined by the 6-m isobath in Caillou Bay. Radiometric analysis indicates that the Bayou du Large distributary network was an active delta between 1620 and 2490 years B.P. The **Caillou Bay shoreline** represents the transgressive coast of the abandoned Bayou du Large delta.

The second Lafourche delta to build in the Terrebonne coastal region was the Bayou Terrebonne distributary network, which consists of Bayou Petit Caillou, Bayou Terrebonne, Bayou Saint Jean Charles, Bayou Point au Chiene, and Bayou Blue (Figure 3). This distributary network prograded between Bayou du Large to the west and the St. Bernard delta complex to the east between 830-1270 years B.P. The seaward limit of this distributary network is defined by the relict transgressive **Terrebonne shoreline**, which consists of a series of flanking barriers and erosional headland beaches. Extending east from the landward side of the Cheniere Caillou beach-ridge plain in the Isles Dernieres, this shoreline has a southwest/northeast strike that extends through Wine Island Shoal, Caillou Island, Brush Island, Casse Tete Island, Devil's Bay Point, and the most landward of the Cheniere Caminada beach-ridges to Fifi Island north of Grand Isle.

Approximately 910 years B.P., the third delta of the Lafourche delta complex, Bayou Grand Caillou, was active between Bayou du Large to the west and Bayou Petit Caillou to the east (Figure 3). Its distributary network, comprising Bayou Grand Caillou, Bayou Chauvin, Four Point Bayou, and Bayou Sale and is terminated at its seaward boundary by the Isles Dernieres barrier island arc. At one time, Bayou Grand Caillou built seaward of the Terrebonne shoreline immediately west of Wine Island. Dominant sand transport along this shoreline was westward; as a consequence, the Bayou Sale and Bayou Grand Caillou distributaries intercepted westward-moving material, which resulted in the simultaneous progradation of the beach-ridge plain called Cheniere Caillou (Penland and Suter, 1983). Distributary and beach progradation continued until approximately 420 years B.P. With abandonment, shoreface erosion reworked the Cheniere Caillou beach-ridge plain and Bayou Grand Caillou distributaries, generating the **Isles Dernieres shoreline.**

The Bayou Lafourche delta built seaward of the Terrebonne shoreline near Devil's Bay point (Figure 3). The distributaries of Bayou Lafourche, Bayou Moreau, Bayou Ferblanc, Bayou Fourchon, Bayou Raphael, and West Fork Bay L'Ours were active 710 years B.P. (Gerdes, 1985). Progradation of Bayou Lafourche seaward of Devil's Bay Point trapped material moving westward along the Terrebonne shoreline from Fifi Island and Grand Terre. Longshore interception of sediments resulted in the seaward progradation of the Cheniere Caminada beach-ridge plain along the eastern levee of Bayou Moreau. The Bayou Lafourche distributaries were abandoned approximately 300 years B.P. Following abandonment, shoreface erosion reworked the Bayou Lafourche distributaries and Cheniere Caminada, and supplied sand for the formation of the Timbalier Islands to the west and Grand Isle to the east, forming the **Bayou Lafourche shoreline.**

SEA LEVEL HISTORY

Teche Transgression

The **Teche transgression** took place between about 2490 and 3340 years B.P., during which sea level rose 6 m to its approximate current position at a rate of about 0.70 cm/yr. The relationship between the regional Teche ravinement surface and delta plain stratigraphy indicates that a rapid increase in the eustatic component of relative sea level is the primary driving factor. During and after the transgression, a hiatus in active delta progradation of some 850 years occurred in the Terrebonne coastal region until deposition of the Lafourche delta complex began. Due to the rapid sea level rise, the base level of the Mississippi River was constantly decreasing during this time period. In response the river had to aggrade its alluvial valley and delta plain to keep pace with this decreasing base level before a new period of delta plain progradation could begin. As a result, sediments that would normally be available to prograde the delta plain seaward under conditions of sea level stillstand were trapped inland by aggradational processes. The thick salt marsh sequences found landward of the Teche shoreline are evidence of wetland aggradation under the conditions of a rapid and sustained sea level rise (Figures 4 and 5). As evidenced by the formation of Ship Shoal and the Teche shoreline, the sea level rise was sufficient to lead to the complete **transgressive submergence** of the entire Teche delta complex, driving the shoreline more than 75 km inland and producing a regional ravinement surface (Penland et al. in press).

Lafourche Transgression

The Teche transgression ended about 2490 years B.P., at which time the Mississippi River had aggraded its alluvial valley and delta plain to the new stable base level. Concurrently, the Mississippi River began building the Lafourche and St. Bernard delta complexes. The Lafourche delta complex built seaward of the Teche shoreline to a position 50 km farther south before being abandoned. Four individual transgressions can be identified within the Lafourche delta complex ranging from 300-1600 years B.P. in age. These, collectively termed the **Lafourche transgressions**, were primarily driven by a hiatus in deltaic sedimentation due to the delta switching process followed by a slow rise in sea level driven by compactional subsidence. The amount of subsidence-induced relative sea level rise ranges from 1-3 m in these abandoned Lafourche deltas.

In order to determine rates of isostatic-enhanced sea level rise during the Lafourche transgressions, in-situ peat horizons which were assumed to be stratigraphic indicators of mean sea level at the time of deposition were radiocarbon dated. An average long-term rate of relative sea level rise of 0.18 cm/yr over the last 500-3000 years was determined. Using only young sediments, 0-500 years B.P. in age, a short-term rate of 0.62 cm/yr was determined, while an average rate for the Terrebonne coastal region is 0.31 cm/yr over the last 0-3000 years. This trend of decreasing rates of relative sea level rise with increasing age reflects the diminishing effects of sediment dewatering (Penland et al. 1987a).

Modern Sea Level

The term Modern sea level is used to describe the recent documented rise in relative sea level rise in the Terrebonne coastal region over the last 40 years (Penland et al., 1986b, 1987a). Through the analysis of 29 tide gauge records from the National Ocean Survey (NOS) and the U.S. Army Corps of Engineers (USACOE) in the Terrebonne coastal region, the rate of relative sea level rise was determined to range from 1.03-1.28 cm/yr since 1945 (Figure 9). By comparing relative sea level rise rates of different lunar epochs, it can be seen that the rate of relative sea level rise is accelerating. The relative sea level rise rate in the 1940's and 1950's was 0.07-0.30 cm/yr, increasing to 1.92-1.94 cm/yr in the 1960's and 1970's.

The rate of relative sea level rise in the 1940-1950 period is comparable to the average rate of relative sea level rise associated with the Lafourche transgressions. This suggests that the rate of rise detected by the tide gauges in the 1940-1950 period is driven primarily by compactional subsidence. However, the radiocarbon data suggest the acceleration in relative sea level rise in the 1960-1970 period is primarily eustatic because compactional subsidence is a decelerating process and therefore can not explain this acceleration (Penland et al. 1987a). These acceleration rates are consistent with the forecasts of the National Academy of Sciences and the U.S. Environmental Protection Agency of accelerated relative sea level rise rates due to the Greenhouse Effect (Barth and Titus 1984). This trend in accelerating relative sea level rise rates in the Modern transgression is evidenced by the increasing land loss occurring in the Terrebonne coastal region.

DISCUSSION AND CONCLUSIONS

Frazier's (1967) Lafourche delta complex chronology has been revised to consist of 4 deltas: Bayou du Large, Bayou Terrebonne, Bayou Grand Caillou, and Bayou Lafourche (Figure 3). The **Bayou du Large delta** comprises the Bayou du Large, Bayou La Pointe, and Bayou Bois Mauvais distributaries, which are not recognized by Frazier (1967). The **Bayou Terrebonne delta** lies east of Bayou du Large and consists of Bayous Petit Caillou, Terrebonne, Point au Chien, and Blue. The Terrebonne delta incorporates Frazier's (1967) Bayou Terrebonne (number 6), Bayou Blue (number 10), Bayou Black (number 12), and Bayou Lafourche-Terrebonne (number 14). The **Bayou Grand Caillou delta** is not included in the chronology of Frazier (1967). This delta comprises Bayou Grand Caillou, Bayou Sale, and Four Point Bayou. The **Bayou Lafourche delta**, comprising Bayous Lafourche, Moreau, Ferblanc, Raphael, and Fourchon, corresponds to Frazier's (1967) number 15 Bayou Lafourche delta. The distribution of Indian middens and other artifacts supports these new interpretations (Table 1).

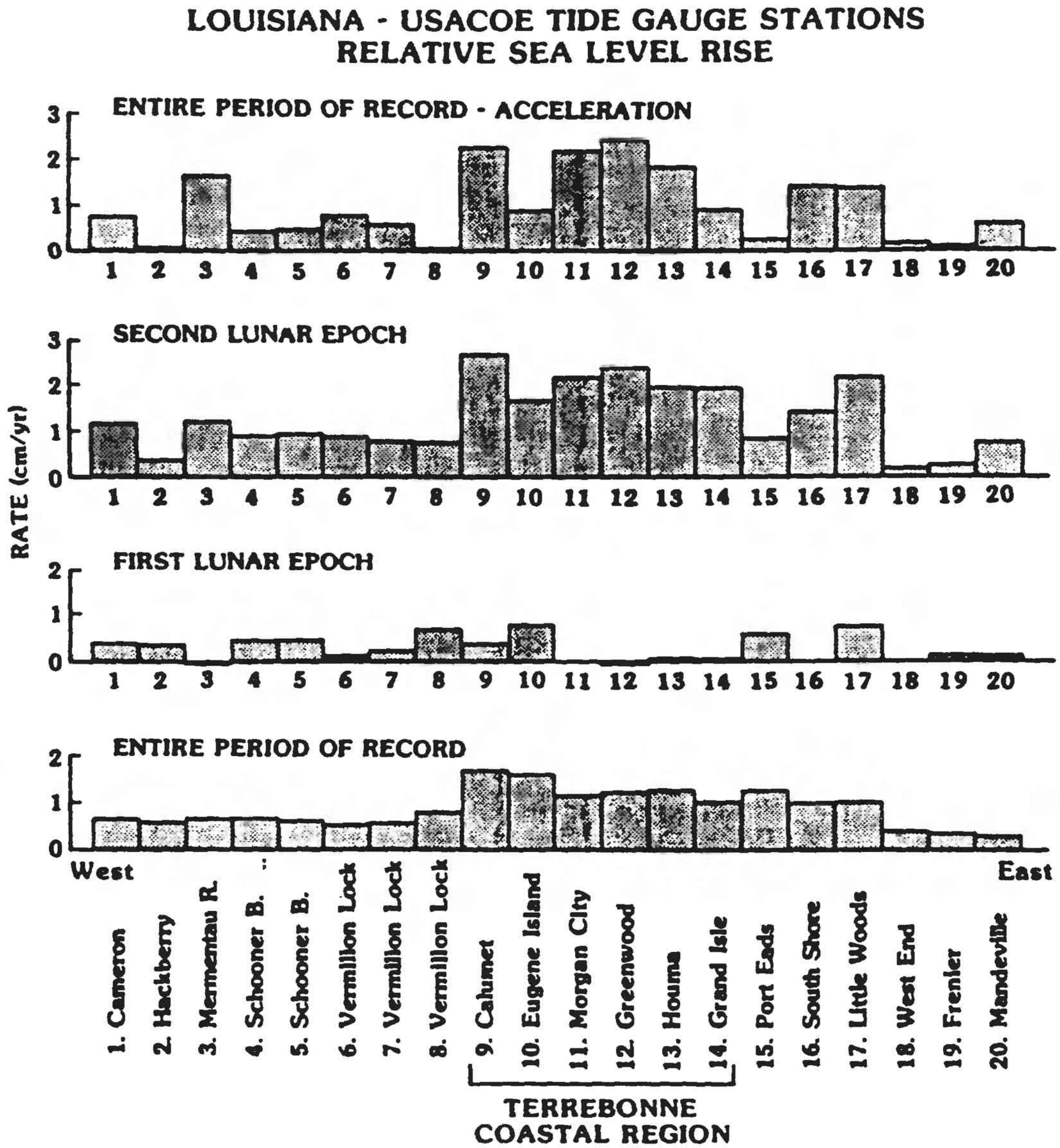

Figure 9. Relative sea level rise histograms for 20 tide gauge stations west to east across coastal Louisiana with periods of record exceeding 2 lunar epochs. Diagram illustrates rates of change for the entire record, first lunar epoch, second lunar epoch, and acceleration (Penland et al. 1987b).

Frazier (1967) identified the Teche to the north of the Lafourche delta complex and the Maringouin offshore to the south as separate delta complexes within the same delta plain as the Lafourche. However, our data indicate that in the Terrebonne coastal region Frazier's (1967) Maringouin delta complex is the seaward extension of the Teche delta complex. This observation is based upon the recognition of the Teche shoreline and the regional Teche ravinement surface, which can be traced throughout the entire region at the base of the Lafourche delta complex offshore to beyond Ship Shoal. The occurrence of the same ravinement surface at similar depths in vibracores from the Barataria Basin and the St. Bernard delta complex (E. Kosters, pers. comm.) emphasizes the regional character of the Teche transgression. This regional ravinement surface indicates that the Maringouin-Teche and Lafourche delta complexes actually belong to two distinct delta plains which developed at different stillstands of sea level. In the Terrebonne coastal region the term late Holocene delta plain is used to describe that of the Maringouin-Teche complex, deposited when sea level stood about 6 m below present, whereas the term Modern delta plain is used for that of the Lafourche delta complex (Figure 10).

Transgression of the Maringouin-Teche delta complex and the Lafourche delta complex produced different stratigraphic signatures. Abandonment of the Lafourche complex produced a localized transgression driven by compactional subsidence, displacing the shoreline landward by some tens of kilometers. In contrast, transgression of the Maringouin-Teche delta plain created a regionally traceable ravinement surface hundreds of kilometers in extent, similar to ravinement surfaces produced by glacioeustatic sea level rises on the southwest Louisiana continental shelf (Suter et al., in press). Thus, the Maringouin-Teche transgression is considered to be eustatic-enhanced, associated with a rise in sea level which occurred some 3340 years B.P.

Due to greater rates of relative sea level rise during a eustatic-enhanced transgression, the vertical component of submergence dominates over the horizontal component of shoreface erosion, resulting in greater preservation potential than exists for a purely isostatic transgression in which shoreface erosion is more important. The pattern of delta plain deposition, transgression, and preservation observed in the Terrebonne coastal region illustrates the importance of relative sea level as a controlling factor in deltaic deposition. The stratigraphic signature of these processes is an en echelon series of stacked shallow-water delta plains terminated by transgressive barrier islands and inner-shelf shoals.

TABLE 1

DELTA PLAIN CHRONOLOGY

IN THE

TERREBONNE COASTAL REGION

DELTA PLAIN	DELTA COMPLEX	DELTA	RADIOCARBON AGE	ARCHEOLOGICAL AGE[1,2]	
		Bayou Lafourche	300- 710 yBP	Natchez:	1700-1500 A.D.
		Bayou Petit Caillou	420- 910 yBP	Plaquemines:	1500-1200 A.D.
MODERN	LAFOURCHE	Bayou Terrebonne	830-1270 yBP	Coles Creek:	1200- 850 A.D.
				Troyville:	850- 700 A.D.
		Bayou du Large	1220-2490 yBP	Marksville:	700- 500 A.D.
				Tchefuncte:	500 A.D.- 500 B.C.
LATE HOLOCENE	TECHE	Bayou Teche	3340-7220 yBP	Archaic:	500-6000 B.C.
		Bayou Sale'			

[1] McIntire (1958)
[2] Weinstein and Gagliano (1982).

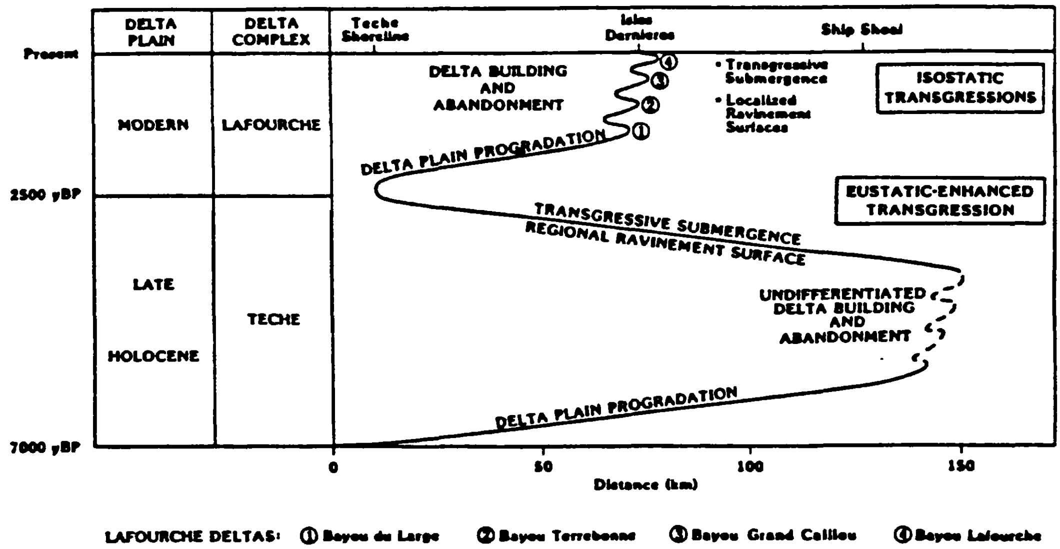

Figure 10. A chronostratigraphic model depicting the development of the Terrebonne coastal region as a function of sea level changes and sediment supply.

Future Coastal Conditions

The relative sea level rise rates of Modern sea level classify it as a eustatic transgression. The 1960-1970 sea level rise rates far exceed those of the Teche transgression, indicating that the Modern sea level rise is capable of transgressing and submerging the entire Terrebonne coastal region. To complicate matters, flood control structures in the Terrebonne coastal region have cut off the sediment supply for delta plain aggradation. As a consequence, the magnitude of land loss occurring today can be expected to increase to catastrophic proportions.

ACKNOWLEDGEMENTS

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THE PEOPLE, BOATS, HOMES, AND ECONOMICS OF "THE BAYOU COUNTRY"

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Introduction

For more than 200 years the United States' marshlands were thought to be of no economic value. Today, they are recognized as a valuable and highly productive environment. To exist in this dynamic and sometimes inhospitable physiographic province, man has had to develop and utilize innovative engineering techniques, unconventional wisdom, and unique cultural occupancy patterns. Since the late 1930s, Louisiana's wetlands have had rapid economic development. Much of this growth is a result of the hydrocarbons discovered on and offshore. Oil and gas resources represent a multibillion-dollar industry. In addition, alluvial wetlands provide a habitat for more than two-thirds of the Mississippi Flyway's wintering waterfowl, a large portion of North America's fur and alligator harvest, more than 20% of the country's commercial fisheries, and serve as a barrier against the full force of hurricanes. Few regions worldwide can compete with Louisiana in the production of renewable and nonrenewable resources. Further, Louisiana's largest city and the nation's leading seaport, New Orleans, is directly or indirectly tied to the economics of the marsh.

Louisiana's coastal lowlands are facing a serious dilemma. The problem is directly related to man's interference with the Mississippi River's flow regime and the effects of erosion induced by natural processes, subsidence, and relative sea level rise. Construction of flood levees and numerous canals has upset the sedimentation balance. Collecting water from 31 states and 2 Canadian provinces, the Mississippi is now confined within a conduit of artificial levees. It can no longer inundate its historic flood plain. Sediments are channeled off the continental shelf, depriving the coast of the "material" necessary to build new land at a rate slightly greater than subsidence.

Consequently, marsh losses in 1980 exceeded 10,000 ha--a rate that is increasing geometrically and not arithmetically. The state has lost about 450,000 ha since the turn of the century--more land than all of the United States' other coastal states combined. It is a serious environmental problem. Every 49 minutes another hectare becomes open water. "High" land, already scarce, will soon be at a premium and the cumulative economic impact will be measured in the billions of dollars.

Human Aspects and Coastal Problems

The history of Louisiana's coastal settlement has been generally dictated by the availability of "high" ground. From barrier islands, to beaches, natural levees, cheniers, coteaus, bays, and estuaries, man has had to adjust to floods, subsidence, and relative sea level rise. His response has varied, depending on the time, place, and number of people involved.

The coastal zone is a region rich in natural flora and fauna. Extensive vegetation and the abundant aquatic, terrestrial, and avian animals offered many inducements to early settlers. The earliest Indians made their homes on the highest ground and took advantage of many natural food resources. Mollusks were their most important edible resource, and extensive shell heaps or "middens" continue to attest to the importance of this resource--particularly the edible clam Rangia cuneata.

Prehistoric Indians established their villages on the area's natural levees, exposed salt domes, beach ridges, and other high-ground features. Since early man had to adapt to a changing environment, settlements were rarely continuously occupied. In Louisiana, prehistoric man followed the changing pattern of the Mississippi River. As new natural levees were built and old ones decayed because of the reduction of fresh water and sediments, the Indians moved. They had no choice; their subsistence requirements could no longer be met. For at least 12,000 years, the Indians followed the coastal zone's changing topography.

Detailed written records are nonexistent, so each group is "finger printed" by their material culture. The artifacts in or on the ground provide the data necessary to unravel the regional settlement succession as well as document the archaic physiographic features. The cultural remains, therefore, provide many clues in assessing the natural setting during aboriginal time.

As Europeans immigrated, they mixed freely with the local Indians. By example, the aboriginals taught the settlers how to survive in a new environment. The newcomers adapted local resources to meet their needs. These included food, clothing, shelter, and boats. With time, the Europeans displaced the population. Nevertheless, from prehistoric Indian sites to the modern community of New Orleans, the coastal lowlands have supported a range of cultures and settlements.

Numerous ethnic groups colonized the aquatic lowlands, establishing their homes and villages on protected and well-drained land or on stilts in remote bays, estuaries, rivers, or bayous. Like the Indians, these "folks" preferred the available "high" ground, but as the population expanded, the demands exceeded the available supply, so they "made" or "modified" land in response to changing conditions. Unlike the Indians, they turned to engineering solutions in response to coastal changes. They had an option, and they continue to exercise it, particularly around New Orleans.

The Ethnic Mix

Spanish, French, Italian, Yugoslavian, Irish, German, Cuban, Greek, Latin American, Vietnamese, and Chinese have settled within the coastal borderlands. Each group interpreted the environment differently. Louisiana exhibits a unique ethnic and cultural heterogeneity, but its biggest and oldest ethnic group is of French descent. These settlers came from two sources: directly from France and indirectly from French Canada. Most of the wetland inhabitants were refugee Acadians who were expelled from British-controlled Nova Scotia. After their deportation in 1755, nearly 4000 of these Canadian expatriots settled in Louisiana. They arrived in small groups over a 30-year period (1760-90). However, as early as 1718 the colony was populated by Frenchman, individuals enticed to move to Louisiana by the propaganda of John Law's Mississippi Company. These settlers came from the south of France; their surnames are still common in southern Louisiana. Unlike the Canadian adventurers de bois, these Frenchmen preferred the comforts of New Orleans, ignoring the alluvial wetlands. They were generally the more prosperous and better educated of the French class living in Louisiana.

The Acadian newcomers, accustomed to working the land, settled on the "prairies," cheniers, and bayous of south central and southeastern Louisiana. They were French-speaking, Roman Catholic, fun-loving individuals, who provided southern Louisiana with its unique ethnic character. Education was not important, so with time they abandoned French as a written language. Their language is no longer spoken in France and many of the family surnames survive only in literature from the colonial period.

Since the Acadians were small landowners, they enjoyed the isolation provided by southern Louisiana's physical geography. As farmers, trappers, and fishermen, they found the rich alluvial soil of the Mississippi Valley and the area's abundant hide- and furbearing animals and easily harvested aquatic life infinitely attractive. The solitude of the wetlands was an ideal setting to start a new life.

They considered the semi-aqueous real estate an attractive location for their new settlements. The communities were accessible by means of winding streams called bayous (from the Choctaw bayuk or creek) and not too far from their fishing, hunting, trapping, and agricultural areas.

With time, the French were joined by Balkan immigrants from Serbia, Montenegro, Greece, and Albania. Germans, Spanish, Irish, Italian, Filipinos, and Chinese also settled within the region. A group of Yugoslavian oyster fishermen, for example, settled along the bayous, bays, and lakes southeast of New Orleans. Adjacent to the Mississippi, they built the villages of Olga, Empire, Ostrica, and Oysterville.

A settlement pattern was initiated that developed from the region's distinctive deltaic morphology. Each settlement was economically homogeneous in that all inhabitants were supported by variations of the same means of making a living. Each hamlet's farmer-trapper-fisher folk were aware of their environment and developed skills that allowed them to harvest local wildlife. Today, many people consider the wetlands only for their intrinsic qualities. Les Acadians, Yugoslavians, and other ethnic groups recognized the area for its resources and were willing to make their living from them.

Bayou Lafourche Settlement

Bayou Lafourche's natural levees were first settled about 1765. Property was divided into arpents of 58.5 m. With each unit bordering the bayou, a linear pattern made up of long, narrow, lots fronting on the bayou was produced. By tradition the French and German immigrants were farmers. Anglo-American plantations developed behind the French habitant farms, but also had access to Bayou Lafourche.

Bayou Lafourche was the region's lifeline. As the Paroisse de la Fourche Interieure began to acquire its distinctive agricultural identity, an efficient transportation system was tantamount to expanding local markets. Boats, moving along the bayou, played a major role in the economic development and utilization of the area's natural resources: timber, fur, fish, and hydrocarbons, as well as the well-documented growth of agriculture. Bayou Lafourche has been, and continues to serve in its lower reach, as a commodity artery of the firs order.

Often described as "The Longest Main Street in the World," the banks o: the bayou's natural levees are occupied nearly continuously. As the Lafourche is a distributary of the Mississippi, it provided a natural link into North America's preeminent river. Indeed, the term "Lafourche" is derived from the "fork" where it joins with the Mississippi, a connectivity closed in 1904.

Prior to the Spanish regime, 1763-1803, Acadian expatriots were well established on the Mississippi's west bank. These "folks" built their homes near "the fork" and expanded beyond the confines of Bayou Lafourche's upper reach. By 1755, a number of settlements were along the bayou. In 1785, a second wave of Acadian exiles immigrated to the Paroisse de la Fourche Interieure. They settled the bayou's middle reach. The riverine strips proved to be perfect settlement sites.

The gaps in these linear communities were filled by colonists from France and Spain, along with descendants of the Acadians, Canary Islanders (or Islenos who arrived in 1779), Germans, French, Canadians, and Anglo-Saxons. By the early to mid-1800s, Bayou Lafourche was an ethnic melting pot. Long-lots were a visible index of settlement extending from Donaldsonville to Lockport settled in the 1830s. In the 1850s, the Larose/Cut Off section was inhabited. By the 1870s Golden Meadow was settled. "The Longest Main Street in the World" was completed. On their march down the bayou, the habitant established small farms (six arpents on the front by 40 arpents deep), side by side facing the bayou. From Lockport to Golden Meadow, the bayou was occupied by these small farms that comprised the greater portion of the bayou settlement. "Up the bayou" are the plantations with interspersed small farms. "Down the bayou" trapper-fisher folks increased.

These ribbon farms are distinguished by their dwellings, outbuildings, and cultivated fields occupying a narrow strip of land whose length is many times its width. Dwellings are on "the front." Following Napoleonic inheritance customs, children and grandchildren often build homes one behind the other perpendicular to the bayou. Cultivation extends "to the back" as far as possible. The end of cultivation is not a property line, but a contour.

"Below" Golden Meadow trapping and fishing are dominant. This settlement type is not always restricted to land unsuited for any other use. There may be marsh available for livestock grazing. If so, the animals usually belong to farmers "up the bayou." Only in extreme cases is land for a garden lacking, yet gardens are rare. Their choice is fishing and trapping.

Houses are smaller, more closely spaced, and closer to the bayou. Outbuildings are few; fenced enclosures are absent; piers, boats, and related equipment replace farm machinery.

The bayou settlement pattern is, therefore, a long line of habitations with occasional breaks and small urban developments every 12-15 km. The simplest historical expression was the nucleus containing a church, cemetery, school, dance hall, bar, and several small stores. The focal point was the church and cemetery. The whitewashed, aboveground graveyards are always adjacent to the church.

With population growth, three types of urban centers developed at the point of the traditional school, church, and store nuclei. These morphological forms are called linear hamlets, T-towns, and grid cities. Linear hamlets represent the earliest stage in the growth sequences; they are characterized by one business thoroughfare parallel to the bayou. The intermediate state is the T-shaped town; expansion takes place along streets perpendicular to the bayou road. Today, the grid city represents the final stage.

In all cases, Bayou Lafourche was the focus of these linear communities. It was the main artery of commerce. Everyone depended upon it.

These colonial "pioneers" opened the "The Lafourche Country." But concomitant with the region's settlement history was development of the area's waterways. Each house had a boat of some type docked in front attesting to the bayou's importance. Bayou Lafourche was navigable. Commodities were being produced for foreign markets, and affluent planters required luxury items. Trade was essential; consequently, boats and waterways were a necessity.

Folk Boats of the "Bayou Country"

The oldest type of boat found in French Louisiana is the pirogue (pettyaugre), a copy of an aboriginal dugout that become an indispensable tool for the first inhabitants. It was the principal means of transportation and a direct descendant of those utilized by native Americans. Pettyaugres were the earliest craft to ply the waters of southern Louisiana with any regularity. Made from a single tree, they were capable of carrying a large number of men and cargo.

Perfectly rectangular, flat-bottomed, with no sheer and ends with a sharp angular upward slant, the 1-m-wide and 2-to-3-m-long chalands were used to cross a bayou. It was essentially a ferry. Always operated by hand and never used for going even a shorter distance, chalands transported goods and people from one side of the bayou to another. A variation is sometimes called a "plank boat." Occasionally used for logging, it is distinguished by a narrow hull generally less than 60 cm wide. A special chaland used for moss gathering is propelled by oars (Knipmeyer 1956).

"Of all the folk boats in French Louisiana, none is more carefully distinguished than the esquif of "skiff" (Knipmeyer 1956:165). A skiff is flat bottomed with a pointed bow and blunt stern--an ancient design called by most people a rowboat (a term not used in French Louisiana). Skiffs, propelled by sails and oars and identified as peniche, chaloupe, and galere, were used to move goods (Knipmeyer 1956).

Variations of the skiff include the canotte and "standing skiff." The canotte is a large skiff powered by an inboard engine and often fitted with a cabin and decking. Equipped originally with a sail, a canotte could move well with the right wind in Louisiana's coastal lakes and bays. To navigate along Bayou Lafourche, canottes, along with other shallow-draft boats, had to be pulled with tow ropes called "la cordelle."

Unlike the canotte that could be cordelled, the "standing skiff" was operated in a standing position using a rowing device called a joug. A joug elevated the oars and "extended the fulcrum beyond the sides of the boat"

(Knipmeyer 1956:169). In the late 1800s this type of vessel was common throughout French Louisiana.

Beginning about 1790, cargo pirogues were being replaced by keel-less, flat-bottomed boats with a blunt bow and stern. Settlers in French Louisiana called these vessels bateau plat (Chambers 1922). Probably developed from flatboats, they were in use by 1720 (Knipmeyer 1956). Bateau plats could be propelled by sails, but oars and poles were generally used. Now they are called simply bateaus.

Folk boats were superseded eventually by steamboats and flatboats. These vessels plied the bayou from Donaldsonville to Lockport. On occasion, they went into the Gulf of Mexico. Advertisements noted regular service to Bayou Lafourche.

While water level was of some concern, steamboats traveled anywhere "the mate could tap a keg of beer and float the boat 4 miles (6.4 km) on the suds" (Way 1947). This is an exaggerated statement; but true in the sense that steamboats needed little water to stay afloat. In high water, these vessels often floated through a planter's field, in many cases several kilometers from the main channel. On occasion, they would go aground and have to wait for the next high water to float off. On Bayou Lafourche, the channel was too shallow to risk entering in the summer months.

During this period, Bayou Lafourche served principally rice and sugarcane plantations. These products had to be shipped to the New Orleans' market, either up the bayou to the Mississippi River at Donaldsonville, or to Morgan's Texas and Louisiana Railroad at Raceland or Lafourche Crossing, or through several canals leading from the Lafourche to the Mississippi.

House Types of the Common People

The "Bayou Country" has served as a primary source area in the study of "folk house types." these dwellings were built without benefit of plans, books, or architects. Builders followed concepts established by their forefathers. Five house types are significant: the Acadian or Cajun, Creole, Creole Raised Cottage, Shotgun, and Bungalow.

The Acadian house is the dwelling of the small farmer. This structure may be one room under a continuous-pitched sideward-facing gabled roof and has a full gallery with a chimney built into the end wall. It is sometimes two rooms wide with a center chimney.

The Creole house was constructed by more prosperous people. Often called a larger Acadian house, it may have two main rooms with one common chimney and a T-addition of three smaller rooms. Some versions have four basic rooms with a full center hall, gabled-end roof, built-in chimney, and the T-addition. On either side of the addition is a porch--one is always in the shade.

Similar to the Creole house, the raised cottage sat between a hipped roof and a brick ground floor. There are usually a larger number of front openings, full-length "French" doors and windows. The house evolved into a form with a sideward-facing gabled roof, a central hall, and light shutters that replaced the heavy board doors over the long windows.

The shotgun is one room wide and at least three rooms long, with a long, front gabled roof. Most include a small front porch. Almost all are built of lumber. Chimneys may be external or internal, on side or traverse walls. The shotgun is always raised on piers. This house is common in three contexts: as a plantation quarters, as an urban lower-class house, and as a trapper-fisher dwelling. It is common throughout southern Louisiana's alluvial wetlands.

The bungalow is nothing more than a double shotgun, two rooms wide, and at least three rooms long, all under a gabled-front roof. It is the most common house in Louisiana for the 1930-1950 period, after which comes the "ranch-style" slab house. The bungalow is common in rural and urban landscapes. It is rarely used as a quarter house though it is often found as a small independent farmer's dwelling.

Commerce and Agriculture

On Bayou Lafourche commerce varied. Principal goods moved were indigo, cotton, rice, sugarcane, and molasses. In return, plantations and habitant accepted household goods and coal to fire sugar refinery boilers.

In 1742, indigo was Louisiana's principal crop. Nevertheless, planter's records indicated that an inferior quality sugar was being produced. This changed in 1794 when Etienne de Bore granulated sugar successfully. As a result, plantation-type operations emerged between 1803 and 1810. By 1860, plantations had planted enough sugarcane that Louisiana's "sugar fever" was set in motion.

The plantation landscape is conspicuous for its dominant "big house," overseer's house, organized cluster of quarter houses, sugar house, and groups of barns and sheds. Some are laid out perpendicular to the bayou. Others, called the nodal-block form, are laid out in a grid pattern about 3 km from the bayou "toward the back."

Running the plantation's mill and sugar kettles required wood, at least two and a half cords per open kettle. Considering a cord cost $2.50 in the 1840s, this was a significant cost. In Louisiana, an abundance of wood could be cut from the swamps. By the 1830s, wood was difficult to obtain; the easily accessible stands had been depleted. Planters needed a reliable fuel. Their wood supply was declining, what was available was going into steamboat boilers. By 1840, planters began to use coal in their sugarhouses. By mid-century, many Bayou Lafourche sugar plantations were receiving Pittsburgh coal.

Small farmers along Bayou Lafourche were content to harvest cotton, corn, rice and peas. These were their contribution to river trade; they did not need any coal. Coal became important when sugar gained a foothold on Bayou Lafourche. This did not occur until the middle 1800s, when Anglo-Americans acquired large tracts that could support the sugar industry. These Anglo-Saxon Protestants, in many cases, bought out the habitant so they could acquire the land necessary to support their mill, refinery, slave quarters, and sugar fields. They were willing to make the necessary investments required to support the industry. The land was ideally suited for this crop. With no roads and swamps framing the "back land," Bayou Lafourche provided irrigation water and most of all the needed transportation artery to move their crops to market.

The fortunes of sugarcane planters fluctuated with worldwide economic cycles. Total production increased until the catastrophic arrival of the mosaic disease in 1926. Sugar planters and sugar factories folded. With introduction of the Java P.O.J. variety, sugar again prospered. Production has remained high with yields of 60 tons/ha. Current sugar prices have drastically affected sugar farmers. At present, world retail sugar prices do not support production costs. Sugar farmers and sugar factories are again in trouble. Unfortunately, the best agricultural land is being converted to subdivisions because the return is greater than from agriculture.

A visible culture trait, that was passed from generation to generation, is the small family garden near the edge of the bayou--a site selected for the moderating influences of the watercourse.

Agricultural activities have, therefore, occupied an important position in the Mississippi delta plain's social and economic environment. The wealth gained from hydrocarbons, commercial fishing and trapping, industrial development, and tourism does not overshadow the value of the agricultural products. The favorable climate and fertile alluvial soils allow almost every crop indigenous to the western hemisphere to be raised.

The Renewable Resource Base

In the marsh dwellers' annual-use cycle, the winter trapping season is followed by the May shrimp season. Due to the absence of ice, the shrimp harvest was brought to isolated platforms, where shrimp were dried for market. With improved availability of ice, the use of otter trawls in 1915, and engine-driven boats, the shrimp industry moved to permanent bayou settlements. These communities served the trapper-fisher folk well.

Muskrat, Nutria, and Alligator

the earliest muskrat (*Ondatra zibethicus*) pelts were offered to northern markets in 1870; they were considered useless and returned. By 1900, muskrat had become a permanent resident of Louisiana's marshes. By 1914 the animal was on the fur market and destined to become the state's number one furbearer, a title it would eventually lose to the nutria (*Myocastor coypus*).

Unlike the indigenous muskrat, the nutria, or South American coypu, is an alien animal. the Argentina rodent was introduced into the wetlands in 1938 and is now well established. After escaping into the marsh, this prolific animal expanded its range. As a result, by the early 1950s trappers were harvesting nearly 80,000 per year. Six years later more than 500,000 pelts were processed--a tremendous increase in less than 20 years (Davis 1978).

The rodent was originally considered a nuisance, since it was heavy to carry out of the marsh, difficult to skin, and confined to a single area. It was a liability, but attitudes have changed. The nutria harvest yields annually more than $7,000,000 and represents more than half of the state's fur income--all from a dozen South American coypu that escaped from captivity and diffused throughout the state. In less than 30 years the nutria supplanted the muskrat to become the principal animal trapped. For 27 years it has maintained its lead, but with the state's current problems with saltwater intrusion, the muskrats habitat is expanding, while that of the nutria is declining. Muskrat, therefore, may return as the number one animal.

Although present throughout the state, alligator mississippiensis is primarily concentrated within the coastal marshes. At least 500,000 "gators" live in the coastal zone's fresh to slightly brackish habitats. First described in 1718, the alligator has survived two centuries of hunting. In the late 1800s alligators 4.5-6.0 m were rather common. They were so commonplace they did not attract considerable attention. The giant reptiles were everywhere and were generally considered a nuisance.

Called by the Spanish El lagarto, the lizard, alligator mississippiensis has been harvested commercially since the mid-1800s. As late as 1890 some 280,000 alligator skins were being processed annually. Unfortunately, between 1880 and 1904 hide hunters reduced the species significantly. Despite a continuous decline in their numbers, no protective measures were initiated until 1960, when a 1.5-m size limit and 60-day season were established.

The season was closed in 1962. Eventually, the alligator was placed on the federal list of rare and endangered species. In 1970, laws were enacted to prohibit the interstate shipment of illegally taken alligators, thereby curtailing bootlegging. Hunters could go to jail if they were dealing in alligator pelts. Throughout the southeast, the protective legislation, along with habitat preservation, allowed the reptile to make a dramatic recovery. Louisiana considers the animal a renewable resource and since 1972 has sanctioned a controlled hunt.

In the 1986 season more than 17,000 "gators" were harvested, averaging 2.1-2.3 m long. The once-endangered species brought Louisiana trappers about $1.5 million. The alligator has become another source of revenue. Further, alligator meat is now on the menus of a number of restaurants. Always a popular item at southern Louisiana fairs, if now accepted as a serious food, the trapper will have another important income source.

The alligator hunter realizes that his quarry has a dollar value in skin and meat. Hunters often shoot a swimming "gator," and although the dead reptile sinks almost immediately, it can be retrieved easily. Another harvest technique involves the use of a baited hook attached to about 15 m of line suspended 15 cm above the water. When the bait is taken, the hook becomes embedded in the reptile's stomach. The alligator is caught and must be handlined to the surface and shot.

Trainasses, Pirogues, Mudboats, and Marsh Buggies

To exploit these resources people throughout the coastal zone gained access to the marsh by digging a trainasse, a term derived from a French word meaning "to drag," but used locally as a "trail cut through the marsh grass for the passage of a pirogue" (Read 1937:74). These deep channels 1.5 m wide by 15-30 cm deep provided the marsh dweller with a convenient artificial watercourse (Davis 1976).

To use these routes, people relied on marsh buggies, mudboats, and pirogues. While the pirogue antedates the arrival of Europeans in the New World, its simple design made it a useful watercraft to ply southern

Louisiana's swamps and marshes. In many parts of coastal Louisiana it became the principal mode of transportation. In some isolated cases, it was the only way to travel. It continues to be a vital part of a trapper's way of life. In many cases, access to trapping areas can only be obtained by using a pirogue--often described as a boat that draws so little water it will "float on a heavy dew."

Mudboats, flat-bottom vessels powered by air-cooled inboard engines, and marsh buggies have improved marsh travel considerably. Mudboats are used exclusively in the firmer southwestern section; however, the marsh buggy is used throughout the wetlands. It existed first as a wheeled and today as a tracked vehicle (Detro 1978).

These tools became a significant factor in the marsh dwellers' systematic exploitation of the environment and a prominent element in this process. The trails were developed to provide access. In a sense they were man's response to the environmental constraints placed on the coastal dweller. As trapping became a more lucrative seasonal trade, more ditches were required; thus, the trapper methodically added a unique element to the coastal zone.

Trapping: A Seasonal Occupation

Before the 1914-22 increase in fur prices from $0.08 a pelt to $0.50 (Chatterton 1944), hunting was more profitable than trapping, with a brace of ducks selling for $0.25. With the 500% increase in fur prices, local people changed their winter subsistence activity from hunting to trapping. By 1916, the muskrat had become the mainstay of the trapping industry.

Ten years later approximately 20,000 people were involved in Louisiana's trapping industry. Most of these people were French-speaking descendants of the Acadians. At this time the industry was essentially uncontrolled. A trapper set his "lines" on any land that suited him. Marsh folks did not bother to lease their trapping land since they felt it was free for everyone to use. Leasing agreements destroyed traditional areas of family trapping and legally barred the marsh dweller from what he considered "his" land.

The trapper's lease has made trapping a truly commercial operation. Fees are based on the land's carrying capacity, on a percentage of the catch, or on a cash-per-hectare basis. In some cases, leases may be based on the land company's estimate of what a trapper is capable of handling. Whatever system is used, the modern-day trapping operation has become more extensive.

In order to work his trapping land, a trapper must have hundreds of traps. He must also have hundreds of the U-shaped, spring-wire stretchers for drying pelts. In the past, a dull knife was used to clean the tiny flesh fragments from a muskrat pelt. Now the wet skin is run through a clothes wringer. After this is completed, the furs are clean, dry, and ready for the stretchers. It is an easy process. Cleaning nutria pelts is more involved and time consuming, since the pelts must be stretched on a fleshing board meat side out and skinned, then washed, line dried, and reattached to the board hide side down.

To improve the commercial annual harvest (December, January, and February are the trapping months), marsh dwellers burn the paludal surface, removing the less desirable vegetation. The conflagrations were a rarity before 1910, but by the 1920s, burning was well established. It is now a local culture trait, considered by some to be an annual necessity.

Men who have trapped all of their lives go into the marsh because they enjoy the out-of-doors; for them, trapping is a form of recreation or therapy. At times the "sport" or job can be quite profitable. It is, however, a fluctuating industry. Indeed, throughout its history the industry has had its economic problems. Low prices, competition from synthetic fibers, closing of trapping areas, and other factors contribute to the industry's success or failure. To many young people this is not an attractive life. To others, it is an important part of their winter employment activity.

Fishing: By Weight or Value, the Wetlands are a Seafood Factory

Each year Louisiana fishermen catch more than 450 million kg of estuarine-dependent fish and shellfish, primarily menhaden, oysters, shrimp, and the nearly ubiquitous blue crab (Larson et al. 1979). With time and increased demand, Louisiana's seafood catch has escalated in value to more than $220 million annually--more than 20%-25% of the United States' landings. Nationally, the state's harvest is number one by weight and second in value.

This phenomenal harvest is directly related to Louisiana's marshes. With nearly 35% of the major United States' commercial fisheries dependent on wetland nursery areas, Louisiana's coastal habitats provide numerous wetland-dependent avian and aquatic wildlife with the food necessary for their survival.

A mutual dependency exists between the people and the resources of the marsh-swamp complex. Although there are thousands of marsh/estuarine systems worldwide, Louisiana's coastal lowlands are the principal breeding area in the northern Gulf of Mexico. It is a "protein factory" of the first order, producing record harvests of shrimp, oyster, crabs, and menhaden.

Shrimp

Two shrimp species are harvested, brown shrimp (*Penaeus aztecus*) in the spring and white (*P. setiferus*) in the fall. Originally harvested by cast nets and haul seines, many commercial fishermen now use a Lafitte skiff outfitted with an otter trawl or *poupier* (butterfly net).

With more sophisticated boats and equipment, the shrimp harvest has grown rapidly. Expansion of the industry resulted in shrimp becoming the most valuable seafood in Louisiana. The catch is second only to menhaden (*Brevoortia patronus*) in quantity, but first in dollar value--worth more than $100 million annually.

Oyster

Oystermen rely almost totally on one species, American oyster (*Crassostrea virginica*). Louisiana currently leads the Gulf states with an average yield of about 4 million kg of meat yearly. This figure has remained constant over the last 20 years, even though environmental perturbations occasionally affect production. Louisiana generally ranks second nationally (after Maryland) in yields. Dockside value is between $3 million and $4 million annually.

Louisiana's oyster industry was a most profitable enterprise for Louisiana's Dalmatian settlers. They made the industry what it is today. The Yugoslavians took oysters from the east side of the Mississippi River, large and small, keeping the large ones and "seeding" the smaller ones on bedding grounds on the River's west side--a process that continues. These folks have permanently identified themselves with the Louisiana oyster, many are third- and fourth-generation fishermen.

Unfortunately, as salinities increase, predators attack the oyster beds and reduce the harvest. Oysters can survive in sea water, but so can their predators. Oystermen must relocate their beds into brackish water to escape the saltwater-dependent predators. The end result is that the distribution of the oyster beds depends on the salinity content of the water. In many of the interdistributary basins salinities are increasing due to the coastal deterioration that has accompanied land subsidence, erosion, and canalization.

Menhaden

The third valuable commercial marine resource is the menhaden or "pogie." Since the first landings in 1940, menhaden have become Louisiana's principal industrial fish. The reason for its apparent late development is that the species' oily flesh is not suitable for human consumption, but when processed it is a valuable source of oil and animal feed.

Louisiana's "pogie" fleet harvests annually from 270 million kg to more than 450 million kg. The area located in and around the Mississippi delta is particularly productive. Menhaden fishermen can harvest a catch that will exceed $50 million annually.

Although "shrimp is king," by weight the menhaden industry is the state's most important fishery. The catch has made the towns of Cameron, Empire-Venice, and Dulac-Chauvin among the United States' top five fishing ports. Combined, these ports can account for more than half of the United States' menhaden/shrimp harvest.

Although it has been suggested that menhaden-derived protein meal could be used in the diets of many underdeveloped countries, the notion has never materialized. The future of the industry looks favorable, since most of the protein meal is used as a chicken feed.

Recreation

With one out of every two Americans involved in outdoor recreation, and with water serving as the largest single attraction, the water bodies and biologic resources of coastal Louisiana attract both resident recreationalists and out-of-state tourists in rapidly increasing numbers. The economic value of recreational fishing may even exceed that of commercial fishing.

The state is a wintering area for between 6 and 8 million waterfowl per year; approximately 75%-80% concentrate in the coastal marsh. The 36 waterfowl species that winter in the state make hunting an extremely important and popular recreational activity.

As a renewable resource, the migratory populations can be maintained by properly managing the wetland environments. Habitat preservation is the key to maintenance of the waterfowl resource and an annual reoccurring income that in most years exceeds $80 million. Fishing is a year-round leisure-time activity that varies with the breeding cycle of the various fish species, water levels, fishing pressure, and habitat productivity. Fishing-related expenditures in Louisiana exceed $50 million annually.

It is apparent that recreational sportsmen benefit greatly from Louisiana's wetlands. As lowlands are lost, the habitats preferred by game birds and fish will dwindle, and an industry that annually contributes directly or indirectly from $175 million to $200 million to the regional economy will be affected.

Non-Renewable Resources

In the early 1900s, discoveries at Jennings and Spindletop, Texas, confirmed southern Louisiana's hydrocarbon potential, particularly in stratigraphic traps associated with salt domes. Development of these known structures was hampered by the complicated logistics and economics involved in operating in the alluvial wetlands. The problem was accessibility. Wetland exploration required boats and other forms of floating equipment to survey potential drilling sites. Unlike dry land operators, oilmen needed port facilities to support their waterborne operations, service their fleets, and store other supplies needed to work in the poorly drained soils of southern Louisiana. To acquire the necessary infrastructure took a large investment, commitment, and time; therefore, the marsh and swamp were, until the 1930s, virtually unexplored.

Though southern Louisiana got a slow start, it developed rapidly into an important energy supply region. Once the petroleum resources were discovered, a chain of events occurred to guarantee that the hydrocarbons could be moved from the source area to centers of demand. The landscape is now dominated by oil and gas fields, crossed by canals and lined with pipelines, giving the marshes a unique man-made appearance. An extremely vital element in this triad is the canals. They provide the accessibility so necessary in resource development and have influenced the high proportion of the population involved in extractive and transportation industries.

Canals and the Oil Industry

Sailors exploring the coast of Louisiana and Texas in the 1600s recorded seeing a black slick floating on the sea. This seepage provided a small clue to the hydrocarbons trapped in a geosyncline stretching from Mississippi, through Louisiana, and into the coastal provinces of Texas. The resource was not drilled until the turn of the century. Since then, more than 40,000 wells have been drilled in the coastal zone of Texas and Louisiana.

The world's first producing offshore oil well was drilled in 1937 by the Pure and Superior Oil Companies less than 1 km from the shore of Louisiana in 4.5 m of water. On 14 November 1947 the first producing well out of sight of land was brought in by Kerr-McGee Industries in 5.5 m of water. It was 16.8 km off the Louisiana coast and added a new chapter to the history of the petroleum industry. Since completion of this first well, more than 3000 drilling and production platforms have been anchored to the floor of the Gulf of Mexico, collecting fluids from nearly 20,000 offshore oil and gas wells. Consequently, Louisiana produces more than one-third of the United States' natural gas and between 15% and 20% of the nation's crude oil. The state's leadership is not surprising since in 1981 its estimated proven oil reserves in state and federal waters were 2026 million barrels with natural gas reserves estimated at 890 billion m^3. In addition, Louisiana offshore oil was valued in 1980 at $4.5 billion.

Hydrocarbons produced offshore move through a labyrinth of pipelines ranging in size from 5 to 100 cm in diameter. The end result is one of the most complex pipeline networks in the United States. The interconnected system is utilized by more than 50 companies to move mineral fluids to gas processing plants, refineries, residential markets, tank storage sites, and ultimately to transport areas where the fuels are shipped nationwide.

In exploiting the region's resources, numerous artificial structures aided in the harvesting or exploitation process. The most visible of these artificial elements are canals. The coastal lowlands are now subject to a massive and still-growing matrix of oil and gas canals, pipelines, spoil banks, and associated ancillary activities. Virtually no section of the coast has been spared from the canalization process; it is the coastal zone's major engineering feature.

One cannot help but be impressed by the complex web of interconnecting channels. Like fine Belgian lace, there is a delicacy to the landscape's geometry. For more than 200 years canals have been a part of Louisiana's geography. Once cut, they endure. The region has been crisscrossed, ringed, cut, bisected, and otherwise dominated by a massive network of waterways. Until recently, new channels were added continually. Old ones were rarely filled in; thus, the complex intertwines and expands into a well-defined pattern. The network is by no means the product of planning. Each canal or appendage represents one well. It is a one-well, one-canal system. Numerous individual decisions went into deciding where to drill--the canal pattern is the end result.

Land Use

Since the region has become more populous, more prosperous, more urbanized, and more industrialized, land is at a premium. The dynamic nature of this growth trend is derived essentially from the long-term development of the area's vast hydrocarbon resources, accompanied by extensive service-industry expansion at the expense of agricultural production and commercial fishing and trapping activities. The area also has prospered because of the relatively low cost of living, a favorable tax structure, an attractive climate, and the region's unique cultural/recreational amenities. Suburban expansion is occurring throughout the area. Competition for space is fierce. Settlements are agglomerated into "strips: owing to the reciprocal relationships between each and the natural environmental restraints placed on urban and built-up land. The strips are limited by a finite quantity of suitable property, reflected in land-use patterns and threatened by continued land loss.

In Louisiana the oil-related firms have consolidated into industrial complexes or development corridors. Distinct patterns, typical of the petroleum industry's regional impact, emerged. These onshore support facilities are expected to continue to meet the needs of the onshore industry for the remainder of the century. Relative sea level rise, subsidence, and wetland loss cannot be ignored as factors that will determine the fate of these sites and any others planned for the future.

The response to the land loss problem has been to adapt support sites and industrial complexes to the available land. The land that can be used is at best marginal. Human settlement in coastal Louisiana was historically confined to beach ridges and natural levees. With expansion of urban/industrial land, extension of farmlands, development of oil, natural gas, and sulphur industries, and the associated demand for improved navigation channels and construction of hurricane-protection levees, man has extended his activities well into the wetlands and along the shoreline.

The suitable land is not convenient, then draining and reclaiming swamps and marshes has been the solution. New Orleans' reclamation practices, although more than 200 years old, follow those outlined in the United States since the colonial period. Within the last two centuries more than one-half of the nation's wetlands have been converted to other uses. New Orleans serves as an excellent example.

New Orleans: North America's Below Sea-Level City

Since its inception, New Orleans has faced a continuous battle with drainage. When the city was surveyed in 1720, each block was circled with drainage ditches. When it rained, these ditches filled with water, creating little islands. Residents continue to refer to these blocks as "ilets." These channels established the "Crescent City's" dependence on a drainage network. It became apparent that New Orleans would always face drainage problems. The city has for more than 250 years fought a continuous battle with flooding--a battle yet to be won. It is one of the country's most flood-prone cities and probably the most precarious in the United States.

To ensure that settlers confronted the drainage problem, Governor O'Reilly in 1770, issued land-grant regulations that provided every settler a tract of land. This property was forfeited if within three years a levee, highway, and parallel ditches were not completed around the property. These regulations guaranteed that Louisiana's lowlands would be drained adequately.

Arable land was in short supply. It was felt that the only practical way to solve the land shortage problem was to reclaim swamps and marshes that were at or near sea level. Around New Orleans, and in general throughout southern Louisiana, these wetlands were considered "worthless" wastelands in themselves. They were, however, recognized as a valuable undeveloped resource, one that could be drained and reclaimed easily.

The challenge was to ensure flood control and adequate drainage measures. Improved machinery and engineering techniques were imported from Europe to meet this challenge. New Orleans expanded beyond the confines of its natural levees; at 4.5 m above sea level these features are the region's only high ground. They provided the original inhabitants with a relatively dry, firm foundation of building. As the city expanded, its population grew. The city's strategic location encouraged this growth. As a result, by the 1830s New Orleans was one of the largest cities in North America. The end result has meant that the city must fight a continuous battle with flooding.

The age-old fight to keep New Orleans dry is made increasingly difficult as parts of the city continue to sink below the level of the surrounding waters. General regional subsidence over the past 4500 years has been calculated from 12 to 21 cm/century (Saucier 1965). In point of fact, the soft, easily compacted sediments of Louisiana's delta plain do not provide the ideal foundation for a metropolis. Nevertheless, New Orleans has developed and prospered within this inhospitable environment.

Drain and reclaim measures have resulted in parts of the levee-protected city being nearly 5 m below sea level. Levees and drains protect the populace. A single pump failure, levee crevasse, hurricane, or 25 to 30 cm thunderstorm can be disastrous. Levee systems are essential to keep floodwater out, but they also keep rainwater in. This water is in most cases pumped uphill by a system of pumps that operate continually to discharge surface runoff and groundwater seepage.

Currently, New Orleans operates 140 km of canals and 92 km of large pipelines. These conduits, along with 21 pumping stations, are capable of removing approximately 85.1 million liters of water per minute from the city streets, through over 50,000 curbside catch basins and 2024 km of subsurface drainlines (Wagner and Durabb 1976). The entire system drains more than 220 km^2 of Orleans and Jefferson parishes. The pumps can remove 5 cm of rainwater the first hour and 1.2 cm every hour thereafter. When 15 cm has fallen, the system is at capacity. Rainfall exceeding capacity results in "ponding" on the streets until the pumps are able to handle the excess runoff. To further protect the city, a concrete floodwall and new outfall canals are under construction. Both will provide an added element of protection from flooding.

When established in the early 1930s, the drainage system was adequate and considered excellent. Although more than 200 years old, New Orleans was still in its infancy. Major population increases had not yet occurred. After 1920 the alluvial wetlands, much of them near or slightly below sea level, began to be reclaimed. The problem was how to drain them in a cost-effective manor.

The drainage solution was a heavy-duty pump, designed by A. Baldwin Wood, capable of removing large volumes of debris-laden water; it quickly revolutionized the urban geography of New Orleans. Areas that were thought inaccessible were opened to settlement, but draining the swamps was a major undertaking. Pumps, canals, and levees had to be built or installed. Soils "were not soils at all, but a thin gruel of water and organic matter that shrank and settled when the water was removed" (Lewis 1976:62). When drained, they compacted and sank below sea level.

In building New Orleans, no one apparently considered the high shrink swell rates of these peat and muck soil types. Consequently, within the greater New Orleans area net subsidence rates of from near zero to 5 m have been reported (Snowden et al. 1980). The problem ranges from severe to minimal. This is particularly true on the reclaimed lands associated with New Orleans' suburbanization, where marsh/swamp peats often shrink more than 1 m during the first 50 years after drainage. Coupled with a natural regional subsidence estimated between 1 cm to nearly 4 cm annually (Boesch et al. 1983;

Nummedal 1982), these new areas face severe problems. Drainage water must be pumped over the surrounding levees to sea level water courses. Water in these channels often stands at a level that is even with the second story of many homes. Flood protection is literally a matter of life or death.

Prior to 1955, only a few subdivision had expanded into the drained cypress/tupelo swamps and marshes. Housing contractors built homes with raised-floor foundations, supported by masonry blocks, or wooden pilings. These pilings must be driven to a depth of at least 12 m deep into the underlying clay unit. By utilizing this procedure, the low-bearing strength of the peats is counteracted (Snowden et al. 1977). Pilings are necessary since most of these soils are poorly suited for urban uses; they have extremely high shrink/swell rates. Even so, peat and muck lands are 90% urbanized. Drainage and protection from flooding are possible only by constructing large water-control structures. This is often quite difficult, as the soil material is poorly suited to the construction of levees because it shrinks and cracks as it dries, causing the levees to often fail (Mathews 1983).

A raised-floor, supported by pillars withstands subsidence well, since the pillars can be raised and releveled easily. As New Orleans' urban geography expanded, builders began to use concrete-slab foundations. This type of construction is disastrous. The soft, unconsolidated, highly compressible peats cannot support heavy concrete slabs. Slabs simply sink, tilt or break and in general the homes have a distorted angular geometry. Within a few short years, these structures have few right angles.

Ordinances were passed 25 years after initial marshland development requiring residential contractors to use pilings in thick peat areas. Even so, commercial and residential developers must expect at least an additional $14,000 per hectare (in 1976 dollars) to counteract subsidence. In 1975, homeowners had an average maintenance cost of $200 per year for cracked sidewalks, driveways and broken sewage and gas lines (Wagner and Durabb 1976). These costs have, of course, increased. The subsidence problem is so acute that as gas lines break homes sometimes explode (Snowden et al. 1980). Many homes in New Orleans are lifted by pumping mud under them. This "mud jacking" process compensates for subsidence under the home. There is still a difference in subsidence between the house and the surrounding ground surface. To correct this differential subsidence, homeowners fill their yards with 9 to 18 m^3 of topsoil (Snowden et al. 1980). Nevertheless, when these organic soils subside, foundations are exposed, and unsupported driveways, patios, air conditioner slabs and walkways crack and warp and gradually drop below original levels. Unfortunately, streets, sewage lines, driveways, and sidewalks are not similarly raised.

To alleviate the financial hardships associated with subsidence, a number of municipalities have enacted laws to try and reduce development in areas where the soils have a high subsidence potential.

Investigation of New Orleans' negative land surface reveals that humans act as catalysts to initiate subsidence. In the reclaimed wetlands that surround the Crescent City, natural accretion has been terminated; the sediment supply has been reduced to zero. The Mississippi River is no longer allowed to flood, because in 1927 the need for flood control became apparent. The Mississippi inundated 6.5 million ha in parts of 7 states displacing nearly 800,000 people. After this devastating flood, the U.S. Army Corps of Engineers began to construct the Mississippi's "guide levees." The issue was simple: drain, reclaim, and protect the city from Mississippi River flooding by constructing levees. The river was then locked into an artificial conduit; it could no longer flood New Orleans. The entire system of levees protects against high tides, rain runoff, and hurricane storm surge.

In retrospect, the intricate network of interconnecting levees had a dramatic impact on the general ecology of the wetlands because they altered the annual natural distribution of fresh water flowing over the banks of the river into the surrounding marsh-estuary complexes. Natural wetland processes, deposition of the rich sediment load, interlevee-basin drainage regimes, and vegetation patterns were altered permanently. The natural system is now superseded by an artificial one.

With a projected sea-level rise of 1.2 cm/year, coupled with a constant battle with subsidence, New Orleans faces a questionable future.

EVOLUTION OF CAT ISLAND PASS, LOUISIANA

John R. Suter[1] and Shea Penland[2]

ABSTRACT

Cat Island Pass, located within the abandoned Lafourche delta complex of the Mississippi River delta plain, separates the barrier shorelines of the Isles Dernieres and Timbalier Island. Currently some 9 km wide, the inlet consists of three main channels with a maximum depth of 9 m. Despite a tidal range of 36 cm and relatively low wave energy, the inlet morphology is mixed-energy, with both tidal deltas confined to the inlet throat. Historical maps show that the Cat Island Pass system originally comprised three separate inlets, which eventually coalesced to form the modern pass.

High resolution seismic profiles and vibracores document the occurrence of two major sand bodies associated with the development of this area. The ebb-tidal delta/spit platform reaches a maximum thickness of 7-9 m near the inlet throat, and is characterized by wavy horizontal reflectors on seismic profiles and a sequence of fine sand and shells in vibracores. Underlying this unit is an acoustical package characterized by high-angle clinoform reflectors interpreted as tidal inlet channeling. Vibracores through this deposit consist of large-scale trough cross beds of sand and shell.

The development of Cat Island Pass illustrates a process of tidal inlet evolution within the Mississippi River delta plain under conditions of relative sea level rise. Typically generated by hurricane breaches, tidal inlets are initially flood-dominated, but become ebb-dominated due to increasing tidal prism resulting from relative sea level rise and backbarrier wetland loss.

INTRODUCTION

Cat Island Pass, located within the abandoned Lafourche complex of the Mississippi River delta (Frazier 1967), separates the Isle Dernieres and Timbalier Island and provides tidal exchange between the Gulf of Mexico and Timbalier and Terrebonne bays (Fig. 1). Mean diurnal tide range in the area is about 36 cm, while modal deep water wave height is 1 m with a period of 5-6 seconds (Bretschneider, 1962). Thus, this area

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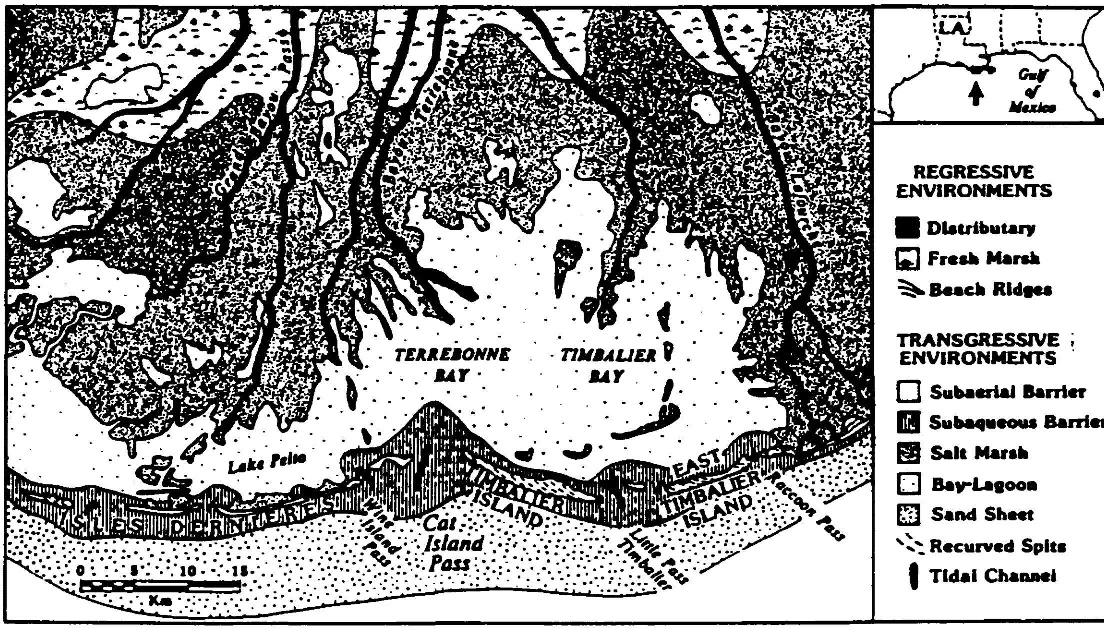

Figure 1. Cat Island Pass is a part of the transgressive depositional system of the LaFourche delta complex. The inlet separates the Isles Dernieres from Timbalier Island, providing tidal exchange between the Gulf of Mexico and Timbalier and Terrebonne Bays.

fits easily into the morphological classification of Hayes (1979) and disciples as a microtidal, medium-wave-energy coast. Over 99% of the deep-water wave energy is dissipated on the shallow Louisiana continental shelf before reaching the shore (Wright et al. 1974). The energy regime of this region is complicated by hurricanes, tropical storms, and extratropical cyclones that generate meteorological tides in excess of the astronomical range, create overwash conditions during passage, and significantly increasing wave energy.

Abandonment of the Bayou Petite Caillou delta and development of the Isle Dernieres began around 420 years B.P., while development of the Bayou Lafourche barrier shoreline commenced sometime after the abandonment of the Bayou Lafourche delta some 300 years B.P. (Penland et al. 1987). The growth of recurved spits and flanking barrier islands away from the Bayou Lafourche headland resulted in the enclosure of the interdistributary Timbalier and Terrebonne bays (Fig. 2). Concurrent hurricane impacts eventually breached the barrier shoreline, initiating tidal inlet development. As the evolution of the Lafourche system continued, relative sea level rise resulting from compactional subsidence and eustatic factors coupled with ongoing backbarrier wetland a consequence, the volume of water stored within the backbarrier basin

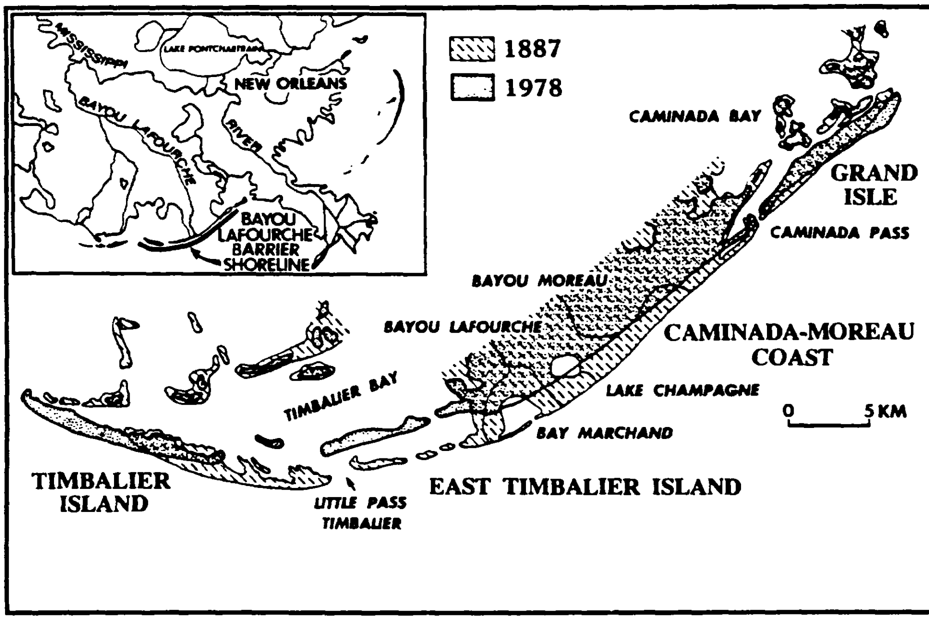

Figure 2. Shoreline changes for the Timbalier Islands from 1887 to 1978, illustrating the westward migration of the recurved spit of Timbalier Island.

increased, causing an increase in the volume of water exchanged through the tidal inlets.

This tidal prism/tidal inlet relationship represents an important process affecting barrier island shape and tidal inlet sediment dispersal, evolution, and sand body development. A long-term increase in tidal prism will eventually lead to an increase in inlet size (O'Brien 1969; Oertel 1975) either through expansion of the inlet throat or increased depth. In an inlet system subject to rapid migration this could result in the volume of sediment stored within the tidal inlet being comparable to, if not greater than, the volume of sediment stored within the adjacent flanking barrier islands. In the Mississippi River delta plain, as the tidal prism increases, the morphology of the individual tidal inlets changes from wave-dominated to tide-dominated. The evolution of Quatre Bayou Pass (Howard 1984) is illustrative of this process, which results in the creation of large ebb-tidal deltas within a microtidal setting. Other inlets in Louisiana such as Caminada Pass, Barataria Pass, and numerous inlets in the Chandeleur Islands system, also show larger ebb- than flood-tidal deltas.

Another process that occurs during the transgression of an abandoned delta complex is marsh degradation due to compactional subsidence and salt water intrusion. Through time, this leads to conversion of backbarrier areas from predominantly marshy environments to open water bodies. As this occurs, the tendency of the inlets to ebb-dominance should be diminished, according to current models (Nummedal and Humphries 1978; Boon and Byrne 1981). However, as stated above, Louisiana inlets tend to become more ebb-dominated with time. This seeming contradiction may be explained by the observation that the meteorological tides in this area often exceed the astronomical tidal range. In a typical year, frontal passages (10-25 per season) elevate and depress sea level between 30 and 120 cm (Boyd and Penland 1984). Thus, increasing backbarrier basin size results in increased fetch and perhaps greater setup on the landward portions of the barrier shorelines, producing stronger ebb currents. Tidal inlets on the Texas coast are known to be strongly influenced by these processes (Price 1952). Hurricanes are capable of generating storm surges of from 2 to 7 m in this area (Boyd and Penland 1984). Surge elevations in backbarrier basins are generally greater than on Gulf shorelines, resulting in enhanced surge ebb flow.

To attempt to understand the effects of the increasing tidal prism, inlet coalescence, and land loss on the stratigraphy of the area, Cat Island Pass has been studied by the use of historical shoreline charts, bathymetric surveys, high resolution seismic profiles, and vibracoring. This paper presents some preliminary results of these investigations.

MORPHOLOGY OF CAT ISLAND PASS

Cat Island Pass, currently some 9 km wide (Fig. 1), actually consists of two major ebb-dominated channels, Wine Island Pass to the west, and Cat Island Pass proper to the east. The inlets are separated by Wine Island Shoal, which was a barrier island in the 1880's. Wine Island Pass has a maximum depth of 11-12 m, while Cat Island Pass reaches a maximum depth of 7-8 m. The deepest point in the system is a 16-m scour hole in Lake Pelto landward of the minimum cross section of Wine Island Pass.

Both Wine Island Pass and Cat Island Pass have small to non-existent flood tidal deltas with little or no bathymetric relief. The major flood tidal delta sand body in the inlet system is Wine Island shoal itself. At one time the shoal was a subaerial feature (Figs. 3 and 4), and was probably part of the same barrier shoreline trend of the Caillou-Brush-Casse Tette Islands (Fig. 1) associated with the Bayou Terrebonne delta, abandoned some 1270 years B.P. (Penland et al. 1987). By 1934, the former island had become an intertidal shoal. Its current morphology represents a large, landward-shallowing flood ramp, forming an ebb shield with seaward-oriented spits. Two small ebb-dominated spillover lobes dissect the crest of the shoal, and the associated channels dissect the shoal into three separate sand bodies (Figs. 3, 4). The depths in these channels reach 6 m.

The ebb-tidal deltas are confined to the seaward margin of the minimum cross section, and are defined by the 8-m isobath (Fig. 3). The thalweg of the main channel is pushed against the eastern margin of Wine Island shoal by westward-oriented longshore currents, as well as tidal currents flowing out of the present-day Caillou Pass (Fig. 3). Extending from Timbalier Island westward into Cat Island Pass is a spit platform terraced at the 1-, 3-, and 6-m isobaths. Part of this spit platform was subaerially exposed in 1985 and was informally designated as Aaron's Island. The broad 3-m platform serves as the marginal flood channel of the system, while the lower terrace and 8-m thalweg are bifurcations of the main channel of Cat Island Pass. The eastern channel terminates seaward as an ebb-spillover lobe, while the thalweg terminates seaward at the 8-m isobath. The ebb tidal delta of Wine Island is smaller and attaches to the eastern Isles Dernieres in the form of a large swash platform. The stability of this stretch of coastline is evidenced by the recurved spit morphology of the eastern Isles Dernieres, which attests to a steady supply of sand by tidal inlet bypassing (see FitzGerald 1982).

SEDIMENT DISPERSAL

The descriptions of sand transport given here are subjective, based upon morphological observations and comparison to published reports. Patterns of sediment dispersal for the Isles Dernieres barrier shoreline are under study as part of a cooperative research project between the United States Geological Survey (USGS) and the Louisiana Geological Survey (LGS). That study should help to confirm or deny these interpretations. Sand moving westward along the beaches of Timbalier Island enters Cat Island Pass through the marginal flood channel located between western Timbalier Island and the ebb-spillover lobe and ebb-tidal delta of Cat Island Pass. Once within the inlet system sand travels across the ebb-spillover lobe and ebb-tidal delta of Cat Island Pass up the flood ramp of the Wine Island Shoal flood-tidal delta in the form of sand waves, megaripples, and swash bars. Sand is then either recycled within Cat Island Pass or passes westward through Wine Island Pass onto the eastern Isles Dernieres across a wide swash platform.

Although sediment transport has been greatly affected by human activities, including the construction of jetties at Belle Pass and the dredging of the Houma Navigation Canal through Cat Island Pass (Meyer-Arendt and Wicker 1982), this pattern of sediment dispersal is reflected by the recurved spit of Timbalier Island, the downdrift nearshore bar morphology, and historical shoreline changes (Figure 2). At Cat Island Pass and Wine Island Pass the deflection of the main channels towards the west across the ebb-tidal deltas supports a net westerly component of longshore sediment transport. In addition, the occurrence of a well-developed marginal flood channel at the western end of Timbalier Island and the absence of a swash platform indicates that sand moves directly into Cat Island Pass with little exchange taking place from the ebb-tidal delta onto Timbalier Island. Evidence of a net westerly longshore transport at the Isles Dernieres includes a well-developed swash platform associated with Wine Island Pass and the absence of a marginal flood channel at this location. This is the only stable shoreline along this barrier island arc. All of this evidence points to the fact that this tidal inlet system is not totally a sediment sink but does in fact interact with the adjacent barrier shorelines.

HISTORICAL CHANGES

Historically this system has been characterized by rapid inlet migration (Figs. 3, 4). In 1891 (Fig. 4) Caillou Island separated Pass

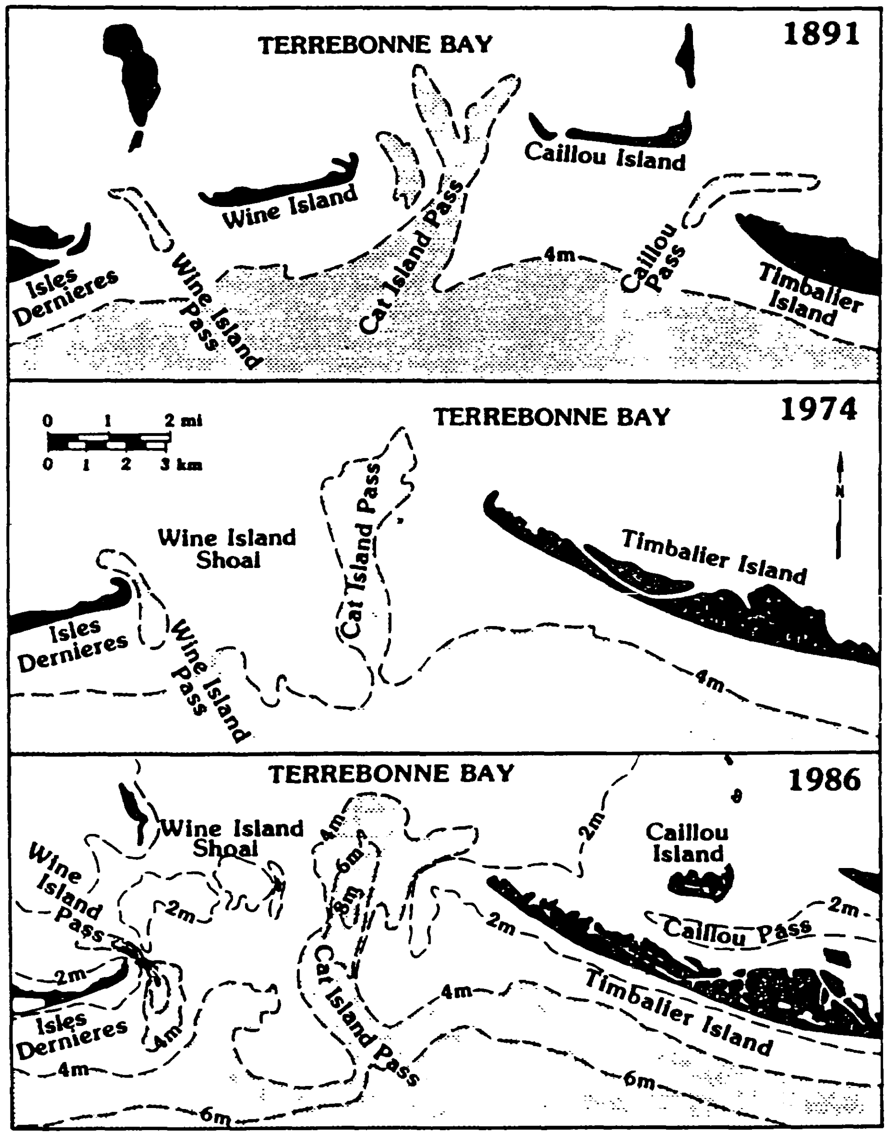

Figure 3. Generalized bathymetric charts for the Cat Island Pass area, 1891-1974-1986. Note the transformation of Wine Island to Wine Island Shoal and the capture of Caillou Pass by Cat Island Pass.

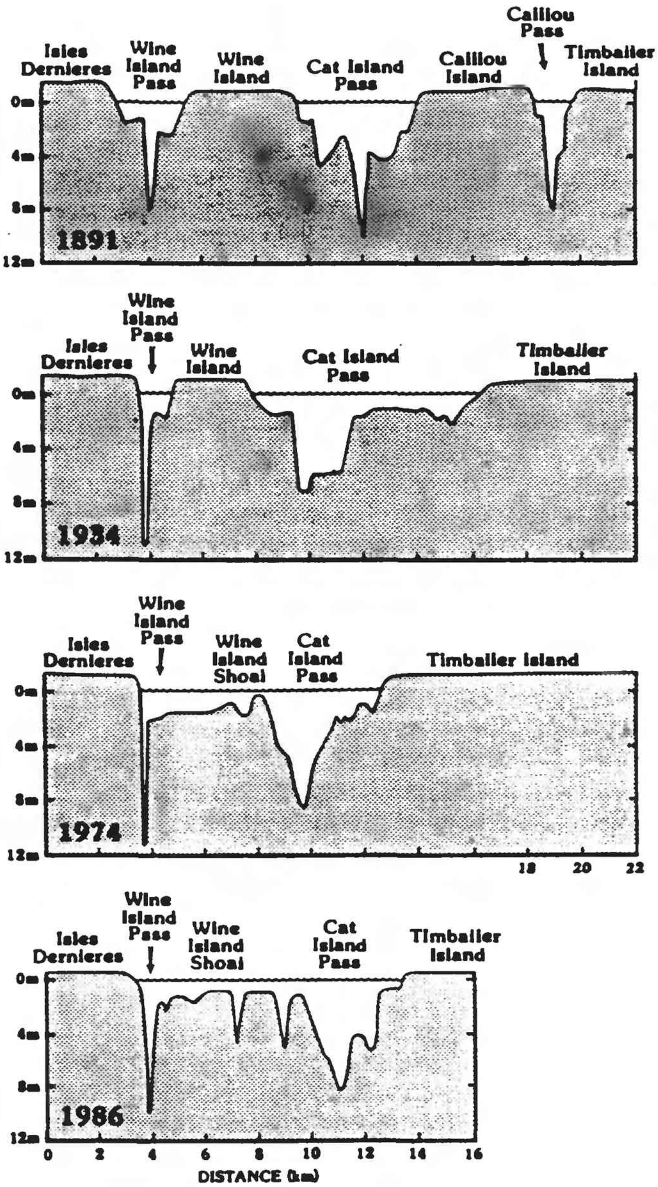

Figure 4. Cross-sectional profiles of the Cat Island Pass area, 1891-1934-1974-1986. Profiles are drawn on minimum inlet cross section for each period, but are fixed longitudinally. Note the stability of Wine Island Pass, disappearance of Caillou Pass, and the variability of Cat Island Pass (some data from USACE 1962).

Caillou from Cat Island Pass, while the separation of Wine Island Pass was maintained by Wine Island. The inlets reached maximum depths of 8 m. A spit platform extended westward into Caillou Pass from Timbalier Island, and all the main channels of the tidal inlets showed westward deflection across their ebb-tidal deltas.

By 1934, the westward migration of Timbalier Island had forced Pass Caillou to merge with and flow out Cat Island Pass (Fig. 3). The new single inlet increased in cross sectional area, shoaled to less than 8 m, and possessed a width of about 9 km. Deflection of the main channel to the west caused the severe erosion of Wine Island Shoal on its eastern end. By contrast, Wine Island Pass was relatively stable, and increased in depth from 8 m to 11 m. The stability of Wine Island Pass is probably due to its being cut into underlying deltaic clays (USACE, 1962). The spit at the eastern end of the Isle Dernieres migrated some 10 km to the east, resulting in the shoaling of the marginal flood tidal channel (Fig. 4).

Continued westward migration of Timbalier Island resulted in the coalescence of Cat Island Pass and Wine Island Pass by 1974. The walls of the main channel of Cat Island Pass had steepened, and the maximum depth increased to about 9 m. Wine Island had been completely reworked into a flood-tidal delta, separating the various channels of what had become a single inlet system.

This pattern of tidal development has continued, as indicated by the 1986 bathymetric survey conducted by the USGS. Timbalier Island has continued to migrate westward, while the position of Wine Island Pass and the eastern Isle Dernieres has remained fairly stable. The major differences shown in Figures 3 and 4 from earlier periods are the formation of a terrace at 2-3 m on the eastern wall of Cat Island Pass, and the formation of an ebb-spillover lobe terrace at 4-5 m.

STRATIGRAPHY OF CAT ISLAND PASS

A number of hypothetical stratigraphic sequences have been proposed for transgressive tidal inlet deposits (Hayes and Kana 1976; Hubbard and Barwis 1978; Hubbard et al. 1979; Hayes 1980). Boothroyd (1985) stated that the hypothetical sequence of Hayes (1980), quite similar to the sequence given for Fire Island inlet, New York, by Kumar and Sanders (1974, 1975) was effectively a regressive sequence that should be applicable to inlets subject to rapid spit migration. As this is the case for Timbalier Island and Cat Island Pass, a documentation of the actual facies seems in order.

The occurrence, facies, and geometry of the Cat Island Pass area were examined by high resolution seismic profiles and vibracores. Several cooperative cruises between the LGS, the USGS, and the Terrebonne Parish government took place in 1982, 1983, and 1985. The profiles used in this report were gathered in 1982 and 1984 (Fig. 5). Both ORE Geopulse and Datasonics 3.5 kHz subbottom profiler systems were used to provide both penetration and resolution of the area. The 1982 cruise was staged during the month of December under adverse weather

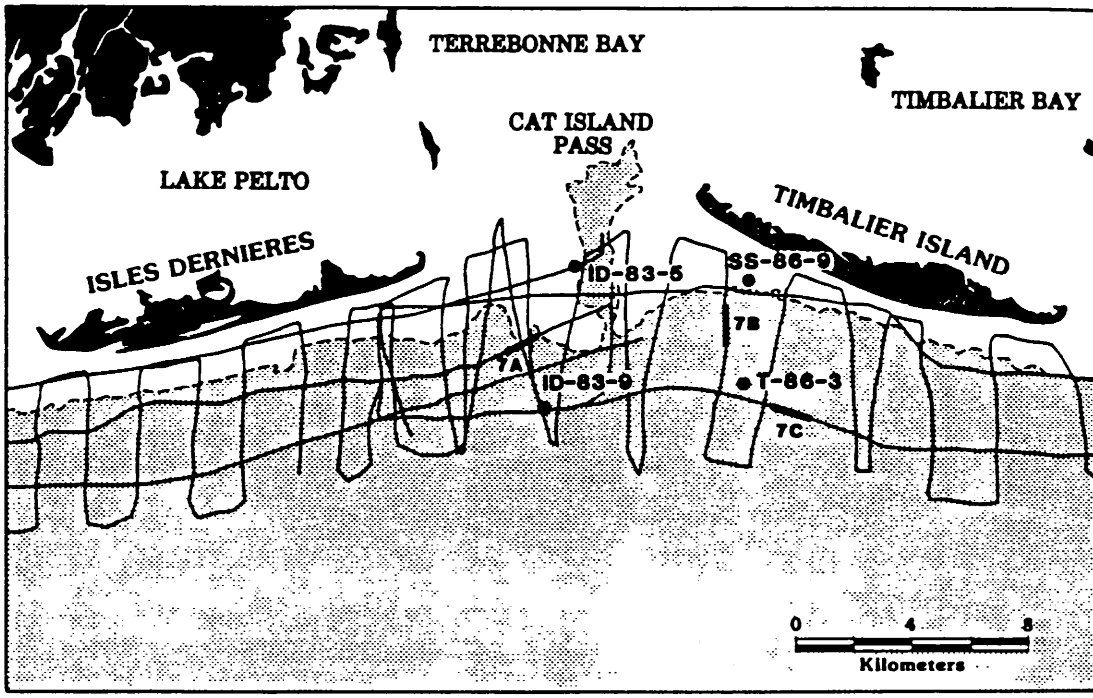

Figure 5. Location of high resolution seismic profiles and vibracores used in this report.

conditions resulting in relatively poor data, while better weather and calmer seas in 1984 produced better results.

Vibracores were obtained in 1983 and 1986 in the Cat Island Pass area (Fig. 5). In 1983, the area of the eastern Isles Dernieres was examined as part of a pilot project to determine the occurrence and location of nearshore sand resources. In 1986, vibracores of the Isles Dernieres and Timbalier Island areas were gathered as part of the statewide Louisiana Nearshore Sand Resource Inventory and a cooperative project between the LGS and USGS (see Sallenger et al. 1987).

Two major acoustical packages were identified on the high resolution seismic profiles (Figs. 6, 7, 8). The upper sand body corresponds to the bathymetric expression of the ebb-tidal delta/spit platform. The unit is characterized by wavy horizontal reflectors that gradually pinch out on the inner shelf and back barrier lagoon (Figure 7A). The maximum thickness is 7-9 m near the inlet throat. The 8-m isobath marks the seaward limit of the deposit. The thickness of this unit is significant to its preservation potential. The depth of the shoreface in this area is 3-5 m (Penland and Suter 1983), so that the distal portions of the ebb-tidal delta have relatively low preservation potential, while the basal portions of its more landward parts are more likely to be incorporated into the stratigraphic record. Figures 8A-8C show the vertical sequence through various parts of this unit. The

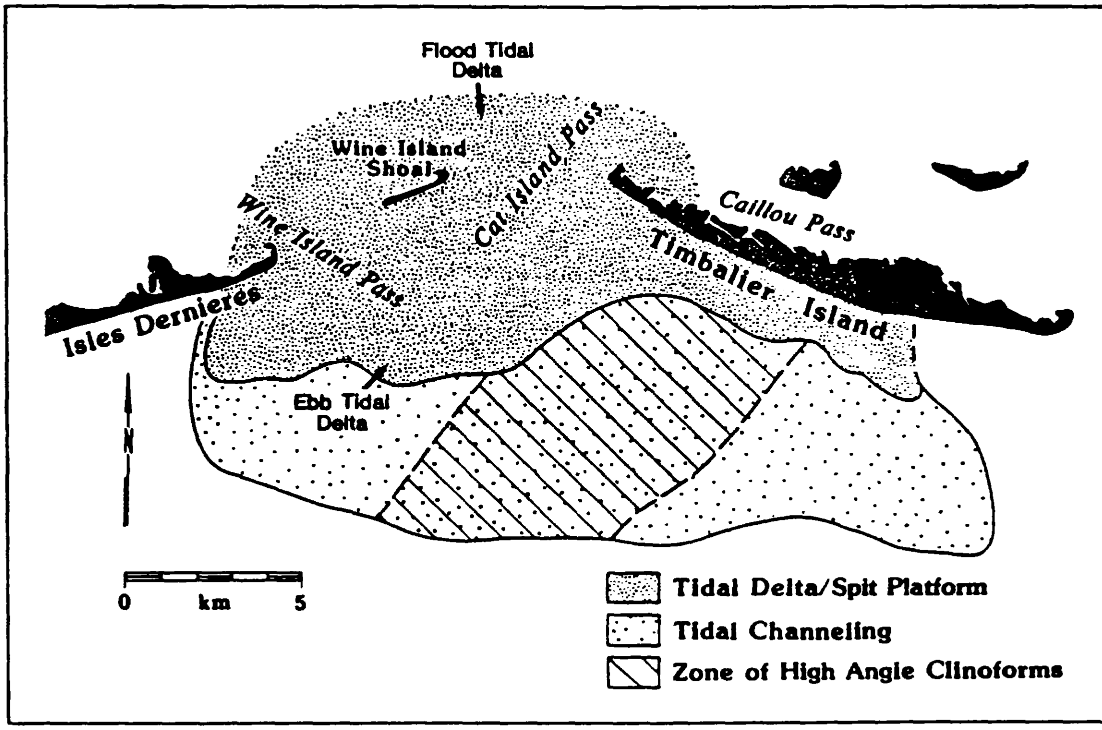

Figure 6. Location of the two major acoustical packages visible on high resolution seismic profiles. Zone of high-angle clinoforms represents the migration path of the main channel.

dominant sedimentary structures are low-angle to subhorizontal laminations with ripple cross beds, often obscured by considerable burrowing.

Below the ebb-tidal delta sand body is another deposit marked in the seismic records by high-angle clinoform reflectors that dip to the northwest (Figs. 7B, 7C; 8A, 8C-D). This unit is interpreted as a channel fill within the inlet migration path of Cat Island Pass. The channel fill also contains chaotic as well as high amplitude reflectors. Chaotic reflectors are attributed to attenuation of the sound signal by coarse- grained deposits, while the high amplitude reflectors mark the occurrence of shell beds within the sequence. Vibracore SS-86-9 documents a shell-rich vertical sequence within the buried channel (Fig. 8C). The common occurrence of large shell valves and shell hash beds with well-defined scour surfaces provides an excellent variant on what can be expected to characterize ancient deposits. The interbeds of sand and shell are believed to be the surfaces responsible for the high angle clinoform reflectors in Figures 7B and 7C.

This deposit has a high preservation potential. It reaches a maximum thickness of 12 m in the thalweg of the channel system offshore, and extends up to 7 km offshore. The advancing shoreface has already truncated much of the deposit. As a consequence, much of this inlet sequence is already preserved. Currently, the tidal channel sand body

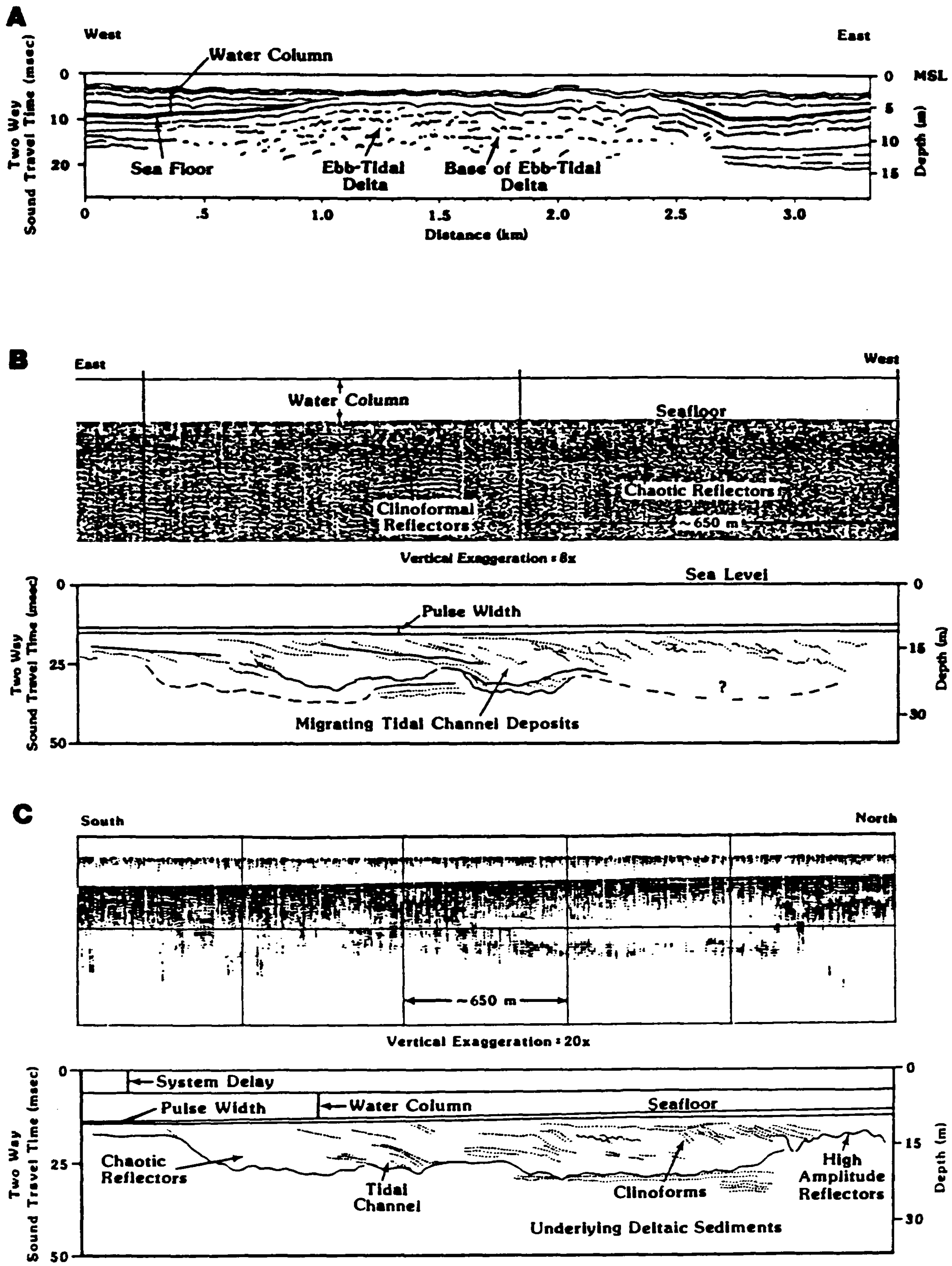

Figure 7. High resolution seismic profiles and interpretative line drawings of the ebb-tidal delta and tidal channel system of Cat Island Pass.

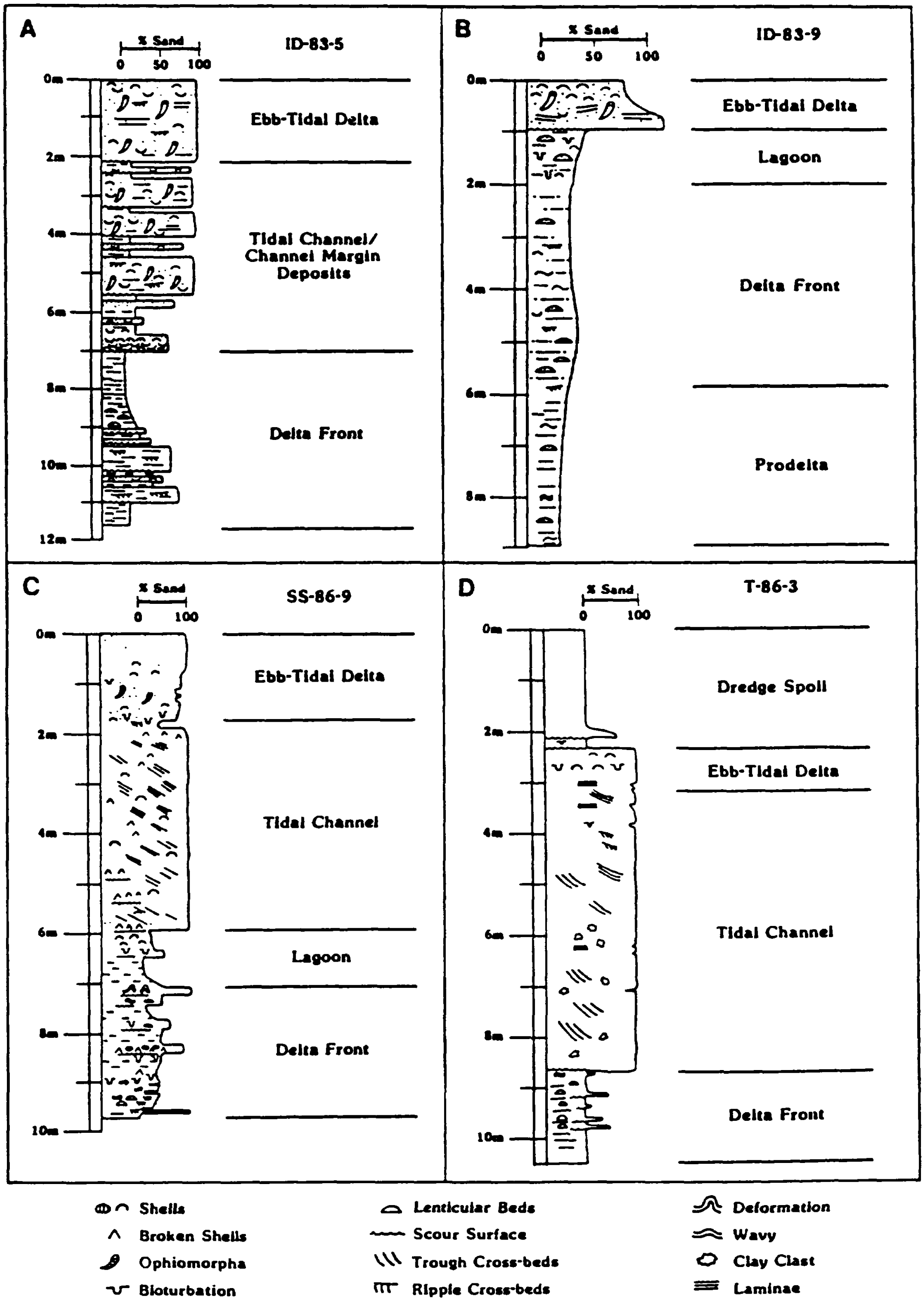

Figure 8. Vibracores through the Cat Island Pass tidal system. For location, see Figure 3.

covers an area of about 150 km^2 with a volume of approximately 640,000,000 m^3, assuming an average thickness of 4 m. This compares favorably with the amounts of sand stored within the Isles Dernieres and Timbalier Island barrier shorelines, which have not yet been fully submerged and truncated by shoreface erosion. Continued transgression of the inlet system will result in the presence of a large tidal channel sand body, overlain by a reworked sand sheet. This is a characteristic of other barrier retreat paths in the Mississippi River delta plain such as the Chandeleur Islands (Penland and Suter 1983; Penland et al. 1985) and possibly Trinity Shoal (Suter et al. 1985). The Cat Island Pass sand body is the largest such tidal channel sand identified offshore of the Mississippi River delta plain. The greater size of this feature is a combination of a number of factors. The inlet drains two interdistributary bays and thus began with a relatively large tidal prism. Appropriate orientation to wave approach caused the migration of the Timbalier Island spit, forcing the migration of the Cat Island Pass, resulting in extensive channel fill sands. Increasing tidal prism due to relative sea level rise and wetland loss resulted in the growth of the inlet and the creation of one of the largest transgressive sand bodies in the Mississippi River delta plain.

SUMMARY AND CONCLUSIONS

Cat Island Pass is an example of a tidal inlet in a microtidal, transgressive setting, which has a morphology more typical of mixed-energy, tide-dominated inlets. This condition is attributed to a process of tidal prism growth resulting from backbarrier landloss due to relative sea level rise. Ebb dominance from increased tidal flow is presumed to be enhanced by increased setup by meteorological tides on the landward margins of the barrier shorelines owing to greater fetch as the backbarrier basins grow.

Two major facies are preserved in the retreat path of Cat Island Pass. Tidal channel fill, characterized by high-angle clinoforms and chaotic reflectors on high resolution seismic profiles, showed a sequence of up to 5 m of trough cross beds of fine sand and shells. The ebb-tidal delta/spit platform deposit, comprising a relatively thin sequence of fine sand and shells, is volumetrically less significant. However, increasing rates of relative sea level rise may lead to the preservation of more of the landward portions of the current ebb-tidal delta.

ACKNOWLEDGMENTS

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TRANSGRESSIVE EVOLUTION OF THE CHANDELEUR ISLANDS, LOUISIANA

John R. Suter[1], Shea Penland[1], S.J. Williams[2] and Jack L. Kindinger[3]

ABSTRACT

Analyses of over 2500 line miles of high resolution seismic profiles, supplemented by vibracores and soil borings, illustrate the evolution of the Chandeleur Islands through transgressive processes associated with the abandonment of the St. Bernard complex of the Mississipi Delta some 1500 years B.P. Historical maps show that the system has been eroding, migrating landsward and losing area for the last 100 years. Hurricane impacts accelerate erosion and segment the islands, followed by limited recovery during fair-weather periods. Relative sea level rise from subsidence and eustatic factors contribute to the loss of island area.

From south to north, the geomorphology of the system varies from small, ephemeral islands and shoals to wide beached, hummocky dune fields, flood-tidal deltas, and washover fans. The last two overlie and interfinger with the lagoonal muds of Chandeleur and Breton Sounds, indicating landward migration, a fact confirmed by landward dipping clinoformal reflectors in seismic sections. The numerous tidal inlets and recurved spits of the Chandeleur Islands have offshore equivalents in the form of buried tidal-inlet scars and truncated spit platforms. Two major distributary zones, probably relating to different delta lobes, occur both landward and offshore of the islands in their southern and central portions. Individual channels within these zones reach 1300 feet in width and 50 feet in depth. Landward of the islands, distributary-associated deposits in the upper few feet of sediment show more complex reflection patterns than their offshore equivalents, resulting from truncation of the latter by shoreface erosion. Adjoining the central distributary system is a zone of high angle, seaward dipping clinoformal reflectors as thick as 20 feet that extends several miles offshore. This deposit, evidence of former progradation, is interpreted as a truncated beach-ridge plain similar to the modern day Cheniere Caminada. Erosional and depositional trends and the distribution of facies within the system clearly demonstrate the ongoing transgressive submergence of the Chandeleur Islands.

INTRODUCTION

The Chandeleur Islands are the oldest and largest barrier island system in the Mississippi River delta plain. The system, which includes the smaller barriers of the Breton Islands, Curlew Island, Grand Gosier Island, as well as the Chandeleurs proper, is more than 45 miles long, and island widths range from 600 feet to about one and one-half miles (Figures 1&2). Historical charts show that the islands have been eroding, migrating landward and losing area for the last 100 years (Penland et al., 1985; Figure 2). Hurricane impacts, such as those of Hurricanes Danny, Elena, and Juan in 1985, accelerate the erosion and segment the islands, followed by limited recovery during fair weather periods. This recovery is not sufficient to maintain the islands and as a result, long term net land loss ensues. Relative sea level rise from both ongoing subsidence and eustatic factors contributes to the loss of island area.

The oblique orientation of the Chandeleur chain to the dominant southeast wave approach leads to the preferential transport of sediment northward. Toward the north, large washover channels and fans separated by hummocky dunefields, with wide beaches, and multiple bars in the surf zone, dominate the geomorphology. Farther south, as island widths narrow and heights decrease, washover channels and fans give way to discontinuous washover terraces. In the southernmost section, the island arc is fragmented into a series of small ephemeral islands and shoals separated by tidal inlets. As the islands evolve, net subaerial area is decreasing and net shoal area is increasing.

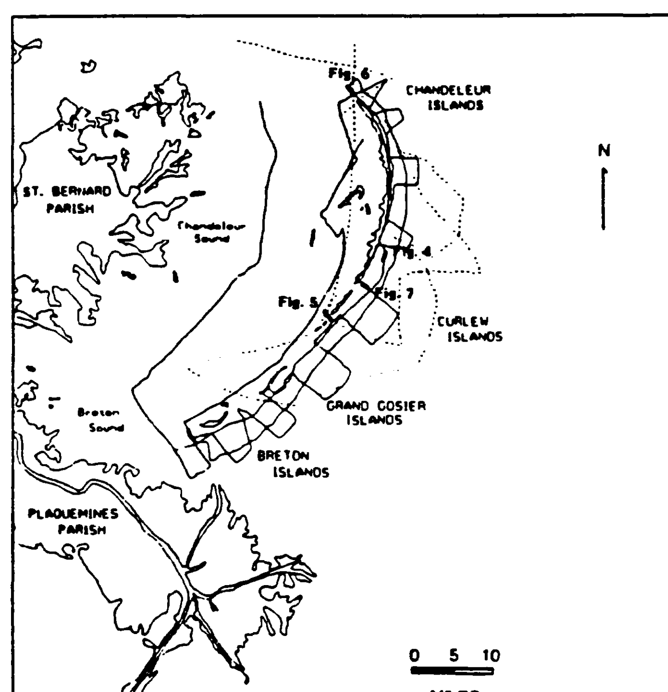

Figure 1. The Chandeleur Island barrier system, located to the northeast of the modern Mississippi Delta, contains the Breton Islands, Grand Gosier Island, Curlew Islands, and the Chandeleurs themselves. Tracklines of high resolution seismic profiles from cruises in 1981 (dashed lines) and 1985 (solid line) are shown, along with locations of figures used in this paper (after Suter and Penland, 1987).

Transgressive barrier systems in the Mississippi River delta plain appear to follow a recognizable evolutionary sequence (Penland and Boyd, 1981; Penland et al., 1981). A key element of this hypothesis lies in the interaction of shoreface retreat (Swift, 1975) and ongoing subsidence.

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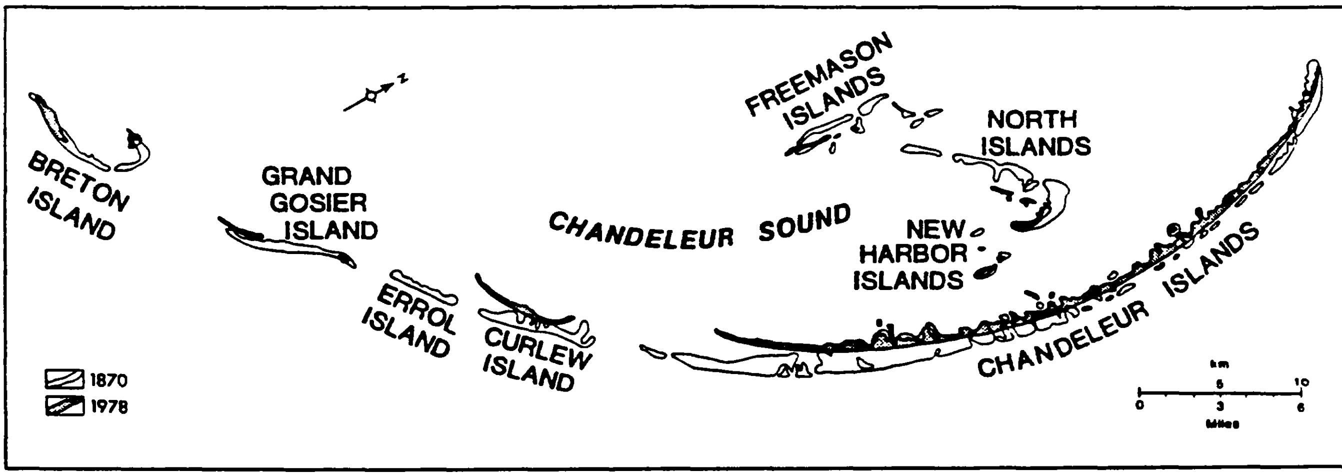

Figure 2. Shoreline changes in the Chandeleur Islands between 1870 and 1978 (from Penland et al. 1985).

Erosion of coarser-grained deltaic deposits provides the sediment source for the formation of coastal barriers. Continuing subsidence and transgression isolate the barrier sand sources on the inner shelf, so that they eventually lie at depths from which they no longer contribute sediment to the subaerial components of the system. Diminishing sediment supply and continuing transgression culminate in the complete submergence of the barriers and the formation of inner-shelf shoals. Penland et al. (in press) used the term "transgressive submergence" to describe this evolutionary model. During transgressive submergence, preservation or destruction of coastal barrier facies and the resulting stratigraphic record is a competition between the depth of shoreface erosion (i.e., wave energy or the depth of the shoreface) and the rate of subsidence. Those sediments which lie above the depth of shoreface erosion, or the ravinement surface, will be eroded away, while those that lie below will be preserved. Penland and Suter (1983) and Penland et al. (1985) reported on some aspects of the transgressive evolution of the Chandeleur Islands. The purpose of this paper is to determine the applicability of transgressive submergence to the Chandeleur Islands in light of more recent seismic information.

DATABASE

The Chandeleur Islands were surveyed using high-resolution seismic-profiling techniques in 1981 and 1985) (Figure 1). Approximately 2500 line miles of profiles, including ORE Geopulse and 3.5-kHz data were collected and analyzed for this paper. The quality of data was quite variable, ranging from poor in the areas near the modern Mississippi Delta to outstanding in the extreme northern end of the island arc. In 1987, an additional 2200 line miles of high-resolution seismic profiles were collected offshore of the Chandeleur Islands and in Chandeleur Sound as part of a cooperative project between the Louisiana Geological Survey and the U.S. Geological Survey. These data, along with 78 forty-foot offshore vibracores and 68 vibracores from the island system itself, also taken in 1987, are currently being analyzed. Preliminary results are expected to be available in late 1988.

STRATIGRAPHY

Earlier studies show that the Chandeleur Islands are retreating landward over the underlying sediments of the abandoned St. Bernard delta (Kolb and van Lopik, 1958; Frazier, 1967; Frazier et al., 1978; Penland and Suter, 1983; Penland et al. (1985). Major distributary headlands, the original sandsources for formation of the Chandeleurs, now lie on the lower shoreface and inner shelf and extend seaward under the thin and discontinuous central and southern Chandeleur Islands (Figure 3). These distributary deposits are up to 50 feet thick and some 1300 feet wide. Shoreface erosion has removed any transgressive sediments that may have once accumulated in this area, so that the distributary channel fills are exposed on the surface of the inner shelf (Figure 4). Landward of the islands, distributary-associated deposits in the upper few feet of sediment show more complex reflection patterns than these offshore features.

In the southern portion of the system, the barrier sand body is some 12 to 15 feet thick. The entire deposit lies above the depth of ravinement (about 20 to 30 feet, Penland and Suter, 1983) and thus has a low preservation potential. The basal portion of truncated distributaries of the St. Bernard delta, and former tidal inlet channels can be seen in seismic profiles. Landward of the islands, flood-tidal delta deposits overlie lagoonal muds that extend seaward under the island and are exposed on the inner shelf in the retreat path (Figure 5).

Northward, the barrier sand body is thicker and more continuous, averaging 15 to 20 feet and reaching over 30 feet in some places. Portions of the deposit in this area lie below the depth of shoreface erosion (about 13 feet, Penland and Suter, 1983) and are preserved on the inner shelf. The thickest deposits occur in the recurved spit at Hewes Point at the extreme northern end of the Chandeleur Islands (Figures 1,6).

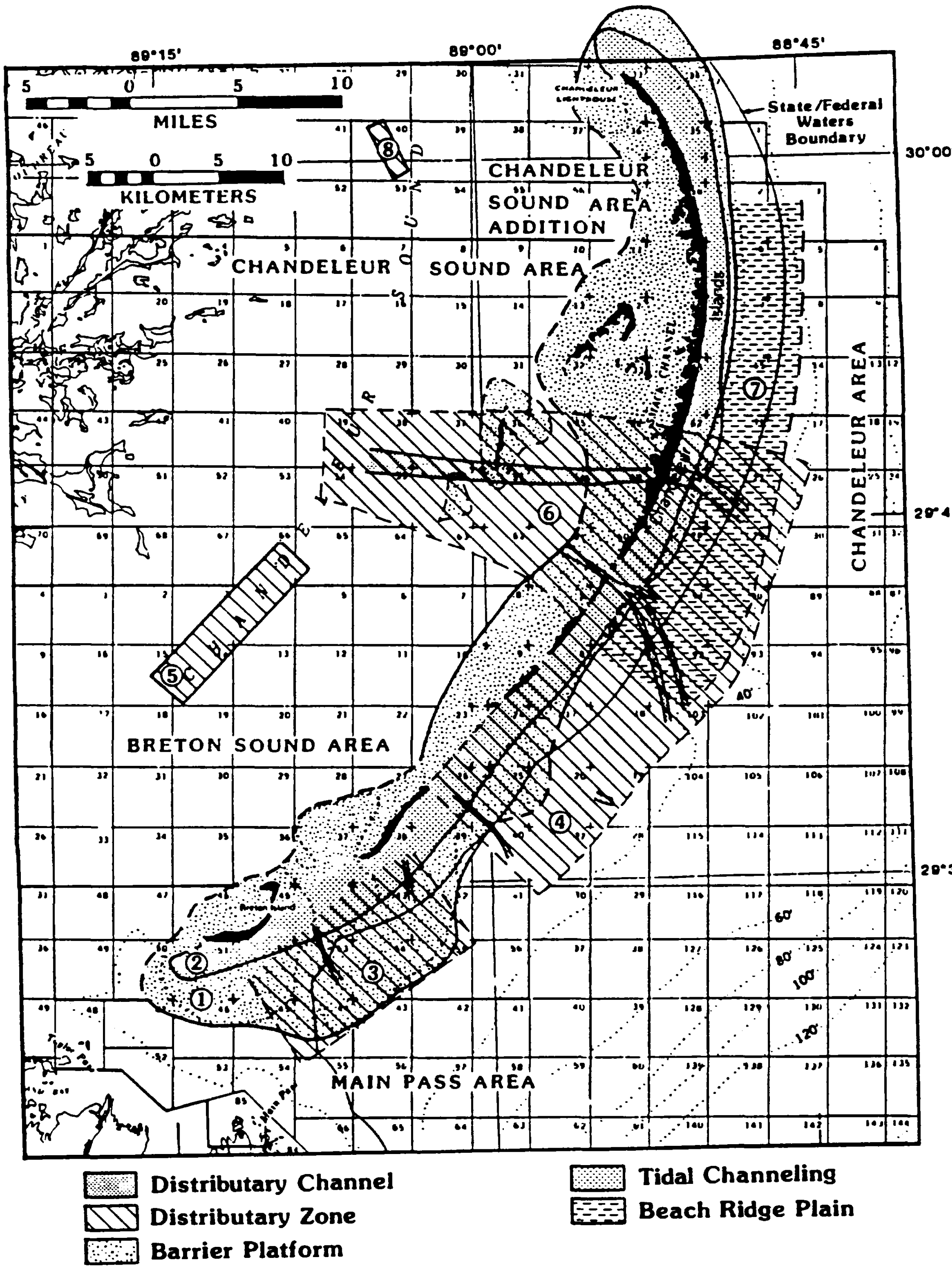

Figure 3. Distribution of nearshore facies within the Chandeleur system as mapped from seismic profiles (from Sutter and Penland, 1987).

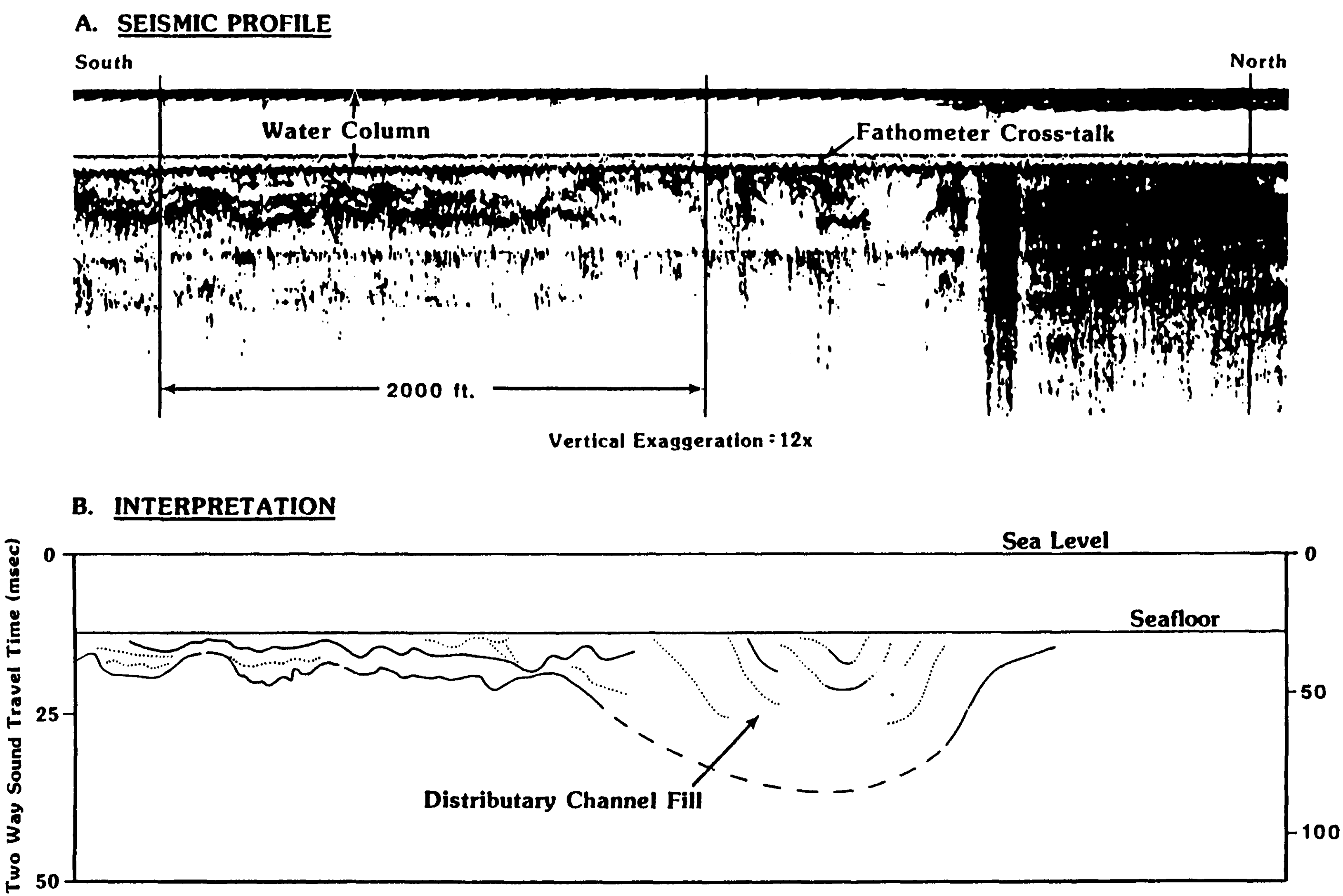

Figure 4. A 3.5-kHz high-resolution seismic profile and interpretative drawing of distributary channel in the Chandeleur Islands area. For location, see Figure 1 (after Suter and Penland, 1987).

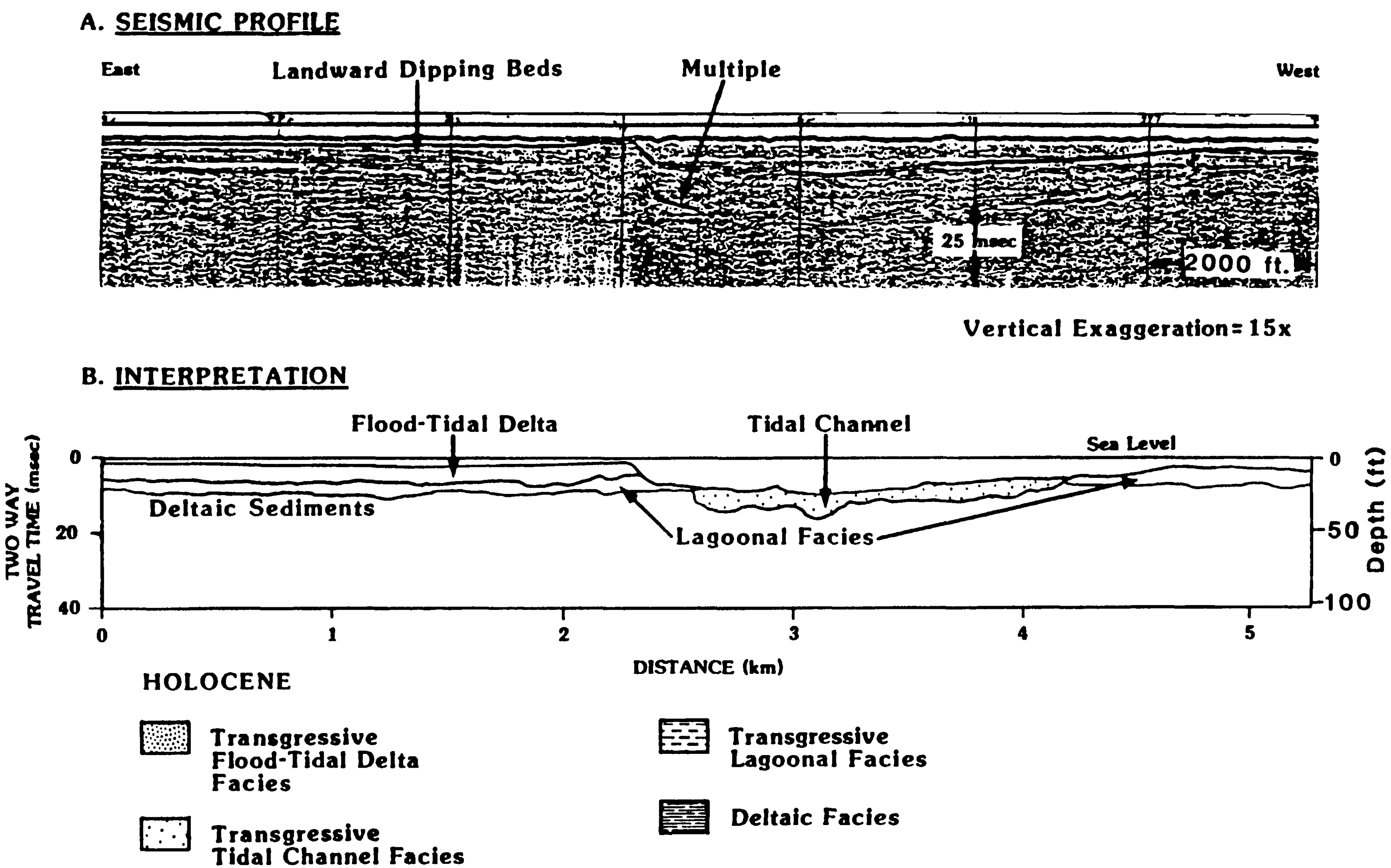

Figure 5. ORE Geopulse high-resolution seismic profile and interpretative drawing of flood tidal delta and tidal deposits of the Chandeleur barrier platform. For location, see Figure 1 (from Suter and Penland, 1987).

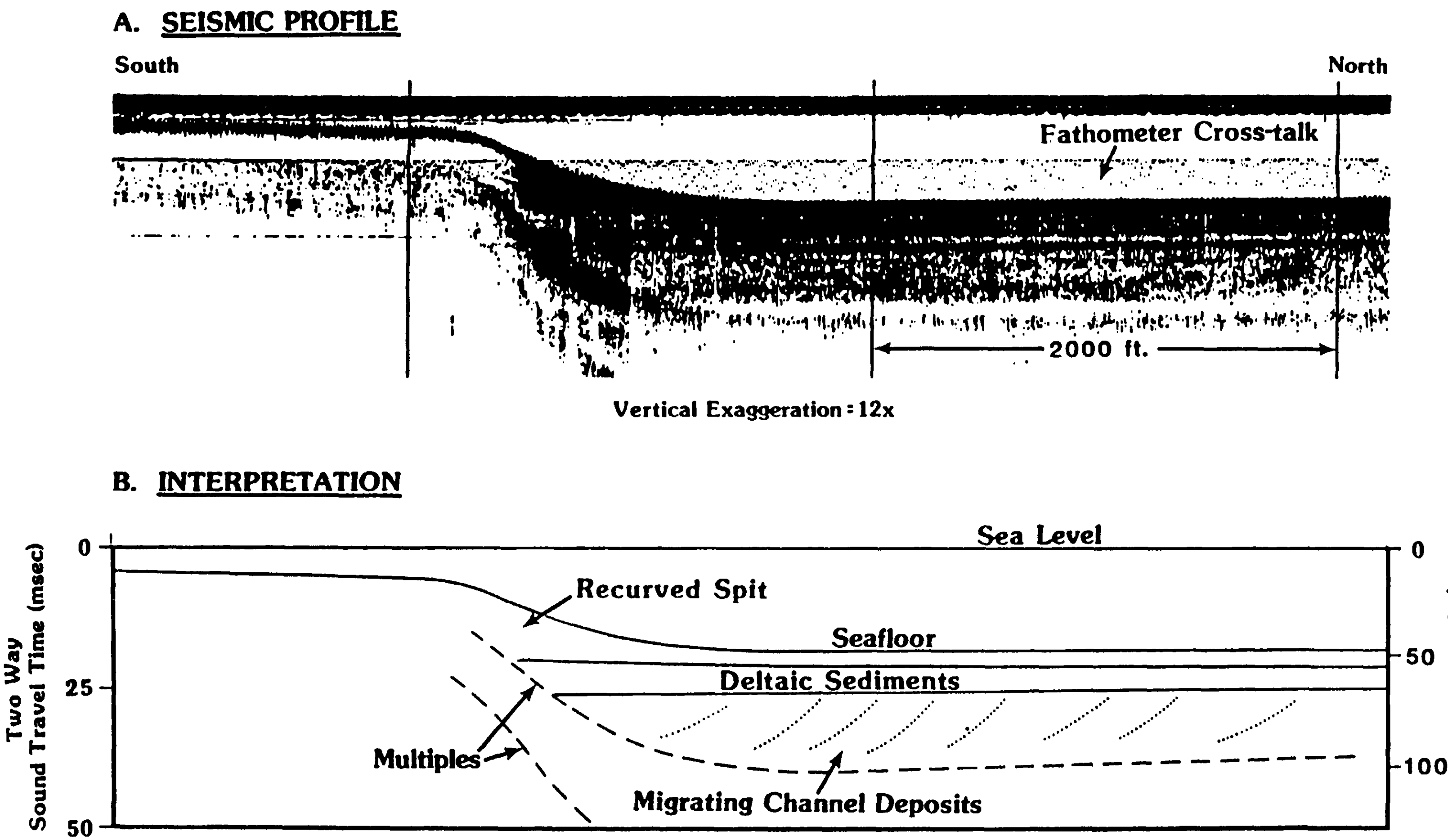

Figure 6. ORE Geopulse high resolution-seismic profile and interpretative drawing of recurved spit deposits off Hewes Point, northern Chandeleur Islands. The spit overlies St. Bernard deltaic sediments, which in turn overlie migrating fluvial/distributary deposits of probable late Pleistocene age. For location, see Figure 1 (after Suter and Penland, 1987).

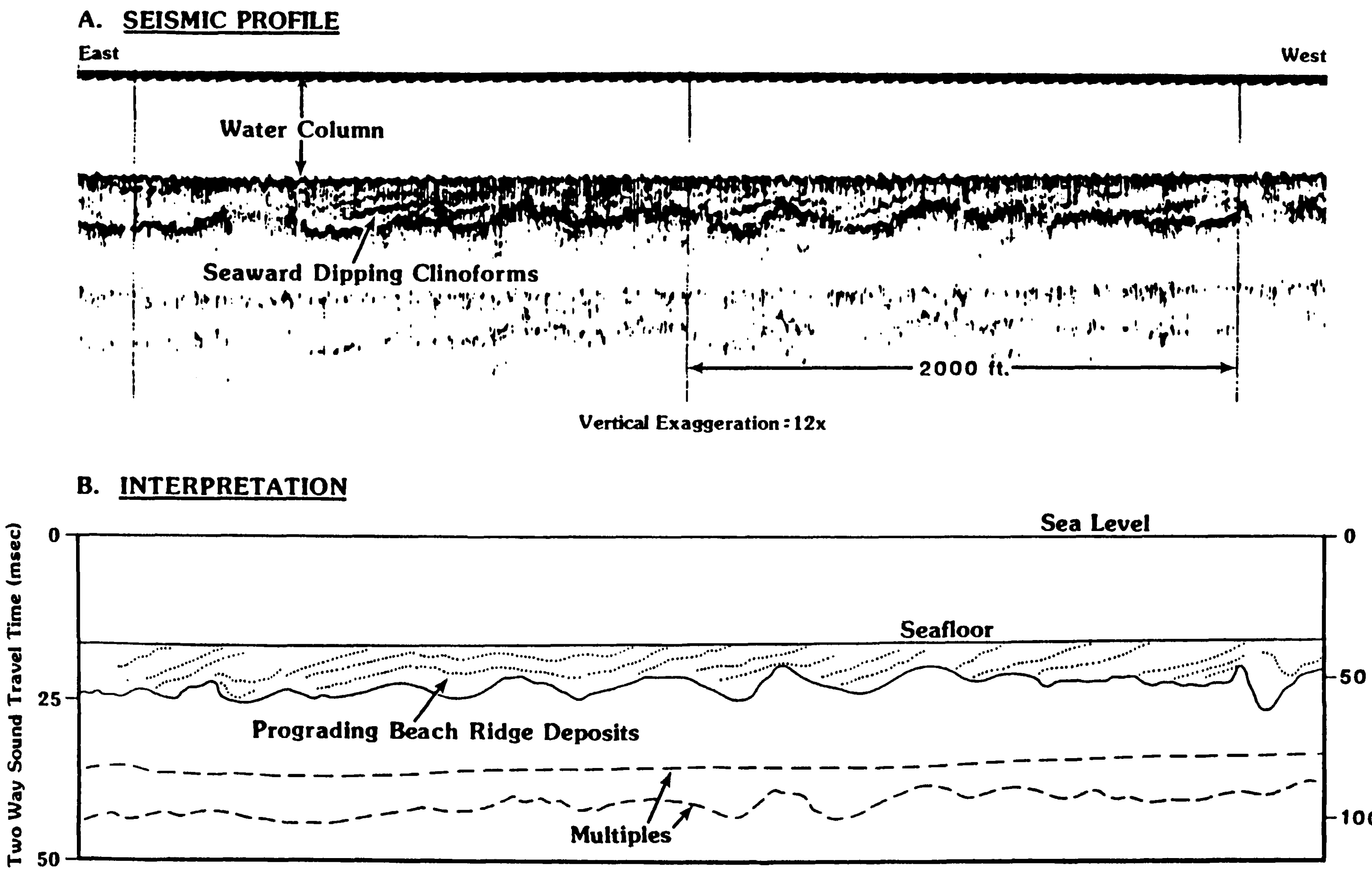

Figure 7. A 3.5-kHz high-resolution seismic profile and interpretative drawing of possible beach ridge plain deposit seaward of the central Chandeleur Islands. For location, see Figure 1 (after Suter and Penland, 1987).

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Most of the island arc shows some indication of tidal channeling in nearshore areas (Figure 3). These ubiquitous features are probably remnants of surge channels cut by hurricanes, which can remain open for some time as ephemeral tidal inlets. The channels reach depths of about 18 feet below the base of the barrier platform itself. Offshore the central island arc, a zone of high angle clinoform reflectors is interpreted as submerged beach-ridge plain deposits (Figure 7). This unit adjoins the major distributaries identified in the area, and is probably analogous to the Cheniere Caminada beach-ridge plain on the Caminada-Moreau headland)Gerdes, 1985). The beach-ridge unit is about 20 feet thick and extends several miles offshore.

SUMMARY AND CONCLUSIONS

Historical maps and modern photography show that the Chandeleur Island system is continuing to undergo net coastal erosion and land loss. Analysis of high resolution seismic profiles has shown the ubiquitous occurrence of submerged barrier and associated facies, including lagoonal, tidal inlet, tidal delta, recurved spit, and beach ridge deposits in the nearshore areas of the system. Major distributary channels in the central Chandeleur extend more than eight miles seaward of the present shoreline. Together these data provide clear evidence of ongoing transgressive submergence. The southern portions of the system appear to be in the incipient stages of conversion to inner-shelf shoals, while the northern islands still maintain their subaerial character. However, ongoing erosion and submergence due to depletion of the barrier sand sources and relative sea level rise will eventually completely submerge the islands.

ACKNOWLEDGMENTS

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A GEOMORPHOLOGIC MODEL FOR MISSISSIPPI DELTA EVOLUTION

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ABSTRACT

The Mississippi River has established six delta complexes in the last 9000 years. Sediments are currently supplied only to two of these complexes, neither of which is more than 500 years old. Deltaic sedimentation during most of the Holocene has occurred in shoal-water deltas unlike the modern Balize lobe which is located at the shelf break. Mississippi delta sedimentation is cyclic and consists of a regressive and a transgressive phase. Each delta complex first experiences progradation until over-extension leads to abandonment and reworking. Mississippi deltas undergoing transgression are dominated by subsidence and marine basin processes leading to the formation of sandy barriers and lagoons.

Each of the six delta complexes followed a common pattern of development after-abandonment. Current delta geomorphology reflects the variation in age of each delta complex and can be summarized in a three stage model beginning with Stage 1, Erosional Headland and Flanking Barriers. Here, distributary sands are reworked by the retreating shoreface and dispersed laterally by longshore transport into flanking barriers which enclose interdistributary bays. In Stage 2, Transgressive Barrier Island Arc, submergence of the erosional headland generates an intradeltaic lagoon which separates the barrier island arc from the retreating mainland. The model ends with Stage 3, Inner Shelf Shoals, where the retreating barrier island arc is unable to keep pace with relative sea level rise or the more rapidly retreating mainland. This results in submergence of the barrier island arc, which continues to be reworked as a sandy shoal on the inner continental shelf. This model of delta evolution illustrates mechanisms for generation of both barrier islands (in Stages 1 and 2) and continental shelf sand bodies (in Stage 3).

INTRODUCTION

The Holocene Mississippi River delta plain is located in southeast Louisiana and occupies 300 miles (500 km) of coastline on the northern Gulf of Mexico (Fig. 1). Sediment is currently supplied to only two active delta complexes within the delta plain, the Modern and the Atchafalaya (Fig. 2). Sandy barriers and lagoons occupy the remaining 220 miles (350 km) of transgressive delta plain coastline.

Many classic studies, (e.g. Kolb and van Lopik, 1958; Fisk, 1955, 1961; Coleman and Gagliano, 1964; Frazier, 1967) have focused on the regressive phase of Mississippi delta sedimentation. However, for the corresponding transgressive component no comprehensive description or model currently exists. The primary objective of our study is to develop a geomorphologic model describing the genesis, evolution, and characteristics of Mississippi delta complexes undergoing transgression. A second objective is to examine the implications of this model for concepts of shoreline and shelf evolution.

Relative sea level (RSL) in the Gulf of Mexico is inferred to have risen from depths of -425 ft (130 m), 15000 yr BP (before present), Curray, 1960) to around -30 ft (9m) by 8000 yr BP. A subsequent rate of RSL rise around eight inches (20 cm) per century then occurred until eustatic sea level reached its present position around 3600 yr BP (Coleman and Smith, 1964). Since this time RSL along the Mississippi Delta coastline has continued to rise, mainly in response to submergence of the land surface. Subsidence is primarily caused by the compaction and dewatering of deltaic deposits and varies as a function of sediment thickness and age (Morgan and Larimore, 1957). Present rates range from three inches (7.5 cm) per century for old shallow-water delta complexes (Coleman and Smith, 1964), to 24 inches (60 cm) per century for intermediate age deltas, to 240 inches (600 cm) per century for the presently active deepwater Balize Delta (Kolb and Van Lopik, 1958).

The northern Gulf of Mexico is a storm-dominated environment experiencing relatively low energy levels resulting from wind and wave processes, except for the winter passage of cold fronts and the summer occurrence of hurricanes and tropical storms. Tides in the region are mixed and predominantly diurnal with a microtidal range of 12 inches (30 cm).

The depositional history (delta cycle-Scruton, 1960) of each Holocene Mississippi delta complex starts with the progradational phase in which the Mississippi River deposits its sediment load into the Gulf of Mexico. Longterm delta lobe progradation leads to overextension of the distributary network, a decrease in hydraulic efficiency, followed by upstream distributary diversion. The channel switches to a shorter, more efficient course with a steeper gradient and generates a new delta complex. Upstream diversion results in the transformation of the older, regressive delta complex into the transgressive phase of the delta cycle. Flow through the abandoned distributary does not transport sufficient quantities of sediment to maintain the delta surface against the effects of subsidence. Marine processes erode and rework the seaward periphery of the abandoned delta complex and concentrate the sand-sized sediments into transgressive barrier shorelines (Kwon 1969). Although the abandoned deltas no longer receive fluvial input, they contiñue to evolve and accumulate transgressive sedimentary sequences. As is the case with the Atchafalaya and Teche complexes, abandoned deltas may later be occupied by a new regressive phase of sedimentation. When this occurs, Mississippi River sedimentation has completed a full cycle of regression, abandonment, transgression and reoccupation. During the Holocene the Mississippi River has built at least six delta complexes (Frazier, 1967). It has abandoned four (Maringouin, Teche, St. Bernard, Lafourche) and continues to supply two (Plaquemines/Modern and Atchafalaya).

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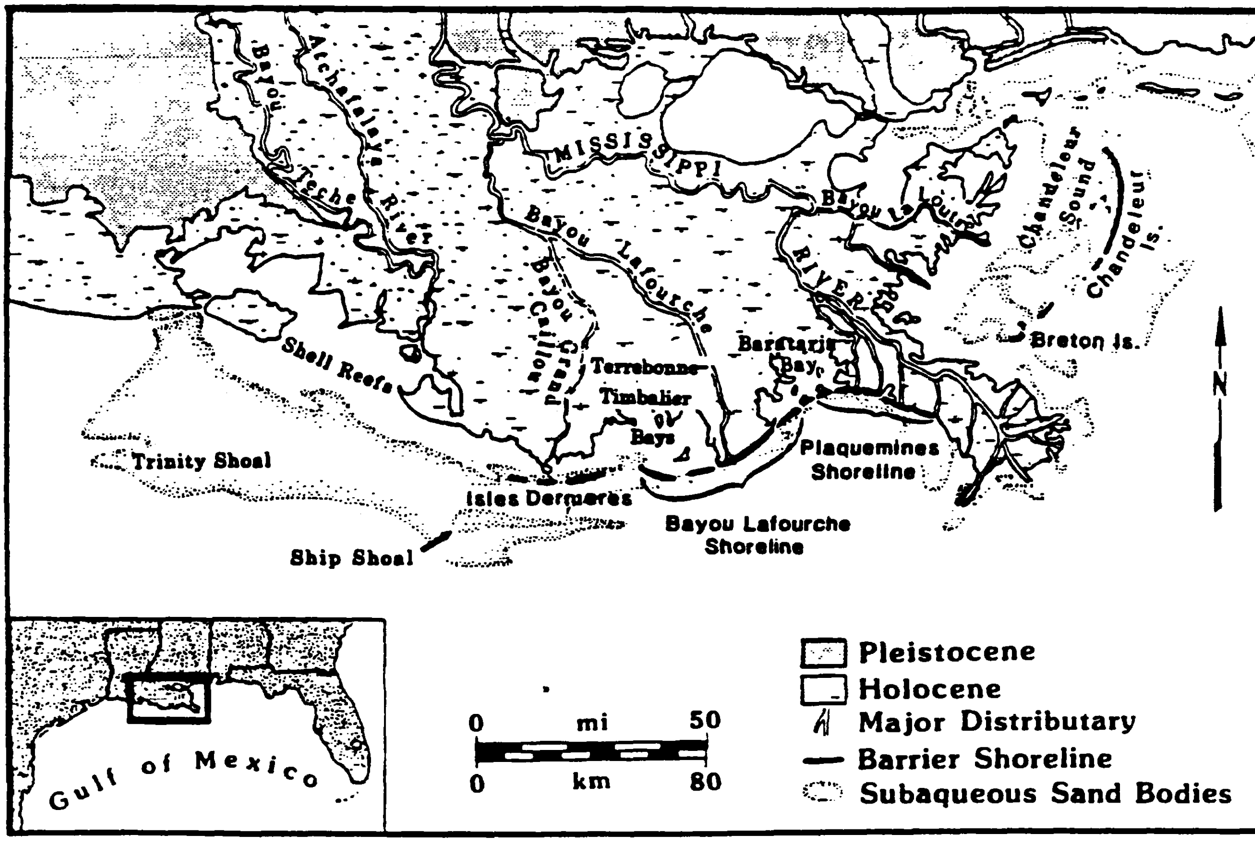


Figure 1. Location of the Mississippi river delta plain. Transgression of abandoned delta complexes creates coastal systems fronted by barrier shorelines and subaqueous sand bodies. Transgressive coastal systems cover the majority of the delta plain shoreline.

A MODEL FOR THE TRANSGRESSIVE PHASE OF MISSISSIPPI DELTA EVOLUTION

General Model

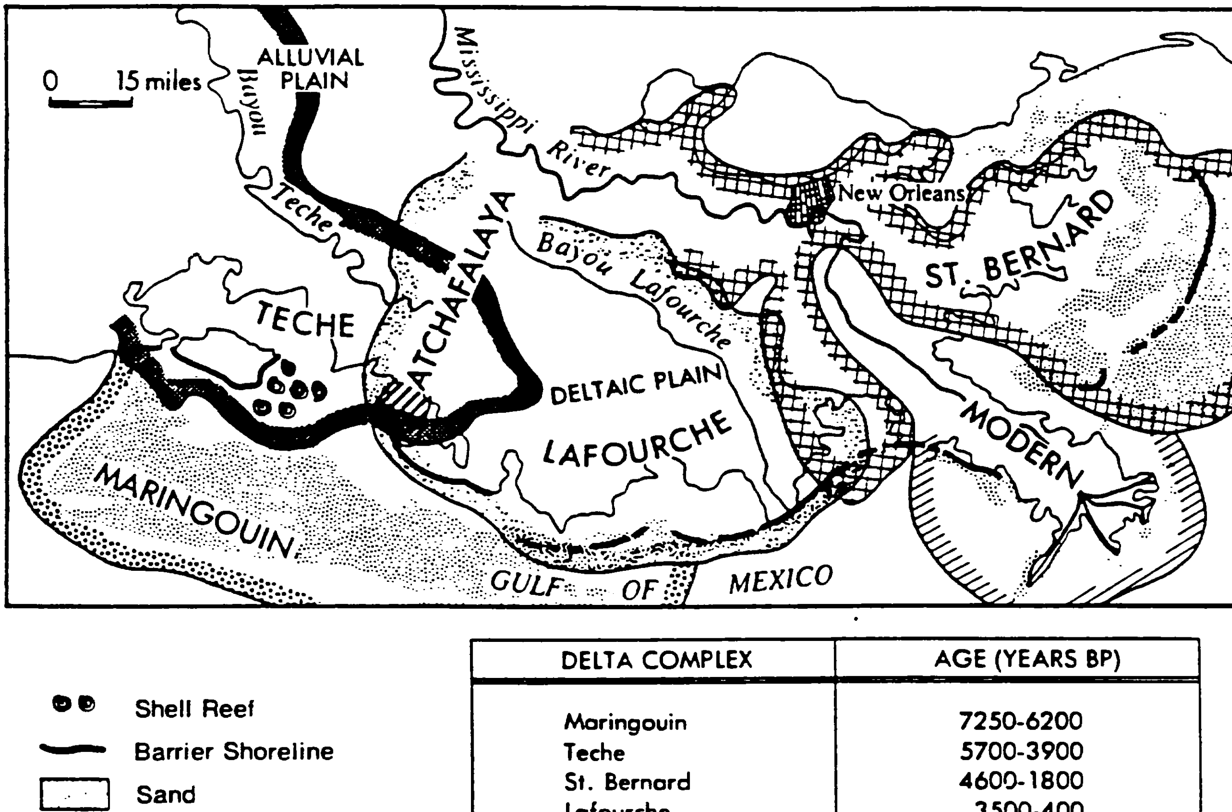
Each abandoned Mississippi delta complex evolved in a well established temporal sequence (Frazier, 1967). Following abandonment, each delta complex was reworked into a transgressive coastal system. Therefore, each resulting transgressive coastal system also exists in an evolutionary sequence. Its position in that sequence is determined by the age of the delta complex from which it was derived (Fig. 2). The genesis and evolution of Mississippi deltas during transgression can be summarized (Fig. 3) in a three stage model. The model sequence begins with STAGE 1 - Erosional headland and flanking barriers. Here regressive deltaic sand deposits are reworked by the retreating shoreface and dispersed laterally by longshore transport into contiguous flanking barriers. Next comes STAGE 2 - Transgressive barrier island arc. Submergence of the erosional headland generates an intra-deltaic lagoon separating the barrier island arc from the retreating mainland. The sequence ends with STAGE 3 - Inner shelf shoals. The retreating barrier island arc is unable to keep pace with RSL rise or the retreating mainland and subsides below sea level. Following submergence the barrier island arc continues to be reworked as a sandy shoal on the inner continental shelf.

Stage 1 - Erosional Headland and Flanking Barriers

Two Stage 1 coastlines are currently found on the Mississippi delta plain, the first derived from the Lafourche delta complex (Late Lafourche delta) and the second from the Plaquemines-Modern delta complex. The Stage 1 coastline is composed of four basic components: 1) erosional deltaic headland, 2) flanking barrier spits and islands, 3) tidal inlets and 4) restricted interdistributary bays (Fig. 3).

Late Lafourche Coastline

The Late Lafourche coastline consists of the erosional headland of Bayou Lafaourche fronted by the Caminada-Moreau coast and two nearly symmetrical sets of flanking barriers; Caminada Pass Spit and Grand Isle to the east and the Timbalier Islands to the west (Fig. 4). Fifty-two percent of the Late Lafourche delta shoreline is composed of a low barrier beach in the form of a thin continuous washover sheet approximately 40 inches (1 m) above mean sea level (Boyd and Penland, 1981). Salt marsh has replaced freshwater marsh and is accumulating landward of the beach and also crops out in the surf zone seaward of the beach, indicating a negative sediment budget and rapid retreat. The eastern half of the erosional headland (Fig. 5) consists of a beach ridge plain (Ritchie, 1972;



DELTA COMPLEX	AGE (YEARS BP)
Maringouin	7250-6200
Teche	5700-3900
St. Bernard	4600-1800
Lafourche	3500-400
Modern	Active
Atchafalaya	Active

Figure 2. The Holocene Mississippi delta plain is composed of six major delta complexes which evolved over the past 7000 years. Each of the four abandoned delta complexes has an associated transgressive coastal system (see Figure 1) whose age and characteristics are determined by the delta complex from which they were derived.

Gerdes, 1985) composed of sediments probably derived from the earlier Bayou Blue erosional headland further east. Shoreface retreat is actively occurring along the Caminada-Moreau coast reworking the distributary sand bodies of Bayou Lafourche and Bayou Moreau and the beach ridge plain of Cheniere Caminada. The dominant wave approach direction to the Caminada-Moreau coast is from the southeast. This, together with the convex shoreline, produces a longshore sediment transport divergence from the central erosional headland. Moving away from the central erosional headland, increasing downdrift sediment abundance leads to the development of small washover fans and low, hummocky dune fields which eventually coalesce further downdrift to form a higher, more continuous washover terrace, and eventually, a foredune ridge (Ritchie and Penland, 1985). Downdrift flanking barrier islands migrate laterally, in the direction of longshore sediment transport, by erosion at the updrift ends and accretion downdrift. Washover sheets and multiple shallow breaches are common on the updrift or erosional ends of these islands. Downdrift, longshore bars become more prominently developed in the nearshore zone and, toward the end of the system, bars become attached. In these downdrift zones, lateral building of recurved spits is taking place. Recurved spit morphology formed during the growth of both Timbalier Island and Grande Isle indicates the importance of an updrift sand source in the Late Lafourche erosional headland. In the erosional headland and flanking barrier stage, the greatest shoreline erosion occurs within the erosional headland itself (33-65ft/yr or 10-20m/yr on the Caminada Moreau coast) and on the updrift ends of the flanking barrier islands. Maximum accretion rates of 33-65ft/yr (10-20m/yr) are found on the downdrift ends of the Timbalier Islands-Grand Isle flanking barriers.

During regressive deltaic sedimentation active delta complexes are separated by interdistributary bays. Following delta abandonment, sand moving alongshore from the erosional headland source into flanking barriers builds across the mouth of the interdistributary bays. Bay volume and hence potential tidal prism is continually increasing in response to delta plain subsidence and land loss, creating an environment suitable for tidal inlet generation. Tidel inlets are formed during storm events and especially during hurricanes when elongated flanking barrier spits are breached by overwash processes. The increasing tidal prism of the interdistributary bay is then sufficient to maintain permanent fluid exchange through the barrier resulting in the production of flood and ebb tidal deltas (Howard, 1985). The result of flanking barrier island growth and tidal inlet generation is to produce a restricted interdistributary bay with intermediate salinities. This environment accumulates bioturbated muds often accompanied by prolific oyster reef growth (Coleman and Gagliano, 1964; Van Sickle et al., 1976). Current examples of restricted interdistributary bays on the Late Lafourche coastline are Barataria Bay and Timbalier Bay (Fig. 1).

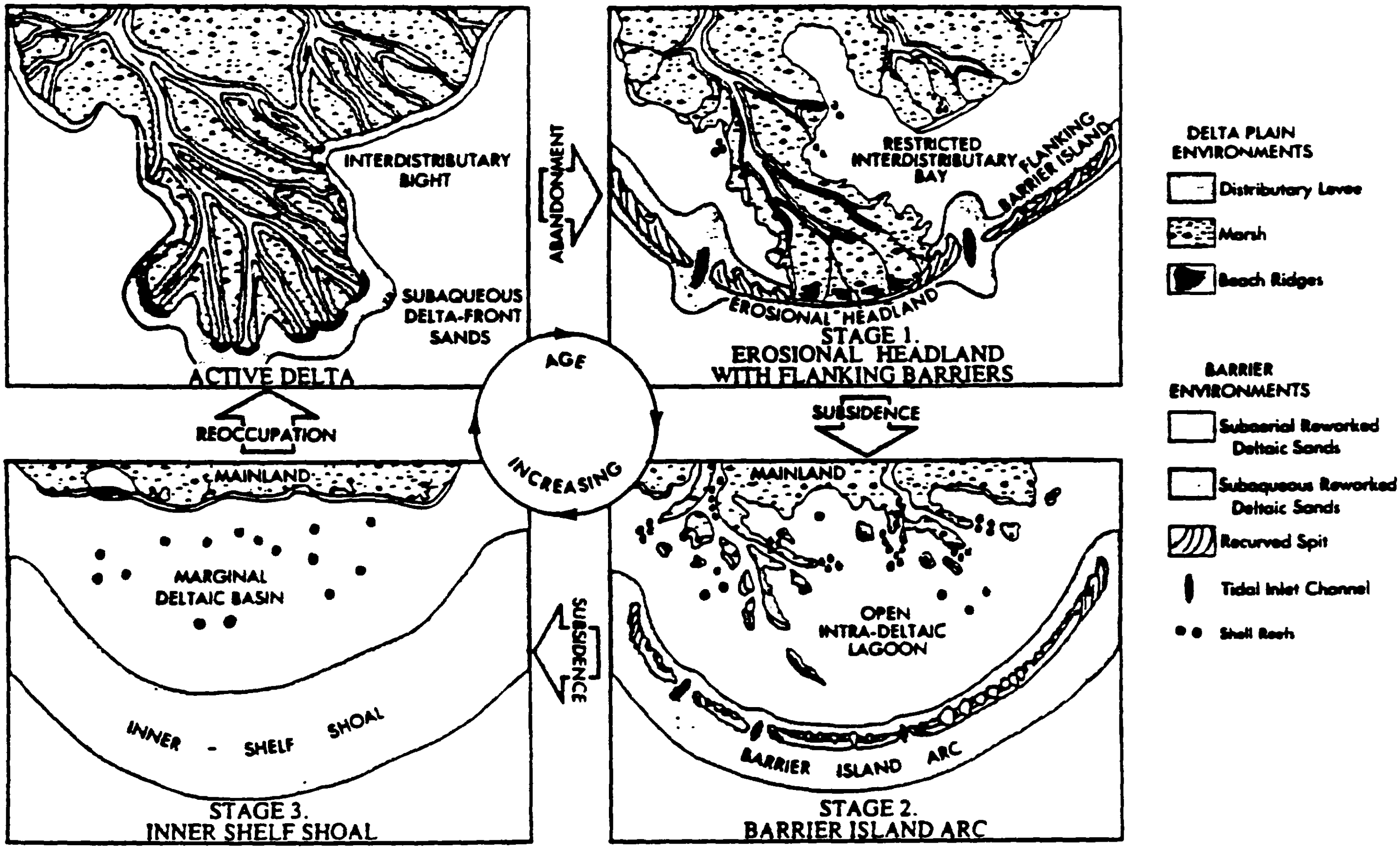


Figure 3. The genesis and evolution of Mississippi deltas following abandonment can be summarized in a three stage model. The geomorphology in each stage is primarily a result of increasing age since abandonment acting together with subsidence and marine reworking.

Plaquemines Coastline

The Plaquemines delta was actively receiving river-borne clastics between approximately 905 and 350 yr BP and prograded southeastward, building a delta between Barataria Bay and Sandy Point (Fig. 6). As Bayous Grand Cheniere and Robinson built seaward, they intercepted sediment moving from the eroding Bayou Blue headland of the Lafourche delta complex forming the westward-flaring Cheniere Ronquille beach ridge plain. The remainder of the Plaquemines lobe prograded from Grand, Long and Dry Cypress Bayous, with each accumulating minor beach ridges in the regressive phase.

Following abandonment the distributary mouth bars and beach ridges of the Plaquemines delta were transformed into numerous small erosional headland sand sources. Sediments derived from the Robinson Bayou headland were transported predominantly westward into the Grand Terre and Chaland Pass flanking barriers. The Bayou Grand erosional headland supplied the Bay Joe Wise spit (west) and Bastian Island (east) flanking barriers while the Bayou Long-Dry Cypress Bayou headland supplied the Shell Island (west) and Sandy Point (east) flanking barriers.

Plaquemines delta transgression is influenced by a sand deficiency and low wave energy resulting from a sheltering effect provided by he Balize delta. As a result, shoreline erosion patterns do not reflect a single coalesced Stage 1 headland as in exposed locations, but a series of small individual headlands experiencing high erosion rates about 49 ft/yr (15 m/yr) with intervening flanking barriers eroding at slower rates between 16 and 49 ft/yr (5-15 m/yr).

Stage 2 - Transgressive Barrier Island Arcs

There are two major Stage 2 barrier island arcs on the Mississippi deltaic coastline, the Isles Dernieres derived from the Lafourche delta complex (Early Lafourche delta) and the Chandeleur Islands derived from the St. Bernard delta complex.

Early Lafourche Coastline

The Early Lafourche delta originated from Caillou headland distributaries, and was abandoned 600-800 years B.P. (Fig. 1). The resulting Isles Dernieres transgressive barrier island arc encloses Caillou and Terrebonne Bays and Lake Pelto (Fig. 7). Coastal changes observed between 1853 and 1978 on the Early Lafourche coastline illustrate the barrier shoreline transition from Stage 1 to Stage 2 (Fig. 8). In 1853, Pelto and Big Pelto Bays separated the Caillou headland and flanking barriers from the mainland by a narrow tidal channel less than 1600 ft (500 m) wide. by 1978, these bays had increased in size threefold and coalesced to form Lake Pelto. The Isles Dernieres were located 4.4 miles (7 km) offshore from the retreating mainland. During this time, the Gulf shoreline of the Caillou headland

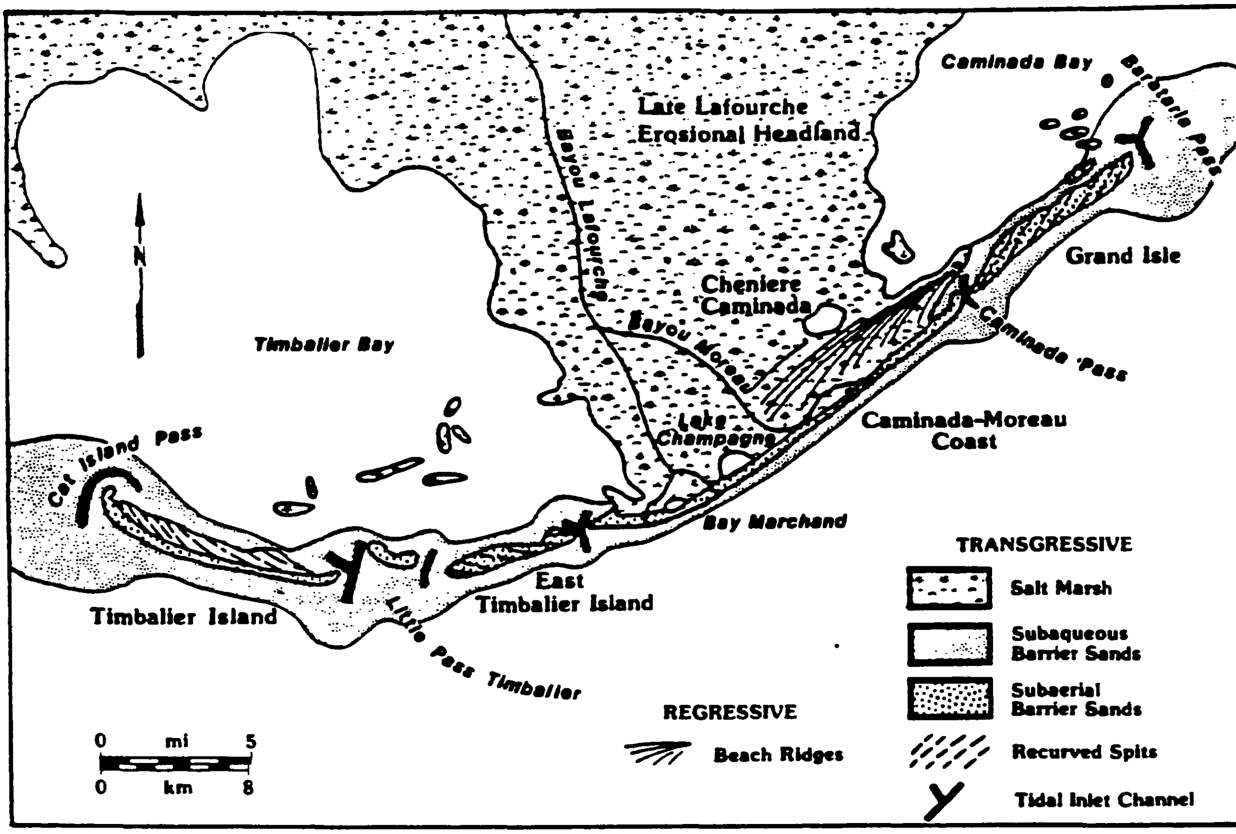


Figure 4. The Late Lafourche coastline consists of: 1) the Lafourche headland containing Cheniere Caminada, 2) the flanking barriers of Caminada Pass spit and Grand Isle (east) and the Timbalier Islands (west), and 3) the restricted interdistributary bays of Caminada Bay and Timbalier Bay.

had also retreated landward over 0.6 miles (1 km) and segmented to form the five small islands of the Isles Dernieres transgressive arc. This arc presently consists of two central islands cored by delta plain remnants and Cheniere Caillou beach ridges fronted by a thin beach consisting of alternating sheet washovers and small dune fields (Penland et al., 1985a). Low elevations between delta plain remnants are preferentially chosen as overwash sites transferring shoreline sediment to back-barrier locations, initiating future tidal inlets and eventually further fragmenting the islands (Fig. 9). Storm impacts combined with the increasing tidal prism of Lake Pelto and Terrebonne Bay have led to the development of Whiskey Pass, Wine Island Pass, Coupe Colin, and Coupe Carmen since 1850. Inlet morphology varies between wave-dominated, mixed energy and tide-dominated depending upon tidal prism-sediment transport relationships.

Shoreline erosion patterns indicate that the highest erosion rates within the Isles Dernieres occur along the central portion of the island arc where erosion rates in excess of 49 ft/yr (15 m/yr) are common (Penland and Boyd, 1981). Downdrift, both east and west of the central island arc, erosion rates decrease to approximately 16 ft/yr (5 m/yr). The island area of the Isle Dernieres diminished from 13.4 square miles (34.8 km^2) in 1887 to 3.9 square miles (10.2 km^2) in 1979 and the islands may disappear within 50 years.

St. Bernard Coastline

The St. Bernard coastline consists of the Chandeleur transgressive barrier island arc and the Chandeleur Sound intradeltaic lagoon (Fig. 10). This transgressive coastline represents a more advanced Stage 2 evolution than the Early Lafourche delta, reflecting the longer time interval of approximately 1800 years since abandonment of the St. Bernard delta complex. The St. Bernard deltaic plain lies at a depth of 23-29 ft (7-12 m) below present sea level beneath the Chandeleur Islands and Chandeleur Sound (Frazier, 1974; Shepard and Lankford, 1959; Penland et al., 1985a). Chandeleur Sound, an intradeltaic lagoon more than 19 miles (30 km) wide currently separates the Chandeleur Islands from the retreating mainland. The Chandeleur barrier island arc displays a longshore progression from fragmented barrier in the south, through a thin washover sheet fronting a marsh platform to a series of 7-16 ft (2-5 m) high dune fields in the north, incised by waashover channels and backed by extensive washover fans. This assymmetry in sediment abundance reflects the north-south alignment of the barrier island arc in relation to the dominant southeast direction of wave approach. Moving northward along the Chandeleur Islands, beach width, dune height, number of nearshore bars and width of the nearshore zone all increase, reflecting the corresponding northward increase in sediment abundance. Along the southern part of the Chandeleur Islands, erosion exceeds 49 ft/yr (15 m/yr) and is characterized by periodic hurricane destruction followed by partial island rebuilding. Northward along the islands, erosion rates decrease from 49 ft/yr to around 16 ft/yr (15 m/yr to 5 m/yr) at the northern end. The landward retreat path of the barrier island arc is delineated offshore by the presence of a transgressive sand sheet which extends seaward of the southern Chandeleur Islands for over 12 miles (20 km) (Fig. 10).

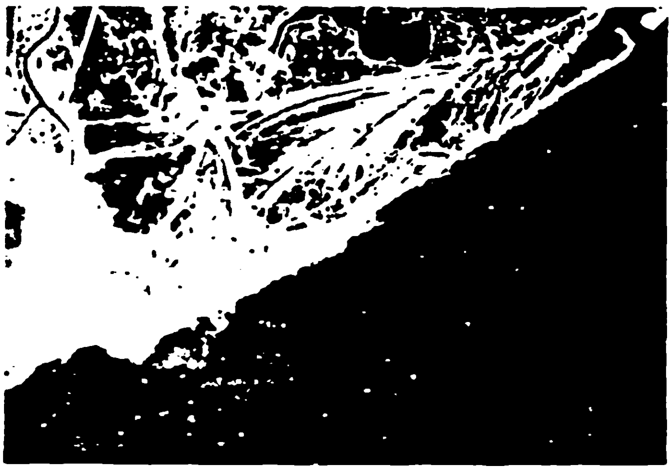


Figure 5. A high altitude aerial photograph of the subsiding Late Lafourche erosional headland shows the distributaries of Bayou Lafourche and Bayou Moreau (left-center), the beach ridge plain of Cheniere Caminada (right-center) and the flanking barriers of Caminada Pass spit and Grand Isle (far right). Dark colored areas on the headland are open water bodies forming and coalescing under the control of 50 cm/century subsidence rates. Photograph width is approximately 12 miles (20 km).

Although overwash processes are active along the Chandeleur Islands, the resultant breaches are wave-dominated and quickly heal from sediment supplied by longshore transport. This reflects the offshore location of the barrier island arc and the ability for tidal exchange around the northern margin of the Island (Hart, 1975). The contiguous length of the Chandeleur Islands proper, therefore, do not presently contain any permanent tidal inlets. However, Penland et al. (1985a) found evidence for older tidal inlets located on the shoreface 2.5 miles (4 km) seaward of the present barrier shoreline, indicating a Stage 2 configuration earlier in the transgressive history of the Chandeleur Island barrier island arc. The 1800 years since delta complex abandonment has allowed Chandeleur-Breton Sound to attain maximum water depths of 26 ft (8 m). This environment is currently accumulating fine-grained bioturbated muds (Kolb and van Lopik, 1958) and extensive *Crassostrea* sp. shell reef deposits (Coleman and Gagliano, 1964).

Stage 3 - Inner Shelf Shoals

Inner-shelf shoals develop from the transgression and submergence of barrier island arcs. Shoal morphology can be divided into five basic components: 1) shoreface, 2) back shoal, 3) shoal, 4) platform and 5) ramp (Penland et al., 1985b). Two major subaqueous shoals are found on the Louisiana inner continental shelf, Trinity Shoal and Ship Shoal.

Trinity Shoal

Trinity Shoal is the westernmost inner-shelf shoal offshore of south-central Louisiana (Fig. 1). Located 25 miles (40 km) offshore of Cheniere au Tigre and Marsh Island, Trinity Shoal is a shore-parallel lunate shoal 19 miles (30 km) long, and 3-6 miles (5-10 km) wide. This shoal occurs in 23-33 ft (7-10 m) of water and has an inner-shelf shoal relief of 7-13 ft (2-4 m). Trinity Shoal appears to retreat landward by erosion of the seaward shoal ramp and deposition on the back shoal. Rates of shoal retreat between 1887 and 1932 are less than 33 ft (10 m) per year.

Ship Shoal

Ship Shoal is the largest and most prominent inner-shelf feature offshore of Louisiana (Figs. 1,11). Approximately 30 miles (50 km) long, widths along Ship Shoal range from 3-4 miles (5-7 km) in the central area of the shoal and increase to 5-7 miles (8-12 km) at the east and west ends. Relief varies from 21 ft (6.4 m) to 16 ft (4.9 m) between the western and eastern portions of Ship Shoal. Water depths over the shoal crest range from 26 ft (7.9 m) in the east to 9 ft (2.7 m) in the west. On the inner shelf in water depth less than 33 ft (10 m), the landward-oriented asymmetry of Ship Shoal indicates that it is migrating onshore towards the north-northwest. Analysis of repetitive hydrographic surveys show that Ship Shoal has migrated 1.2 miles (2 km) from a more seaward location to its present position on the inner shelf at a rate of 33 ft/yr (10 m/yr) since 1853. Early nautical surveys from the 1700s and 1800s show Ship Shoal with a small circular island located at its western end. This small, ephermal islet has not been reported subaerial since 1816. Between 50-100 percent of surficial sediments on both Ship and Trinity Shoal are composed of very fine sand with secondary shell and organic components (Krawiec, 1966, Frazier, 1974). These sediments are texturally similar to shoreline barrier sands such as the Isles Dernieres but contrast markedly with the surrounding shelf muds.

DISCUSSION

Barrier Island Formation

The mechanisms controlling barrier island formation have been a subject for debate since the early nineteenth century (Schwartz, 1973). The available hypotheses consist of bar emergence (deBeaumont, 1845), longshore spit progradation and subsequent breaching (Gilbert, 1885), coastal submergence (McGee, 1890; Zenkovitch, 1962; Hoyt, 1967) and multiple causality (Schwartz, 1971). The well-defined evolutionary sequence of Mississippi delta coastlines includes direct evidence of barrier shoreline genesis and displays all the major mechanisms proposed for barrier island formation. In Stage 1 Erosional Headland and Flanking Barriers, Gilbert's (1885) concept of longshore spit building and subsequent breaching is the dominant mode of barrier island genesis. Evolution from Stage 1 to Stage 2 clearly demonstrates Hoyt's (1967) concept of barrier island formation by mainland detachment through coastal submergence.

Coastal and Continental Shelf Evolution

Recent debate has focused on the relative merits of erosional shoreface retreat and in-place drowning to describe barrier shoreline transgression and its resulting stratigraphy (Sanders and Kumar, 1975; Rampino and Sanders, 1980; Swift and Moslow, 1982). Stage 2 Chandeleur and Isles Dernieres barrier island arcs and Stage 3 Trinity and Ship Shoals illustrate a

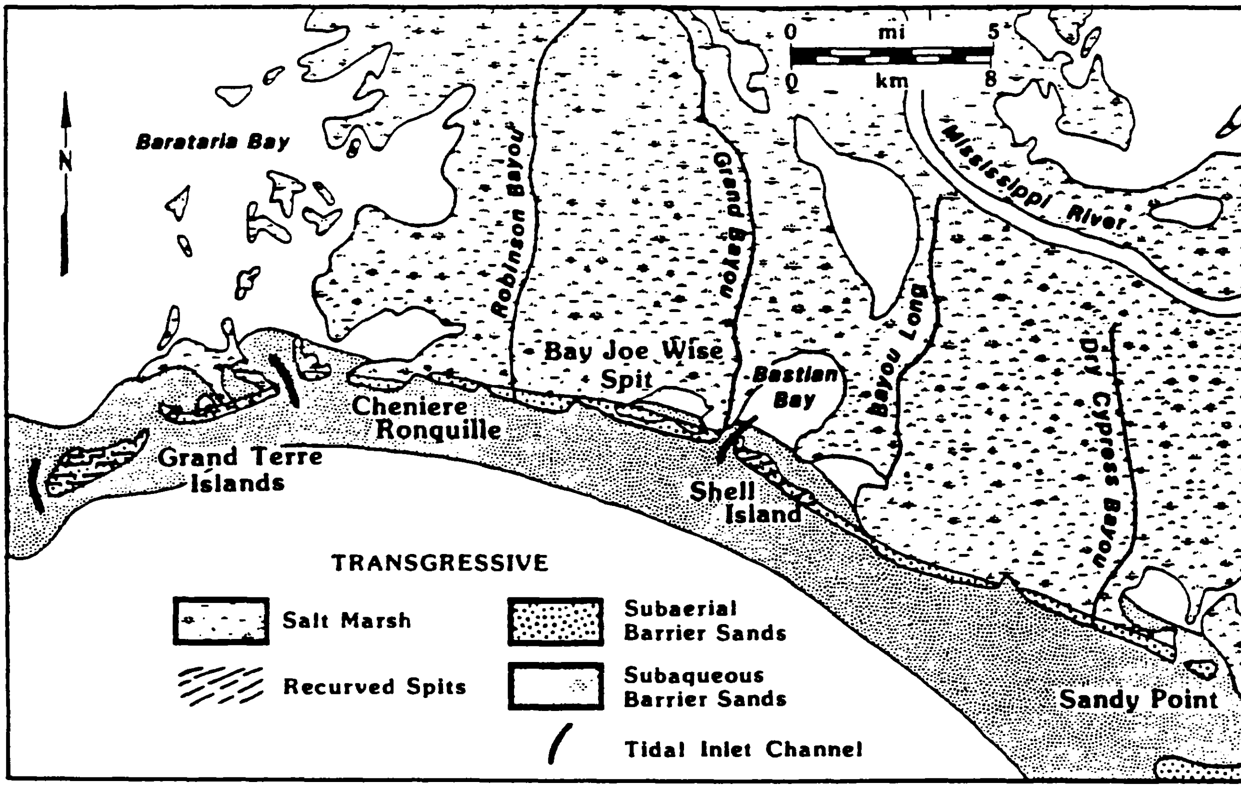
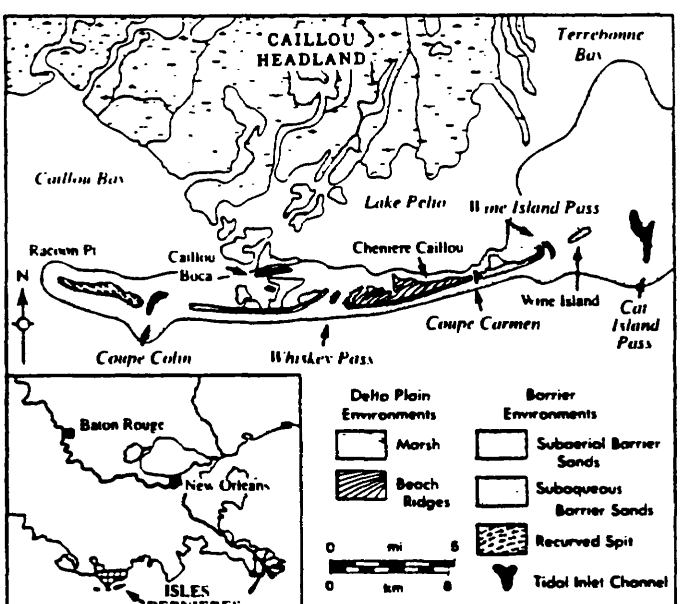


Figure 6. The Plaquemines coastline stretches from the Grand Terre Islands to Sandy Point. It consists of numerous small erosional headlands each associated with a Plaquemines distributary such as Grand Bayou or Robinson Bayou. Flanking barriers such as Shell Island or Grand Terre are attached to each headland.



LOUISIANA GEOLOGICAL SURVEY

Figure 7. The Early Lafourche coastline consists of a submerged erosional headland at Cheniere Caillou, the four barrier islands of the Isles Dernieres and the intradeltaic lagoons of Terrebonne Bay, Lake Pelto and Caillou Bay. To the north lies the subsiding Early Lafourche delta plain (Penland et al., 1985a).

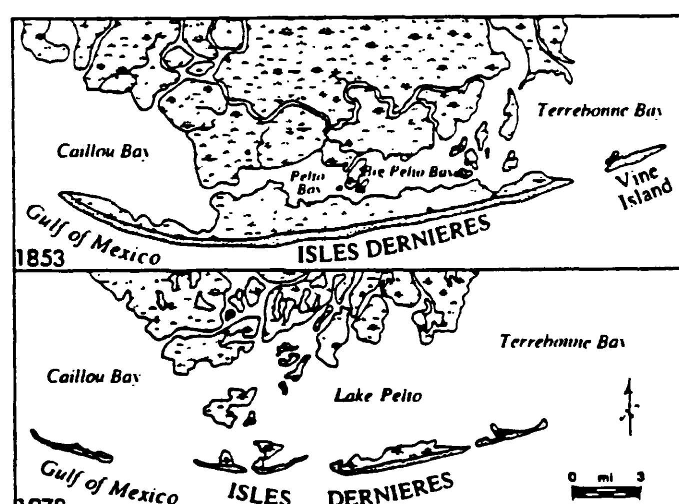


Figure 8. Shoreline changes in the Isles Dernieres clearly illustrate the transition from a Stage 1 to a Stage 2 barrier shoreline between 1853 and 1978. During this 125 year period the mainland shoreline retreated over 4.3 miles (7 km). The erosional headland retreated landward over 0.6 miles (1 km), underwent submergence and the Isles Dernieres fragmented into four islands. This pattern of barrier shoreline change illustrates Hoyt's (1967) concept of barrier island formation through mainland detachment by the process of submergence.

Figure 9. Oblique aerial photograph of the central Isles Dernieres. This photograph illustrates the geomorphology found in an advanced Stage 2 barrier island arc. Marsh remnants of the Early Lafourche headland (upper center) are being transgressed at 33-66 ft/yr (10-20 m/yr) by a thin washover sheet. Channelized washover occurs between the headland remnants, eventually forming tidal inlets such as Whiskey Pass (top left). Spits formed adjacent to the eroding headlands display sheet washover.

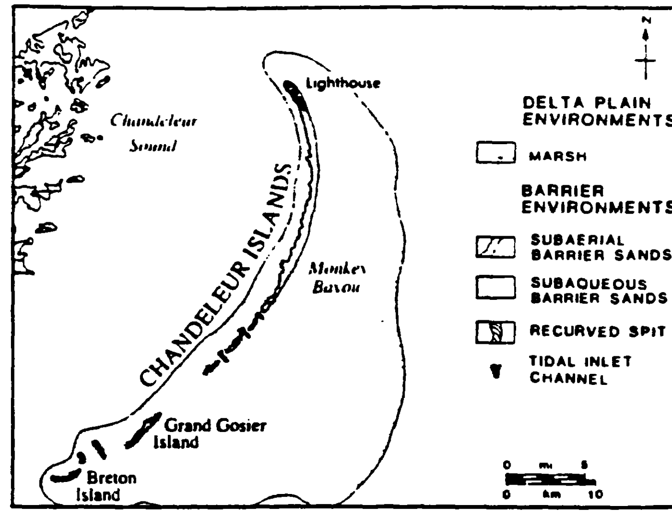


Figure 10. The St. Bernard coastline consists of the Chandeleur barrier island arc, the Chandeleur Sound intradeltaic lagoon and a 12 mile (20 km) wide transgressive sand sheet seaward of the Chandeleur Islands. The submerged St. Bernard delta plain lies beneath Chandeleur Sound, while the mainland shoreline is 19 miles (30 km) landward of the Chandeleur Islands.

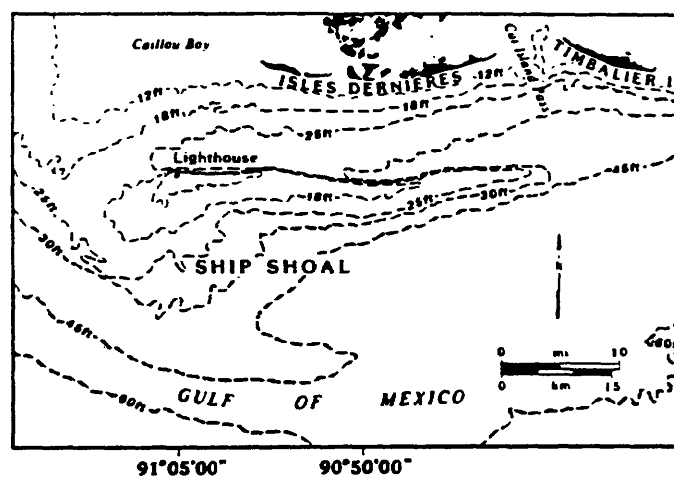


Figure 11. Ship Shoal is a Stage 3 shelf sand body derived from the transgressed Maringouin delta.

presently observable process whereby barrier shoreline sandbodies are submerged during transgression and incorporated into the continental shelf stratigraphic record. Erosional shoreface retreat appears to operate during Stage 1 and Stage 2 evolution leaving behind a thin transgressive sand sheet. However, during the transition from Stage 2 to Stage 3, the barrier island arc undergoes gradual submergence while landward migration continues. This is not an example of shoreline overstep in the sense of Sanders and Kumar (1975). The barrier island arc does not build upward inplace and lagoons do not build to sea level but continuously deepen. After submergence, barrier sand bodies are not preserved in situ, instead they continue to be reworked and dispersed on the inner shelf. Submergence is aided by the extremely low gradient of the abandoned delta plain over which the barrier transgresses (Boyd and Penland, 1984).

Reworking and submergence of barrier shorelines and their subsequent preservation as transgressed shelf sand bodies represents one of the few sound models for interpreting the origin of ancient shelf sands located far seaward of identified paleoshoreline positions. Preservation of these transgressed sands would be greatly enhanced by the presence of topographic relief on a paleoshelf. Such relief may be considered a common feature of exposed continental shelves at low sea level stands (Suter and Berryhill, 1985). Sea level transgression could then be expected to concentrate and isolate submerged barrier deposits on the paleotopographic highs (Slatt, 1984) or the margins of abandoned deltas. Heward (1981), in a major review of wave-dominated clastic shorelines, identified transgressive sheet sands associated with deltas as one of the four end members in the most suitable model for interpreting the ancient stratigraphic record, and included the St. Bernard delta as a type example. The Gulf of Mexico appears to contain examples of all evolutionary stages seen in the Mississippi delta. Headland-flanking barriers are found in the Padre Island barriers of the Rio Grande delta, the Galveston Island-Mustang Island barriers of the Brazos delta and the Summerville Lobe of the Guadalupe delta (Donaldson et al., 1970). The Appalachicola delta (Tanner, 1966) was reworked during the Holocene transgression and appears to possess a Stage 1 headland with flanking barrier at Cape San Blas to St. Joseph Spit, a Stage 2 transgressive barrier island arc at St. George Island and a Stage 3 subaqueous shoal stage in Cape San Blas Shoal. Further afield, erosional headlands and flanking barriers characterize the Po delta (Nelson, 1970), the Rhone delta (Oompkens, 1970), the Ebro (Maldonado, 1975), the Danube and the Godavari (Naidu, 1966).

Significance of the Delta Model

Earlier research identified the presence of transgressive shorelines on abandoned Mississippi deltas (eg Kwon, 1969) and their general transgressive stratigraphy (eg Frazier, 1967; Coleman and Gagliano, 1964). Recognition of the correlation between transgressive coastal systems and the deltas from which they were derived has allowed us to classify each coastal system in an evolutionary model. The geomorphologic features which develop during each stage of this model result primarily from the increase in age of each coastal system from Stage 1 to 3. This increasing age results from delta switching during Mississippi delta evolution.

The development of an integrated regressive-transgressive delta model highlights the problems of characterizing the sedimentology of the Mississippi delta by the modern Balize lobe alone. The Balize lobe is a thick, deep water delta unlike the thinner (33-100 ft or 10-30 m), shallower Maringouin-Lafourche delta complexes. The time for re-occupation of delta complexes is around 5000 years. With subsidence rates of 20 inches (50 cm) per century, a significant volume of the total shallow water delta sequence could accumulate during the transgressive phase. In addition, over 70 percent of the Mississippi delta coastline and land area is occupied by transgressive coastal systems, generating widespread marker horizons for correlation in otherwise complex deltaic stratigraphy.

ACKNOWLEDGMENTS

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TRANSGRESSIVE DEPOSITIONAL SYSTEMS OF THE MISSISSIPPI DELTA PLAIN: A MODEL FOR BARRIER SHORELINE AND SHELF SAND DEVELOPMENT[1]

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ABSTRACT: Depositional sequences generated in the Mississippi River delta plain consist of a regressive and a transgressive component. The transgressive component has been considerably less studied but accounts for the majority of the surface area on the lower Mississippi River delta plain and up to 50 percent of the total sequence thickness in shallow-water deltas. The development and preservation of transgressive depositional systems in abandoned delta complexes follows the process of *transgressive submergence* in which the horizontal component of reworking occurs during shoreface retreat, combined with a vertical component of submergence acting to preserve the sequence. The evolution of transgressive depositional systems in each of the abandoned Holocene Mississippi River delta complexes can be summarized in a three-stage model beginning with stage 1, an *erosional headland and flanking barriers*. In this stage, regressive sand deposits contained within abandoned deltaic headlands are reworked by the eroding shoreface and dispersed longshore into contiguous flanking barriers enclosing restricted interdistributary bays. Submergence of the delta plain during relative sea-level rise generates an intradeltaic lagoon separating the former stage 1 sand body from the shoreline, forming stage 2, a *transgressive barrier island arc*. The landward-migrating barrier island arc is unable to keep pace with relative sea-level rise and the retreating mainland shoreline, resulting in submergence and the formation of stage 3, an *inner-shelf shoal*. Following submergence, the former barrier island arc sand body continues to be reworked into a marine sand body on the inner continental shelf during stage 3. This sequence of coastal evolution provides direct evidence of barrier island formation, with each stage producing a distinctive stratigraphic signature. The current sea-level-rise models of *shoreface retreat* and *in-place drowning* developed for the U.S. Atlantic continental shelf do not adequately explain either the morphology or the stratigraphy of transgressive Mississippi River delta sand bodies. Current models of Mississippi deltaic stratigraphy emphasize the deep-water, artificially maintained Balize delta, which differs considerably from the shallow-water, shelf-phase delta complexes that are the primary depositional constituents of the Holocene Mississippi River delta plain.

INTRODUCTION

Mississippi River sediments accumulate in deltaic depositional sequences consisting of a regressive, or constructional phase followed by a transgressive or destructional phase (Fig. 1). Scruton (1960) used the term *delta cycle* to refer to these alternating phases of deltaic sedimentation. Many studies have focused on the regressive phase (Russell et al. 1936; Fisk 1944; Kolb and Van Lopik 1958), resulting in the development of a composite Mississippi delta stratigraphic column that emphasizes the artificially maintained deep-water Balize delta (Coleman and Wright 1975) and omits the sediment accumulated during transgression in abandoned delta systems.

The objective of this paper is to provide a comprehensive model for the transgressive phase of Mississippi River delta-plain depositional systems. Previous research has identified many of the components of an abandoned Mississippi River delta complex (Coleman and Gagliano 1964) and the stratigraphic relationship between the regressive and transgressive phases of the deltaic sequence (Frazier 1967; LeBlanc 1972). The present study provides a detailed description of transgression in abandoned Holocene Mississippi River delta complexes, and an evolutionary model that links delta complexes into an ordered spatial and temporal sequence of development. The evolutionary model is based on a synthesis of more than 200 vibracores, 7,000 km of high-resolution seismic profiles, and 150 soil borings, supplemented by an analysis of more than 45 historical coastal charts dating back to the early 1700s. Analysis of the vibracore and seismic data resulted in the development of cross sections depicting major facies relationships, sequence boundaries, and regional ravinement surfaces (Fig. 2). The historical coastal charts provide information on shoreline changes, shoreface erosion, and the morphology of the coastline at different dates.

Difficulties arise with terminology in a study that covers both geomorphology and stratigraphy and integrates findings on deltaic and coastal sedimentary environments. We shall use the term *delta* to indicate a surficial landform. The sediments that accumulate in a deltaic environment constitute a deltaic depositional sequence (terminology of Vail et al. 1977) that accumulates locally in a single delta or as several deltas grouped together in a *delta complex*. Each complete deltaic depositional se-

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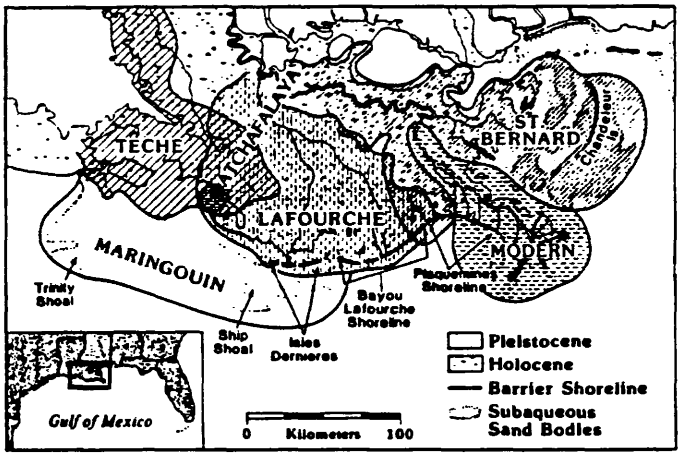

FIG. 1.—Location map of the Holocene Mississippi River delta plain showing the distribution of transgressive barriers and shoals. Over the last 7,000 years, the Mississippi River has built a delta plain consisting of six delta complexes; four are abandoned (Maringouin, Teche, St. Bernard, and Lafourche), and two are active (Modern and Atchafalaya). More than 75 percent of the Mississippi River delta plain is abandoned and is in various stages of transgression due to submergence (modified from Frazier 1967, 1974).

quence consists of a regressive component and a transgressive component. Although initially difficult to conceive of in a deltaic setting, transgressive sedimentation is an integral part of river-dominated, cyclic, deltaic sequences such as those formed by the Mississippi River, where such sedimentation can contribute up to 50 percent of the total sequence thickness. In this study we concentrate on sandy barrier and shoal systems, recognizing that the term *barrier* implies the existence of lagoonal or estuarine environments and that such environments predominantly occur during transgression rather than regression.

Current models for preservation during transgression, such as *shoreface retreat* (Fisher 1961; Swift 1975) or *in-place drowning* (Sanders and Kumar 1975) models do not adequately explain the existence of shelf sand bodies derived from transgressive reworking and submergence of abandoned Mississippi River delta complexes. The evolutionary model presented here provides a new mechanism for converting deltaic sand bodies into barrier sand bodies, and then into shelf sand bodies, a mechanism that can be applied to interpreting the problematical formation of many ancient shelf sandstones.

In this paper we first present in detail the geomorphology of selected abandoned delta complexes and then summarize vibracore and high-resolution seismic data. The sequential development of Mississippi River delta complexes is then synthesized as an evolutionary model that introduces a new mechanism for preservation during transgression and submergence.

MISSISSIPPI RIVER SEDIMENTATION

Apart from the Modern delta complex located in deep water near the shelf edge (Fig. 1), Holocene Mississippi River sediments have accumulated in shallow-water, shelf-phase delta complexes (terminology of Suter and Berryhill 1985). The delta-building process consists of prodelta

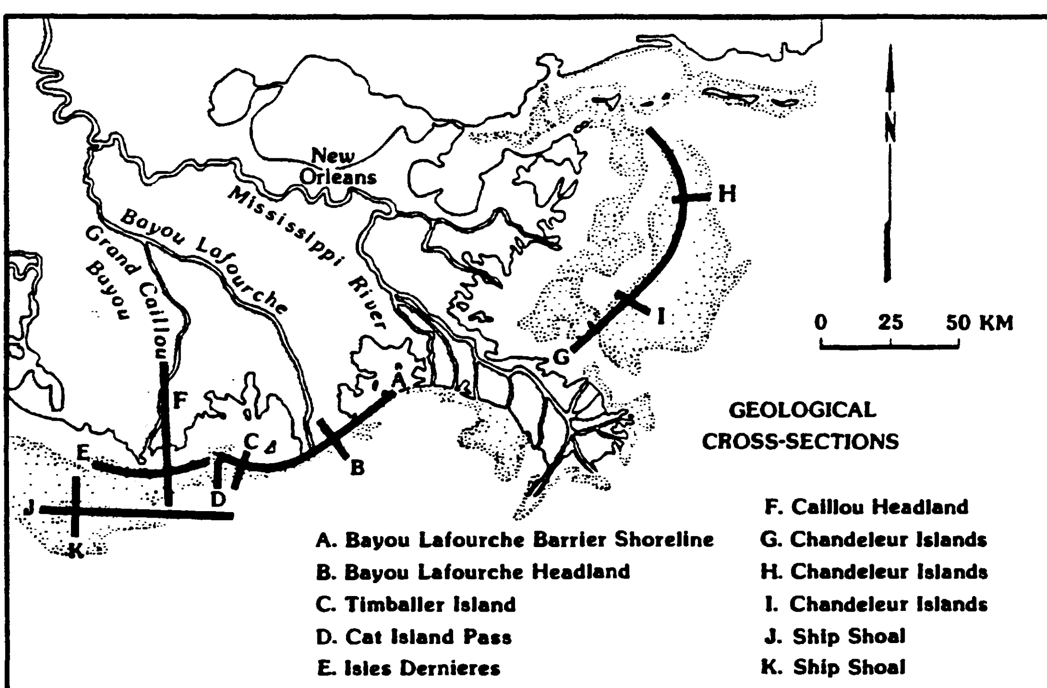

FIG. 2.—Location map and explanation of the geologic cross sections presented in the text. These cross sections were built from the following data bases: seismic and vibracore data from the Louisiana Geological Survey (unpubl. data), U.S. Army Corps of Engineers (1962, 1972, 1975), Neese (1984), Gerdes (1985), Conatser (1969), Frazier (1967), Frazier et al. (1978), Kolb and Van Lopik (1958), Penland and Suter (1983), Penland et al. (1986b, 1987), and Suter and Penland (1987).

platform establishment, followed by distributary progradation and bifurcation, which results in delta-plain consolidation. This process continues until the distributary course is no longer hydraulically efficient. Abandonment occurs in favor of a more efficient course, initiating the transgressive phase of the *delta cycle*. The abandoned delta complex subsides, and coastal processes rework the seaward margin, generating a sandy barrier shoreline backed by bays and lagoons (Kwon 1969; Penland et al. 1981). Each transgressive depositional system is derived from a single abandoned delta or delta complex (Fig. 1).

The Mississippi River has built six major delta complexes consisting of more than 18 smaller deltas over the last 7,000 years (Frazier 1967). Between 7,000 yr BP and the present (Fig. 1), delta-complex building began in the area of the Isles Dernieres (Maringouin) and switched sequentially west near Marsh Island (Teche), east near New Orleans (St. Bernard), west again south of Donaldsonville (Lafourche), then southeast of Belle Chase (Modern), and finally back to the west, below Morgan City (Atchafalaya). Today, the delta plain can be divided into two distinct physiographic regions, active deltas and abandoned deltas. Delta building occurs in 20 percent of the delta plain and is restricted to the Modern delta complex and the Atchafalaya delta complex. The four remaining complexes, the Maringouin, Teche, St. Bernard, and Lafourche, are abandoned. In addition, the Plaquemines delta of the Modern complex is abandoned (Fig. 1).

COASTAL PROCESSES

Sea level in the Gulf of Mexico is inferred to have risen from depths of 130 m, where it stood 15,000 yr BP, to around −9 m by 8,000 yr BP (Curray 1960), to its present position around 3,600 yr BP (Coleman and Smith 1964). Since this time, relative sea level along the Mississippi River delta plain has continued to rise, mainly in response to compactional subsidence, which varies as a function of sediment thickness, composition, and age (Morgan and Larimore 1957). Present rates of relative sea-level rise based on radiocarbon analysis of in situ peat horizons range between 30 cm per century and 60 cm per century on the Mississippi delta plain (Penland et al. 1987).

The northern Gulf of Mexico is a storm-dominated environment experiencing relatively low energy levels resulting from wind and wave processes, except during the passage of winter cold fronts between September and May and the occurrence of hurricanes and tropical storms between June and November. Modal wave conditions in deep water offshore of Louisiana are characterized by wave heights of 1 m and wave periods of 5–6 sec. On average, modal wave conditions occur 4 percent of the time (Bretschneider and Gaul 1956), and average deep-water wave power is only 1.8×10^3 W m^{-1}. Wright and Coleman (1972) indicated that over 99 percent of the deep-water wave power offshore from the Modern delta complex is dissipated before reaching the shoreline. Wave-refraction analyses for the Louisiana coast show that under nonstorm conditions, significant sediment transport is restricted to the upper shoreface landward of the 5-m isobath (Boyd and Penland 1984). Dominant wave approach is from the southeast, but the local wind and wave variability combined with a complex coastal orientation results in variable longshore transport directions, even within individual barrier systems. The base of the shoreface lies at a depth of 5–8 m offshore of most Louisiana barrier islands and exhibits a flattened gradient of 1:3,000. Shoreface sediment dispersal is such that storm impacts disperse sand farther offshore than fair-weather processes can return it to the beach; therefore, a net export takes place (Penland and Boyd 1981). Tides in the region are mixed and predominantly diurnal with a microtidal range of 30 cm. Storm surges frequently accompany tropical cyclones and cold fronts, elevating sea level from 0.5 m to over 7 m with concurrent intense overwash events (Boyd and Penland 1981).

TRANSGRESSIVE DEPOSITIONAL SYSTEMS

Bayou Lafourche Barrier System

Geomorphology.—The Bayou Lafourche transgressive depositional system consists of a central erosional headland fronted by the Caminada-Moreau coast with a pair of recurved spits and flanking barrier islands on either side, the Caminada Pass spit and Grand Isle to the east, and the Timbalier Islands to the west (Fig. 3). Behind the flanking barriers lie two restricted interdistributary bays, Barataria Bay and Timbalier Bay. Since the abandonment of the Bayou Lafourche delta some 300 yr BP, shoreface erosion has actively supplied sand for flanking barrier development. The primary sand sources are the Bayou Lafourche distributaries and the Cheniere Caminada beach-ridge plain (Penland et al. 1986a).

The Caminada-Moreau coast is a thin, discontinuous mainland beach with marsh outcropping on the lower beach face. Sediment abundance increases downdrift to the east and west, as evidenced by washover terraces that eventually coalesce farther downdrift to form a higher, more continuous dune terrace and eventually a continuous foredune ridge on the margins of the headland (Ritchie and Penland 1985). The Caminada Pass spit was formed by downdrift spit accretion through lateral migration away from the Bayou Lafourche erosional headland. The Timbalier Islands and Grand Isle developed through this same process. Washover sheets and multiple washover channels are common on the updrift, erosional end of Timbalier Island. Downdrift, longshore bars become more numerous and better developed because of increasing sediment abundance. Dune ridges form by onshore bar migration and welding, followed by aeolian reworking and dune development.

A historical map comparison for the years 1887 to 1978 shows rapid retreat of over 3 km on the erosional headland in the vicinity of Bayou Lafourche and Bay Marchand, and westward lateral migration of over 5 km at Timbalier Island. A similar pattern of shoreline change is seen at Grand Isle. This pattern of longshore spit building and breaching illustrates Gilbert's (1885) model of

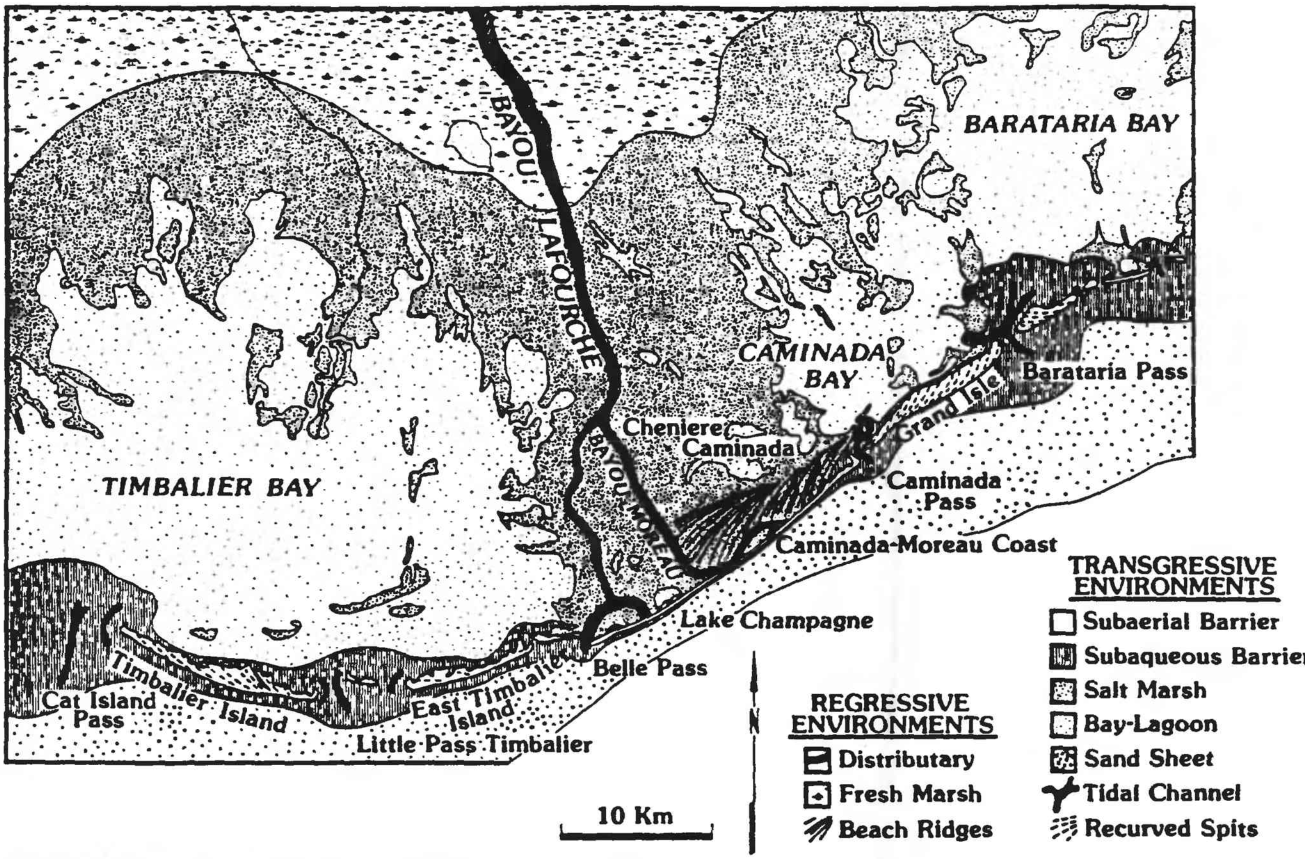

FIG. 3.—The Bayou Lafourche transgressive depositional system consists of 1) the Bayou Lafourche headland containing Cheniere Caminada, 2) the flanking barriers of the Caminada Pass spit and Grand Isle to the east, 3) the Timbalier Islands to the west, and 4) two restricted interdistributary bays, Barataria Bay and Timbalier Bay.

barrier island formation. Once detached from the mainland, flanking barrier islands migrate by updrift erosion and downdrift spit building. The recurved spit morphology of Timbalier Island reflects this process.

Flanking barrier-island growth and breaching have led to the development of large tidal inlets at Cat Island Pass, Little Pass Timbalier, Caminada Pass, and Barataria Pass. Due to submergence and land loss, the Timbalier, Caminada, and Barataria bays are continually increasing in size and depth, resulting in an increase in the volume of water stored within these restricted interdistributary bays. Therefore, the volume of water exchanged through tidal inlets during a tidal cycle increases, leading to increases in inlet cross-sectional area, tidal current velocity, and sediment storage capacity.

The tidal-prism/tidal-inlet relationship represents an important process affecting barrier island shape and tidal-inlet sediment dispersal, evolution, and sand body development. A long-term increase in tidal-prism volume will eventually lead to a situation in which the volume of sediment stored within the tidal inlet is comparable to, if not more than, the volume of sediment stored within the adjacent flanking barrier islands. As the tidal prism increases, the morphology of individual tidal inlets changes from wave-dominated with flood-tidal deltas to tide-dominated with large ebb-tidal deltas.

Stratigraphy.—Along the Caminada-Moreau coast, distributaries associated with Bayou Lafourche and Bayou Moreau are seen in the subsurface and are depicted in the stratigraphic strike section of Figure 4A. Between Bayou Moreau and Caminada Pass spit, Cheniere Caminada beach ridges are exposed on the eroding surface. The Bayou Lafourche barrier sand body thickens downdrift from 1–2 m thick in the central headland to 4–5 m thick at Grand Isle, and reaches a maximum thickness of 5–6 m near Cat Island Pass at Timbalier Island (Fig. 4A).

A stratigraphic dip section through the central Bayou Lafourche erosional headland, Figure 4B, shows the facies relationship between the eroding shoreface and distributary and beach-ridge sand bodies. The Caminada-Moreau barrier is a prism of washover sediment 1–2 m thick. A thin sequence of salt marsh overlying fresh marsh outcrops on the eroding beach face. The relatively thin nature of the salt marshes overlying the headland reflects the initial effects of submergence and salt-water intrusion acting on the Bayou Lafourche delta over less than 300 years. A stratigraphic dip section through Timbalier Island west of the headland shows this sand body overlies a sequence of regressive deltaic muds (Fig. 4C). The sand body, which has a maximum thickness of 5–6 m, pinches out seaward on the erosional shoreface and interfingers landward with a sequence of restricted interdistributary bay muds. Surficial sediment samples show a thin, discontinuous sand sheet spreading seaward of the shoreline (Krawiec 1966).

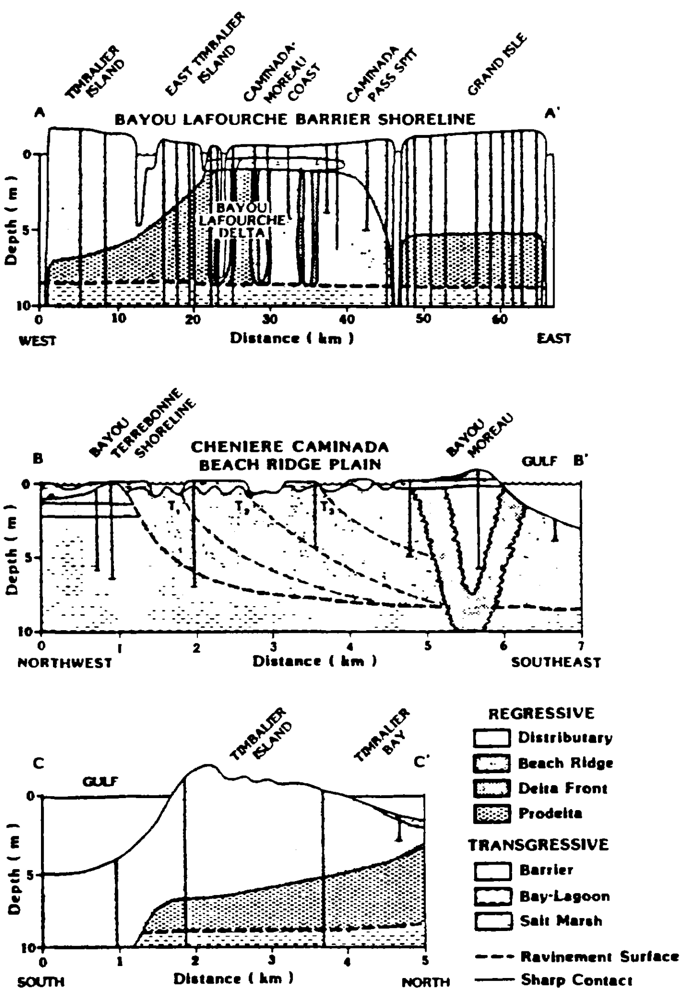

FIG. 4.—A) Stratigraphic strike section A-A' is of the Bayou Lafourche barrier shoreline. The shelf-phase Bayou Lafourche delta lies on a shallow ravinement surface 7–8 m in the subsurface. Distributary and beach-ridge sand bodies core the headland and supply sand through shoreface erosion for flanking barrier development. The transgressive barrier sands increase in thickness from 1 to 2 m at the headland to over 5 m at the downdrift ends of the flanking barrier islands. B) Stratigraphic dip section B-B' from the central portion of the Bayou Lafourche delta headland shows the Cheniere Caminada beach-ridge plain lying seaward of the transgressive Bayou Terrebonne shoreline and interfingering with the Bayou Moreau distributary as it meanders away from the coast (modified from Gerdes 1985). C) Stratigraphic dip section C-C' is from Timbalier Bay across Timbalier Island and onto the inner shelf. Timbalier Island represents a flanking barrier island comprising recurved spit and tidal-channel deposits sourced from the eroding Bayou Lafourche delta headland.

Isolated, filled tidal-channel scars are found offshore of the Timbalier Islands, marking the retreat path of the Bayou Lafourche barrier system (Suter and Penland 1987). A seismic strike section (Fig. 5) depicts westward-dipping clinoforms within a tidal-channel sequence 8–10 m thick associated with the westward migration of Timbalier Island and Cat Island Pass. Large tidal sand bodies are also found east of the Bayou Lafourche headland, where the ebb-tidal deltas of Caminada Pass and Barataria Pass extend 2 km and 6 km offshore of Grand Isle and are 3 km and 8 km wide, respectively. Tidal-channel depths range from 10 to 20 m, and localized scour holes are up to 40–50 m at channel junctions.

Isles Dernieres Barrier System

Geomorphology.—The symmetrical, 32-km-long Isles Dernieres barrier-island arc formed in response to the abandonment of the Bayou Petit Caillou delta within the Lafourche delta complex approximately 420 yr BP (Fig. 6). Typical barrier widths are 1.5–2 km in the central island arc and 0.5–1 km in the downdrift flanks, which are dominated by recurved spits. The Isles Dernieres have fragmented into four smaller islands separated by tidal inlets. These inlets are 300–1, 200 m wide and 6–18 m deep. Inlet morphology varies from wave-dominated to tide-dominated, depending on the size of the tidal prism. Wine Island shoal, a former barrier island, is the easternmost island member. Remnants of the Cheniere Caillou beach-ridge plain, associated with the progradation of the Bayou Petit Caillou distributaries, core the east-central portion of the barrier island arc. Cheniere Caillou consists of a series of partially submerged beach ridges that spread seaward on their western margin against the Caillou headland distributaries.

The recent history of the Isles Dernieres is one of rapid barrier shoreline detachment, island fragmentation, and land loss. The transition of the Isles Dernieres from an erosional headland with flanking barrier islands to a barrier island arc is illustrated by the historical map comparison in Figure 7. In 1853, Caillou Boca, Pelto Bay, and Big Pelto Bay separated the Isles Dernieres from the adjacent mainland by less than 500 m at the narrowest point. By 1978, these bays had coalesced and increased in size threefold to form the modern-day Lake Pelto. The northern shore of Lake Pelto had greater land loss during this time period and retreated faster than the Gulf shoreline, resulting in the detachment of the Isles Dernieres from the mainland by more than 7 km of open water. The Isles Dernieres have steadily decreased in size over time from 34.8 km^2 in 1887 to 10.2 km^2 in 1979, a rate of 0.25 km^2 yr^{-1} (Penland and Boyd 1981).

Stratigraphy.—The stratigraphic strike section in Figure 8 shows that the subsurface of the Isles Dernieres consists of a complex set of interfingering distributary, interdistributary, and beach-ridge facies overlain by a sequence of lagoonal and barrier shoreline facies. A set of bifurcating distributaries 4–5 m thick associated with the Bayou Petit Caillou delta extends seaward under the east-central portion of the Isles Dernieres and interfingers with the Cheniere Caillou beach-ridge plain (Penland and Suter 1983). The Cheniere Caillou beach-ridge plain is 5–6 m thick and interfingers with regressive prodelta and delta-front deposits lying on an older ravinement surface. The top of this beach-ridge sequence lies about 2 m below mean sea level. In the central Isles Dernieres, the Bayou Petit Caillou delta is overlain by a thin sequence of washover sands resting on lagoonal deposits 1–2 m thick. The barrier sand body increases in thickness to 4–5 m toward Wine Island and Raccoon Point. The bulk of the transgressive barrier sands are stored west of the central head-

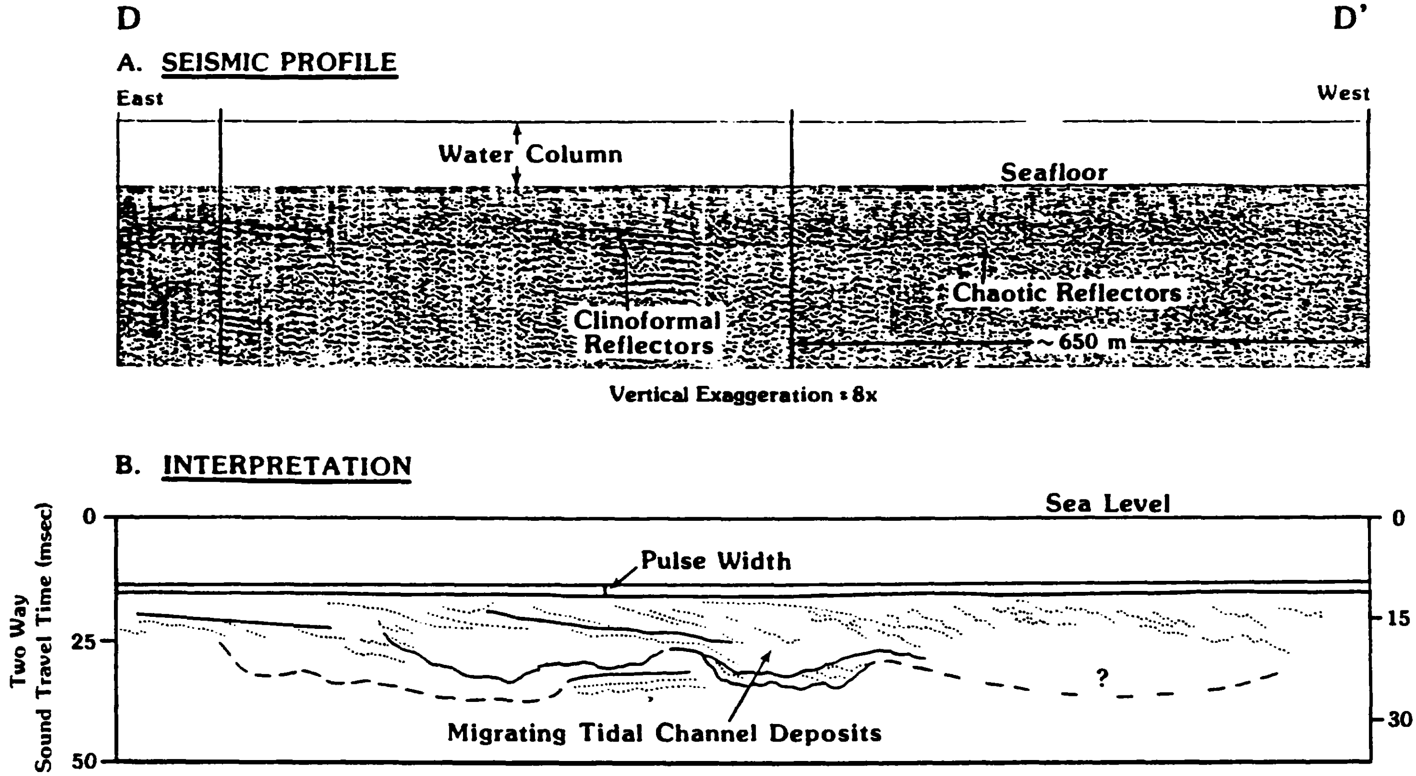

FIG. 5.—High resolution seismic profile and interpretative drawing along strike section D-D' through the tidal-inlet scar of Cat Island Pass. Westward-dipping clinoforms characterize the tidal-inlet deposits generated by the westward migration of Cat Island Pass; sequences reach thicknesses of 10 m or more (modified from Suter and Penland 1987).

land in recurved spits and ebb-tidal deltas associated with Coupe Colin and Raccoon Island. The present barrier island arc sand body and back-barrier deposits pinch out on the upper shoreface and overlie the regressive core of the submerged Bayou Petit Caillou delta.

Figure 9 shows a vibracore dip section across Lake Pelto from the mainland Terrebonne salt marshes, seaward across the Isles Dernieres, illustrating the relationship between the underlying Bayou Petit Caillou delta facies and the overlying transgressive Isles Dernieres facies. The fine-grained lagoon sequence averages 1–2 m thick, and the adjacent salt marshes around Lake Pelto

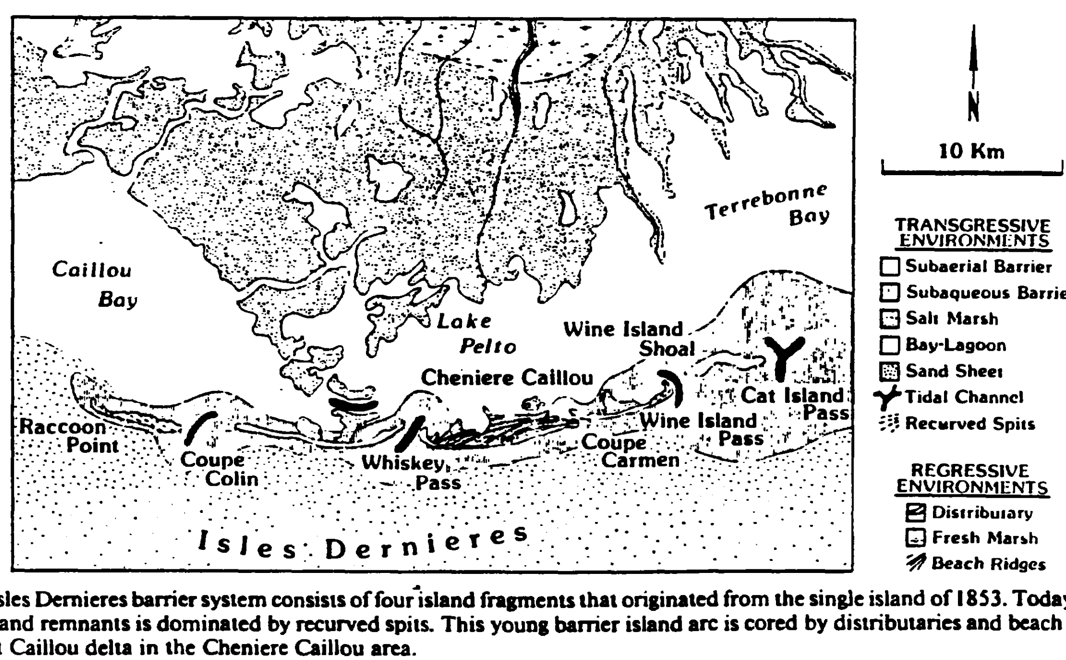

FIG. 6.—The Isles Dernieres barrier system consists of four island fragments that originated from the single island of 1853. Today the morphology of these small island remnants is dominated by recurved spits. This young barrier island arc is cored by distributaries and beach ridges associated with Bayou Petit Caillou delta in the Cheniere Caillou area.

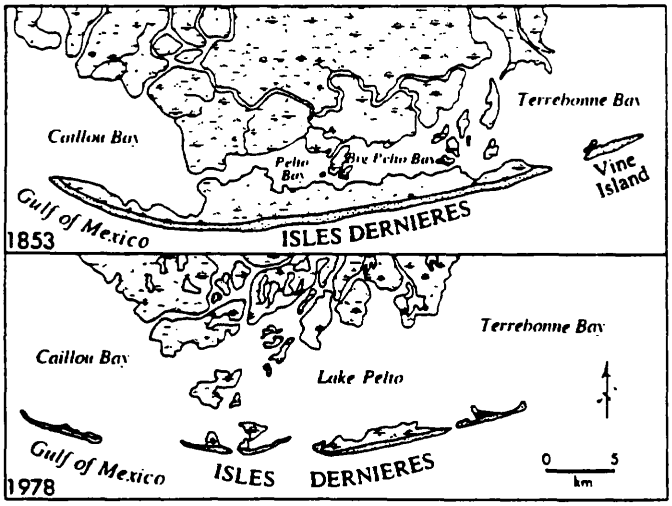

FIG. 7.—The shoreline changes in the Isles Dernieres barrier system between 1853 and 1978 illustrate the transition, through Hoyt's (1967) mainland detachment-submergence process, from an erosional headland with flanking barriers to a barrier island.

are typically 1 m thick. Beneath these transgressive deposits lie regressive distributary and beach-ridge deposits which supplied the sands for the development of the Isles Dernieres. The Isles Dernieres here consist of a 2–3-m-thick sequence of recurved spit sands overlying a sequence of lagoonal muds 2 m thick.

Within the Isles Dernieres, Whiskey Pass and Coupe Carmen are shallow, wave-dominated inlets with well-developed, flood-tidal delta sand bodies 1–2 m thick (Neese 1984; Penland et al. 1985). Maximum channel depths are 3–5 m. Coupe Colin and Wine Island Pass are mixed-energy inlets with tidal-delta sand bodies confined to the inlet throat. Vibracores and high-resolution seismic profiles reveal that the Wine Island Pass ebb-tidal delta is 6 m thick and pinches out seaward, overlying tidal-channel scars.

Chandeleur Barrier System

Geomorphology.—The oldest transgressive barrier island arc found in the Mississippi River delta plain is the Chandeleur Islands (Fig. 10). The asymmetric shape of the Chandeleur Islands is due to their oblique orientation to the dominant southeast wave approach, which leads to the preferential transport of sediment northward. The Chandeleur Islands are more than 75 km long, and island widths range from 200 m to over 2, 500 m. Northward, large flood-tidal delta and washover fans separated by hummocky dune fields dominate barrier island mor-

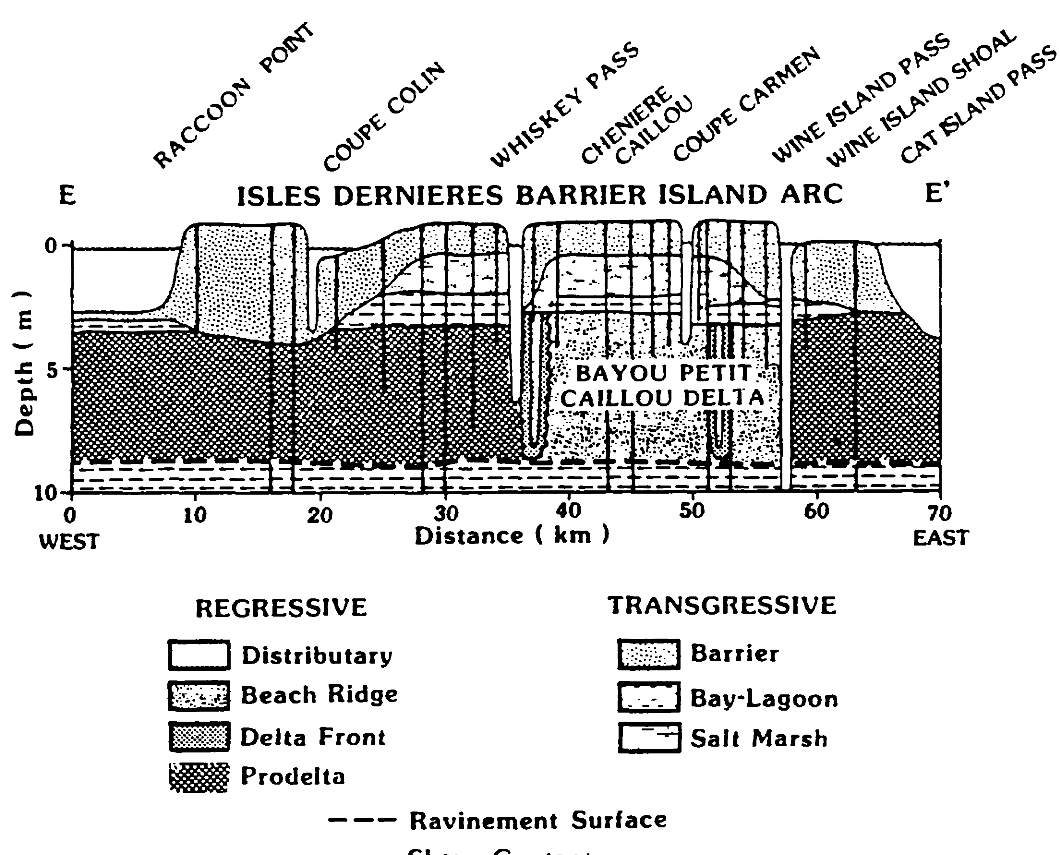

FIG. 8.—The Isles Dernieres barrier island arc in strike section E-E' is cored by a sequence of distributary and beach-ridge sand bodies associated with the shelf-phase Bayou Petit Caillou delta. The transgressive barrier sands increase in thickness from 1 to 2 m over the central headland and from 5 to 6 m at the downdrift end of recurved spits. This delta of the larger Lafourche delta complex lies on a ravinement surface 7–8 m in the subsurface.

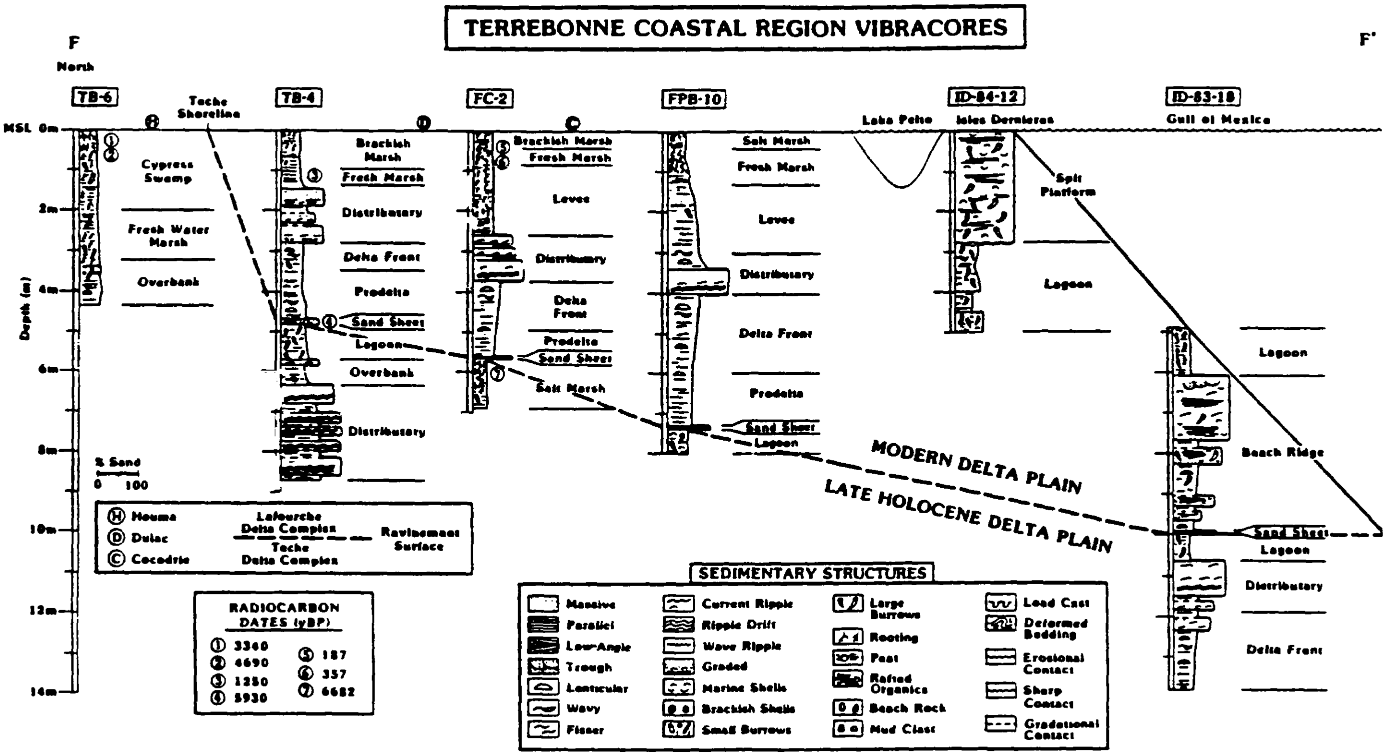

FIG. 9.—Diagram illustrates a vibracore dip section (F-F') of the complete shelf-phase Bayou Petit Caillou delta from the Teche shoreline south to the Isles Dernieres barrier island arc. This shallow-water delta lies on a ravinement surface 7–8 m in the subsurface near the Isles Dernieres that merges up-dip to a relict transgressive barrier shoreline. Note the total thickness of this deltaic sequence and the significance of the transgressive sequence component that becomes thicker toward the coast (Penland et al. 1987).

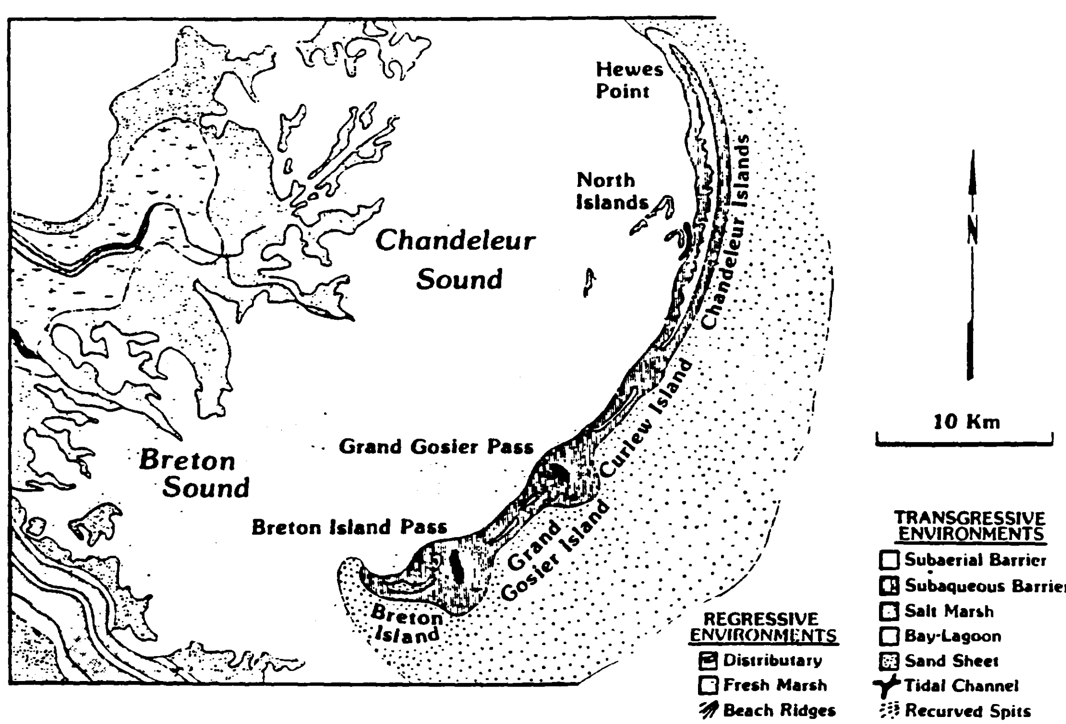

FIG. 10.—The Chandeleur transgressive depositional system represents the oldest barrier island arc on the Mississippi River delta plain. Associated with the St. Bernard delta complex, this barrier island arc sand body is 75 km long and separated from the mainland by an intradeltaic lagoon 25 km wide.

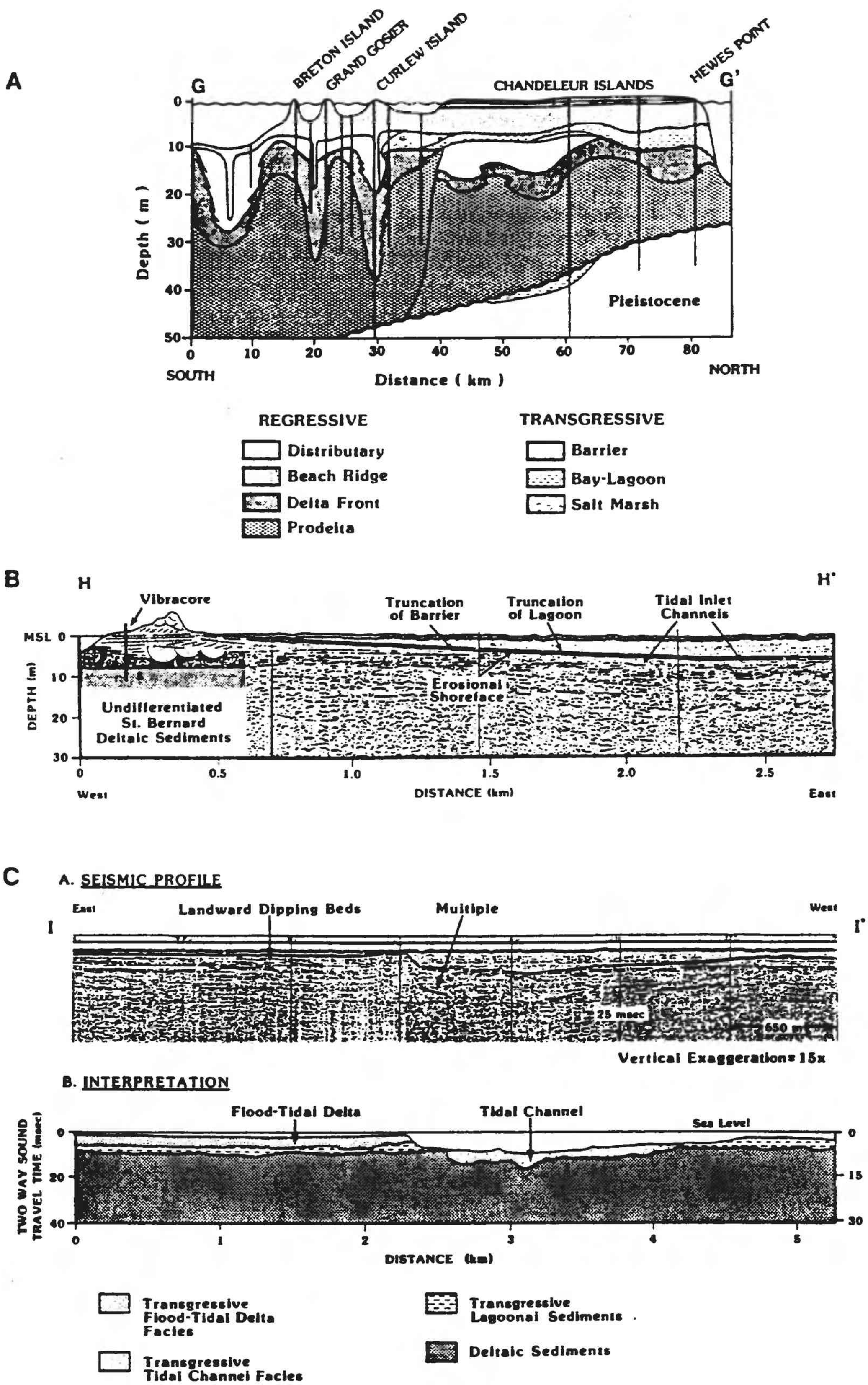

FIG. 11.—A) Strike section G-G' illustrates the relatively uniform 5–10-m sand body thickness of the Chandeleur Islands. A sequence of lagoonal muds 2–4 m thick separates the basal flood-tidal delta sands from the underlying surface of the St. Bernard delta plain. The St. Bernard distributaries lie under the southern half of the Chandeleur Islands (modified from Frazier et al. 1978). B) Dip section H-H' illustrates the transgressive facies relationships through the northern Chandeleur Islands. Flood-tidal delta sands interfinger with the lagoonal muds of Chandeleur Sound. Offshore,

phology. The wide beaches and foreshore, and multiple bars in the surf zone reflect an abundance of sediment. Southward, islands become narrower, dune heights decrease, and flood-tidal deltas and washover fans give way to discontinuous washover terraces and flats. Farther south, the island arc fragments into a series of small, ephemeral islands and shoals separated by tidal inlets. Chandeleur-Breton Sound averages 3–5 m deep and separates the Chandeleur Island arc from the retreating mainland shoreline by more than 25 km of open water.

For the last 100 years, the Chandeleur Islands have retreated landward during fluctuating periods of land loss and gain. Retreat rates along the Gulf shoreline are greater than 15 m/yr in the southern island arc and decrease northward to less than 5 m/yr. The Chandeleur Islands have experienced an average land loss rate of 0.11 km^2/yr since 1879 (Penland and Boyd 1981). Periods of high and low hurricane frequency correspond to periods of high and low land loss. Constructive fair-weather processes lead to island recovery, followed by an increase in island area. However, the historical rate of recovery is not sufficient to maintain the Chandeleur Islands against the frequency of hurricane impact. As a result, these islands experience a net long-term land loss. The mainland shoreline retreat rates exceed those of the Gulf shoreline of the Chandeleur Islands, indicating that the detachment process continues.

Stratigraphy.—In strike section, the Chandeleur Islands sand body overlies a thick sequence of lagoonal deposits resting on the regressive St. Bernard delta complex surface (Fig. 11A). The distributary headlands, once the major sand sources, now lie on the lower shoreface and inner shelf and extend seaward under the central and southern Chandeleur Islands. Here, three major distributaries occur beneath the thin and discontinuous barrier island arc. Towards the north, the Chandeleur Islands sand body is thicker and more continuous and overlies a sequence of lagoonal deposits that increases in thickness northward from 2 to 7 m. The base of the Chandeleur Island transgressive depositional system averages 6–8 m below mean sea level. At tidal inlets, deep, isolated, sand-filled sequences can develop because of channel migration. In areas where recurved spits build into deep water, thick sand bodies develop with the basal portions lying below the advancing ravinement surface, which has an average depth here of 5–8 m (Penland et al. 1985).

The dip section shown in Figure 11B illustrates the facies relationships between the eroding shoreface and the regressive/transgressive components of the St. Bernard delta complex in the northern Chandeleur Islands. The barrier island arc sand body overlying lagoonal muds pinches out seaward on the erosional shoreface. Landward, flood-tidal delta and washover sands overlie and interfinger with the lagoonal muds of Chandeleur Sound. The northern barrier island arc consists of a coarsening-upward sequence of lagoonal, flood-tidal delta and washover deposits capped by beach and dune sands. Average sand body thickness is 5–7 m, increasing to over 10 m where local dune fields occur. A sand sheet spreads more than 5 km seaward of the Chandeleur Islands.

Farther south, the dip section shown in Figure 11C extends from Breton Sound seaward across the subaqueous shoal portion of the southern Chandeleur Islands. In contrast to the northern dip section, here the subaerial superstructure of the barrier island arc has been submerged but continues to be reworked by shoreface erosion. The sand body is 4–5 m thick and pinches out on the lower shoreface. Landward, clinoforms within the flood-tidal delta deposits dip westward and overlie a 2–3-m-thick sequence of lagoonal muds, which extends seaward under the southern Chandeleur Islands and is exposed on the inner shelf in the retreat path.

Ship Shoal System

Geomorphology.—Ship Shoal is approximately 50 km long with widths ranging from 5–7 km in the central shoal area to 8–12 km at the eastern and western ends (Fig. 12). Relief varies from 7 m in the west to 5 m in the east, and corresponding water depths range from 3 m in the west to 8 m in the east. On the inner shelf, in water depths less than 10 m, the landward-oriented asymmetry of Ship Shoal indicates that it is migrating landward (towards the north). The shoal crest is asymmetric shoreward with landward slopes of 1:750 and seaward slopes of 1:900. Westward this asymmetry becomes more pronounced; landward slopes increase to 1:90, and seaward slopes decrease to 1:2,100.

A comparison of bathymetric profiles taken between 1887 and 1983 indicates that Ship Shoal migrated more than 1 km landward and the rates of movement were greatest in the west. The greater landward migration rates in the western region are attributable to the shoal crest's extension into the zone of shoreface wave activity. Rates of landward shoal migration vary from 15 m/yr in the west, to 9 m/yr in the central shoal area, to 7 m/yr in the east. This pattern of landward shoal migration emphasizes the fact that after a barrier sand body submerges, it continues to be actively reworked and driven landward across the continental shelf, forming a marine sand body.

Stratigraphy.—Ship Shoal is uniform in thickness along strike (Fig. 13A); the entire transgressive sequence averages 5–6 m thick through its 50-km length. The higher-energy shoal-crest facies increases slightly in thickness in shallower water over the western shoal, yet overall geometry remains uniform (Penland et al. 1986b). A dip section reveals that the shore-parallel crest of central Ship Shoal overlies the Maringouin delta complex (Fig. 13B).

←
the barrier island sand body is truncated by shoreface erosion, and tidal-inlet scars occur through the retreat path. C) Dip section I-I' illustrates the facies relationships on the southern Chandeleur Islands, where the morphology is dominated by flood-tidal deltas and sand shoals. This seismic section shows landward-dipping clinoforms within the flood-tidal delta sand body overlying lagoonal muds of Breton Sound. A tidal channel is deflected against the landward margin of this flood-tidal delta before it turns seaward at the south end of Grand Gosier Island.

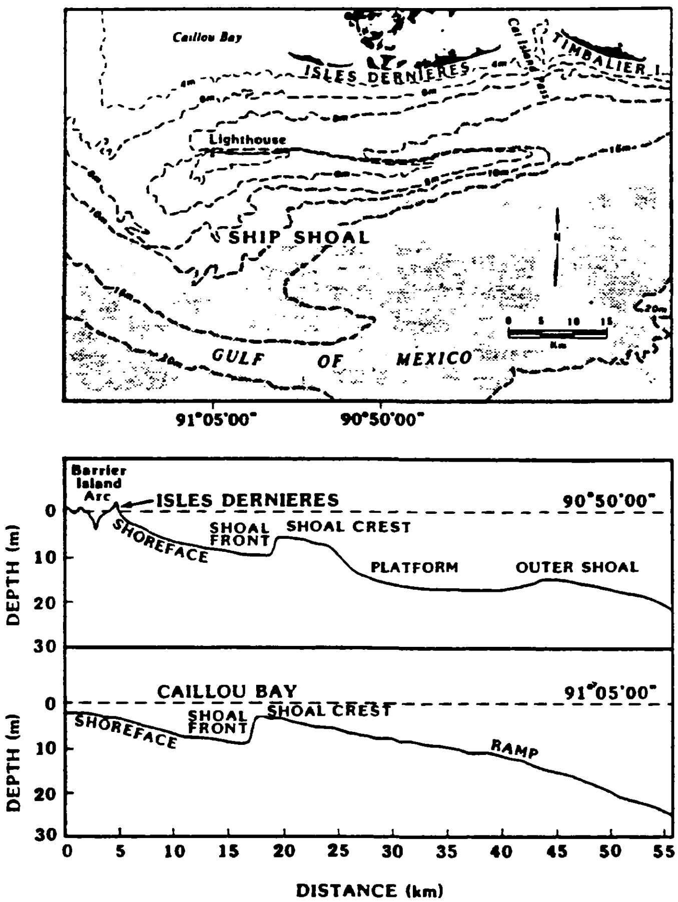

FIG. 12.—Ship Shoal, associated with the Maringouin delta complex, represents the oldest transgressive sand body in the Holocene Mississippi River delta plain. More than 50 km long, Ship Shoal has an inner-shelf relief of 4–6 m. The geometry of the Ship Shoal sand body is skewed landward, indicating that it is migrating onshore across the inner shelf.

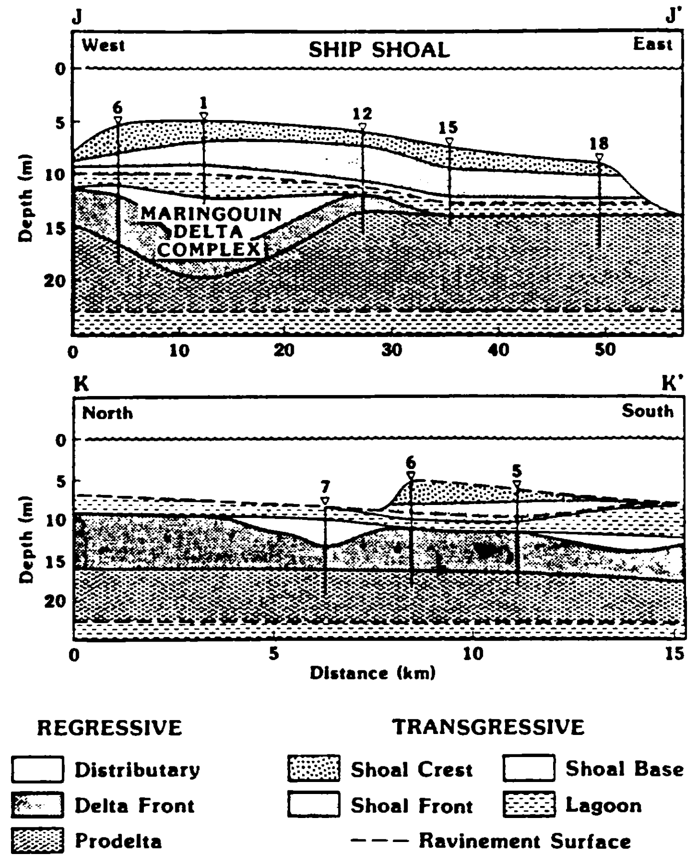

FIG. 13.—A) Strike section J-J' illustrates the facies relationship between the surface of the Maringouin delta complex and the overlying Ship Shoal transgressive sequence.Stratigraphic boundaries are derived from a composite of vibracores (upper boundaries) and seismic data (lower boundaries). The sand body geometry of Ship Shoal is a uniform 4–5 m along its entire 75-km length. The original headland of the Maringouin delta complex underlies the western end of Ship Shoal. B) Dip section K-K' illustrates the facies relationship across Ship Shoal and the adjacent inner shelf. Ship Shoal is composed of sand sourced from the shoreface and inner-shelf reworking of a submerged barrier island arc.

Shoal-crest deposits are 1–2 m thick, and the shoal-front deposits are 2–3.5 m thick. The shoal-base deposits thicken eastward from approximately 1 to 2 m. Lagoonal deposits 1–1.5 m thick are found underlying Ship Shoal throughout the region.

The main Maringouin distributaries extend seaward underneath the western half of Ship Shoal (Fig. 13A). The strike section shows that this zone of distributaries is about 10 km wide and 1–6 m thick. These distributaries lie on a regional unconformity associated with an older transgressed delta complex deposited at a lower sea-level stand. The base of shelf erosion is below the 10-m isobath in the western shoal region, indicating that the entire sand body is being truncated along the seaward shoal margin and reworked into a marine sand body.

Vibracores document that Ship Shoal and the underlying Maringouin delta complex represent a continuous regressive-transgressive depositional sequence. The vertical stacking of facies documents the landward migration of Ship Shoal. No in situ barrier shoreline deposits were found within the sand body of Ship Shoal, while in situ lagoonal muds are present beneath the shoal and exposed landward on the flat inner shelf, which is the ravinement surface upon which Ship Shoal is migrating (Fig. 13). The stratigraphic position of Ship Shoal indicates that it is a transgressive sand body that has migrated to its present position under conditions of sea-level rise, shoreface erosion, and submergence.

Clasts of beach rock, *Crassostrea* sp. shell, and *Rangia* sp. shell are common constituents of the vibracored transgressive sand sequences. These clasts are well rounded, polished fragments, indicating possible exposure to a high-energy environment, such as a surf zone, during their depositional history. Beach rock is found along all of the transgressive barrier shorelines of the Mississippi River delta plain. This rock forms at the water table within the beach and foreshore areas and is composed of sands cemented by calcium carbonate. *Crassostrea* sp. reefs commonly occur throughout the back-barrier lagoon and the lagoon shore of flanking barrier islands and barrier island arcs. *Rangia* sp. shell reefs were once common along the inland margins of transgressive back-barrier bays and lagoons. The occurrence of these reworked clasts and la-

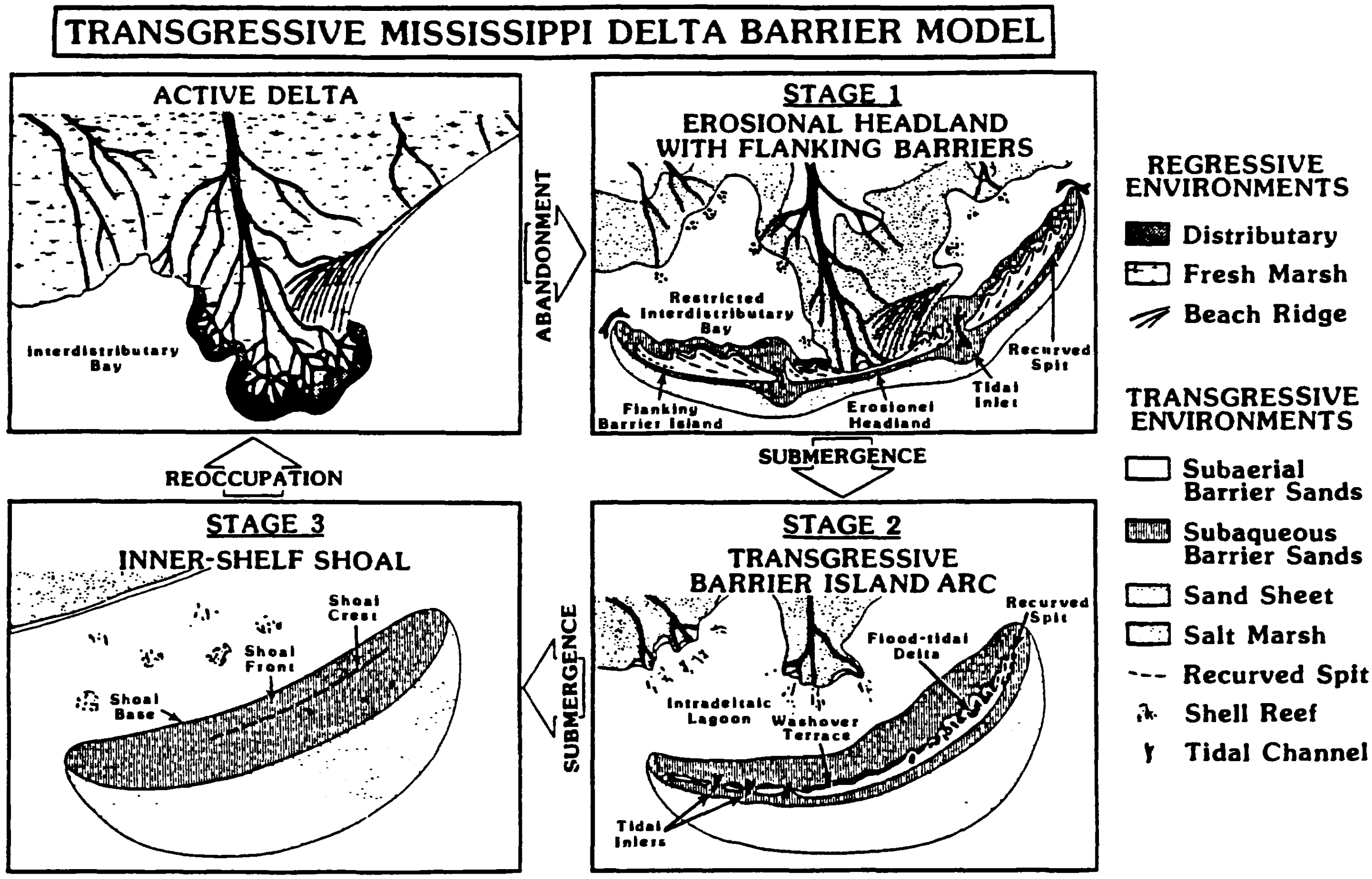

FIG. 14.—The genesis and evolution of transgressive depositional systems in the Mississippi River delta plain are best summarized by this three-stage geomorphic model, which begins with stage 1, *erosional headland and flanking barriers.* Next is stage 2, *transgressive barrier island arc.* The sequence ends with stage 3, *inner-shelf shoals.*

goonal muds indicates that Ship Shoal is a marine sand body originating from the transgression and submergence of a former barrier shoreline.

TRANSGRESSIVE DEPOSITIONAL SYSTEMS MODEL

Mississippi River delta complexes have followed a sequential pattern of development characterized by shifting shallow-water depocenters (Fig. 1). The transgressive depositional systems that evolve in abandoned delta complexes follow a corresponding pattern of sequential development, determined by the age of the delta complex from which they are derived. The morphostratigraphic features characterizing each transgressive depositional system reflect its position in the evolutionary sequence. This sequence begins when marine processes transform the abandoned delta complex into stage 1, an *erosional headland with flanking barriers* (Fig. 14). Flanking barriers are built from headland sand sources supplied by shoreface erosion through Gilbert's (1885) spit-breaching process. Relative sea-level rise, land loss, and shoreface erosion lead to submergence and the separation of the stage 1 barrier shoreline from the mainland by Hoyt's (1967) detachment process, forming stage 2, the *barrier island arc.* The final evolutionary stage occurs when relative sea-level rise and overwash processes overcome the ability of the barrier island arc to maintain its subaerial integrity; submergence of the barrier island arc eventually occurs, initiating stage 3, *inner-shelf shoals.* Following submergence, the former barrier island arc sand body continues to be reworked into a marine sand body on the shoreface and inner continental shelf. This process is termed *transgressive submergence.*

Stage 1: Erosional Headland and Flanking Barrier Islands

Depositional Environments and Processes.—Stage 1 transgressive depositional systems consist of 1) an erosional headland, 2) a mainland beach, 3) flanking spits and barrier islands, 4) tidal inlets and deltas, 5) restricted interdistributary bays, and 6) a sand sheet (Fig. 14).

In stage 1, the sand dispersal pattern consists of a longshore transport divergence in the central headland. Distributary and beach-ridge sand bodies lie on the upper shoreface and are truncated by shoreface retreat, supplying sand for flanking barrier development. Reworked sands are transported away from the headland and accumulate in recurved spits and flanking barrier islands. During storm impacts, sand is transported seaward onto the inner shelf and landward into washover fans. The flanking barriers migrate away from the erosional headland through downdrift, recurved spit growth and/or updrift erosion. The recurved spit morphology of the flanking barrier islands reflects the importance of the updrift sand sources in the central erosional headland.

Flanking barrier migration encloses subsiding interdistributary bays. The sandy superstructure of flanking barriers in stage 1 is built by the lateral migration of tidal inlets and their subsequent infilling by spit platform deposits. Tidal inlets are significant sediment sinks in stage 1 barriers, as frontal and lateral migration result in sediment loss from the active dispersal system. Examples of stage 1 transgressive depositional systems include the Bayou Lafourche barrier system, derived from the Lafourche delta complex, and the younger Plaquemines barrier system, derived from the Modern delta complex.

Stage 2: Barrier Island Arc

Depositional Environments and Processes.—The stage 2 transgressive depositional environments consist of 1) a barrier island arc, 2) tidal inlets, 3) a lagoon, and 4) an inner-shelf sand sheet (Fig. 14). A stage 2 barrier island arc develops from a stage 1 erosional headland with flanking barriers by the process of mainland detachment through submergence, as described by Hoyt (1967). Long-term subsidence leads to submergence of the erosional headland, and back-barrier marshes and restricted interdistributary bays coalesce to form larger intradeltaic lagoons.

The transgressive barrier island arc primarily comprises flood-tidal delta and washover fan environments, which are colonized by salt marsh and mangroves along the lagoon margin. Discontinuous dune fields occur on these surfaces. Recurved spits occur at the downdrift end of individual islands. Tidal-inlet morphology varies between mixed-energy and wave-dominated, depending on tidal-prism size. As barrier island arcs continue to develop, the majority of the tidal flow is exchanged around the island margins. As a result, tidal influence on barrier shoreline morphology is diminished, and the barrier island arc shape becomes wave-dominated. Seaward of the barrier island arc lies a well-developed retreat path of tidal-inlet scars capped by an inner-shelf sand sheet.

Sediment dispersal consists of longshore transport away from a divergence zone, where the greatest shoreline erosion occurs, decreasing downdrift in each direction. Sediment accumulates in recurved spits, flood-tidal deltas, washover fans, dunes, and tidal inlets along the barrier island arc. During storms, coarse-grained sediments are transported offshore onto the inner-shelf sand sheet. Storm overwash transports sand landward through tidal inlets and into flood-tidal deltas and washover fans. Examples of stage 2 transgressive depositional systems include the Isles Dernieres derived from the Lafourche delta complex and the Chandeleur Islands derived from the St. Bernard delta complex.

Stage 3: Inner-Shelf Shoals

Depositional Environments and Processes.—The shoals identified on the inner shelf of the Mississippi River delta plain (Fig. 1) are landward-retreating sand bodies. Landward shoal migration takes place through the erosion of the seaward shoal slope and deposition on the landward shoal slope. Stage 3 transgressive depositional systems are composed of five major components: 1) shoal crest, 2) shoal front, 3) shoal base, 4) sand sheet, and 5) mainland shoreline. The shoal crest is the zone of maximum energy. Stage 3 inner-shelf shoals extend into the shoreface zone of fair-weather and storm-wave processes; as a result, the shoal crest experiences sediment dispersal nearly year-round. The shoal front and shoal base represent the leading edge of landward shoal migration. Seaward, a sand sheet marks the shoal retreat path.

Stage 3, the inner-shelf shoal, develops from the transgression and submergence of stage 2 barrier island arcs (Fig. 14). Long-term relative sea-level rise combined with repeated storm impacts and a diminishing sand supply eventually overcome the ability of the barrier island arc to maintain its subaerial integrity. Ensuing transgression and subsidence eventually lead to complete barrier island arc submergence, forming stage 3, an inner-shelf shoal. This process results in the submergence of the barrier island arc, producing a sand shoal cored by a suite of coastal facies lying on the shoreface and inner shelf. Marine processes continue to drive the sand shoal landward through shoreface erosion, reworking the coastal facies into a sand shoal cored by marine facies. Examples of stage 3 transgressive depositional systems are Trinity Shoal, associated with the Teche delta complex, and Ship Shoal, associated with the Maringouin delta complex.

DISCUSSION

Barrier Island Transgression, Submergence, and Stratigraphy

The mechanisms controlling barrier island formation have been debated since the early nineteenth century. Few previous models allow an evaluation of the processes controlling barrier island formation or an understanding of how the alternative mechanisms are related. The well-defined evolutionary sequence of abandoned Mississippi delta complexes provides direct evidence of barrier origin and displays the major mechanisms proposed for barrier island formation (Fig. 14). In stage 1, Gilbert's (1885) concept of longshore spit building and subsequent breaching is the dominant mode of barrier island genesis. The primary source of sediment available for barrier shoreline development comes from erosion of deltaic headlands and subsequent longshore transport of sand into flanking barrier spits. Spits are breached by storm overwash processes. Submergence ensures the increasing back-barrier tidal prism necessary to maintain storm breaches and lead to tidal-inlet development and flanking barrier island formation.

The formation of flanking barriers by Gilbert's (1885) spit-breaching process produces a characteristic stratigraphic signature (Fig. 15). This sequence reflects the lateral migration of flanking barriers away from headland sand sources. During stage 1, spits first develop at the margins of the erosional headland and build laterally

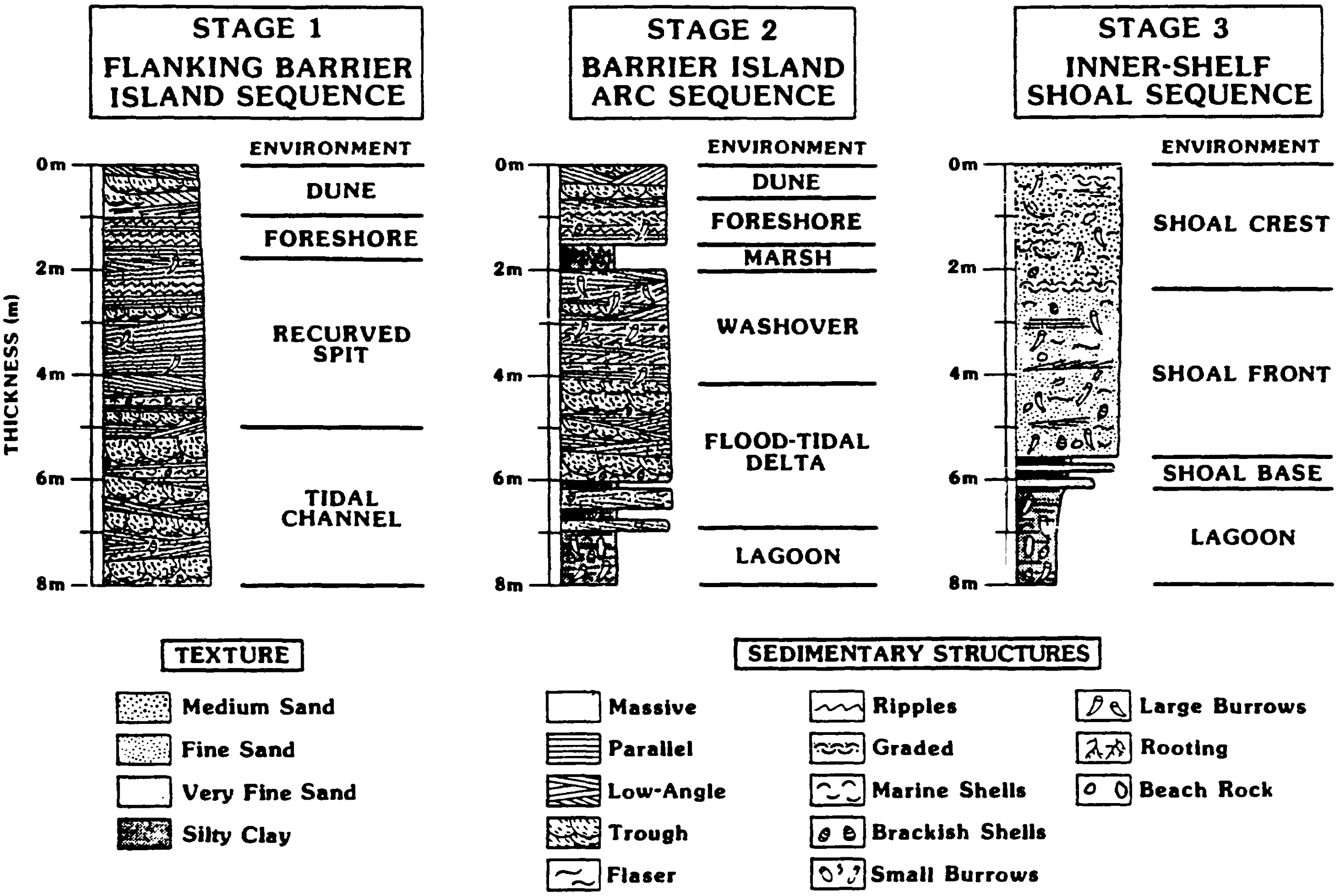

FIG. 15.—Generalized composite stratigraphic sequences for each stage of transgressive barrier and shoal sand body development in the Mississippi River delta plain. Each stratigraphic sequence reflects the dominant processes acting during each stage of sand body development. The *flanking barrier island sequence* reflects the importance of shoreface erosion, recurved spit building, and tidal-channel migration during transgression. The *barrier island arc sequence* reflects the importance of flood-tidal delta and overwash processes during submergence. The *inner-shelf shoal sequence* reflects the importance of shoreface erosion and inner-shelf reworking following barrier island arc submergence.

downdrift, forcing tidal channels to migrate and infill. Spit building leads to the stacking of tidal channel and spit deposits. Flanking barrier stratigraphy reflects the importance of spit and tidal-inlet processes, erosional shoreface retreat, and the erosional headland sand source. The *flanking barrier island sequence* is a fining-upward sequence dominated by tidal-channel sand and shell overlain with recurved spit platform sands capped by a thin sequence of beach, washover, and dune deposits. The contact between the base of the stage 1 sequence and underlying regressive deltaic muds is an erosional tidal-channel surface.

Evolution from stage 1 to stage 2 demonstrates Hoyt's (1967) concept of barrier island formation by mainland detachment through coastal submergence (Fig. 7). While coastal reworking is forming barriers at the seaward margin of an abandoned delta complex, rapid subsidence acts to submerge the back-barrier deltaic plain. The formation of barrier islands in this environment then becomes a question of rate of submergence and landward retreat of the mainland shoreline versus rate of barrier shoreline retreat. The gradient of the mainland behind the Chandeleur Islands or the Isles Dernieres ranges from flat to a seaward slope of around 1:5,000. A relative sea-level rise of 50 cm/100 yr produces submergence and landward retreat of the mainland shoreline at rates greater than 25 m/yr; average barrier shoreline retreat rates are less than 20 m/yr. Landward retreat of the mainland shoreline is not a linear process but consists of progressive enlargement of lakes, distributaries, tidal channels, and interdistributary bays, followed by eventual coalescing to form larger transgressive open-water bays and lagoons (Fig. 7).

The formation of barrier island arcs by Hoyt's (1967) mainland detachment process through submergence produces a characteristic coarsening-upward stratigraphic signature, the *barrier island arc sequence* (Fig. 15). This sequence consists of lagoonal muds grading upward into interbedded lagoonal muds and flood-tidal delta sands to washover sands capped by beach, washover, and dune sediments. The contact between the stage 2 sequence and the underlying regressive muds is gradational, representing the transition of a freshwater delta plain to saltwater marshes, bays, and lagoons. This sequence reflects landward barrier migration in response to relative sea-level rise, in combination with tidal-inlet and overwash processes. In stage 2, barrier island arcs have migrated landward past the position of the ancestral erosional headland and flanking barrier shoreline and are composed of material eroded and reworked from distributary and former stage 1 sand bodies. The stratigraphy of transgressive barrier island arcs is distinctly different from that of tide-dominated stage 1 flanking barriers and reflects the importance of submergence, wave-dominated tidal-inlet and overwash processes, and barrier sand recycling.

The evolution from stage 2 to stage 3 by the transgression and submergence of a former barrier island arc eventually produces a marine sand body (Fig. 15). The inner-shelf shoal sequence coarsens upward from shoal-base silt and sand, rapidly grading into shoal-front sand, capped by shoal-crest sand and shell. The base of the inner-shelf shoal lies on a ravinement surface. Stage 3 inner-shelf shoal stratigraphy reflects the importance of inner-shelf shoal reworking and shoal sand cycling. Note that all vertical grain-size trends in Figure 15 are subdued. This results from the limited range of sediment size available in the Holocene Mississippi delta (essentially fine-medium sand only). Other comparable sequences may display trends with more pronounced variability.

Transgressive Shoreline and Continental Shelf Sand Bodies

The term *transgressive submergence* best describes the process of shoreline and shelf sand generation and presentation on the Mississippi River delta plain. Transgression occurs when the shoreline migrates landward in a horizontal sense in response to delta complex abandonment, leading to erosion and reworking during shoreline and shoreface retreat. Submergence refers to the vertical relationship between sea level and a fixed spot on the surface of a sedimentary sequence. Submergence occurs when the depth of water increases over that spot as a result of eustatic, isostatic, or tectonic processes (Mathews 1984). The high rate of submergence characterizes transgression in abandoned Mississippi River delta complexes and leads to marine sand body generation. Other mechanisms described as producing sand deposits during shoreline transgression, namely *shoreface retreat* and *in-place drowning*, do not adequately characterize either the process or the stratigraphic signature of shoreline transgression identified in the retreat path of abandoned Mississippi River delta complexes (Mathews 1984, fig. 23). These models were developed to explain the transgressive stratigraphy of the U.S. Atlantic continental shelf.

Shoreface retreat (Fisher 1961; Kraft 1971; Swift 1975, 1976) refers to a process whereby the base of the shoreface translates landward, truncating preexisting facies. The stratigraphic signature of shoreface retreat is an erosional unconformity, a ravinement surface, overlain by a thin, often discontinuous sand sheet. Vertical and landward translation of the shoreface allow basal segments of the lagoon and barrier sediments to be preserved in situ (Swift 1975; Field and Duane 1976).

In-place drowning (Sanders and Kumar 1975; Rampino and Sanders 1980) describes a process whereby both barrier and lagoonal sediments accrete vertically, keeping pace with relative sea-level rise. Rapid relative sea-level rise results in transgression of the barrier and generation of a new shoreline farther landward. Both barrier and lagoonal deposits are only slightly reworked and drowned in situ. The stratigraphic signature of in-place drowning consists of a thickened lagoon and barrier sand sequence preserved largely intact and perhaps overlain by an erosional unconformity.

The process of *transgressive submergence* and the stratigraphic sequence for stage 3 inner-shelf shoals are not well described by either *shoreface retreat* or *in-place drowning*. The characteristics of each individual transgressive sequence depend on the process variable combination that operates in the local environment, whether it be *shoreface retreat, in-place drowning, transgressive submergence*, or some other mechanism. There is not one generally applicable model, but rather a spectrum of transgressive stratigraphies corresponding to a spectrum of process-variable combinations. The controlling variables differentiating transgressive submergence from other models are high rates of relative sea-level rise, low-gradient continental shelves with limited local sand sources, and a storm-dominated process environment. It operates when submergence is rapid enough to inundate the barriers while they continue to undergo transgression and shoreface retreat. We suggest *transgressive submergence* is a new mechanism for describing the evolution of shoreline and shelf sands in the Gulf of Mexico (Fig. 16).

The process of *transgressive submergence* may help to explain the genesis of many ancient shelf sandstones. Evidence of the shelf origin of these sandstones is often restricted to the absence of any nearby time-equivalent shoreline deposits and the presence of shallow-marine paleontological indicators. Tenuous dynamic concepts, such as delta sand plumes, shelf turbidity, and density currents (Tillman and Martinson 1984; Walker 1984) are often invoked to explain the shelf location of these sandstones. The model of *transgressive submergence* predicts the generation of shelf sand bodies without preservation of the shoreline sands they were derived from. Such sand bodies can be expected to occur both adjacent to and downdrift of transgressed delta complexes. Preferred environments for *transgressive submergence* include low-gradient coastal plains with a deltaic sediment supply and rapid submergence resulting from eustasy, compaction, or tectonism. Such environments range from river-dominated deltas to subsiding foreland basin margins.

Deltaic Stratigraphy

Classic studies of the Mississippi River delta plain (Russell et al. 1936; Kolb and Van Lopik 1958; Fisk 1955, 1961; Frazier 1967; Coleman and Wright 1975) have emphasized the regressive component of the delta sequence. The facies present in the transgressive part of the sequence have not previously been comprehensively described, although transgressive sedimentation occupies

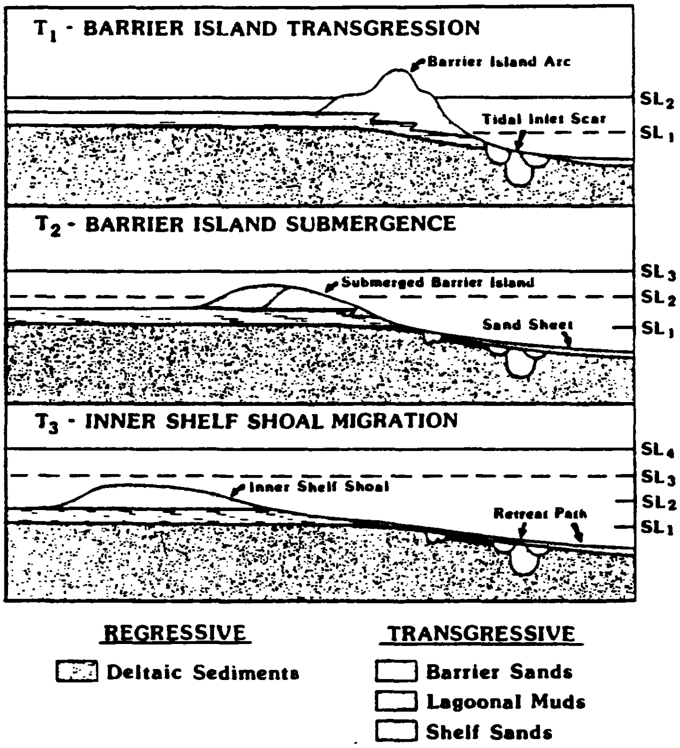

FIG. 16.—This stratigraphic model illustrates the *transgressive submergence* process in which a marine inner-shelf sand shoal is generated by the reworking of a submerged barrier island arc sand body associated with an abandoned delta complex.

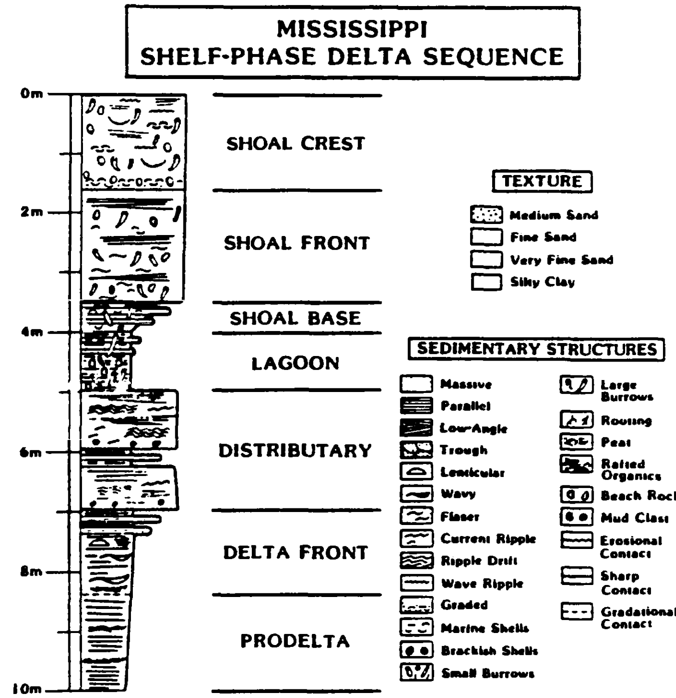

FIG. 17.—A generalized stratigraphic model for an abandoned shelf-phase Mississippi River delta complex illustrates the significance of the transgressive component. In this new stratigraphic sequence, shelf-phase delta complexes, which differ considerably from the traditional deep-water Mississippi River delta complex model, are seen as the primary depositional constituents of the Holocene Mississippi River delta plain.

the majority of the depositional surface on the Holocene delta plain. It generates a widespread marker sequence consisting of lagoonal muds, barrier sand bodies, sand shoals, and organic deposits formed in salt-to-brackish marshes. Interpreting deltaic stratigraphy without including a transgressive component is difficult, particularly with respect to predicting the trend of hydrocarbon reservoirs in relation to a paleo-shoreline. Some of the largest, cleanest, and potentially highest porosity reservoir sands are transgressive barriers and sand shoals.

Our three-stage model identifies and emphasizes the transgressive component of the delta cycle and explains the generation and evolution of a transgressive depositional sequence through the process of *transgressive submergence*. A complete shallow-water delta sequence consists of a regressive-transgressive couplet. Figure 17 illustrates a complete shallow-water Mississippi delta sequence, based on the Maringouin delta complex. Here, due to the lack of accommodation space, the regressive sediments are seen to be substantially thinner than for the equivalent sequence developed in the Balize deep-water delta (Coleman and Wright 1975). Completion of the deltaic sequence requires the addition of overlying lagoonal and shoal facies. The transgressive sediments are volumetrically significant, contributing up to 50 percent of the composite sequence thickness. Preservation potential of this complete shallow-water deltaic sequence is likely to be high, either through submergence below the zone of active reworking or by burial during a new regressive phase.

CONCLUSIONS

1) A new three-stage model illustrates the depositional history of abandoned Mississippi River deltas from stage 1, an *erosional headland with flanking barriers*, to stage 2, *transgressive barrier island arcs*, followed by stage 3, an *inner-shelf shoal*, through a process termed *transgressive submergence*.
2) This three-stage model illustrates the formation of barrier islands through both spit breaching and mainland detachment processes. Each stage of the model has a distinctive morphostratigraphy.
3) Transgressive submergence is a new mechanism for describing the evolution of shelf sand bodies. In the Gulf of Mexico it results from high rates of relative sea-level rise on low-gradient continental shelves with limited sand sources in a storm-dominated environment. Sand bodies are submerged as they continue to undergo transgression and shoreface retreat.
4) Transgressive depositional systems in river-dominated delta plains are vertically and spatially significant components of a shallow-water deltaic depositional sequence. These shallow-water, shelf-phase delta complexes, which differ considerably from those included in the traditional deep-water Mississippi delta model, are the primary depositional constituents of the Holocene Mississippi River delta plain.

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BARRIER ISLAND EROSION AND PROTECTION IN LOUISIANA: A COASTAL GEOMORPHOLOGICAL PERSPECTIVE

Shea Penland[1] and John R. Suter[1]

ABSTRACT

Louisiana has the highest rates of coastal erosion and land loss in the United States. Rates of coastal land loss exceed 50 mi²/yr. Louisiana's barrier islands, whose presence creates and maintains an extensive estuarine system and protects the salt marshes from the wave energy of the open Gulf of Mexico are rapidly vanishing, decreasing in area and migrating landward at rates up to 65 ft/yr. Between 1898 and 1978, Louisiana's barrier islands decreased in area by 41 percent, shrinking from 37 mi² to 22 mi². The life-expectancy of individual barrier island systems ranges between 30 years for the Isles Dernieres and 225 years for the Chandeleur Islands. Disappearance of the barrier islands will result in destruction of the barrier-built estuaries and accelerated salt marsh deterioration. Such destruction will severely impact the fishery, fur, and waterfowl industries, valued at an estimated $1 billion per year, whose harvests depend on the habitat provided by these fragile estuaries.

Understanding the coastal geomorphological processes, both natural and human-induced, that control barrier island erosion, estuary deterioration, and salt march loss in the Mississippi River delta plain is essential in evaluating the performance of the various coastal protection methods currently envisioned or being employed. Previous attempts at coastal preservation and restoration have shown that an integrated approach that enhances natural processes, rather than combatting them, is the most effective. Highways are built with regularly scheduled maintenance programs and this same concept should be applied to the coastal zone. Preservation and restoration of our coastal environments requires a dynamic landscape maintenance program of regularly scheduled beach nourishment, barrier restoration, shoreface nourishment, vegetation, and coastal modification projects

INTRODUCTION

Coastal erosion and land loss are serious geomorphological problems of national importance with long-term economic and social consequences (Figure 1). Valuable estuarine barrier islands, bays, and salt marshes are being rapidly altered, and developed areas face billions of dollars in property damage as a result of long-term erosion and potential loss of life from increased vulnerability to storm impacts. Forecasts by the U.S. Environmental Protection Agency (Barth and Titus, 1984) National Academy of Sciences (National Research Council, 1987) of increasing rates of sea level rise indicate that erosion will probably accelerate in the future. This potentially dangerous problem requires careful study and well-planned, managed responses

The Modern Mississippi River delta plain represents North America's largest deltaic estuary (Figure 2). Two distinct types of estuaries occur here: barrier-built and delta-front (Schubel, 1982). Barrier-built estuaries develop as a result of delta abandonment and subsidence-driven transgression, during which barrier islands form, lakes develop into larger bays, and salt marshes encroach upon the surrounding fresh marshes and swamps under the effects of submergence. In contrast, the delta-front estuaries are associated with active delta building.

Today, Louisiana has the highest rates of coastal erosion and land loss in the United States. In Louisiana, rates of coastal loss exceed 50 mi²/yr (Gagliano et al., 1981). Louisiana's barrier islands, whose presence creates and maintains the extensive barrier-built estuarine system, protecting the salt marshes and bays from offshore wave conditions and saltwater intrusion from the Gulf of Mexico, are rapidly vanishing, both decreasing in area and migrating landward at rates up to 65 ft/yr (Penland and Boyd, 1981). Between 1880 and 1978, Louisiana barriers decreased in area by 41 percent, shrinking from 37 mi² to 22 mi². The life-expectancy of individual barrier island systems ranges between 30 years for the Isles Dernieres and 225 years for the Chandeleur Islands. Disappearance of the barrier islands will result in destruction of the large estuarine bay systems and accelerated salt marsh deterioration, which will severly impact the fur, fish and waterfowl industries, valued at an estimated $1 billion per year (Turner and Cahoon, 1987). Harvests from these industries depend on the habitat provided by these fragile estuarine ecosystems.

Analysis of tide gage records for Louisiana over the last 40 years, indicates that relative sea level rise currently exceeds 0.4 in/yr (Penland et al., 1987). This is the rate predicted for the entire United States within the next 100 years by the National Research Council (1987). Louisiana, with its current rates of barrier island erosion and coastal land loss, provides the only modern analog to these predicted conditions. Understanding the coastal geomorphological processes, both natural and human-induced, that control barrier island erosion, estuarine deterioration, and salt marsh loss in the Modern Mississippi River delta plain is essential in evaluating the performance of the various coastal protection methods currently envisioned or being employed. Previous attempts at coastal preservation and restoration have shown that an integrated approach that enhances or counteracts natural processes, rather than combating them, is the most effective.

This paper will review the barrier island erosion and land loss problem in the Modern Mississippi River delta plain, highlighting the critical processes driving the evolution of these estuarine systems. We will then discuss human impacts on this coastal zone and make management recommendations from a coastal geomorphological perspective.

REGIONAL GEOLOGY

The geology of the state of Louisiana is initmately tied to the Holocene history of the Mississippi River (Figure 1). According to current models, the Mississippi has built a delta plain consisting of seven delta complexes, ranging in age from about

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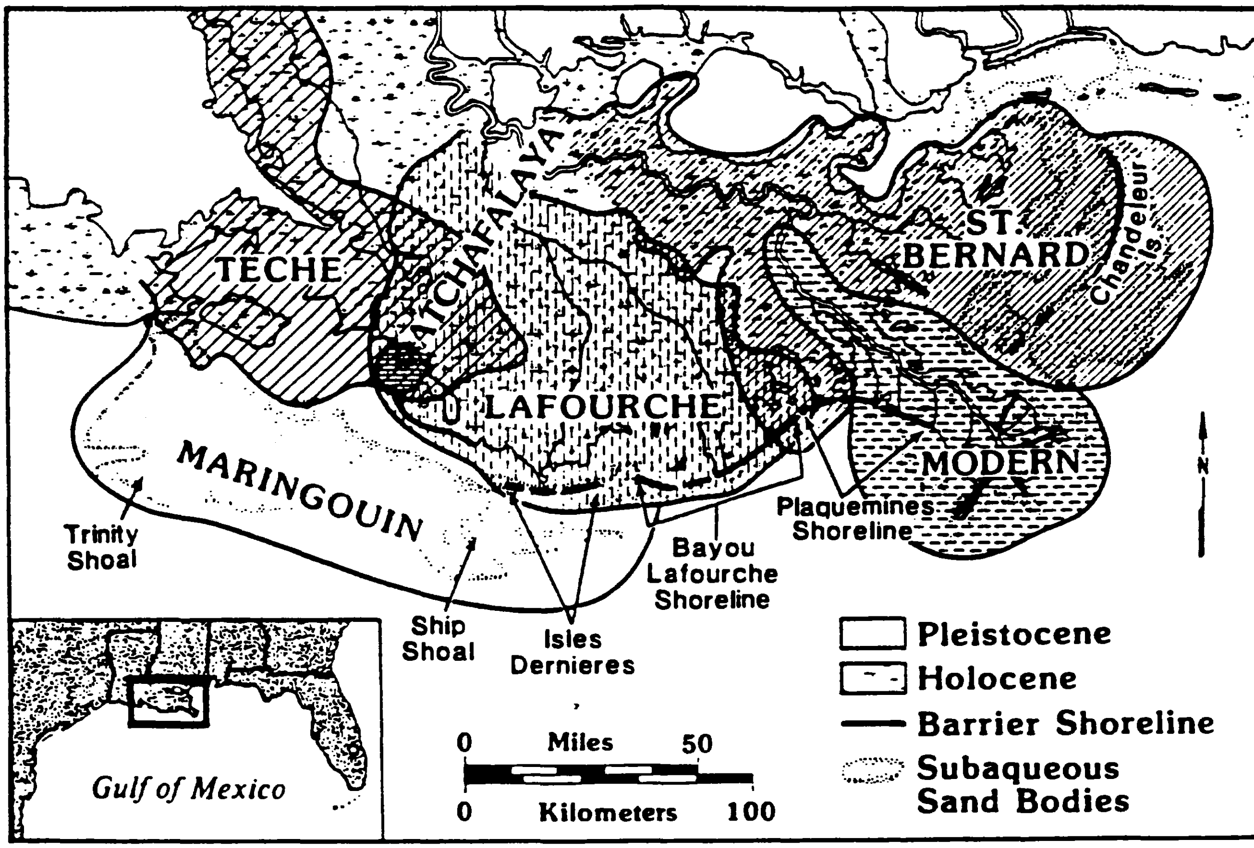

Figure 1. Location diagram depicts the chronologic development of the Mississippi River delta complexes and the position of the barrier shorelines (modified from Frazier 1967).

7000 yr B.P. to the currently active Balize and Atchafalaya complexes (Frazier, 1967). The process of delta switching by the Mississippi River, in which the main distributary location of the river switches about once every 1000 years to a more hydraulically efficient course, is responsible for the geomorphology of coastal Louisiana. When avulsion occurs, a new delta complex begins building in a different area, and the previous complex, deprived of its former sediment supply, begins to undergo transgression. This transgression is a result of relative sea level rise driven by compactional subsidence of the deltaic sediments.

Upon transgression, the landscape is dominated and reworked by marine processes. In what can be visualized as a three-stage process, shoreface erosion transforms the once-active delta into a succession of transgressive depositional environments (Penland et al., 1981 and 1988a). The first stage is the erosional headland with flanking barrier islands, Stage 1. Long-term relative sea level rise and erosional shoreface retreat lead to the detachment of the barrier shoreline from the mainland and the formation of a barrier island arc, Stage 2. The final stage of barrier shoreline evolution occurs when relative sea level rise and repeated storm impacts overcome the ability of the barrier island arc to maintain its subaerial integrity. The barrier island arc is submerged, forming an inner-shelf shoal, Stage 3. Shoreface retreat processes in Stage 3 continue to drive the inner-shelf shoal landward across the subsiding inner shelf and to smooth the mainland shoreline.

The coastline of the Modern delta plain stretches 210 mi from Point au Fer east to Hewes Point in the northern Chandeleur Islands. Within the official Coastal Zone Boundary (CZB) of Louisiana, alluvium, fresh marsh, salt march, bay, and barrier island environments occur, according to the official Geologic Map of Louisiana compiled by Snead and McCulloh (1984). The Bayou Lafourche, Plaquemines, Isles Dernieres, and Chandeleur barrier-built estuarine systems make up 62 percent of the Modern delta plain, whereas the delta-front estuaries account for 18 percent, and the remaining area in the alluvium represents 20 percent. The barrier-built estuaries represent the largest and most productive component of the Modern delta plain (Gagliano and van Beek, 1970).

COASTAL PROCESSES

Northern Gulf Coast Process Environment

The northern Gulf coast is a microtidal, storm-dominated environment. Nearshore energy levels resulting from wind and wave processes are low, except for the winter passage of extratropical cyclones and the summer occurrence of tropical cyclones. The average wave-height offshore of the Mississippi River delta plain is three feet, wave periods are five to six seconds, and the average deep-water wave power is only 1.8×10^3 Wm^{-1} (Boyd and Penland, 1984). On the average, modal wave conditions occur 4 percent of the time. The dominant onshore wave approach is from the southeast.

Tides are diurnal with a mean range of 1.2 ft. The tidal regime in coastal Louisiana is complicated in fall and winter by

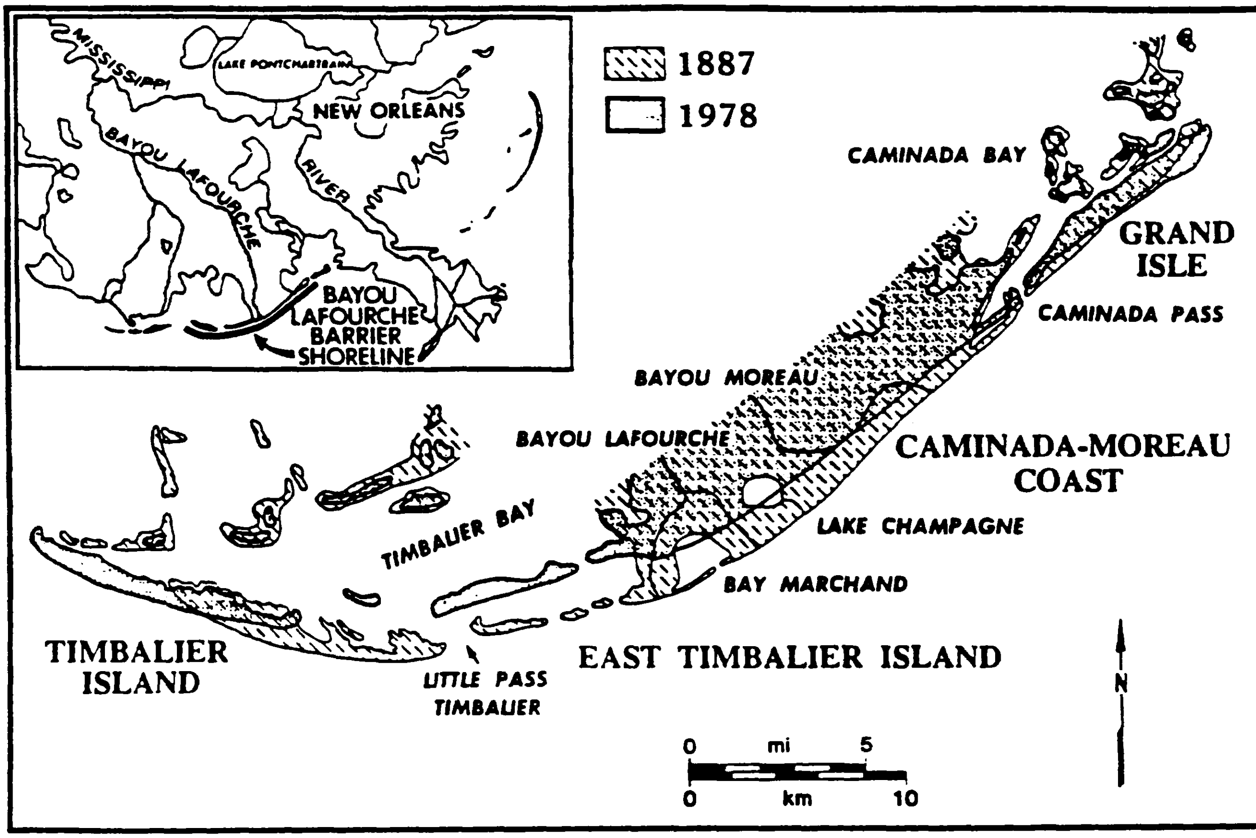

Figure 2. Coastal changes for the Bayou Lafourche barrier shoreline between 1887 and 1978.

extratropical cyclone passages, which generate wind-driven tides in excess of normal astronomical conditions. In a typical year, the 20-30 frontal passages per winter season will elevate and depress mean sea level 1-4 ft (Boyd and Penland, 1981). The highest water levels along the shoreline are produced by tropical cyclones. In Louisiana, tropical storms (winds over 39 mph) have a recurrence interval of 1.6 years, whereas the recurrence interval of hurricanes (winds over 75 mph) is 4.1 years. On the Louisiana coast, hurricanes sometimes generate overwash elevations 6-21 ft above sea level, which can overwash entire barrier shorelines and flood the coast for many miles inland.

Relative Sea Level Rise

Relative sea level rise drives the vertical translation of the erosional shoreface during the transgression of individual barrier-built estuaries. An analysis of tide gage records from areas within abandoned Mississippi River deltas indicates that short-term (<100 years) relative sea level rise within these areas is five times greater than the Gulf of Mexico average and ten times the worldwide average (Penland et al., 1988b). An analysis of 18 tide gage stations in Terrebonne Parish, Louisiana, each with more than 30 years of continuous records, reveals a relative sea level rise rate of 0.40-0.54 in/yr. Based on an analysis of tide gage stations in tectonically stable areas of the Gulf of Mexico, the relative sea level rise rate is 0.08-0.1 in/yr. Eustatic sea level rise is estimated by Gornitz et al. (1982) at 0.04-0.08 in/yr. A comparison of these rates indicates that eustatic factors account for only 5-10 percent of the rate of relative sea level rise observed, showing that compactional subsidence is the primary process driving sea level transgression in Louisiana.

Shoreface Sediment Dispersal

During transgression, barrier shoreline development is controlled by the dispersal pattern on the shoreface of sediments supplied by coastal erosion. During storms, sand is transported seaward and stored lower on the shoreface and inner shelf as the shoreface retreats. Under fair-weather conditions, shoreface erosion diminishes and a variable proportion of this material may again move onshore in the form of multiple near-shore bars and ridge-and-runnel systems (Ritchie and Penland, 1988). The proportion of sediment returned to the beach after storm impact depends on the maximum depth from which waves can transport sediment landward under constructive fair-weather conditions, compared to the maximum depth at which sediments can be transported seaward under erosive storm conditions. Offshore of the Mississippi River, wave-refraction analyses, shelf sediment surveys, and inner-shelf current measurements show that under nonstorm conditions significant onshore sediment transport was restricted to the upper shoreface landward of the 20-ft isobath (Murray, 1970 and 1972). Under storm conditions, sediment can be transported offshore onto the inner shelf, well below the 30-ft isobath. Therefore, since fair-weather wave processes cannot return all the material transported offshore after storm impact, a net export of sediment from the barrier shoreline results.

BARRIER-BUILT ESTRUARINE SYSTEMS

Bayou Lafouche System

The Bayou Lafourche barrier shoreline consists of a central erosional headland, fronted by the Caminada-Moreau coast, and a pair of recurved spits and flanking barrier islands, the Caminada Pass spit and Grand Isle to the east, and the Timbalier Islands to the west. The barrier shoreline encloses Timbalier Bay, Caminada Bay and Barataria Bay and represents a Stage 1 shoreline (Figure 2). Since the abandonment of Bayou Lafourche delta some 300 yr B.P., shoreface erosion has supplied sand for flanking barrier island development (Penland et al., 1986). The primary sand sources are the Bayou Lafourche distributaries and the Cheniere Caminada beach-ridge plain.

The Caminada-Moreau coast is a thin, discontinuous mainland beach with marsh croping out on the lower beach face, reflecting a negative sediment budget and rapid barrier shoreline retreat (Penland and Ritchie, 1979). Sediment abundance increases downdrift to the east and west, leading to the development of washover terraces which eventually coalesce farther downdrift to form a higher, more continuous dune terrace and eventually a continuous foredune ridge on the margins of the headland (Ritchie and Penland, 1988). The Caminada Pass spit was formed by lateral accretion through eastward sand transport away from the Bayou Lafourche erosional headland. The Timbalier Islands and Grand Isle have developed by this same process. The rapid retreat of the erosional headland in the vicinity of Bayou Lafourche and Bay Marchand averaged 60-75 ft/yr and the amount of lateral migration that can be observed at Timbalier Island is more than 5 mi. A similar pattern of shoreline change is seen at Grand Isle.

Plaquemines System

In contrast to the single large headland of the Bayou Lafourche barrier shoreline, the Plaquemines barrier shoreline consists of, west to east, Bayou Robinson, Bayou Grand, and Dry Cypress Bayou, which wer abandoned approximately 350 yr B.P. Bastian Bay contains prolific oyster reefs and is connected with the Gulf of Mexico by small, tide-dominated inlets with relatively large ebb-tidal deltas. Because of the shoreline orientation, southeasterly waves transport available sediment to the west, as evidenced by the geomorphology of barrier islands and spits. Because little sand is available, erosion occurs throughout this area and ranges 15-60 ft/yr (Adams et al., 1978). The largest flanking barrier islands include Shell Island and Grand Terre. Shell Island is a recently breached recurved spit composed primarily of reworked oyster shells. Grand Terre is a sandier example of a flanking barrier island extending across the eastern entrance of Barataria Bay. Over the last 100 years, repeated hurricane impacts have breached Grand Terre, resulting in the development of Pass Abel. Salt marsh loss around the retreating shores of Barataria Bay is increasing its tidal prism, with consequent growth of the tidal inlets. Large ebb-tidal deltas are associated with the tide-dominated inlets of Barataria Pass, Pass Abel, and Quatre Bayoux Pass, which divide Grand Terre into two islands (Figure 3).

Isles Dernieres System

The Isles Dernieres barrier shoreline originated from the Caillou headland distributaries and beach ridges; abandonment occurred 600-800 yr B.P (Penland et al., 1987). The Isles Dernieres barrier island arc encloses Caillou Bay, Terrebonne Bay, and Lake Pelto. Like its Bayou Lafourche counterpart, the Caillou headland of 1853 contains a set of regressive beach ridges and a flanking spit to the west enclosing Caillou Bay and Wine Island, a flanking barrier island lying farther to the east (Penland et al., 1985). Coastal changes observed between 1853 and 1978 in this abandoned delta illustrate the barrier shoreline transition from Stage 1 and Stage 2 (Figure 4). In 1853, Pelto and Big Pelto bays separated the Caillou headland and flanking barriers from the mainland with a narrow tidal channel less than 1500 ft wide. By 1978, these bays had increased in size threefold and coalesced to form Lake Pelto. The Isles Dernieres are now located five miles offshore from the retreating mainland. During this time the Gulf shoreline of the Caillou headland also retreated landward over one mile and segmented to form the four small islands of the Isles Dernieres barrier shoreline.

Chandeleur System

The oldest transgressive barrier island arc found in the Mississippi River delta plain is the Chandeleur Islands (Penland et al, 1985). The asymmetric shape of the Chandeleur Islands is due to its oblique orientation to the dominant southeast wave approach, which leads to the preferential transport of sediment northward (Figure 5). The Chandeleur Islands are more than 45 mi long, and island widths range from 600-7500 ft. Toward the north, large washover fans and flood-tidal deltas separated by hummocky dune fields dominate the island morphology. The wide beaches and foreshore, and multiple bars in the surf zone reflect an abundance of sediment. Southward, island widths narrow, heights decrease, and washover channels and fans give way to discontinuous washover terraces and flats. Farther south, the island arc fragments into a series of small, ephemeral islands and shoals separated by tidal inlets. Shoreline erosion rates range from 45 ft/yr in the south less than 15 ft/yr to the north. Chandeleur-Breton Sound averages 9-15 ft deep and separates the Chandeleur Island arc from the retreating mainland shoreline by more than 15 miles of open water.

COASTAL STRUCTURES

Human Activities

A variety of coastal structures have been constructed along Louisiana's barrier islands in the last 100 years for different purposes (Table 1). Jetties, pipelines, and canals were built to maintain transportation arteries between offshore and onshore areas and through barrier-built estuaries to inland industrial and population centers. Seawalls bulkheads, groins, protective beaches, sand dunes, and vegetation projects were built to protect property against coastal erosion and storm impacts as well as to restore deteriorating barrier island habitats (Mossa et al., 1985).

Navigation

Double jetty systems have been constructed to maintain navigable waterways for the oil and gas industry as well as for coastal fisheries. The impacts of these structures are in accordance with the processes outlined in earlier sections. On their updrift sides the shoreline progrades as sand formerly moving alongshore is trapped. Downdrift the shoreline retreats owing to a lack of sand. Shell Island in 1955 represented

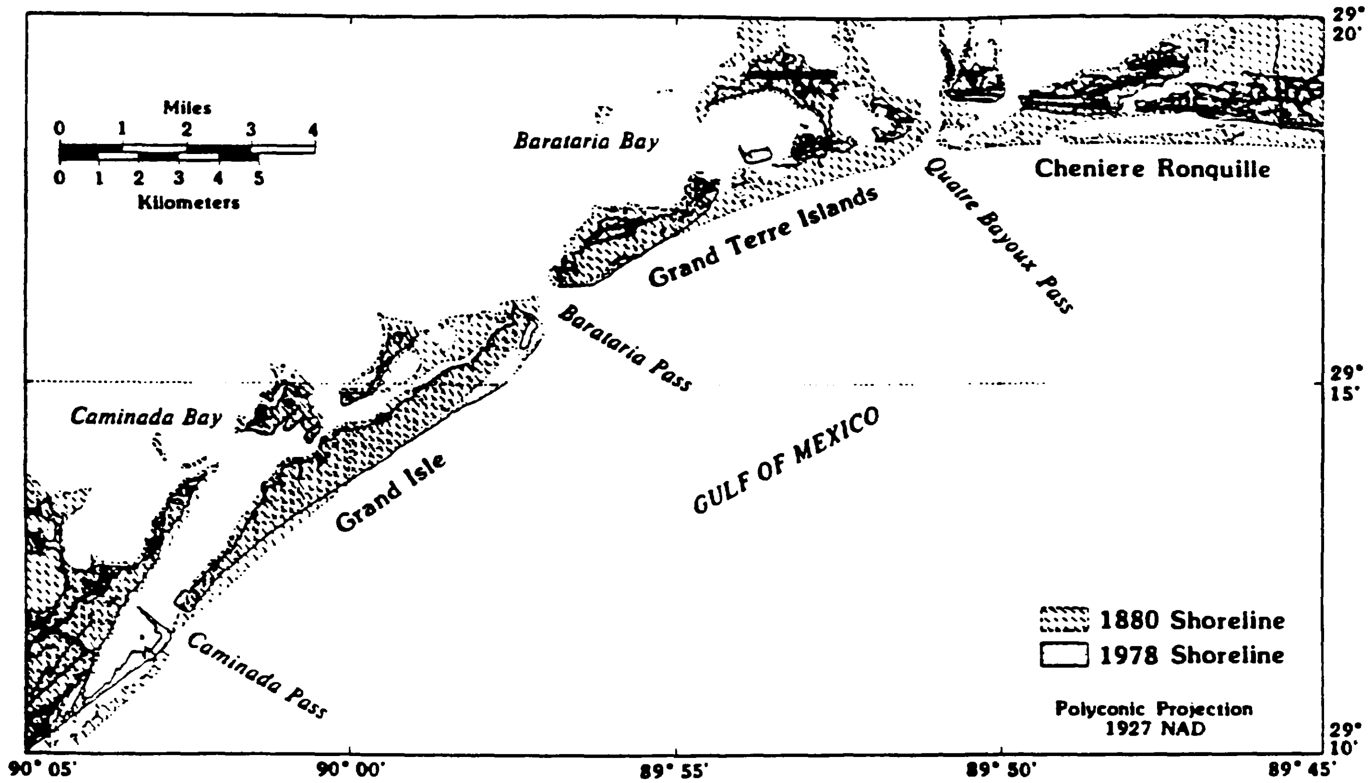

Figure 3. Coastal changes for the Lower Barataria basin between Grand Isle and Chenier Ronquille between 1880 and 1978.

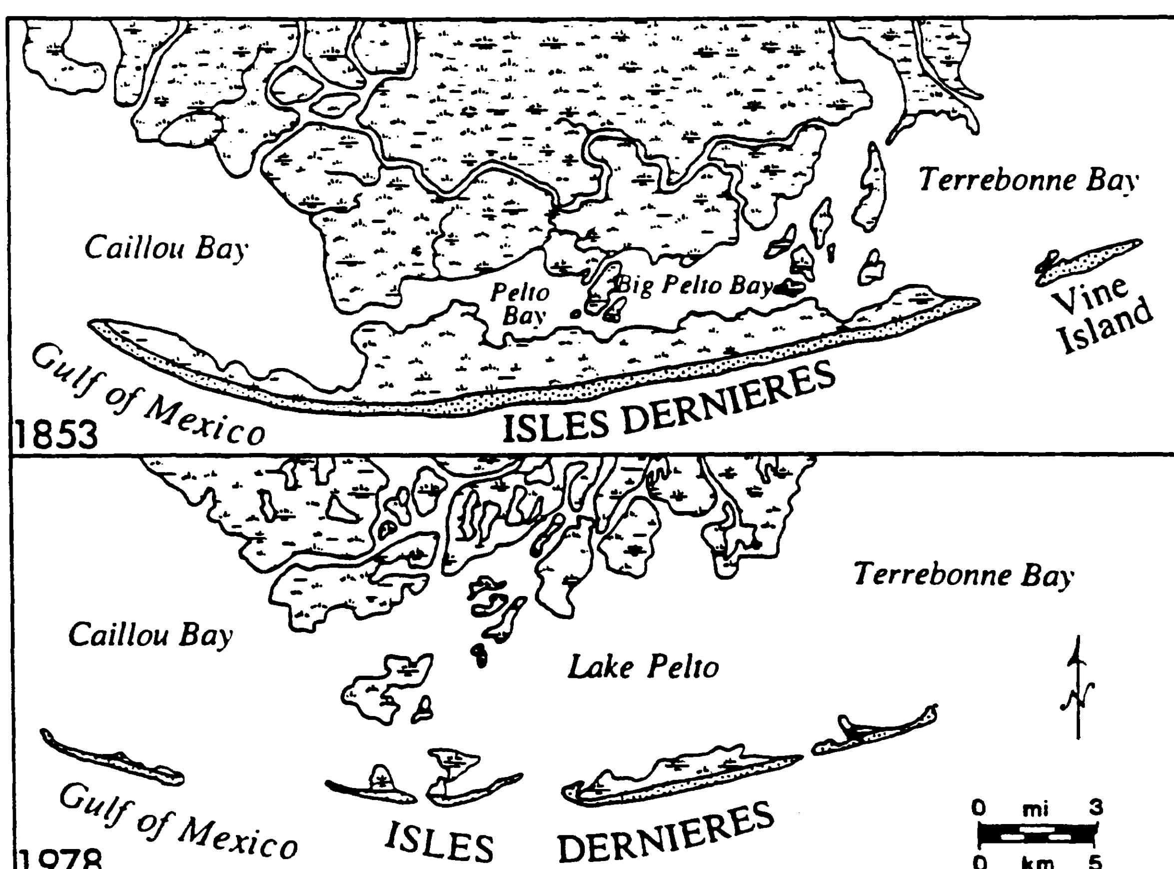

Figure 4. Coastal changes for the Isles Dernieres between 1853 and 1978.

Table 1. Coastal Structure Performance and Impact in Louisiana.

Structure Type	Purpose	Effects	Examples
Updrift jetties	Navigation	Cause severe erosion on downdrift shorelines	Belle Pass Fontenelle Pass
Downdrift jetties	Navigation Erosion control	Reduce erosion locally Impact downdrift shorelines	Barataria Pass Caminada Pass
Dikes	Protection from storms	Reduce or prevent overwash	East Timbalier Island
Riprap revetment (small)	Local erosion control	Reduces erosion locally Impacts downdrift shorelines	Timbalier Island
Riprap revetment (large)	Erosion control	Impedes sediment transport along shoreface	East Timbalier Island
T-Groins	Sediment trapping	May reduce erosion locally Impact downdrift shorelines	East Timbalier Island
Timber groins	Sediment trapping	Reduce erosion locally Impact downdrift shorelines moderately	Grand Isle
Pipeline canals (shore-normal)	Support oil & gas transportation	Act as local sediment sinks for washovers May result in breaching	Throughout study area
Pipeline canals (shore-parallel)	Support oil & gas transportation	Act as sediment sinks for washovers Cause major land loss and may result in breaching	Throughout study area
Beach nourishment	Erosion control Beach building	Rebuilds beaches after storms Reduces erosion	Grand Isle
Dune vegetation	Erosion control	Traps and holds sediment	Timbalier Island
Sand fencing	Dune building	Traps eolian sediment	Caminada-Moreau headland, Timbalier Island, Isles Dernieres
Dune construction	Erosion control Protection from storm surges	May reduce erosion rates, other storm protection	Grand Isle

Source. Mann et al (1984)

a continuous flanking barrier island attached to the Bayou Fontenelle headland (Penland and Boyd, 1981 and 1982; van Beek and Meyer-Arendt, 1982). Construction of the Empire Gulf Waterway jetty system disrupted the natural longshore transport of shell and sand from the headland source and the impact of hurricane Bob in 1979 breached Shell Island. Since then this breach has evolved into a wave-dominated tidal inlet more than two miles wide (Figure 6). At the Timbalier Islands, the construction of the Belle pass jetties cut off these islands from the original sand sources in the Bayou Lafourche erosional headland. Since 1955, the Timbalier Islands have decreased approximately 2 mi² in area due to the reduction in sediment supply. These jetties were placed in an updrift position within the erosional headland sand source thus starving the sand supply downdrift. In contrast, the single jetty at Barataria Pass on the east of Grand Isle was placed in a downdrift flanking barrier island position which lead to the growth of this island at the expense of Grand Terre further east.

Pipelines

The exploration and production of oil and gas in coastal Louisiana during the last 30 years have tremendously impacted coastal Louisiana (Lindstedt, 1985). The most elaborate pipeline network in the world connects production facilities in offshore and coastal Louisiana. The transmission routes make more than 140 landfalls in coastal Louisiana, about 32 of which cross the barrier shorelines (Figure 7). Many of these pipeline transmission routes not only leave large scars through barrier islands, creating weak areas vulnerable to storm overwash and breaching, they can also remove sand from longshore transport. At Cheniere Ronquille a combination of three shore-parallel pipelines dissects the shore, dramatically altering the landscape and increasing erosion (Figure 8). This coastal area represents an old sand-starved erosional headland. In contrast, pipeline landfalls which are properly restored in sandy areas such as Timbalier Island typically have little impact on the landscape. In general one finds in coastal Louisiana that pipelines have greater impact on the morphology of predominantly muddy shorelines than on sandy ones.

Canals

An extensive system of access canals have been dredged in backbarrier bays and marsh areas. Behind East Timbalier island, more than 39 miles of access canals have been dredged in Timbalier Bay in support of oil and gas production. At Timbalier Island, a combination of shore-parallel access canals with shore-normal side channels dissected the island creating several low areas susceptible to storm overwash. Hurricane Danny in 1985 breached a shore-normal access canal in Timbalier Island creating a small tidal inlet (Figure 9). Four months later, 3000 ft to the west, hurricane Juan breached a tidal inlet at the location where the shore-parallel access canal is closest to the coast.

Seawalls

These traditional engineering approaches use static coastal structures such as seawalls or groins constructed of steel, rock, or concrete. This protection concept is designed to stabilize the shoreline in place and minimize the direct impact of coastal processes. Typically, seawalls are built to protect buildings, not beaches. Seawalls constructed of rock have proved expensive and unreliable in stabilizing and protecting barrier islands in Louisiana (Penland and Suter, 1987). Seawalls deteriorate beaches by disrupting the natural patterns of coastal retreat and sediment dispersal, causing accelerated erosion immediately around the coastal structure, as well as downdrift of it. These structures disrupt the dispersal of sand within the island and prevent natural geomorphic processes from operating, as a consequence the island is starved of sand. The length of beach benefited by a seawall is generally much less than the area adversely impacted. The performance of the Timbalier Island and East Timbalier Island seawalls documents that seawalls do not preserve, protect, or restore barrier island habitats in Louisiana.

Since 1970, East Timbalier Island has been the site of the most extensive oil and gas development on Louisiana's barrier islands. To protect these operations and maintain East Timbalier Island, a series of massive seawalls have been constructed. Today, this island is encased in a seawall and is starved of sediment. The first seawall was constructed in stages on the crest of East Timbalier Island several hundred feet landward of the shoreline. The irregular character of the seawall reflects downdrift shoreline retreat between the annual periods of seawall construction and storm impacts (Figure 10). Since construction, the shoreline has continued to retreat landward at a rate of 10-12 ft/yr through and behind the seawall. The 1985 hurricanes breached the East Timbalier Island at more than 10 locations, after penetrating the primary and secondary seawalls. The shoreface profile has oversteepened due to erosion to such an extent that all that remains is a 20 ft vertical wall of rock rubble lying in 15 ft of water.

At Timbalier Island, a small seawall was constructed in the late 1970's to protect an access canal from breaching (Figure 11). Since construction, the beach in front of the seawall has

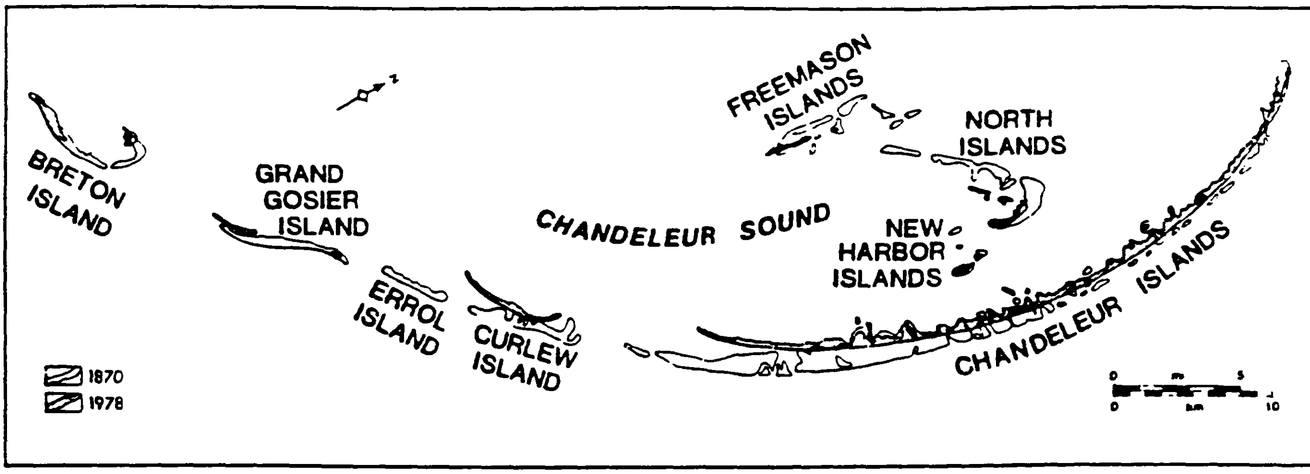

Figure 5. Coastal changes for the Chandeleur Islands between 1870 and 1978.

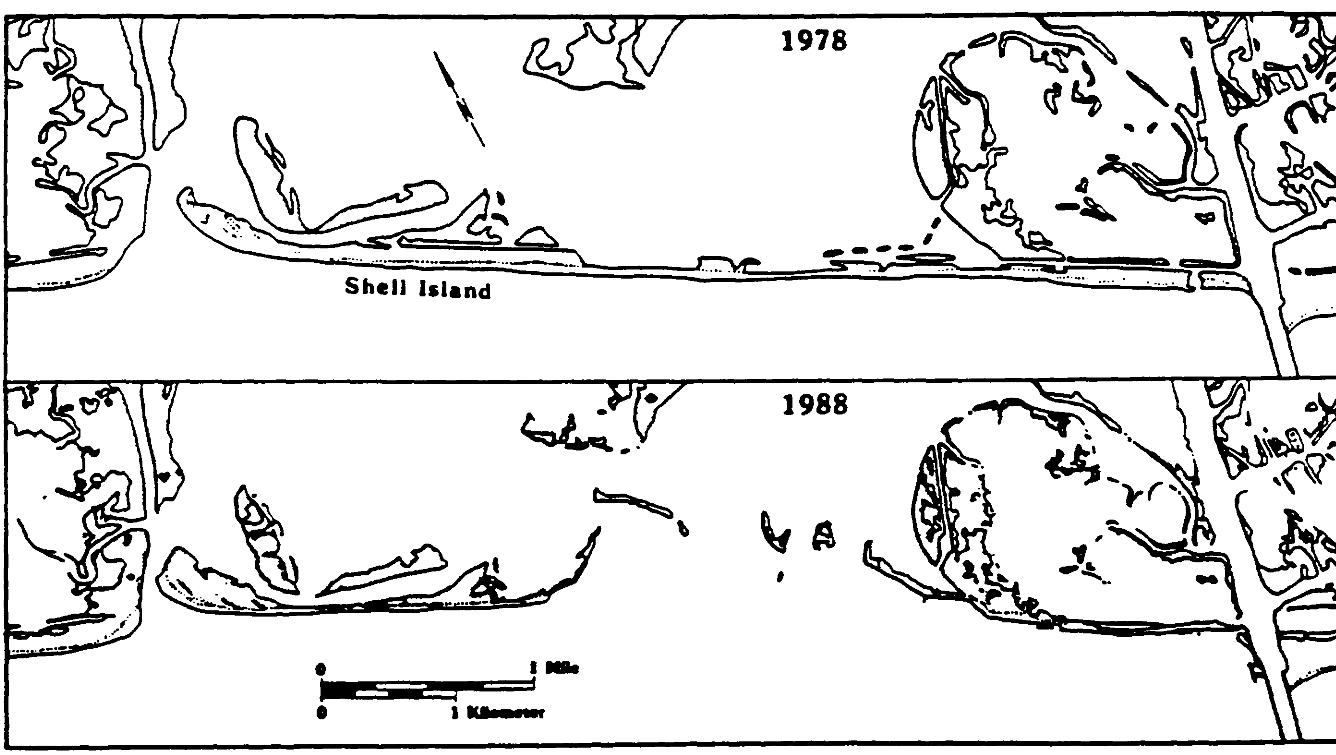

Figure 6. Coastal changes for Shell Island illustrating the impact of the Empire jetty system between 1978 and 1988.

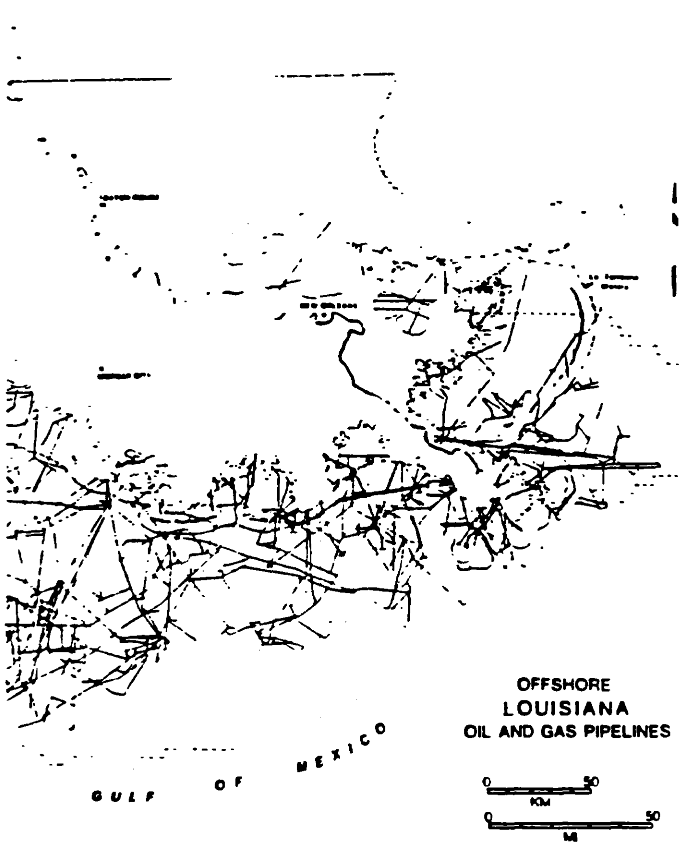

Figure 7. Location diagram of the oil and gas pipelines making landfall in coastal Louisiana (Lindstedt 1985).

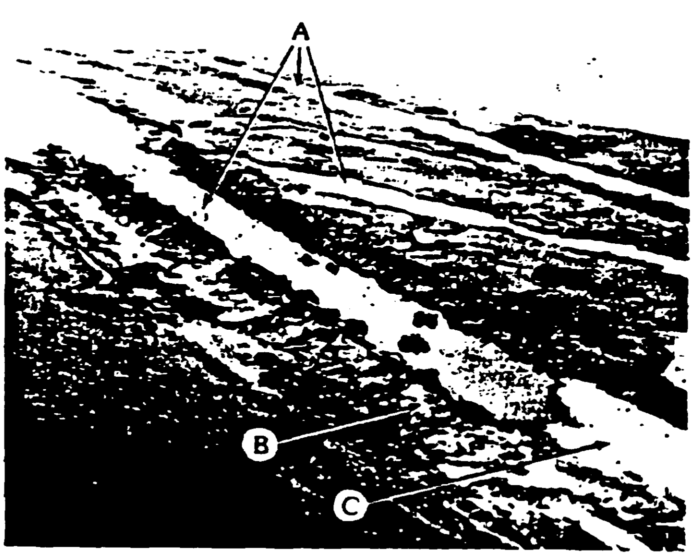

Figure 8. Oblique aerial photograph of the pipeline canals at Cheniere Ronquille: A) pipeline canal, B) dredge spoil, and C) washover sands infilling canal.

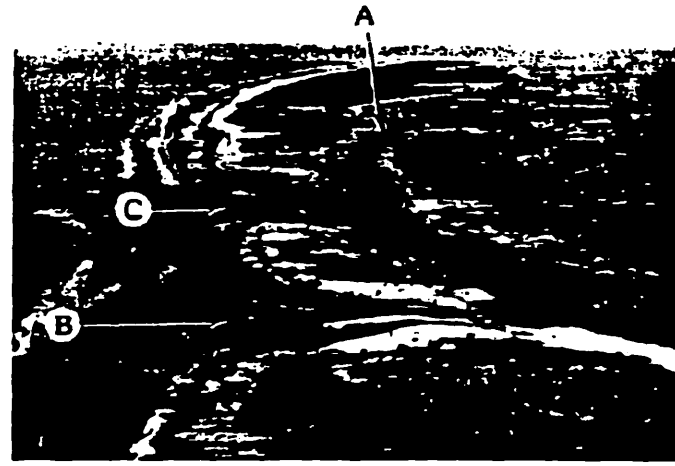

Figure 9. Oblique aerial photograph of the Timbalier Island access canal breaches after the 1985 hurricanes: A) access canal, B) hurricane Danny breach, and C) hurricane Juan breach.

Figure 10. Oblique aerial photograph of the East Timbalier Island seawall: A) primary seawall and, B) secondary seawall.

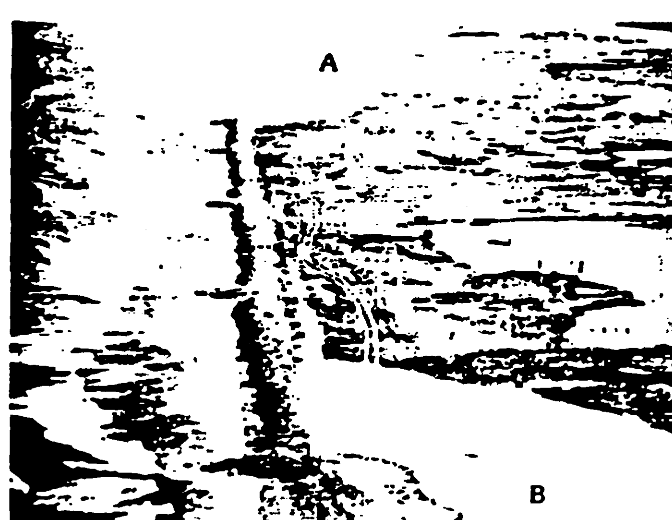

Figure 11. Oblique aerial photograph of the Timbalier Island seawall: A) zone of accelerated downdrift erosion and B) zone of hurricane overwash.

disappeared and downdrift the shoreline in front of a series of access canals has come under increasing erosional pressures due to the deflection of the near-shore bar field further offshore resulting in sand bypassing this area. During the 1985 hurricane impacts, this seawall did not prevent hurricane overwash and channel development into the access canal around its margins.

Groins

Another type of engineering approach is the groin, a shore-normal coastal structure of wood, steel, concrete, or rock, designed to trap sand moving alongshore. On the groin's updift side, material accumulates, while on the downdrift side erosion occurs. This technique has been used at Grand Isle over the last 50 years with little long-term success (Adams et al., 1978). Typically, a series of small groins would be constructed to stabilize a beach in front of developed property. For a short period, the shoreline would be relatively stabilized, however the downdrift shoreline would begin to erode. Eventually, the downdrift property owners had to build additional groins to try to stabilize the eroding beach in front of their property.

Nourishment Projects

Engineering approaches that use coastal structures more compatible with the barrier island environment than are hard structures and lead to island restoration through natural processes. These techniques do not attempt to hold the island in place, a virtually impossible task, but strive to maintain and enhance island integrity as the system migrates landward. These engineering approaches include beach nourishment, shoreface nourishment, island restoration, dune fencing, dune construction, and vegetation management. All of these techniques make use of sediment, vegetation, or a combination of the two

Barrier island restoration involves adding new sediment directly onto the surface of the barrier shoreline. Sand is added to the crest of the beach in order to heighten the dune profile. A mixture of sediment is added to backbarrier areas to increase elevation and widen the island. Dune vegetation is planted on the crest of the island to stabilize the sand, and marsh vegetation is planted to stabilize the newly added material in the backbarrier area. The Terrebonne Parish barrier island restoration project in the eastern Isles Dernieres represents this type of porject (Jones and Edmonson, 1987). Built in 1985, this 38 acre project is 3200 ft long, 1000 ft wide. Sediments were pumped from the margin of Wine Island Pass into a setting basin. The foredune was built to an elevation of eight feet and the average elevation of the backbarrier areas was raised by an average of 3.5 ft. Once the sediments had settled and leached for several months, dune-grass seeds were planted for stabilization. Total cost of the project was $841,980. The restoration work that had been done at this former washover area prevented the Isles Dernieres from being breached in 1985 and reduced by half the amount of hurricane beach erosion in the project area (Figure 12).

Beach nourishment involves the placement of sand directly onto the upper barrier island shoreface to create a protective beach, which can be maintained to provide erosion protection for the shoreline (Figure 13). This technique has been proven cost-effective in Louisiana and other Gulf Coast states. It provides protection from beach erosion and hurricane washover (Combe and Soileau, 1987). This techniques involves building a beach and protective dune onto the upper shoreface.

Figure 12. Oblique aerial photograph of the Terrebonne Parish-Eastern Isles Dernieres barrier island restoration project: A) recently deposited material not yet vegetated, and B) artificial dune with sand fencing.

Figure 13. Oblique aerial photograph of the USACOE Grand Isle hurricane protection and beach erosion project: A) pre-construction shoreline, B) artificial dune, and C) nourished beach.

As a consequence these projects typically experience rapid erosion following construction until a new equilibrium shoreface profile can be established. Typically, about 30 percent of the original volume of material placed on the upper shoreface is required to achieve a new equilibrium profile during the first project year, in subsequent years one can expect a 10 percent per year volume reduction.

The U.S. Army Corps of Engineers' Grand Isle hurricane protection and beach erosion project is an example of this approach (Combe and Soileau, 1987). During 1984 and 1985, an artificial dune 11.5 ft high and a nourished beach 200 ft wide were built utilizing 2,540,00 yd^3 of hydraulic sand fill and ~~,000 yd^3 of mechanically placed fill. The total construction .t was $8,640,000. The impact of the 1985 hurricanes .emonstrated the effectiveness of this design. During hurricanes Danny and Elena, the beaches of Grand Isle eroded and the hurricane protection levee was eroded in three localized areas. A total of 110,000 yd^3 were lost from the project area, or about four percent of the original design volume. An additional 370,000 yd^3 were lost from the project after hurricane Juan, this is about 16 percent of the original design volume. The U.S. Army Corps of Engineers estimated the combined impact of these three storms probably exceeded a storm with an average return interval greater than 100 years. Despite the damage, this project prevented at least $12,000,000 of damages to the structures and public facilities on Grand Isle.

PROTECTION STRATEGY

Strategy

Barrier island erosion and land loss is primarily a function of sediment loss, relative sea level rise, and devegetation. Human impacts are secondary, but often serve to drastically inc· :ase coastal deterioration. To effectively manage this coastal problem, a consistent strategy must be developed and proper tactics applied. In Louisiana, two management options have been applie. One management option was to build coastal structures to combat natural processes and hold the remaining habitats in place, while the other management option has been to replace the material lost from the barrier island system and to hold it in place by planting dune and backbarrier marsh habitats. Of the two options above, the later using sediment nd vegetation have proven to be the most cost-effective chniques capable of preserving and restoring Louisiana rrier shoreline habitats. As a consequence, the stategy of .iy comprehensive management plan to preserve Louisiana's barrier shorelines must be to pursue sediment and vegetation proj cts as well as mitigation projects from reversing the human impacts of man. The tactics of this strategy will include beach nourishment, barrier restoration, shoreface nourishment, vegetation, and coastal structure modification. In order for this approach to be successful, a regularly scheduled maintenance program must be developed for each barrier-built estuary.

Barrier Restoration

This is a new technique developed in Louisiana to restore transgressive barrier island habitats and prevent the island from breaching during storms. As described previously, Terrebonne Parish built a barrier island restoration pilot project in the eastern Isles Dernieres which restored the island (Jones and Edmonson, 1987). This technique involves placement of fill material directly on the crest and backbarrier areas. The fill requirements are much less than a beach nourishment project per linear foot of shoreline. The restoration cost per linear foot restoration cost was $263. This project restored the dunes, vegetated backbarrier terraces, and salt marsh which prevented the island for breaching during the 1985 hurricane impacts

Beach Nourishment

Beach nourishment projects require large volumes of high quality sand for construction, as a consequence of the economy of scale results in reduced construction cost per linear foot of beach. The average per linear foot construction cost for the USACOE 1985 Grand Isle project wad $233 for 37,100 linear feet of beach; this is less than the cost of the Terrebonne Parish barrier island restoration project, which required 10 times less material. In terms of cost per yd^3, the average was $2.94 per yd^3 of fill. Nationwide the typical cost of beach nourishment is $1.40-12.08 per yd^3 of fill (National Research Council, 1987).

Shoreface Nourishment

Shoreface nourishment is a new technique which has been tested in Australia, Denmark and at Hilton Head Island, South Carolina (Bruun, 1988a). This technique builds a beach-shoreface profile in equilibrium with its process environment; as a consequence construction and maintenance costs are lower and the rapid beach erosion which immediately follows in the construction of beach nourishment projects does not occur. The advantage of the shoreface nourishment technique is the ease of dumping and the minimal earth moving equipment required. A cost comparison in Queensland, Australia (1986) indicated the average beach nourish cost are $3.50 yd^3 for beach fill and $1.50 yd^3 for shoreface fill (Bruun, 1988b).

Vegetation

Building dunes and backbarrier habitats using vegetation on natural island surfaces or on dredged material is the most inexpensive method of protection (Mendelssohn, 1987). Vegetation programs costs significantly less than the various dredged material techniques and hurricane impact research has shown that dune and marsh vegetation are extremely effective at retarding coastal erosion. When vegetation is used in combination with nourishment or restoration projects, new and diverse barrier habitats can be built. The costs for a typical dune building project is $5-10 per linear foot of barrier island.

Coastal Structure Modification

A variety of coastal structures have been built for different purposes in the barrier-built estuaries. Research has shows these structures are accelerating the erosion of the coast and must be modified or removed before a restoration or nourishment project can be successfully implemented. At Shell Island, the Empire to Gulf jetty system should be removed. Further east at Cheniere Ronquille and the Timbalier Islands, the extensive series of pipeline canals should be backfilled. A barrier habitat creation plan using the maintenance dredge spoil from the Barataria Waterway, Belle Pass navigation channel, and the Houma navigation channel needs implementation. The small seawall located on the central beach of Timbalier Island must be removed. Removing the massive East Timbalier Island is not practical, but is recommended from a coastal system point-of-view.

DISCUSSION

State- and federal-supported research on coastal erosion as well as our coastal protection experience in Louisiana has documented that the most cost-effective methods for preserving and restoring Louisiana's coastal environments are ones that work with or enhance coastal geomorphological processes. When sand loss is a problem, it should be replaced; when vegetation loss is a problem, it should be replaced; do not build a seawall on a retreating barrier island to preserve its habitat quality and diversity. Sediment and vegetation are the only tools that will be effective in preserving Louisiana's barrier islands and shoreline. The protection of barrier-built estuaries must be placed on the same parity as navigation and flood control in order to ensure the future of this important natural coastal resource.

CONCLUSION

1. Jetties, seawalls, canals, and groin systems generally accelerate barrier shoreline erosion and deteriorate estuarine habitat quality.

2. Previous attempts at coastal preservation have shown that an integrated approach which enhances or works with natural processes, rather than combatting them, is the most effective. Highways are built, with regularly scheduled maintenance programs and this same priority and concept should be applied to the coastal zone. Preservation of our coastal environments requires a dynamic landscape maintenance program of regularly scheduled barrier restoration, beach nourishment, shoreface nourishment, vegetation, and coastal structure modification projects.

3. Sediment and vegetation are the most cost-effective tools for restoring and preserving Louisina's barrier-built estuaries.

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LOUISIANA BARRIER ISLAND EROSION STUDY: FURTHER RESULTS

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Introduction

Of any region around the United States, Louisiana has the greatest rates of shoreline erosion and wetland loss. Gagliano and others (1981) estimated rates of wetland loss in the Mississippi River delta plain to be greater than 102 km^2/yr. In places, erosion of the barrier islands exceeds 20 m/yr. Unlike the model of barrier islands migrating landward with no change in width, Louisiana's barrier islands are eroding on both the Gulf and bay sides. Between 1890 and 1979, for example, Louisiana's barrier islands have decreased in area by 37%. A concern is that the barriers will eventually disappear. Without the barriers, the circulation and salinity regimes in the back bays will be altered, thus altering the natural habitats. Furthermore, the loss of barrier islands will alter the wave energy in the back bays and along the marsh shorelines potentially accelerating erosion and land loss. The potential loss of Louisiana's coastal wetlands is important to the state and Nation; Louisiana's wetlands comprise 41% of the Nation's total coastal wetland area and support a one billion dollar a year fishery industry.

The physical processes actually causing the erosion of barrier islands are not well understood. Through developing a better understanding of these processes, we should be able to better predict the erosion of barrier islands. Improved capability to predict erosion is particularly important given the forecasts of increased sea-level rise in the future. In 1986, the U.S. Geological Survey and the Louisiana Geological Survey began a cooperative study of the processes causing the extreme rate of erosion of Louisiana's barrier islands and of the shallow geologic framework within which the erosion takes place. At this writing, we have completed 3.5 years of the planned 5 year effort. Sallenger and others (1987) provided an overview of the study objectives and initial research activities. In this paper, we will review study objectives and will present selected results. Results discussed here are the promising offshore sand resources of potential use for beach nourishment and bypassing of large volumes of sand-size sediment via natural processes around a tidal inlet.

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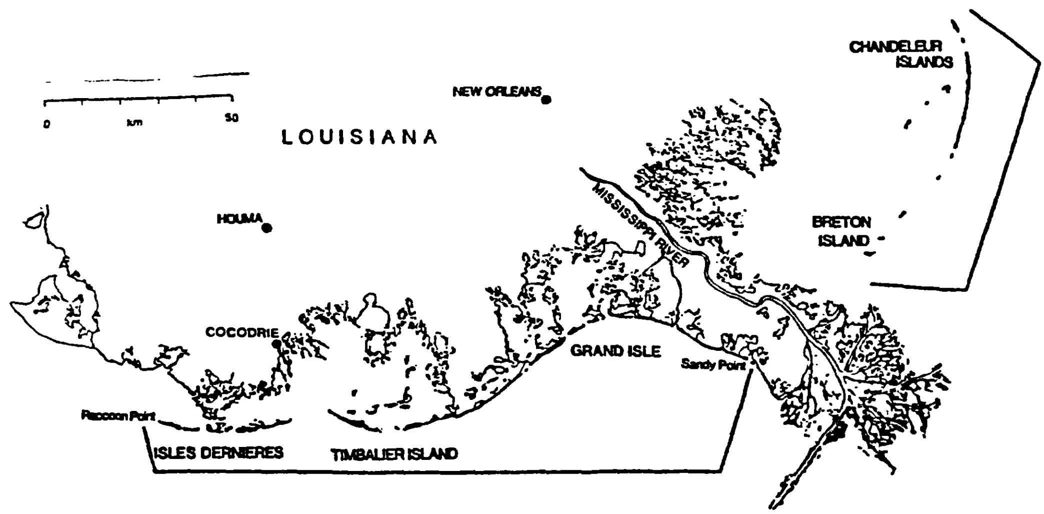

Figure 1. Study location

Study Overview

The study area includes most of the barrier islands in the delta plain province of coastal Louisiana (Figure 1). The study is divided into three overlapping elements: geologic development of barrier islands, processes of barrier island erosion, and transfer and application of results.

Geological Development of Barrier Islands

An initial step in determining processes of erosion was to establish the shallow geologic framework within which the barriers formed and migrated landward. These efforts, which involve both stratigraphy and geomorphology, are developing a regional understanding of the processes involved.

The development of barrier islands in Louisiana is related to the development and subsequent erosion of abandoned Mississippi River deltas (Kolb and van Lopik, 1958; Fisk, 1944; Frazier, 1967; Penland and Boyd, 1981; Penland and others, 1988, Coleman, 1988). Over the past 7,000 years, the changing course of the Mississippi River has lead to the creation of at least six delta complexes which, together, create complicated facies relationships (Coleman and Gagliano, 1964; Frazier, 1967). A primary objective of this study is to decipher and map facies relationships and stratigraphy between the different transgressive shorelines and their associated deltas. The facies are being determined with high-resolution geophysical profiles and 12-m long vibracores, supplemented by detailed surface sediment sampling. Sea-level history and age relationships are being determined through geochronological techniques and analyses of tide gauge records.

Storms such as hurricanes and cold fronts contribute significantly to the erosion of Louisiana's barrier islands. The impact of storms on the coastal geomorphology of the islands is being investigated with pre- and post-storm aerial video-mapping, vertical mapping photography, and beach profiles. These studies are providing regional scale information on the variability of shoreline erosion and of the processes responsible for the erosion.

Processes of Barrier Island Erosion

Many processes contribute to the erosion of Louisiana's barrier islands. In our study, we focus on a few of the processes that are not well understood but that are approachable experimentally. These processes are sea-level rise, storm overwash, net offshore loss of sand, and longshore sediment transport.

In coastal Louisiana, sea level is rising rapidly, up to 1.3 cm/yr, relative to the land (Penland and others, 1987). Most of the sea-level rise, roughly 90%, is due to subsidence. Models which predict erosion due to sea-level rise (e.g. Everts, 1985) are being tested with data on erosion measured from comparisons of historical bathymetry.

Waves overtopping the low barrier islands during storms transport sand landward and contribute to the landward migration of the barrier islands. However, the magnitude of this overwash relative to other processes is not well known. We are conducting experiments on the Isles Dernieres to better understand overwash dynamics. A transect across the barrier has been instrumented with a variety of sensors to measure overwash speed and the response of the beach to overwash.

Due to a variety of processes, sand potentially could be transported seaward to the inner shelf during storms. It may be possible for sand to be driven so far offshore that it is difficult for the sand to be returned during non-storm conditions. Several experiments have been conducted to measure the water movement and flux of sediment offshore a barrier island during storms.

Gradients in longshore sediment transport lead to patterns of erosion and accretion along the shoreline. We are conducting a major effort in comparing historical (1890s to the present) bathymetry in the study area. The results are relevant to the role of longshore transport to the erosion of the islands.

Application of Results

The results of this study can be applied to various practical problems. For example, a better understanding of the rates of removal of sand from the beaches is applicable to determining how often an artificially nourished beach will need to be renourished. Investigations of the geologic framework within which barriers formed also leads to assessments of sand resources useful for beach nourishment.

Selected Results

In this section we provide example results of the study. From the geologic framework part of the study, we focus on some initial results of the extensive geophysical and vibracore surveys that are relevant to geologic framework and offshore sand resources. From the processes part of the study, we discuss some of the results of comparing historical bathymetry which shows massive bypassing of a tidal inlet due to longshore transport processes.

Geologic Framework and Offshore Sand Resources

During the course of the present study and for several years prior to this study, the U.S. Geological Survey has been working cooperatively with the Louisiana Geological Survey to decipher the shallow geologic framework offshore coastal Louisiana. A total of ten high-resolution seismic surveys have been conducted using side scan sonar and subbottom profiling systems. Also, three offshore vibracore surveys were conducted acquiring a total of more than 300 core samples measuring 7-12m in length.

Using this data base, the geologic framework studies to date have focused on two major themes, geologic history and nearshore sand resources. In order to predict future coastal conditions, it is important to understand how the coastal zone formed, what processes drive coastal evolution, and the rates at which the coastal zone changes. The distribution and quality of nearshore sand resources are needed for planning and constructing coastal erosion control projects, such as barrier island restoration or beach nourishment projects.

The continental shelf offshore of the Mississippi River delta plain contains the geologic record of 18,000 years of coastal change during the Holocene transgression. The continental shelf record tells a history of delta plain development, barrier island formation, and coastal submergence. These studies have refined our knowledge of the timing and development of delta plain formation. Originally, the formation of the delta plain was described within the context of a single Holocene delta plain model which began forming about 5,000 years ago at the end of the Holocene transgression. The interpretation of new high resolution seismic and vibracore data has shown that the single delta plain model can be re-interpreted as a series of three stacked delta plains representing transgressive system tracts deposited during stillstands in the Holocene transgression (Figure 2). Each of these tracts is chronologically separated by a sea level rise event which submerged the entire margins of each of these delta plains.

The cooperative USGS/LGS geophysical surveys have also documented 55 potential sediment sources suitable for beach nourishment, barrier island restoration, and backbarrier marsh creation between Raccoon Point and Sandy Point. The resource targets include inner shelf shoal, beach ridge, recurved spit, barrier shoreface, tidal delta, tidal channel, and distributary channel sand bodies. Figure 3 illustrates the location of sand resource targets in the central Terrebonne Parish coastal waters. The most promising sand resources in this area are Ship Shoal and the sand bodies associated with Cat Island Pass (see area 27, in Figure 3). As an example of our resource results, we discuss Ship Shoal below.

Ship Shoal is 15 km offshore of the Isles Dernieres (Figure 4). It is the largest and highest quality sand body in the south-central Louisiana region. Ship Shoal is a shore-parallel sand body 50 km long and 8-12 km wide, lying in 10 m of water; it has a relief above the surrounding shelf ranging from 3-7 m. Four major sand facies are present within Ship Shoal including, 1) shoal crest, 2) shoal front, 3) shoal base, and 4) sand sheet. The shoal-crest deposits average 1.5 m thick. The shoal-front deposits are thickest in the central region, averaging 3-4 m; the shoal-base deposits are 0.5-1.0 m thick. Ship Shoal contains over 1.3 billion m^3 of sand in the grain size range of 2-3 phi, similar in texture to the sand from the beaches of Isles Dernieres and Timbalier Islands. The western portion of the shoal is the thickest, and is underlain by the sandy fill of the distributary channels. The amount of borrow material in this deposit alone could meet the needs for barrier island restoration, beach nourishment, and project maintenance of the Isles Dernieres and Timbalier Island for the foreseeable future.

Comparisons of Historical Bathymetry

Part of the study involves comparing historical bathymetry of the nearshore region to determine patterns and volumes of sediment eroded and accreted. By the conclusion of the study, we will complete this type of effort for the part of the study area to the west of the Mississippi River (Figure 1). For this paper, we focus on the nearshore areas near the Isles Dernieres. The islands known as Isles Dernieres have undergone extensive shoreline changes over the past century (Figure 5). Between 1890 and 1986, 76% of the island area was eroded. In the present study, we

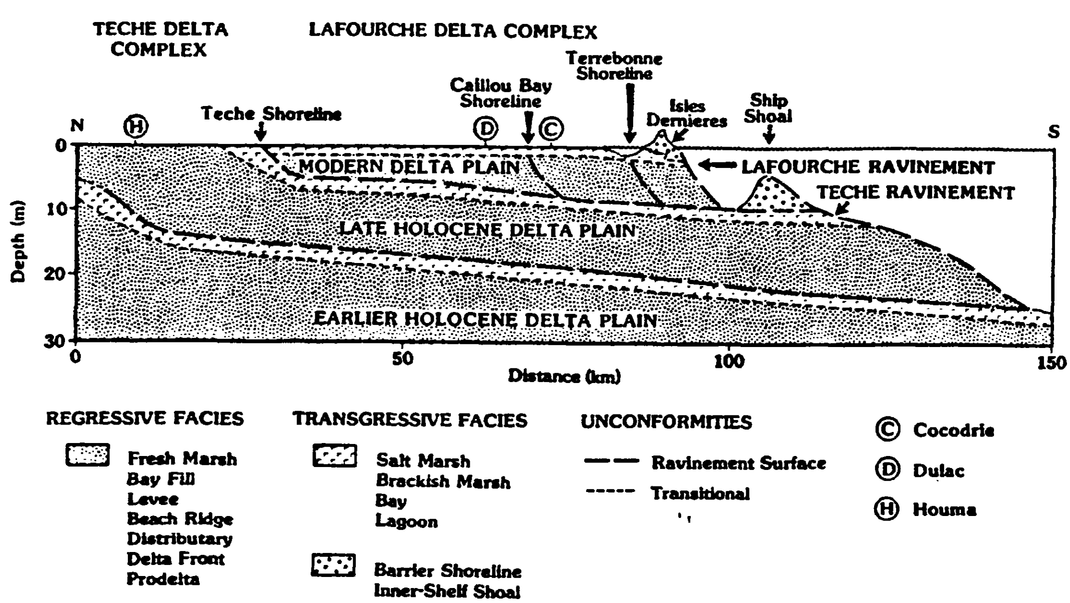

Figure 2. Facies associated with the LaFourche delta complex.

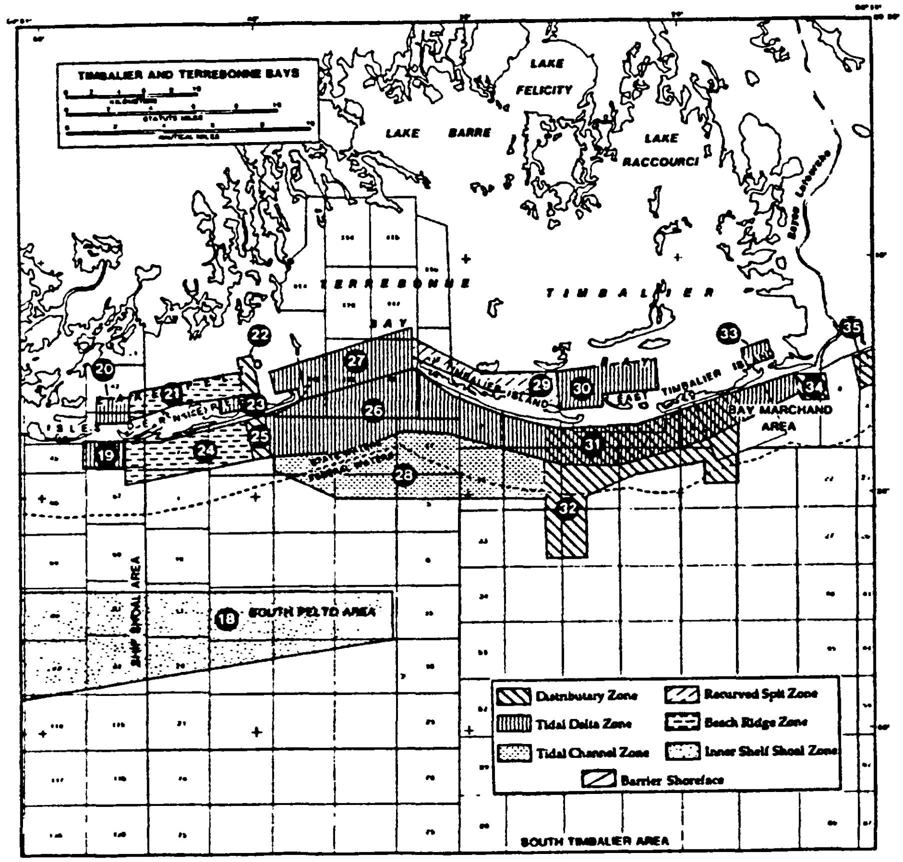

Figure 3. Potential sediment sources suitable for beach nourishment, barrier island restoration, and back barrier marsh creation.

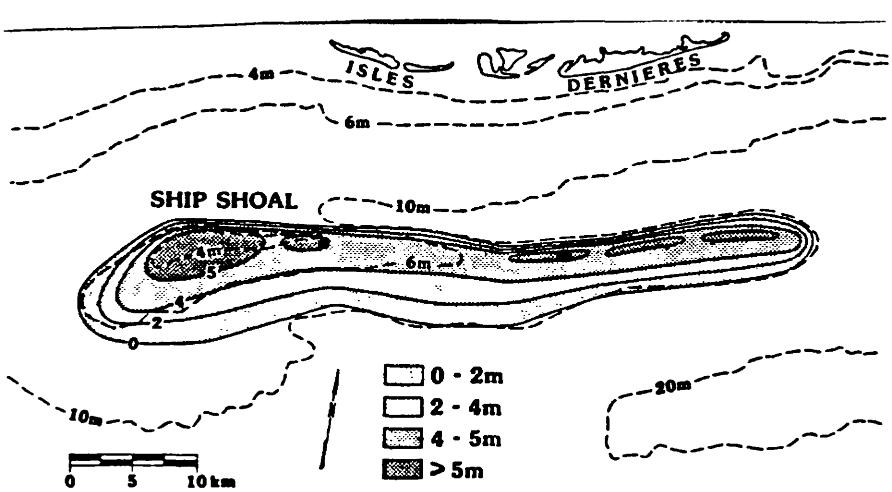

Figure 4. Sand isopachs and bathymetry in the vicinity of Ship Shoal.

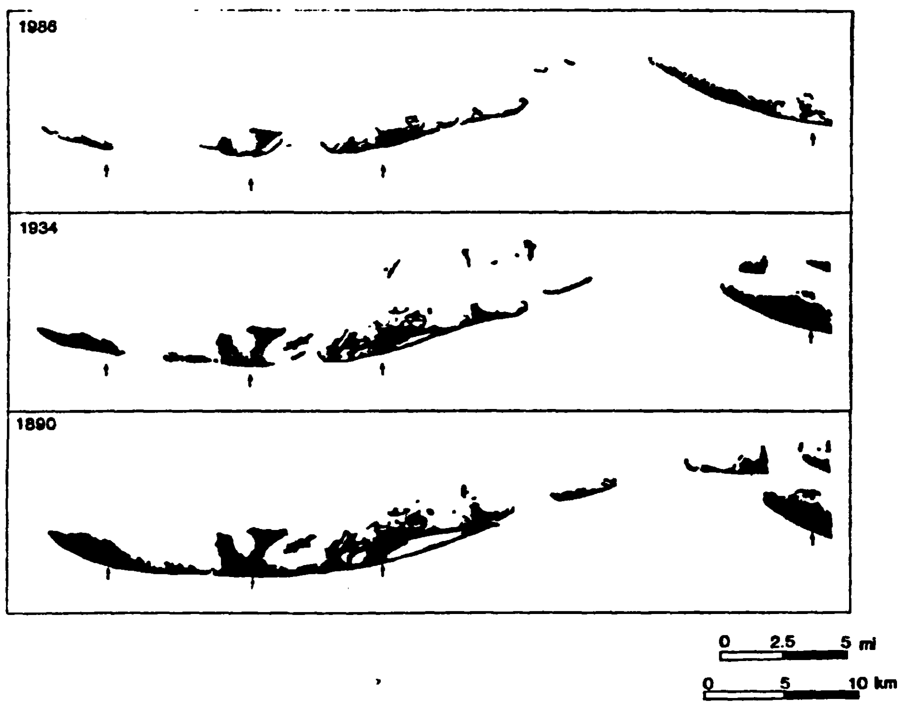

Figure 5. Shoreline changes in the Isles Dernieres. The Gulf of Mexico is to the bottom of each map. The arrows are in the same horizontal position in each map.

have extended the shoreline change analyses by comparing bathymetry from three different dates: 1890, 1930's, and a precision survey done specifically for this study in 1986 (Figure 6A; Williams and others, 1989)

Digital data were available for the 1930's (from the National Ocean Survey) and for the USGS survey in 1986. The data from the 1890's were available on stable base smooth sheets. These data were digitized and are available to other investigators (Jaffe and others, 1988). Using surface modeling software, we have gridded the data. The vertical datums of the bathymetry are essentially mean low water at the time of the surveys. As noted earlier, the area has undergone extensive relative sea level rise mostly due to subsidence. As a consequence of the relative sea level rise, we must adjust the vertical datums in order to compare the historical bathymetry. Since there were no direct measurements of sea level spanning the times of the bathymetric surveys, we examined several indirect methods for adjusting datums. These included extrapolating time series of measurements of sea level change to the time of each survey and examining depth changes between surveys in areas where we do not expect significant erosion or accretion. Each of the methods produced consistent results, and, in regard to the interpretations made here, the use of one method over another would not result in significant changes in the interpretations of patterns of erosion and accretion. A full discussion of the rationale used in adjusting datums is given in Jaffe and others, 1988.

The gridded bathymetric data from each time period were subtracted from grids of other time periods in order to determine patterns of erosion and accretion. A simplified example shows patterns of change greater than 0.5 m that occurred between 1934 to 1986 (Figure 6B). The comparison shows a number of interesting features, some expected some not.

Ship Shoal, the large shoal offshore of Isle Dernieres that was discussed as a significant source of sand in the earlier section, shows clear evidence of onshore migration. Over a 52 year period, vertical accretion in excess of 0.5 m has extended landward over horizontal distances as much as 3 km. The broadest extent of accretion occurs onshore of the shallowest portion of the shoal in depths less than 4 m. This accretion is consistent with shoaling, asymmetric waves forcing net landward

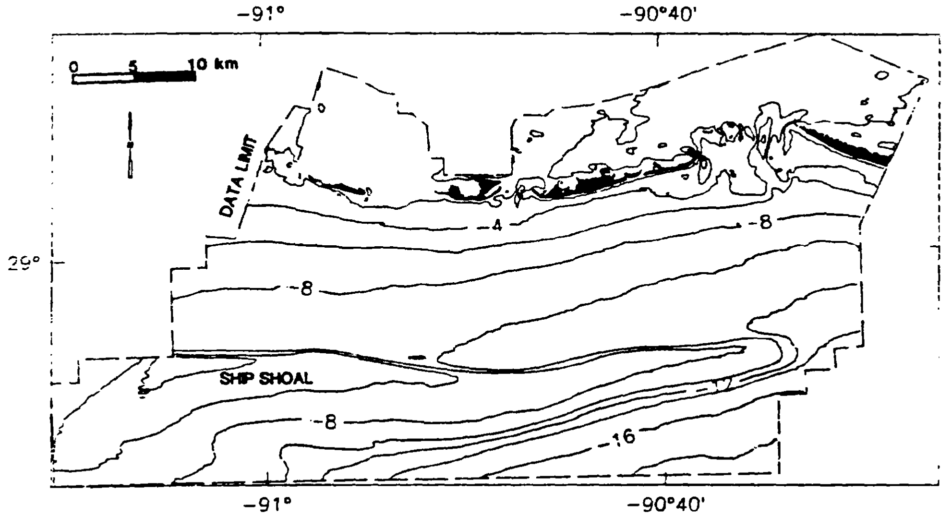

Figure 6A. Bathymetry surveyed in 1986 in the vicinity of Isles Dernieres and Ship Shoal. Contour intervals are in meters.

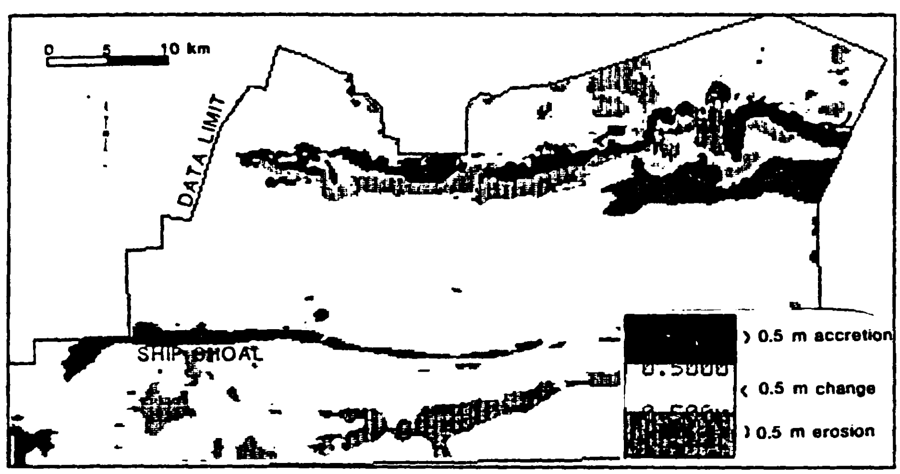

Figure 6B. Sea-floor change from 1934 to 1986.

sand transport over the crest of the shoal.

The seaward margin of the Isle Dernieres has undergone extensive erosion. The erosion extends offshore over distances of 2 to 3 km. The qualitative pattern is consistent with expected erosion of the shoreface in response to sea-level rise relative to the land. Since much of the eroded sediment is mud, which may be widely dispersed, there may not necessarily be a balancing amount of accretion.

Tidal inlets along the length of Isle Dernieres have, in general, migrated from east to west in response to the net direction of longshore transport. For example, over the 52 year period, Cat Island Pass has migrated westward 1 km, or about 20 m/yr.

The most surprising aspect of the bathymetric comparison is the sand body that has developed seaward of Cat Island Pass. This sand body is 18 km long, 4 km wide, and as much as 1.8 m thick. The sand body occurs in water depths of 6 to 8 m. The sand body has built to the west and is effectively bypassing the inlet. This and adjacent sand bodies could make valuable sand resources for beach nourishment. Also, should the sand body continue to grow to the west, the Isle Dernieres will be naturally nourished. To some extent, this may already be occurring. Note that the shoreface erosion on the east end of Isle Dernieres, in the vicinity of the offshore sand body, is not as extensive as erosion elsewhere on Isle Dernieres.

Concluding Remarks

At this writing, the Louisiana Barrier Island Erosion Study is 3 1/2 years into a 5 year study. Examples of some initial results are given in this progress report. By the end of the study, we plan to publish a series of final reports that include:

1.) an atlas on historic shoreline changes of Louisiana's barrier islands.
2.) an atlas on the geologic framework and evolutionary development of Louisiana's barrier islands and continental shelf including seismic cross sections, cores, surficial sediments and isopach maps of sediment thicknesses.
3.) an atlas on historic bathymetric changes including patterns and quantities of material eroded on the innershelf.
4.) a multi-chaptered final report detailing the scientific findings of the study as well as discussions of what the results mean in regard to the problems of forecasting erosion and managing coastal resources.

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SEA-LEVEL RISE AND SUBSIDENCE IN LOUISIANA AND THE GULF OF MEXICO

Karen E. Ramsey and Shea Penland[1]

ABSTRACT

Data from two tide gauge networks established and maintained by the National Ocean Survey (NOS) and the U.S. Army Corps of Engineers (USACE) were analyzed to determine rates of sea-level rise and subsidence in Louisiana. Eighty tidal stations along coastal Louisiana were initially examined in this study. Only 20 of these stations had long-term records, records of 20 or more years of data, and quality data sufficient for analysis. The tidal data indicated that Louisiana is facing the highest rates of subsidence and sea-level rise in the United States. Within the Mississippi River delta plain, the Houma tide gauge documented a relative sea-level rise rate of 1.09 cm/yr (0.43 in./yr) from 1946 to 1988. On the coast, Eugene Island documented a slightly higher relative sea-level rise rate of 1.17 cm/yr (0.46 in./yr). Representative water-level histories from the Chenier plain, Teche basin, Terrebonne delta plain, Barataria basin, Balize delta plain, St. Bernard delta plain, and Pontchartrain basin indicate the regional rates of relative sea-level rise decreased to the east and the west from the Terrebonne coastal area.

In comparison with other National Ocean Survey tidal records throughout the U.S. Gulf Coast, Louisiana is experiencing the highest relative sea-level rise at 1.04 cm/yr (0.41 in./yr) for Grand Isle. The rates of sea-level rise decrease from 0.63 cm/yr (0.25 in./yr) at Galveston, Texas to 0.15 cm/yr (0.06 in./yr) at Biloxi, Mississippi. Mean relative sea-level rise in Louisiana is more than five times the Gulf of Mexico average, and 10 times faster than the rest of the globe.

Rapid rates of sea-level rise observed in Louisiana can be attributed to compactional subsidence in the Mississippi River delta plain. Louisiana directly overlies the entrenched Pleistocene valley of the Mississippi River, which is filled with Holocene deltaic sediments more than 150 m (490 ft) thick. Subsidence contributes up to 80% of the observed relative water-level rise rate at the tidal stations. In Texas, subsidence contributes up to only 60% of the water-level rise rate. Mississippi and Florida tidal stations show only the effects of eustasy.

INTRODUCTION

Louisiana has the highest observed sea-level rise, coastal land loss and barrier island erosion rates in the United States (Fig. 1). Rapid relative sea-level rise induced by delta-plain subsidence and a deficit of terrigenous wetland sedimentation are the primary factors driving the deterioration of Louisiana's coastal zone. Land loss rates in the Mississippi River delta plain exceed 102 km^2/yr (39 mi^2/yr) (Fig. 2) (Gagliano et al, 1981). Shoreline erosion in some areas exceeds 5-20 m/yr (16-66 ft/yr) (Penland and Boyd, 1981). In 1880, Louisiana's barrier islands covered 92.4 km^2 (35.7 mi^2) in total area. By the year 1979, the barrier islands decreased by 37.4% to 57.8 km^2 (22.3 mi^2). At these rates, the barrier islands will be converted into submerged sand shoals in 56 years (Penland and Suter, 1988). Plaquemines Parish will be converted into open water within 52 years and Terrebonne Parish will be converted into open water within 102 years (Gagliano et al, 1981). The Environmental Protection Agency (EPA) and National Research Council (NRC) forecast sea level will rise at a rate between 0.44 and 3.04 cm/yr (0.17 and 1.20 in./yr) (National Research Council, 1987; Titus, 1988). With these increased sea-level rise rates, coastal erosion and land loss will far exceed the currently severe rates in Louisiana. The objective of this paper is to document the trends of sea-level rise and subsidence in the

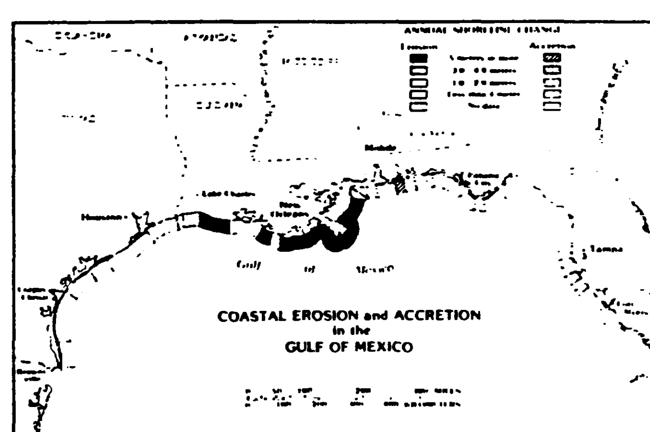

Figure 1. Annual shoreline change in Louisiana (after U.S. Geological Survey, 1989).

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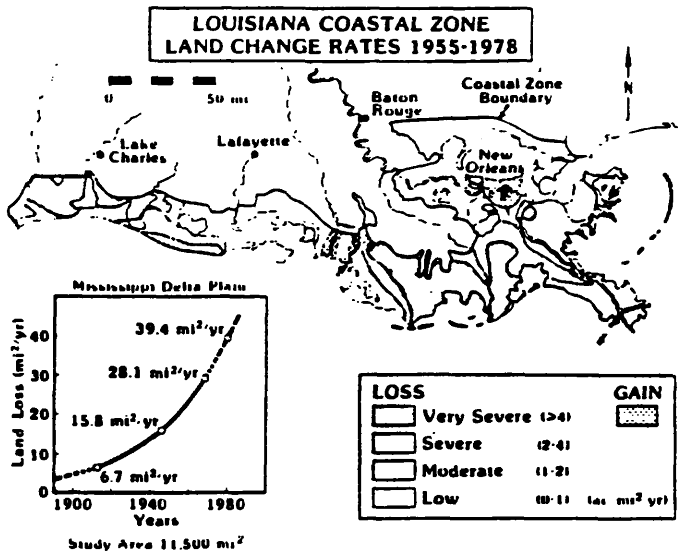

Figure 2. Louisiana has the highest rates of land loss in North America (after Gagliano et al, 1981).

Gulf of Mexico and Louisiana in order to understand the magnitude of this coastal process.

PREVIOUS STUDIES

Previous studies have indicated that analysis of tidal data from tide gauge stations is a viable method of determining relative sea-level rise (Marmer, 1954; Gornitz et al, 1982; Hicks et al, 1983; Pirazzoli, 1986; Gornitz and Lebedeff, 1987; Hicks and Hickman, 1988; Penland et al, 1989). Hicks (1968) indicated the period of record should exceed 20 years to balance out any water-level variations from the lunar nodal tidal cycle, which takes the moon 18.6 years to complete. Hicks (1968) also determined that by using records exceeding 20 years or more, non-tidal effects will balance out such as wind, direct atmospheric pressure, river discharge, currents, water temperature and salinity. Therefore, this investigation used only stations with long-term records exceeding 40 years or more of data.

DATA BASE AND STUDY OBJECTIVES

Two tide gauge networks exist in the northern Gulf of Mexico region. National Ocean Survey (NOS) established and maintains nine long-term tidal stations along the coastal zone (Fig. 3a). The oldest station, established in 1908, is in Galveston, Texas. Only two long-term stations were established in Louisiana. The station located at Eugene Island has been in existence since 1933. The other station is Bayou Rigaud on the east end of Grand Isle. The U.S. Army Corps of Engineers (USACE) maintains over 70 stations in coastal Louisiana, but only 20 of these stations have records of sufficient data quality (Fig. 3b).

The objectives of this study were to document the rate, regional distribution, and character of relative sea-level rise rates in Louisiana and to compare them to the global and Gulf of Mexico trends. Regional variability was determined by the comparison of the Louisiana stations to stations in Texas, Mississippi and Florida. The third objective was to separate eustasy from subsidence in the tide gauge records.

SEA-LEVEL RISE

Relative sea level (RSL) refers to the long-term vertical relationship between land and water. Eustasy refers to global sea level changes, and is a function of the changing volume and density-temperature relationships of the earth's oceans due to the melting of glaciers and ice caps. Gornitz et al (1982) studied more than 190 tide gauge records worldwide to determine causes of sea level change and global rates of rise. They concluded that mean global sea level is rising at a rate of 0.12 cm/yr (0.05 in./yr). In the Gulf of Mexico, Gornitz calculated a mean sea-level rise of 0.23 cm/yr (0.09 in./yr) (Fig. 4). This rate coincides with the sea-level rise trend found at the Pensacola, Florida station, a presumably stable craton (Penland et al, 1988).

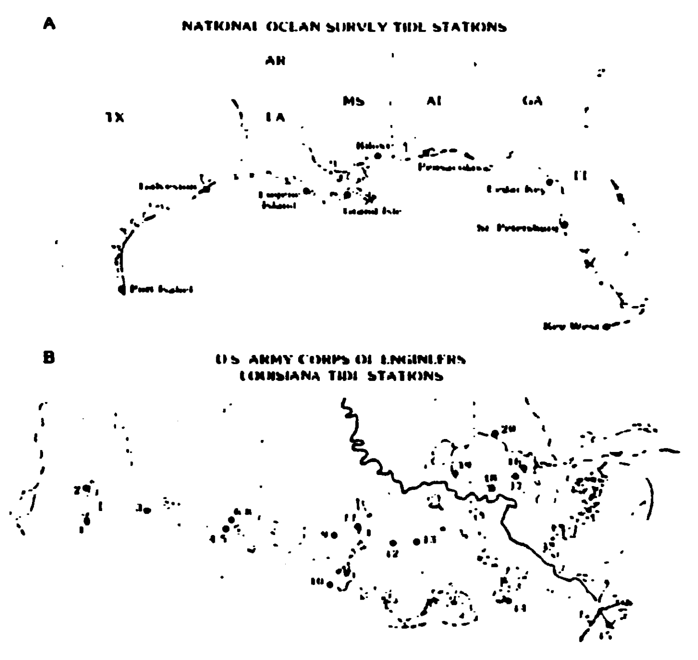

Figure 3. (a) Locations of the National Ocean Survey (NOS) tide gauge stations used in this study. (b) Locations of the U.S. Army Corps of Engineers (USACE) tide gauge stations used in this study.

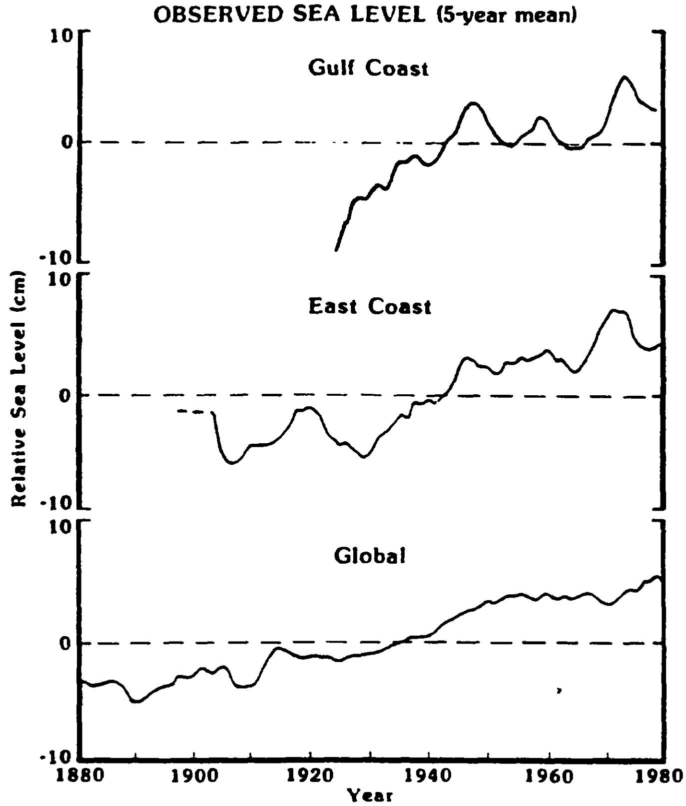

Figure 4. Global and U.S. Gulf Coast mean sea level curves from Gornitz et al (1982). Mean global sea level rise is 0.12 cm/yr (0.05 in./yr) and mean U.S. Gulf Coast relative sea level rise is 0.23 cm/yr (0.09 in./yr).

The National Ocean Survey records water level every six minutes, whereas, USACE records only the 8:00 a.m. reading. USACE stations were capable of detecting over 92% of the sea-level rise recorded by NOS (Penland et al, 1988). Monthly and yearly means were calculated for the 20 USACE and nine NOS long-term stations. The mean annual water level history for these stations was then plotted against time, and a linear regression was performed to produce a best-fit straight line with a slope equal to the rate of sea-level change. The individual tide gauge history and maintenance record was examined to correct errors in the data set. The USACE data set allowed a regional comparison within the state, whereas the NOS data set allowed a comparison of sea-level rise in the Northern Gulf of Mexico.

Regional Distribution: Louisiana

The USACE tide gauge stations were studied in seven geomorphic regions to compare sea-level rise in the basins within the Mississippi River delta and chenier plains. The geomorphic regions include: (1) Chenier plain, (2) Teche basin, (3) Terrebonne delta plain, (4) Barataria basin, (5) Balize delta plain, (6) St. Bernard delta Plain, and (7) Pontchartrain basin (Fig. 5).

Chenier Plain

The Chenier plain in western Louisiana is a series of transgressive shell or sand ridges separated by regressive mud flats about 2,500 years in age (Gould and McFarlan, 1959). The surface area is mostly salt and fresh marsh with a stratigraphic sequence 10 m (30 ft) thick along the shoreline which pinches out onto the Pleistocene terrace about 40 km (25 mi) landward (Fig. 6a).

Sea-level rise in the Chenier Plain ranged from 0.53-0.79 cm/yr (0.21-0.31 in./yr) during the period 1942-1988. The Cameron station is located about 3 km (1.9 mi) from the coast near Cameron and is connected to the Gulf of Mexico via Calcasieu Pass: it is representative of the chenier plain. The Cameron station was established in 1942. During the period 1942 to 1988 the station reported a rise in sea-level at a rate of 0.56 cm/yr (0.22 in./yr) (Fig. 6b).

Teche Basin

The Teche basin is a marginal deltaic basin that developed within the erosional remnants of the Teche delta complex. Transgressive submergence of this delta complex over the last 4,000 years has resulted in a series of interconnected bays between the old Teche distributaries (Penland et al, 1987). These bays are partially separated from the Gulf of Mexico by Marsh Island, Atchafalaya Bay shell reefs, and Point au Fer Island (Fig. 7). Holocene deposits range from 10-15 m (30-50 ft) thick near Chenier au Tigre to over 100 m (330 ft) thick westward near Morgan City (Kolb and Van Lopik, 1958; Roberts et al, 1987). Water-level regime in the Teche basin is complicated by the growth of the Atchafalaya River delta complex into the basin (van Heerden and Roberts, 1988). Increasing seasonal flooding combined with high rates of sedimentation associated with

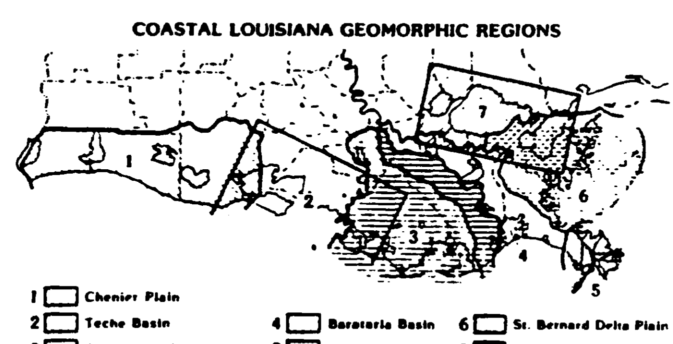

Figure 5. Coastal Louisiana can be subdivided into seven geomorphic regions: (1) the Chenier plain, (2) Teche basin, (3) Terrebonne delta plain, (4) Barataria basin, (5) Balize delta plain, (6) St. Bernard delta plain, and (7) Pontchartrain basin (Penland et al, 1989).

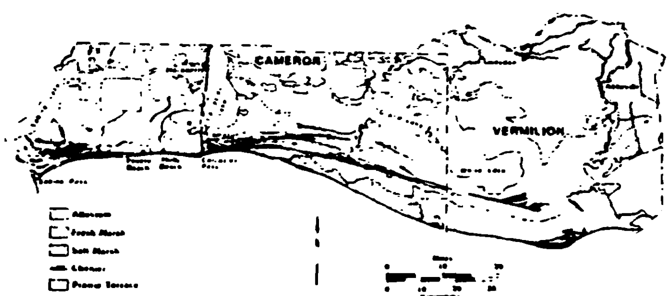

Figure 6a. The Chenier plain geomorphic region in western Louisiana.

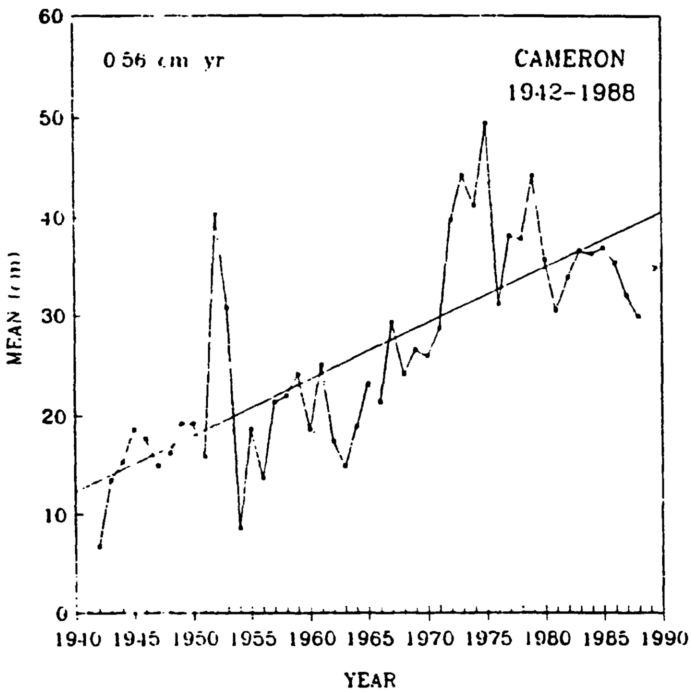

Figure 6b. Water-level time series for the Calcasieu River and Pass near Cameron, Louisiana tide gauge station.

delta growth tend to amplify the effects of relative sea-level rise.

The USACE water-level histories indicated that only three stations were suitable for analysis: Calumet, Eugene Island and Morgan City (Fig. 7). Morgan City, established in 1933, was the longest station in existence in the Teche Basin. The Calumet station has records back to 1942 and the Eugene Island station since 1944. Water-level rise varied from station to station. The rates of relative water-level rise were 1.20 cm/yr (0.47 in./yr) at Morgan City (1933-1987), 1.65 cm/yr (0.65 in./yr) at Calumet (1942-1988), and 1.17 cm/yr (0.46 in./yr) at Eugene Island (1944-1986) (Fig. 8). Flooding events by the Atchafalaya River amplify the effects of relative sea-level rise giving the erratic character of the data set. Therefore, the readings from these stations do not truly represent relative sea-level rise as defined in this study.

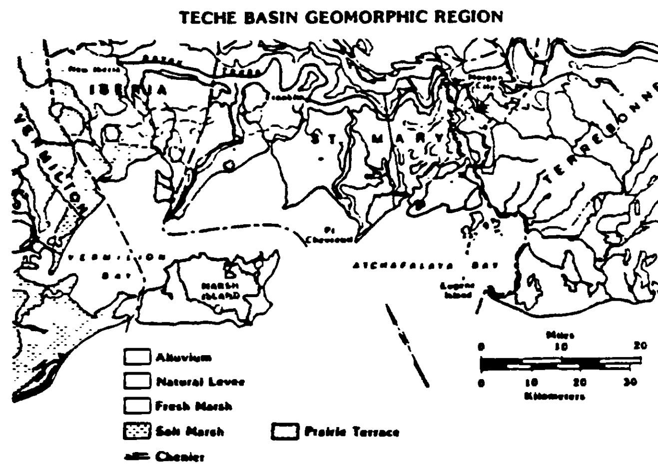

Figure 7. The Teche basin geomorphic region.

Terrebonne Delta Plain

The Terrebonne delta plain is the depositional surface of the Teche and Lafourche delta complexes of the Mississippi River delta plain (Fig. 9a). This delta consists of several small deltas truncated by a series of transgressive barrier shorelines generated by multiple episodes of distributary switching (Penland et al, 1987). The Holocene section in this region is 100-200 m (330-660 ft) thick (Kolb and Van Lopik, 1958; Roberts, 1985). Because of the western margin of the Terrebonne delta plain is adjacent to the prograding Atchafalaya River delta complex, the water levels in this region are becoming increasingly higher and erratic. In contrast, the eastern portions of the Terrebonne delta plain are not affected by the Atchafalaya River.

Two stations in the Terrebonne delta plain had a sufficient data set for analysis. The Greenwood station, established in 1935, is located 0.8 kilometers (0.5 miles) below the junction with Terrebonne-Lafourche Canal. However, the station was only intermittently in service until 1942. Data at this station indicates a water-level rise of 0.98 cm/yr (0.39 in./yr) from 1942-1986. The second station is located on the Intracoastal Waterway at Houma near Highway 24. This station recorded a rise rate of 1.09 cm/yr (0.43 in./yr) from 1946-1988 (Fig. 9b).

Barataria Basin

The Barataria Basin is an interdistributary barrier-built estuary located between the abandoned Lafourche and Plaquemines delta complexes (Fig. 10a). The seaward margin of this deltaic estuary is formed by the Caminada-Moreau Coast, Grand Isle, Grand Terre Islands, and Cheniere Ronquille barriers. The thickness of the Holocene section in the basin increases from 10-15 m (30-50 ft) in the upper basin to over 100 m (330 ft) at Grand Isle (Kolb and Van Lopik, 1958; Kosters, 1989).

The tidal station at Grand Isle was the only record with suitable water-level histories. National Ocean Survey established this station in August 1947 at the Humble Oil Platform on Bayou Rigaud. In 1980 the station was moved to the U.S. Coast Guard base on the east point of the island less than 1 km (0.6 mi) from the Gulf of Mexico via Barataria Pass. Water-level time series show a 1.11 cm/yr (0.44 in./yr) rate of rise from 1949 to 1986 (Fig. 10b).

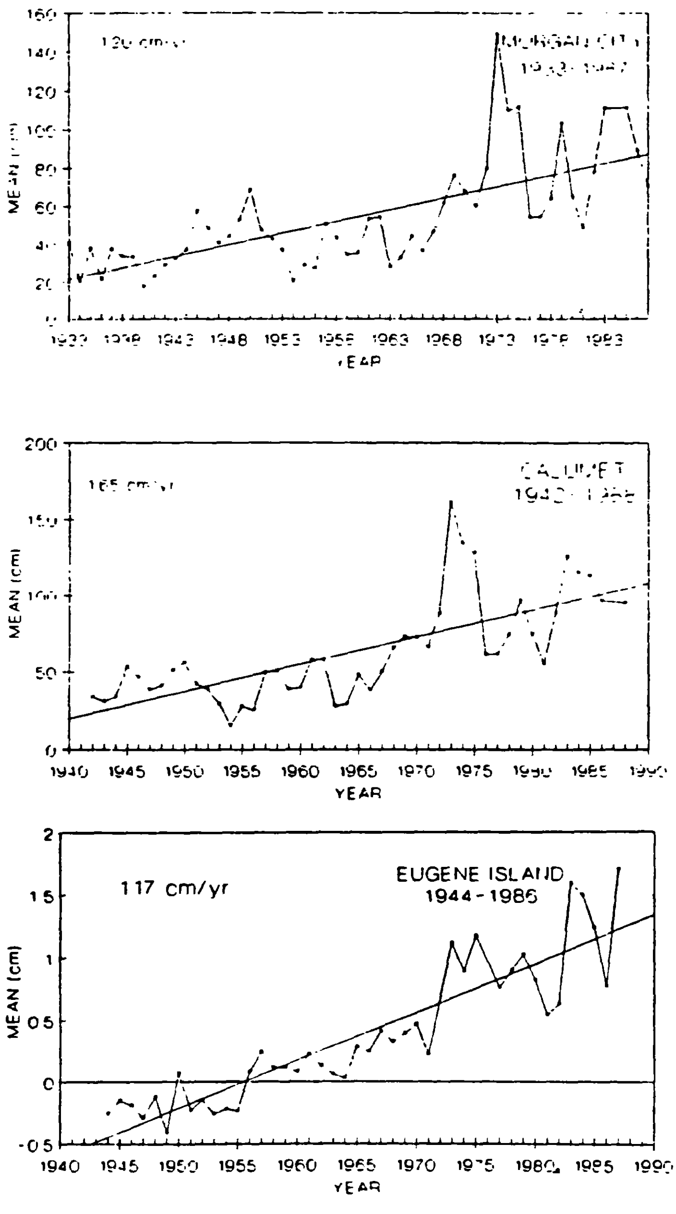

Figure 8. Water-level time series for the tidal station in the Teche Basin.

Balize Delta Plain

The Balize delta plain is a smaller, active deep-water delta of the larger Modern delta complex (Fig. 11a). This delta consists of fresh marsh built from of seven major distributaries (Coleman, 1988). The Holocene section is over 100 m (330 ft) thick. The tidal regime in this coastal region is heavily influenced by the stages of the Mississippi River.

Water-level histories indicated that the South Pass station at Port Eads had sufficient quality and duration of record for analysis. This station is located 17.7 kilometers (11.0 miles) downstream from Head of Passes. During the time period 1944-1988, Port Eads indicated a water-level rise rate of 0.94 cm/yr (0.37 in./yr) (Fig. 11b).

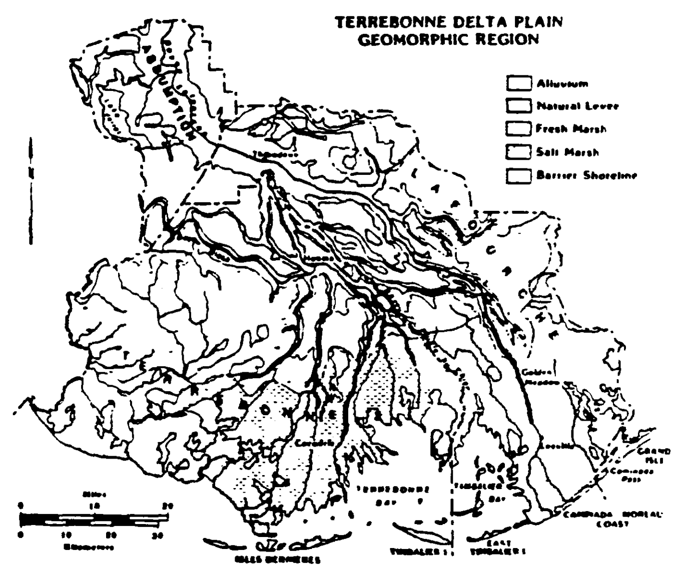

Figure 9a. The Terrebonne delta plain geomorphic region.

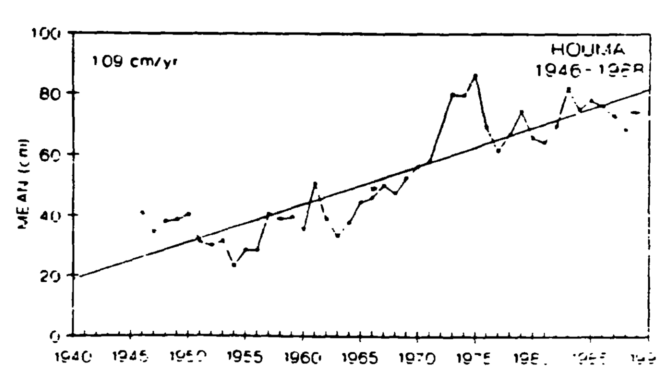

Figure 9b. Water-level time series for the tidal station at Intracoastal Waterway at Houma, Louisiana.

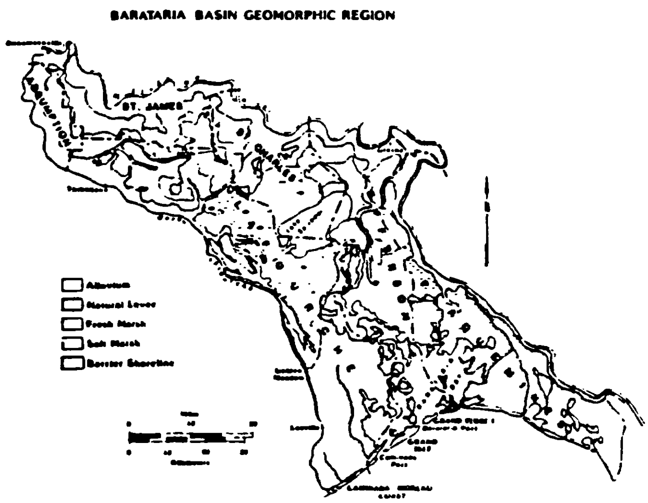

Figure 10a. The Barataria basin geomorphic region.

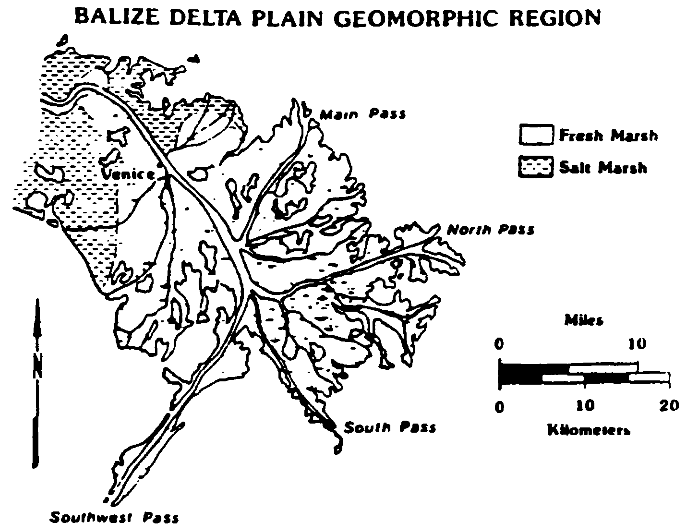

Figure 11a. The Balize delta geomorphic region.

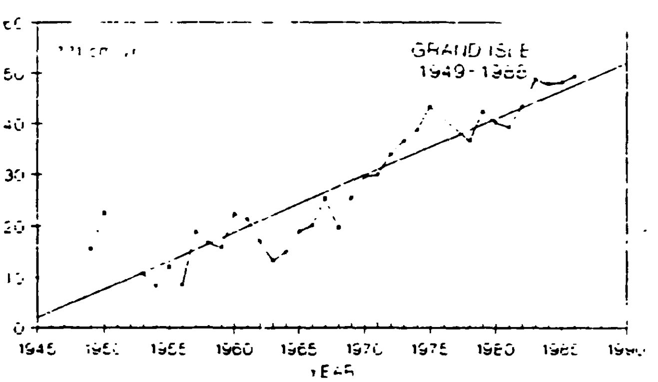

Figure 10b. Water-level time series for Grand Isle, Louisiana.

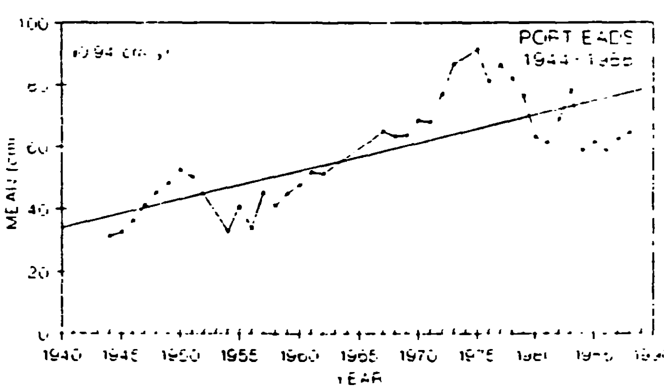

Figure 11b. Water-level time series for South Pass at Port Eads, Louisiana.

St. Bernard Delta Plain

The St. Bernard delta plain represents the depositional surface of the abandoned St. Bernard delta complex, which is more than 3,000 years old (Fig. 12). The transgressive submergence of this delta complex over the last 2,000 years has generated the Chandeleur barrier island arc, which is separated from the mainland by Chandeleur Sound (Penland et al, 1985). The Holocene section in this area increases in thickness from 15-20 m (50-66 ft) near Little Woods to over 100 m (330 ft) near Breton Island.

Two tidal stations in this area were used in the study. The South Shore tide gauge station lies immediately west of Point aux Herbes. During the period 1949-1988, the recorded yielded a rise rate of 1.01 cm/yr (0.40 in./yr) (Fig. 13). The Little Woods tide gauge station is 10 km (6 mi) southwest of the South Shore station. During the period of record (1931-1977) the stations yielded a 1.09 cm/yr (0.43 in./yr) rate of rise in water-level (Fig. 13). This gauge was discontinued in 1977.

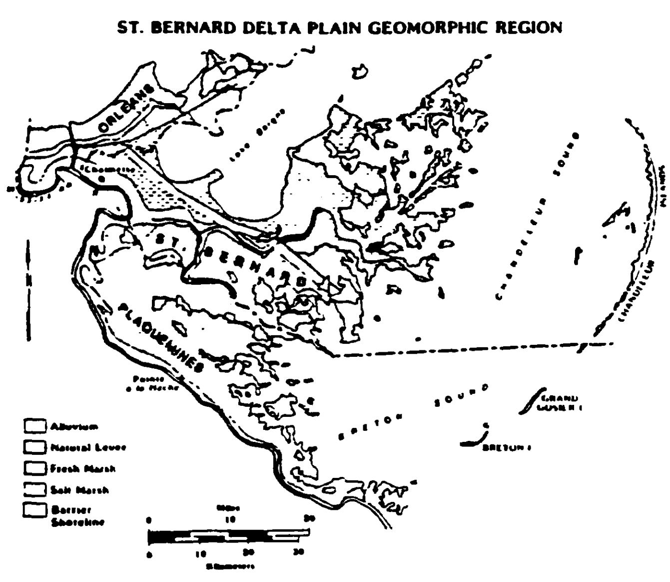

Figure 12. The St. Bernard delta geomorphic region.

Pontchartrain basin

The Pontchartrain Basin is a marginal deltaic basin located between the Pleistocene terraces in the Florida Parishes and the St. Bernard delta complex (Fig. 14). The progradation of the St. Bernard delta complex 2,500 years ago along the eastern side of the Mississippi River delta plain enclosed the Pontchartrain Basin. The Holocene section of the basin pinches out against the Pleistocene terraces to the north and thickens to 10-15 m (30-50 ft) toward the south adjacent to the St. Bernard delta plain.

There are three long-term tidal stations in the Pontchartrain Basin. The Frenier station is located on the southwest shore of Lake Ponchartrain. The West End is located at the western end of Lake Pontchartrain at the Westend Harbor, and the Mandeville station is located on the north shore of Lake Pontchartrain (Fig. 15). These stations were established in 1931. Data analysis indicated water-level to rise at a rate of 0.38, 0.40, and 0.45 cm/yr (0.12, 0.16, and 0.18 in./yr) respectively (Fig. 15).

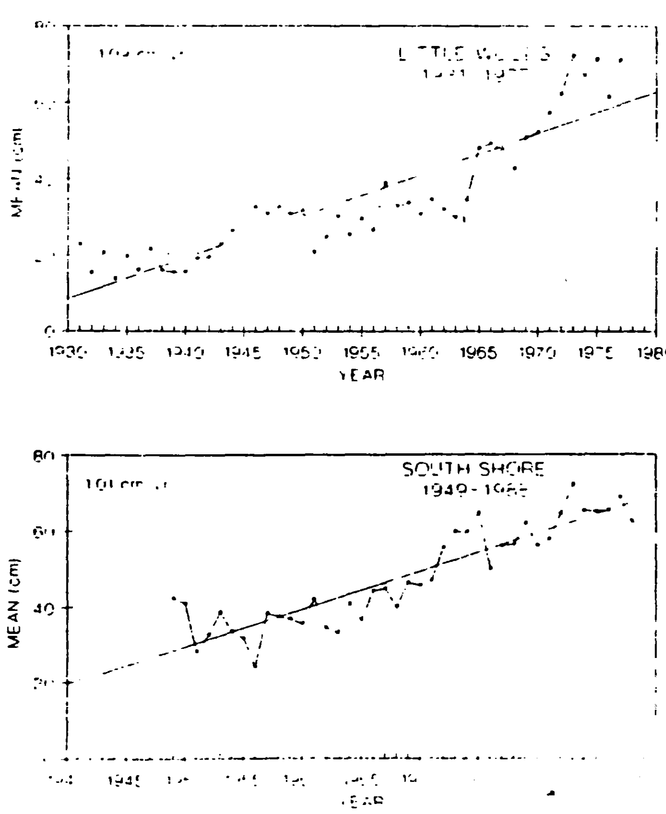

Figure 13. Water-level time series for St. Bernard tidal stations.

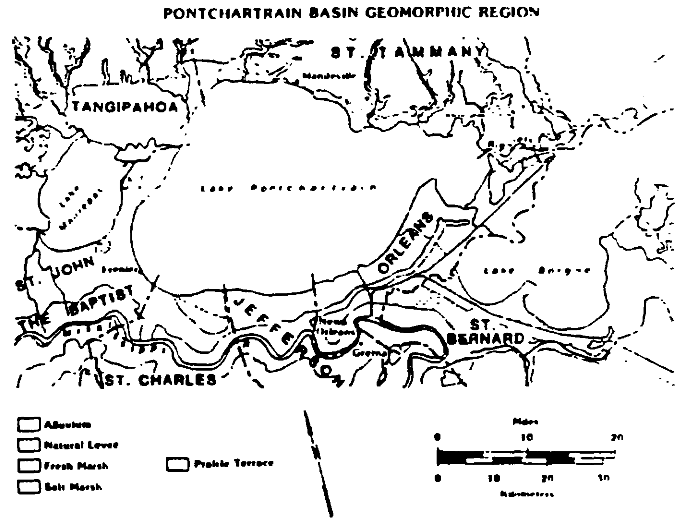

Figure 14. The Pontchartrain basin geomorphic region.

Regional Variability: Gulf of Mexico

Analysis of tidal records from Texas, Louisiana, Mississippi and Florida indicate that Louisiana has a higher rate of sea-level rise than any other state on the northern Gulf coast. According to the USACE and NOS records, the zones of highest sea-level rise are associated with the Mississippi River delta plain, whereas the rates along the Chenier plain to the west of the delta plain and the Pontchartrain basin to the east are comparable to those of adjacent coastal states. In Texas, relative sea-level rise ranges from 0.31 cm/yr (0.12 in./yr) in Port Isabel to 0.63 cm/yr (0.25 in./yr) at Galveston. In Louisiana the average rates range from 0.60 cm/yr (0.24 in./yr) in the Chenier plain to 1.19 cm/yr (0.47 in./yr) at Eugene Island back down to 0.40 cm/yr (0.16 in/yr) in the Pontchartrain basin (Fig. 16). Biloxi, Mississippi indicated a 0.15 cm/yr (0.25 in./yr) rate of rise, whereas Florida ranges from 0.17 cm/yr (0.07 in./yr) at Cedar Key to 0.23 cm/yr (0.09 in./yr) at Pensacola.

SUBSIDENCE

Subsidence is referred to as the downward displacement of a delta plain surface with respect to a vertical datum (national geodetic vertical datum or NGVD). Downwarping of the geosyncline, compaction of Holocene, Pleistocene and Tertiary sediments, local consolidation, tectonic activity and subsurface fluid withdrawal are all factors affecting relative sea-level rise and subsidence at a particular coastal location. Downwarping due to sediments that infill the Gulf Coast geosyncline accounts for a small percentage of the relative sea-level rise observed in coastal Louisiana (Kolb and Van Lopik, 1958). Consolidation of Tertiary and Pleistocene deposits account for a large portion of subsidence, but the

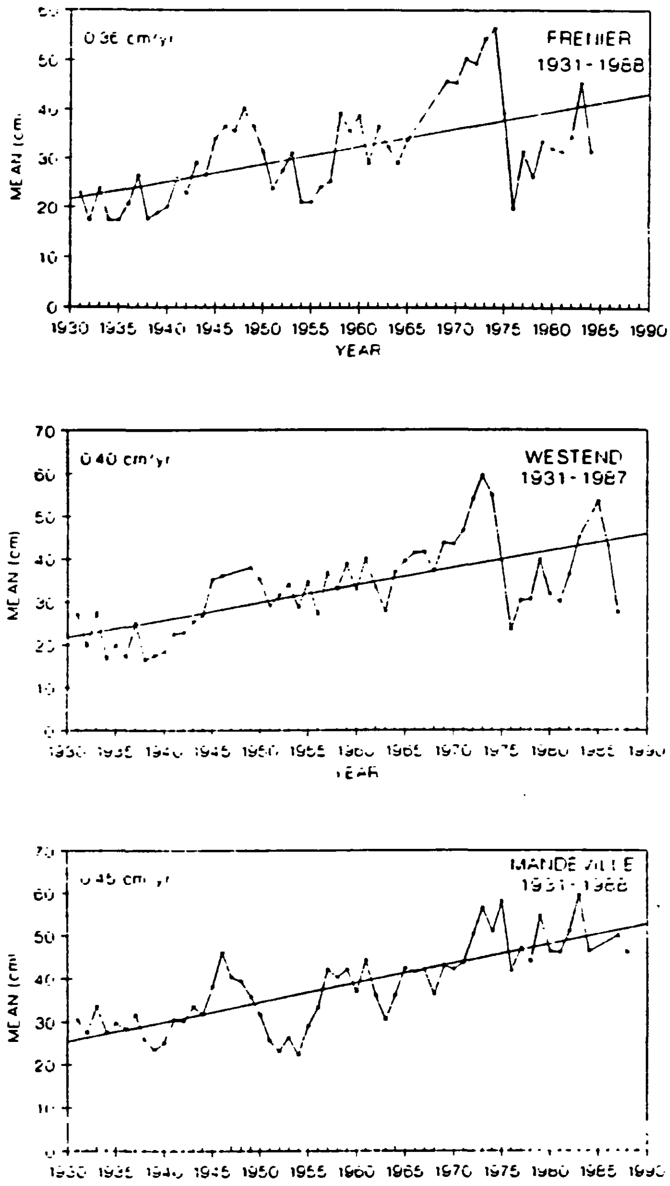

Figure 15. Pontchartrain basin water-level time series.

compaction of Holocene deposits is considered the primary cause of relative sea-level rise at the abandoned Mississippi River delta complexes (Roberts et al, 1987; Penland et al, 1988). The major difference in the factors influencing sea-level rise, as opposed to subsidence, is eustatic sea level. Eustatic sea level was subtracted from the relative rate of water-level rise to obtain a subsidence rate at the tidal station. The difference between the eustatic rise and the Gulf of Mexico sea-level rise can be attributed to regional tectonism and the filling characteristics of the Gulf of Mexico basin.

Regional Subsidence: Louisiana

Subsidence rates vary spatially because of differential compaction (Morgan, 1973). Coarser-grained sediments

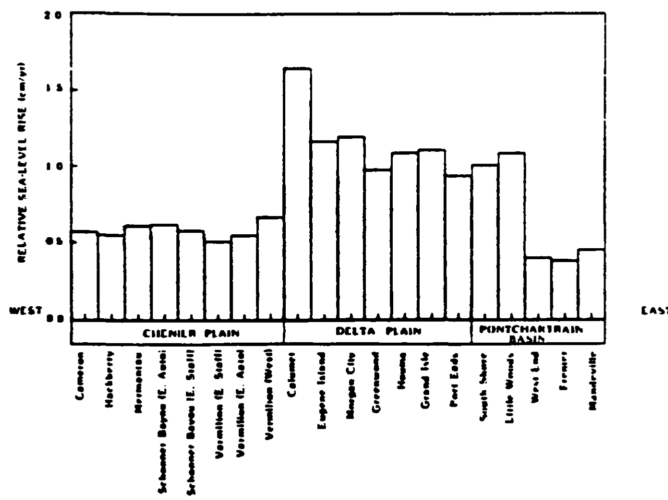

Figure 16. Histogram of relative sea-level rise in the Gulf of Mexico based upon NOS and USACE tidal stations.

with greater density that are associated with distributary courses tend to accelerate compaction. The region with the highest rate of subsidence is the Teche basin with a rate of 1.11 cm/yr (0.44 in./yr). This accounts for about 83% of the water-level rise. Subsidence in the Chenier plain contributes the lowest amount at 0.33 cm/yr (0.13 in./yr) or 59%. According to the tide gauge data, subsidence contributes 76% to the rate of water-level rise in the Terrebonne delta plain, 75% in Barataria basin, 63% in the Balize delta, 74% in the St. Bernard delta plain and 43% in Pontchartrain basin (Fig. 17).

Regional Distribution: Gulf of Mexico

Tide gauge data along the Gulf of Mexico coast shows a regional trend in subsidence that increases in rate towards the north along the Texas, Mississippi, Alabama, and Florida shorelines converging with the highest rates found at the Mississippi River delta plain (Fig. 17). In Louisiana subsidence accounts up to 83% of the observed water-level rise rates. Subsidence at the Texas tidal stations only contribute 29% to 63% of the water-level rise. Tidal records along the Mississippi and Florida coast show only the effects of eustasy.

CONCLUSIONS

1) Analysis of U. S. Army Corps of Engineers tide gauge records from 20 stations in coastal Louisiana indicates that the highest rate of relative sea-level rise is 1.09 cm/yr (0.43 in./yr) within the Terrebonne delta plain. Relative sea-level rise rates up to 1.65 cm/yr (0.65 in./yr) can be found in the Teche basin; however, the average rates from these stations have been elevated due to the effects of flood stages on the Atchafalaya River. Rates of rise decrease east and west away from the Teche basin and Terrebonne delta

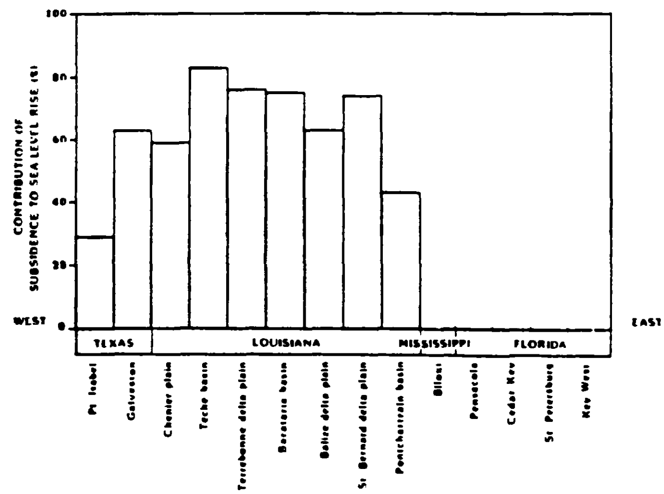

Figure 17. Contribution of subsidence to rates of observed sea-level rise in Louisiana geomorphic regions and surrounding states.

plain. East of the delta plain lies the Pontchartrain Basin where relative sea-level rise rates range from 0.36 cm/yr to 0.45 cm/yr (0.14 in./yr to 0.18 in./yr). West of the delta plain, the rages range between 0.51 cm/yr and 0.67 cm/yr (0.20 in./yr and 0.26 in./yr).

2) The analysis of NOS tidal control stations indicates that Louisiana is experiencing the highest rates of sea-level rise and subsidence in the northern Gulf of Mexico. Maximum relative sea-level rise rates in Louisiana ranged between 1.20 cm/yr and 1.65 cm/yr (0.47 in./yr and 0.65 in./yr) in the Teche basin. Texas ranks second with rates ranging between 0.33 cm/yr to 0.62 cm/yr (0.13 in./yr to 0.24 in./yr). In Florida, the rate of rise averages 0.23 cm/yr (0.09 in./yr).

3) Subsidence is the major factor contributing to water-level rise in Louisiana. In Texas, subsidence contributes from 29% to 63% of the rate of rise. In Louisiana, subsidence ranges from 0.33% to 83%. Mississippi, Alabama, and Florida show only the effects of eustasy.

ACKNOWLEDGEMENTS

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EROSION AND WASHOVER IN COASTAL LOUISIANA

William Ritchie and Shea Penland

Abstract

In 1985 three hurricanes affected the barrier coastline (Caminada-Moreau Headland) of Louisiana. These produced severe coastal erosion and rapid washover extension. Using the 1979 U.S.G.S. topographic map (which was surveyed in 1978) as a baseline, interpretation of aerial photographs taken in 1984 and 1985 (post-hurricane) enabled detailed measurements of the relative importance of hurricanes to be made. The pattern of erosion and washover penetration was essentially similar, but areas that had been relatively protected were altered most during the hurricane period. Washover extension in 1985, however, was relatively much more significant than coastline erosion.

Introduction and Geographical Setting

The Caminada-Moreau barrier headland coast of south Louisiana is oriented in a southwest to northeast direction and stretches in a straight line for approximately 20 km between Belle Pass and Caminada Pass. Subsidence, shoreface erosion, sediment deficiency, and overwash activity have produced a history of rapid coastline retreat (Figure 1). Local changes in coastal orientation occur at the distal ends of the terminal spits at the tidal passes, and at the man-made transverse coastal structures of the Belle Pass jetties. Although eroding rapidly, this straight outline does not represent a sequence of parallel retreat. Examination of old maps shows clearly that the Caminada-Moreau headland is retreating much more rapidly toward the west end. The coastal orientation is, effectively, rotating clockwise around the pivot of Caminada Spit, at a rate of slightly less than one degree per decade. The coastline is totally unconsolidated and the constituent sand bodies are free to respond quickly to constructive and destructive wave forces. Tides are normally less than 36 cm and tidal currents are only of significance in the tidal passes. Ebb and

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flood tidal delta deposits are found associated with these tidal inlets. Wave refraction and diffraction patterns across these tidal delta sand bodies produce inward pointing recurved spit beaches.

BAYOU LAFOURCHE BARRIER SHORELINE 1887-1978

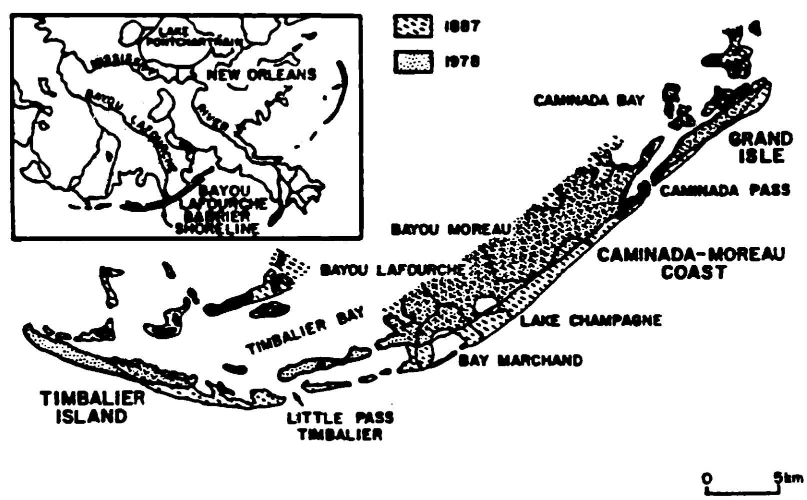

Figure 1 : Location of Study Area and Historical Changes

The coastline consists of a narrow sand beach with associated dunes, dune terraces, washover terraces and wash-over flats, which encroach onto the pre-existing plain of the Lafourche delta complex, formerly the outlet of the Mississippi River, which has been dated as active in this area 300-710 years B.P. (Penland et al, 1987). There is general agreement that active sedimentation ceased approximately 300 years ago, from which date subsidence and marine reworking of deltaic sediments became the dominant coastal geomorphological process. Relative sea level rise has averaged 32 cm per century over the last 2500 years for this region of the Modern Mississippi River delta plain. Over the last 300 years, the average rate of relative sea level rise for the Bayou Lafourche area has been as high as 62 cm per century. Also there may be local changes due to the effect of the abstraction from oil and gas fields at or near the coastline.

The coast is classified as storm-dominated. Normally, the passage of cold front systems elevates water levels up to 90 cm, ten to thirty times per year (Boyd and Penland, 1981). These storms often produce waves 2 to 3 m high. The local average wave heights are about 60 cm. Tropical storms (winds over 63 km/h) have a longer recurrence interval of 4.1 years (Simpson and Lawrence, 1971). These storms raise water levels considerably higher, normally 2 to 7 m above mean water level. During these storms the frequency and intensity of overwash is related to the combination of storm surge, wave set-up, wave run-up and astronomical tide setting against the variable, pre-existing elevations of the coastline, modified to some extent by beach width and gradient. Measurement of overwash events has shown that the lowest, significant regional overwash threshold is 1.42 m above mean sea level. This will produce overwash along 75 per cent of the coastline approximately 15 times per year. At a level of 2.50 m most of the coastline will be inundated and this may be expected once every two or three years. At a level in excess of 3 m, normally during hurricanes, extensive coastal flooding occurs and the barrier dune forms are obliterated.

Method of Study and Sources of Information

The positions of shorelines and the extent of washover penetrations were determined from aerial photographs (true vertical, metric quality) at scales of 1:15,000 and 1:24,000. A Bausch and Lomb Zoom Transferscope was used to transfer topographical detail to a map, based on the 1979 U.S.G.S. 1:24,000 scale topographic sheets of the area.

Beach scarps, berms, strandlines and water levels are relatively easy to discern on the photographs. The water level is also easy to identify, but its position is subject to relatively large horizontal changes due to the tidal rise and fall. Nevertheless, knowing the time of photography, the beach gradient and the record of tidal changes, it is possible to compensate for the difficulty of defining high water mark on the beach on aerial photographs. This problem of coastline definition has to be recognised as a major difficulty in using aerial photographs as a source of such measurements and a constraint on the accuracy of any statistical interpretation of the data. The most consistent and easily defined line on the aerial photographs is the washover limit. This line was also plotted on the 1979 topographic base map. Accordingly, in subsequent calculations of shoreline change the landward shift in washover penetration provides the most accurate measure of change.

To provide a data base for systematic measurement of change, the coastline and overwash limits were measured every 250 m. Thus, a data set of 80 sample distances was obtained. These measurement points are called range lines and are shown in Figure 2.

Caminada-Moreau - Coastal Changes

The coastline can be divided into three main areas - i.e. west of Belle Pass where the jetties interrupt west-going littoral drift and where the west end of the coastal headland is changing rapidly; a central section which is relatively straight but contains a significant number of different types of coastal backshore zones; an eastern area near Caminada Pass where the headland extends as a long spit toward the tidal inlet and where there is natural spit extension and recurvature (Figures 1 and 2).

Several aspects of the geomorphology of this coastline have been studied in detail. Ritchie and Penland (1985) produced an analysis of the overwash processes and subsequent aeolian transport which are the main forces responsible for the evolution of the beach, dune and other morphological features. The pattern of erosion in the centre of the barrier beach with sediment movement to the flanks by longshore drift (Harper, 1977) was confirmed. but there were considerable local variations. The concept of overwash thresholds was introduced whereby different water levels produced by a hierarchy of storm events flood more often across progressively more of the coastline in proportion to the height and intensity of the overwash. The control exerted by the elevation and resistence of specific pre-existing landforms, such as old dunes, levees and spoil banks, was also shown to be important.

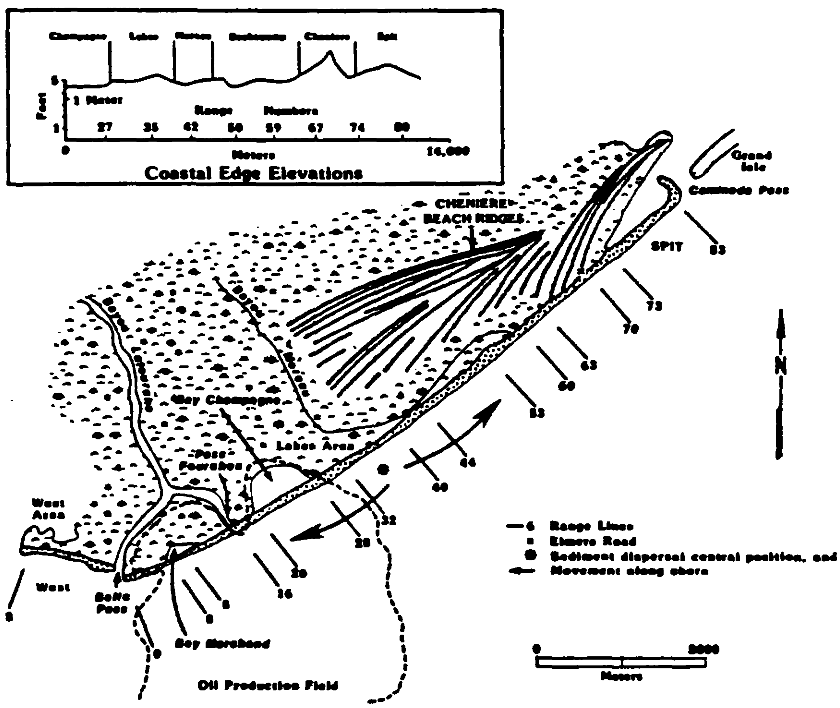

Figure 2 : Caminada-Moreau
Coastal Morphology and Range Lines

In 1988 the same authors (Ritchie and Penland) described the response of sand dunes to overwash events and demonstrated that aeolian depositional forms develop rapidly due to the availability of easily transported, fine grained sand (average size 180 microns) from the upper beach and the washover sheets. Further, vegetation growth is extremely rapid as a result of the variety of plants that are capable of colonising particular habitats quickly and efficiently. The highest, continuous dunes occur at the flanks of the barriers, with dune terraces and intermediate dune types elsewhere. There appears to be a cycle of dune development which begins and ends with a major hurricane event (with an expected return period of approximately 10 to 14 years).

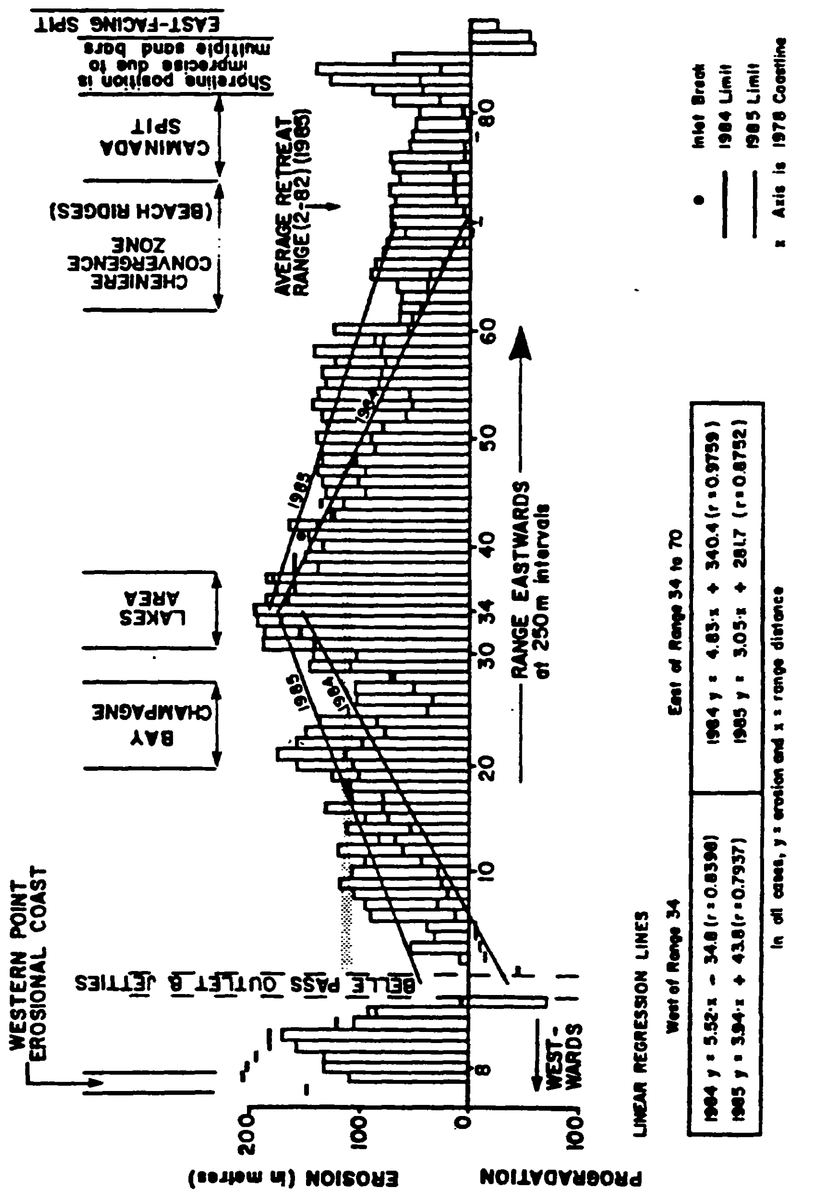

Figure 3 : Caminada-Moreau Headland Coastal Changes
Coastline Recession 1978 - 1984 - 1985.

Within this dune cycle most dunes grow and become more resistant to overwash, but this progression is modified by minor storms that are of lesser intensity than the hurricane event.

Coastline Retreat

West of Belle Pass (Figures 2 and 3) sediment reduction on the downdrift side of the jetties produces a vulnerable area for rapid coastal recession. During the 1985 hurricanes large areas toward the west end of this section, which is low and lacks any type of dune or other resistant landform, were removed.

East of Belle Pass erosion is greatest in the centre of the headland at Range 34 (Figures 2 and 3) in the Lakes Area to the east of Bay Champagne. From this point there is an almost symmetrical pattern of progressively reducing coastline retreat. The central area has high land loss in excess of the average 1978 to 1985 retreat value which is over 110 m. To the west and east lateral sediment dispersal to the beaches reduces the rate of coastline recession so that from a position 3.5 km on either side of Range 34 the rate of coastline erosion falls below the average value.

The regression lines shown in Figure 3 can be used to highlight three 'anomalous' areas, two to the west and one to the east. To the west, the large semi-circular lake, Bay Champagne shows a pattern of particularly rapid recession in the centre and west, but at its east margin there is substantially less than average erosion. Two explanations may be offered. First, at the east edge of the lake there are spoil banks and outcrops of marsh peat in the inter-tidal area. Second, there are several pipeline jetties which extend into the sea at right angles to the coast and these may modify wave action.

East of the central part of the area there is a zone of relatively greater erosion between Ranges 55 and 59 (Figure 3). This area corresponds to the outlet position of Bayou Moreau (Figure 2) which has produced an area of relative weakness and susceptibility to erosion.

East of Range 70, Caminada Spit is identified as an area that responds in a different way from the remainder of the barrier beach. Downdrift beach accumulation, the presence of an ebb-tide delta and associated spit extension and recurvature makes it a zone of relative resistance characterised by continuous dune ridges. Although the area has a pattern of slow retreat, some of this change is due to increasing recurvature of the relatively dynamic beaches and sand bars at the distal end of the barrier headland.

During 1985, hurricane impact produced an acceleration of coastline erosion. The regression lines (Figure 3) show the substantial shift in the coastline with greater relative impact occurring toward the east flank of the system, and least change occurring in the already rapidly retreating central section. Hurricane impact confirmed the trend and pattern of pre-1985 or 'normal' coastline change, but there are local anomalies and differences. The most probable explanation for the greater variability in the 1985 pattern of retreat is that the pre-hurricane geomorphological response is dominated by beach processes, relating to alongshore sediment movements, and although major storms and overwash events occurred in the 1978-84 period, over the six-year time span, these events did not alter significantly the general evolution of the coastline. In 1985, in addition to the general trend of coastline change, the impact of three hurricanes overwhelmed normal shoreline processes and the higher, storm surges were, to some extent, affected by additional local topographic factors. Some of the highest absolute and especially percentage retreats took place in areas that had been relatively resistant to the lower level of storm surges in the 1978 to 1984 period. Areas of unexpectedly high erosion are near Bay Marchand, an area of relatively high continuous dunes; between Ranges 52 and 55 where the area is part of the Bayou Moreau meander belt; in the vicinity of Range 70 which has been identified earlier as a zone of relative resistance due to the presence of the old beach ridges of Cheniere Caminada. Relatively high percentage changes are also found along the Caminada Spit. It is appropriate to consider these changes as evidence of a threshold concept whereby the hurricane surge surmounted the average crestline altitude of the continuous dunes and, having done so, swept easily relatively far inland. carrying the sand that was eroded from the dune ridges.

The most striking observation of these measurements of coastal erosion is the confirmation of the pattern of retreat of the barrier headland with maximum retreat in the centre and progressively less erosion toward the downdrift flanks of the systems. In 1985, the impact of hurricanes produced over one-third of the total erosion in the 1978 to 1985 period. In addition, the influence of local topographic factors produces local variation in the rate of retreat but is insufficient to distort the general pattern. The hurricanes of 1985 did not alter the trend or location of coastline retreat, but they had a relatively greater erosional impact on these coastal landforms that had proved to be resistant previously to lower magnitude storm and washover events.

Overwash Impact 1978 to 1985

It is fortunate that the 1979 U.S.G.S. topographic sheets of the area show the overwash limit for the Bayou Lafourche barrier shoreline. This has allowed measurements to be made of the relative penetration of overwash into bay, marsh, dune, and old washover areas. The identification and measurement of these limits are easier and intrinsically more accurate than water line limits, as they do not require to be corrected for tidal stage.

It has already been demonstrated that there is a symmetrical pattern of beach and nearshore sediment dispersal away from the rapidly eroding central section of the barrier headland. Accordingly, a broad correlation should be expected for overwash penetration, especially in the 1978 to 1984 period, as the greater amount of sediment in the beach zone and at the coastal edge in the form of dunes and dune terraces should reduce the impact of washover progressively toward the flanks of the barrier headland. An examination of Figure 4 shows that this assumption is correct and therefore confirms the importance of the pattern of beach and foreshore sediment movement alongshore away from the centre of the sand dispersal system. Nevertheless, the number and extent of local anomalies and departures from the generalised trend lines as indicated by the relative unevenness of the measurements in Figure 4 underlines the importance of local subaerial landforms, including dunes, old beach ridges, spoil banks and old levees which prevent or minimise washover events. In contrast bays, old distributary channels, marshes and other low areas facilitate extensive washover penetration.

The coastline west of Belle Pass was subjected to extensive washover penetration. It is low and starved of sediment and offers little or no resistance to higher level storm surges. In the 1978 to 1984 period extensive washover sheets crossed the area easily. With the exception of the zone close to the west jetty of Belle Pass (Figures 2 and 4), the average penetration in 1978 to 1984 was over 200 m which was almost twice the average for the coastline east of Belle Pass. In 1985, there was an additional 73 m of overwash penetration (35 per cent of the 1978 to 1985 total).

For the area between Belle Pass and the centre of the headland (Range 34) in the Lakes Area (Figures 2 and 4), the pattern of washover before 1985 was similar to that of coastline retreat, with the amount increasing eastwards from the jetty. Close to the jetty and for approximately 1.5 km eastwards, washover penetration was less than 20 m in the 1979 to 1984 period and, in all but one case, washover did not extend as far as the 1978 limit. The central part of the headland, i.e. Ranges, was overwashed easily and the average penetration in this sector in the 1978 to 1984 period was over 200 m.

In 1985, the pattern of washover in the area between Belle Pass and the central headland was broadly similar, but had much greater local variation. Areas which had not been subjected to extensive washover in the pre-1985 period show the greatest amount of relative change. The greatest single area of penetration was the west end of Bay Champagne where the barrier was surmounted completely. Between Ranges 31 and 36 (Figure 4), both the absolute and percentage increases in washover impact during hurricanes brings the greatest <u>relative</u> change to those more resistant sections of the coastline which are higher or have relatively wide, high beaches. In contrast, land areas that are easily and extensively overwashed under 'normal' conditions are affected relatively less by hurricane events. This may imply that there is little additional sand available in these wide, low washover terrace and sheet areas for further distribution landward. In contrast, the greater volume of sand stored in

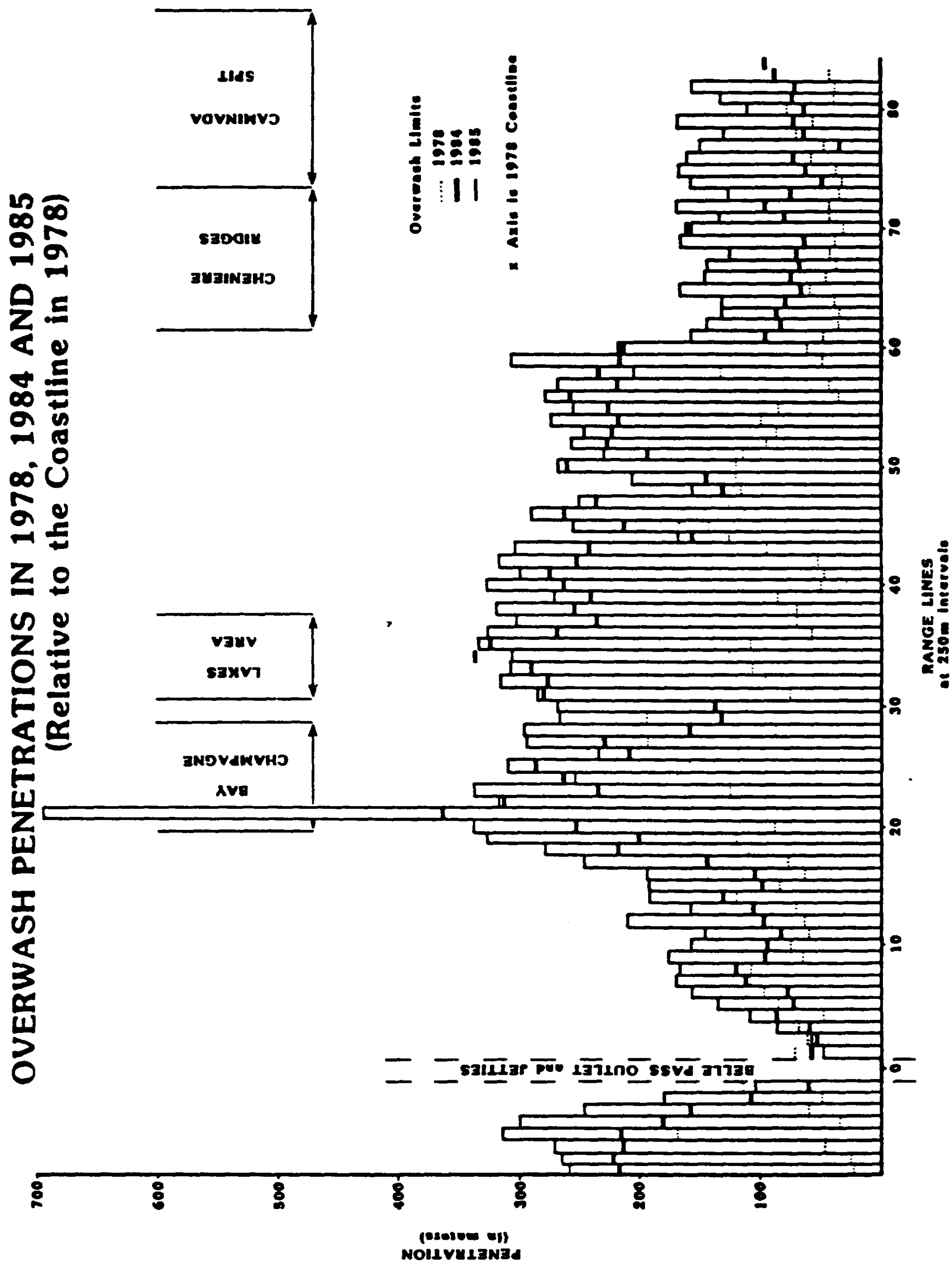

Figure 4
Overwash Penetration Distances

'protective' dunes may be translated inland as a wide washover sheet. A second factor may be the width of the zone that has to be crossed by the storm surge. In crossing this wide flat zone, much of the strength of the surge will be dissipated and its sand transporting capacity will diminish rapidly.

East of the central headland, the 1978 to 1984 pattern of overwash penetration reduces toward Range Line 70, Elmer's Road (Figures 2 and 4), Nevertheless, there are several local variations where topographical features prevent or facilitate overwash penetration. For example, the area of relatively high dunes, where the old beach ridges of Cheniere Caminada reach the coast, is relatively resistant to overwash. West of these beach ridges there is a low area of small lakes, minor bayous and low backswamps (i.e. Ranges 56 to 50) and parts of this area were vulnerable to deep overwash penetration. The course of Bayou Moreau (Figure 2), which has an extensive meander bend in this area but flows essentially in a shore-parallel direction, introduces topographic complexity between Ranges 38 and 50. One meander impinges on the coastline at Range 41 where, with coastal erosion, there was a complete breakthrough. At Range 55, the distributary swings away from the coast and finally returns to meet the coast at Range 58. Thus, as the coastline retreats and cuts across this meandering configuration, there is progressive alteration in height, resistance and sediments. For example, as the coastline erodes across the Bayou, it meets marsh, levee and distributary channel in turn, all of which offer different resistance to erosion and washover penetration.

The Caminada Spit was resistant to washover in the 1978 to 1984 period. Wide, downdrift beaches with nearshore bars and prominent backshore berms enabled high continuous dunes to form, and washover effects were relatively low. In contrast, the 1985 storms had a substantial effect on the spit and the average absolute penetration in that year was over 75 m. Almost 80 per cent of the 1978 to 1985 washover extension in the area of the Caminada Spit occurred during 1985. This area provides further substantiation of the principle that relatively greater overwash impact occurs in areas of continuous dunes when hurricane induced surge levels exceed the average summit elevations of these protective sand ridges.

<u>Comparison of Coastline Retreat and Overwash Penetration</u>

Examining the entire population of measurements for Ranges 1 to 82, the average value for the 1978 to 1984 period was for washover penetration to exceed shoreline retreat by 9.1 m, whereas in the 1978 to 1985 period this value rose to 25.9 m. Thus, in general, the effects of the hurricanes in 1985 were significantly more important for washover extension than coastline retreat. This deduction can also be made on the basis of the two scatter graphs given in Figure 5, which show that in 1985 2.5 times the number of values shift below the 45° line which represents parallel retreat and is therefore another way to demonstrate the greater geomorphological significance of overwash during the 1985 hurricane dominated years.

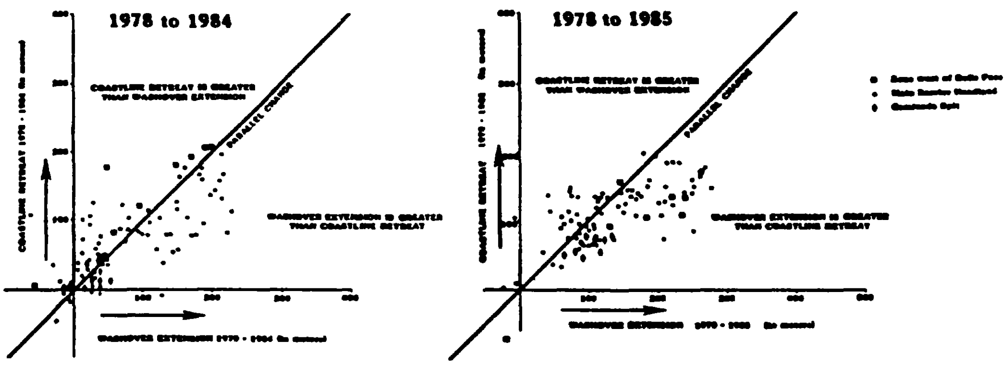

Figure 5 : Comparison of Coastline Erosion and Washover Extensions in 1984 and 1985

For both periods 1978 to 1984 and 1978 to 1985, east to the Belle Pass jetties, overwash penetration exceeds coastline retreat. This fact appears to raise questions associated with the total sediment budget and therefore the general evolution of the barrier headland coastline. Using two-dimensional measurements to deduce changes in sediment volume, however, may be an invalid technique. For example, according to recent measurements, the average beach gradient for the Caminada-Moreau Headland is approximately 1.5 degrees. If the washover sheet has a gradient of 1.0 degrees, then 10 m of beach face retreat produces a washover sheet extension of 12.5 m. This approximate calculation illustrates that the amount by which washover sheet extension exceeds coastline retreat as measured for the Caminada-Moreau coast can be accommodated by redistributing the same volume of material at a lower gradient over a wider area. Further, most sand is stored in dunes, and a reduction in their average height and width will release additional sand for washover sheet penetration. If these explanations are inadequate, then more sand must be transferring from beach to subaerial storage. If this transfer is happening, then the rate of coastline retreat will accelerate through time to compensate for the progressive loss of sediment from the beach system (assuming no fresh sediment input from external sources).

In general, the measurement of washover penetration is based on sample transects at 250 m intersects along the coast and with average differences between coastline retreat and overwash penetration being as low as 3.5 m per year, over the 8-year period, it is unwise to read too much into such statistics, especially as they are obtained by a sampling technique. Indeed, it is probably better to interpret these measurements as being indicative of a relatively consistent pattern of change, whereby beach, dune and washover zones migrate landward as an encroaching prism of sand at the expense of old deltaic and marsh surfaces, and the total volume of sand remains approximately constant with leakage to the tidal passes being balanced by the release of sediment from shoreface retreat. On this basis, there is no reason to expect that the nature of the Caminada-Moreau coast of the future will differ greatly in shape and form from the existing pattern, but its position will continue to retreat as a consequence of subsidence, sea level rise and general sediment deficiency.

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Acknowledgements

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THE 1985 HURRICANE IMPACTS ON THE ISLES DERNIERES, LOUISIANA: A TEMPORAL AND SPATIAL ANALYSIS OF THE COASTAL GEOMORPHIC CHANGES

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ABSTRACT

An airborne videotape mapping system was used to examine the impacts of Hurricanes Danny and Juan on the Isles Dernieres shoreline geomorphology in 1985. Videotape imagery was acquired in July 1984 and in July (pre-storm), August (post-Danny), and November (post-Juan) 1985. We developed a coastal geomorphic classification to map the spatial and temporal changes between surveys.

The Isles Dernieres barrier island arc is a low-profile, transgressive coastal feature. The central islands of the Isles Dernieres, Whiskey Island and Trinity Island, are the lowest in relief and elevation and have the least diverse habitats. Nonstorm morphology is predominately a combination of washover flats and higher dunes and washover terraces. Raccoon and East Islands, the ends of the Isles Dernieres, are higher in relief and elevation and have greater habitat diversity. Hurricane Danny's impact was representative of a rapid shore-normal impact by a minor force-1 hurricane. In general, landform relief on the Isles Dernieres was reduced slightly as a result of Hurricane Danny, which breached 7 major and 32 minor washover channels. After Hurricane Juan a total of 57 minor and 8 major washover channels were left and the higher-relief dunes, dune terraces, and washover terraces were destroyed. The primary morphology of the Isles Dernieres was reduced to and dominated by washover flats, intertidal flats, and other lower-relief landforms.

The spatial morphological variability of the Isles Dernieres indicates that the rate of shoreline change and the sediment supply control landform development. The temporal morphologic variability is a function of the frequency and magnitude of storm impacts and of sediment supply. The lower-relief landforms are more sensitive to storm impacts. Vegetation is important in reducing the effects of hurricanes. The barrier island restoration technique used at East Island effectively reduced erosion and preventing breaching.

INTRODUCTION

In 1985, five hurricanes made landfall in the Gulf of Mexico. The direct impacts of two of these storms, Hurricanes Danny and Juan, severely eroded Louisiana's barrier islands surrounding the Mississippi River delta plain (Fig. 1). Louisiana's barrier islands had not been directly affected by a hurricane since the landfalls of Hurricanes Bob and Frederic in 1979. In 1985 the occurrence in a single year of two storms, which ranged in strength from 1 to 3 on the Saffir-Simpson scale, produced dramatic geomorphic changes in Louisiana's barrier islands (Saffir, 1977)

Before these storms, Louisiana's barrier islands were experiencing average annual erosion conditions driven primarily by relative sea level rise and cold-front effects. Well-developed and vegetated dune and terrace systems had formed under these conditions, and the robust morphology of the barrier islands reflected the influence of constructive eolian and overwash processes. Extensive vegetative cover increased the islands' profiles and resistance to storms. The U.S. Geological Survey/Louisiana Geological Survey's Louisiana Cooperative Barrier Island Erosion and Land Loss Study used data from the

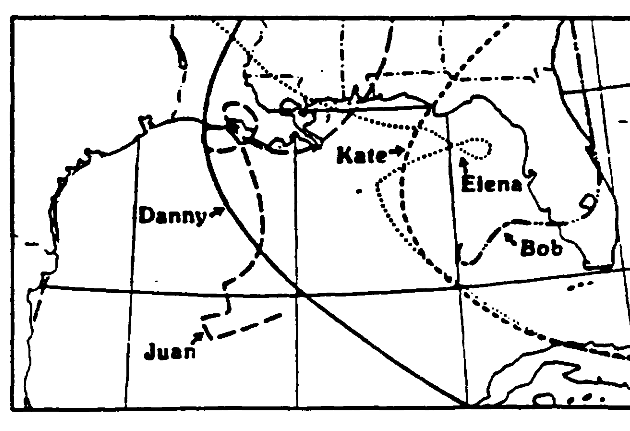

Figure 1. Storm tracks of the 1985 Gulf of Mexico hurricanes (data from the National Hurricane Center).

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1985 hurricane impacts to examine the geomorphic response of the Isles Dernieres barrier island arc to multiple hurricane impacts. The results of this study contribute to a better understanding of landform dynamics for coastal scientists and managers (Sallenger et al, 1987).

This paper describes the 1985 hurricane storm processes, maps the geomorphological storm effects, and interprets the storm process-response characteristics of the Isles Dernieres.

DATA BASES AND METHODOLOGY

We used wind, wave, and tidal process data and imagery from four sequential airborne videotape surveys flown between 1984 and 1985 to interpret the impacts of the 1985 hurricanes on the Isles Dernieres. Information on wind, rain, and atmospheric pressure was supplied by the National Hurricane Center, National Climatic Data Center, National Weather Service, and the Office of the State Climatologist at Louisiana State University. For each hurricane, we used these data sets to produce (1) a storm trackline map, (2) a storm history statistical table, (3) a wind-pressure history, (4) representative surface weather maps, and (5) rainfall distribution patterns (Penland et al, 1989).

Information on water levels was acquired from the National Ocean Survey (NOS), the New Orleans District of the U.S. Army Corps of Engineers (USACE), and the Coastal Engineering Research Center (CERC). These data sets were used to construct regional storm-surge maps and hydrograph time-series for specific stations. Data were used from open-coast tide gauge stations at Galveston, Texas; Cameron, Freshwater Bayou, and Gardner Island, Louisiana; Biloxi, Mississippi; Dauphin Island, Alabama; and Pensacola and Panama City, Florida. Data were used from inland tide gauge stations at Hackberry, Intracoastal City, Morgan City, Cocodrie, Lafitte, and Frenier, Louisiana, and Mobile, Alabama.

We used sequential airborne videotape surveys to assess the geomorphic changes along Louisiana's barrier islands. Between 1984 and 1985, the Louisiana Geological Survey (LGS) flew four videotape surveys covering the period of hurricane impact (Penland et al, 1986, 1987a, 1987b, 1987c). Using a helicopter, LGS acquired color oblique airborne imagery from an altitude of 100 m (328 ft) at a speed of 40 - 50 knots (kn) (46 - 58 mph). The geomorphic changes are mapped at a scale of 1:24,000 on base maps constructed from 1984, October 1985, and November 1985 aerial photography, with a landform classification system developed from the aerial and field surveys. We performed comparative analyses of individual surveys to identify temporal and spatial coastal changes in the geomorphology of the Isles Dernieres shoreline. Other specific studies used to better understand the Isles Dernieres geomorphology include Ritchie et al (1989) and Ritchie and Penland (1988).

1985 HURRICANE IMPACT PROCESSES

Hurricane Danny

A tropical depression moved northwest over the extreme western tip of Cuba and into the southeastern Gulf of Mexico on August 13, 1985 (Fig. 1). This tropical depression went from minimal tropical storm strength to hurricane strength in a 24-h period (National Hurricane Center, 1985a). Named Danny, the hurricane continued northwestward before turning on a more northerly course during the morning hours of August 15 off the Louisiana coast. The center made landfall southeast of Lake Charles, Louisiana around noon on August 15. Hurricane Danny quickly weakened to tropical storm strength as it moved inland.

The highest tides occurred 50 km (31 mi) east of the eye of hurricane Danny at Intracoastal City, where the storm surge was recorded at 2.4 m (7.9 ft) (Fig. 2). The storm surge was over a meter above National Geodetic Vertical Datum (NGVD) 300 km (186 mi) east of the storm center and 100 km (62 mi) to the west. In the vicinity of the Isles Dernieres the storm surge was about 1.25 - 1.75 m (4.10 - 5.74 ft). The tide gauge at Eugene Island was on the east side of the storm and recorded a maximum surge of 1.88 m (6.16 ft) NGVD (Fig. 3 above). The tide gauge record indicates the storm surge preceded landfall by about 12 h, with water levels rapidly rising from −0.15 m (−0.49 ft) NGVD at 1200 August 11 to 1.88 m (6.16 ft) at 0000 August 15. This is a 2 m (6 ft) rise in 12 h. To the west of the storm track at

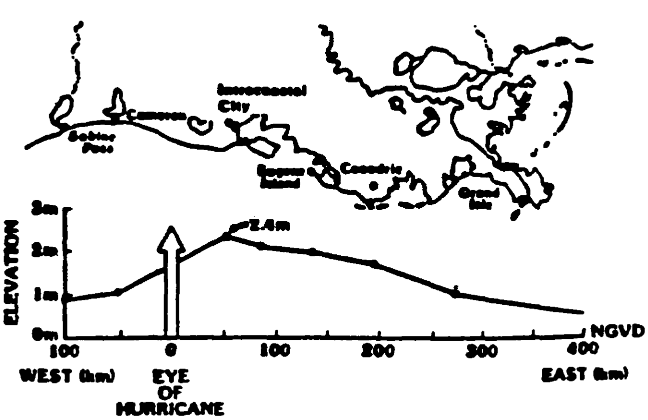

Figure 2. Maximum storm-surge elevation map for the Hurricane Danny impact zone.

Cameron the winds were predominantly offshore, helping to dampen the storm surge, which reached a maximum of only 0.88 m (2.88 ft) NGVD (Fig. 3-below). At landfall, the water levels in Cameron were depressed −0.25 m (−0.82 ft) below NGVD by strong offshore winds.

Hurricane Juan

Hurricane Juan moved erratically throughout its development. Initially, reconnaissance aircraft reported the center to be a wide area of light and variable winds. As the storm became better organized, it began moving northeastward around 10 kn (11 mph) early on October 27. That afternoon the storm turned to the northwest at 15 kn (17 mph) and attained minimal hurricane strength. Hurricane Juan's speed dropped to less than 5 kn (6 mph) by early October 28, and during the next 24 h it made a cyclonic loop off the south-central Louisiana coast. Early October 29 Juan hit near Morgan City, Louisiana, and on the following day made another cyclonic loop around Lafayette, Louisiana, before emerging over Vermilion Bay. On October 30, Hurricane Juan was downgraded to a tropical storm with gale force winds confined to the waters of the northern Gulf of Mexico. After moving offshore the storm became better organized as it passed the Louisiana coast and then moved across the mouth of the Mississippi River near Burwood and was again upgraded to a hurricane. In the morning hours of October 31, Hurricane Juan headed northeast at 15 kn (17 mph), and made a second landfall at midday just west of Pensacola, Florida. Hurricane Juan turned northward and gradually lost strength before finally becoming classified as an extratropical storm on November 1 (National Hurricane Center, 1985b). The maximum sustained wind reported by reconnaissance aircraft was 75 kn (86 mph) on the morning of October 28, 1985 (National Hurricane Center, 1985b). Storm rainfall ranged from 10 – 20 cm (3.9 – 7.9 in.) with some local amounts of 40 cm (15.4 in.) over Louisiana (Fig. 4).

The storm surge of Hurricane Juan was unusually long, lasting three days as the storm looped twice across coastal Louisiana. The maximum water level was associated with the initial landfall of Hurricane Juan at Chenier Au Tigre, Louisiana. The storm surge peaked at an elevation of 2.19 m (7.18 ft) 30 km (19 mi) west of the storm track and peaked at more than a meter as far east as Pensacola, Florida (Fig. 5). West of the storm track, surge levels measuring more than a meter reached as far as Galveston, Texas. The Cocodrie USACE tide gauge station recorded the water-level time series for Hurricane Juan (Fig. 6). The water-level pattern differed from that of Hurricane Danny. The gauge recorded a single storm surge set-up with no set-down before or after the passage of Hurricane Juan. The water level initially reached its maximum elevation of 2.19 m (7.18 ft), then subsided to a level of about 1.50 m (4.92 ft) for the next three days.

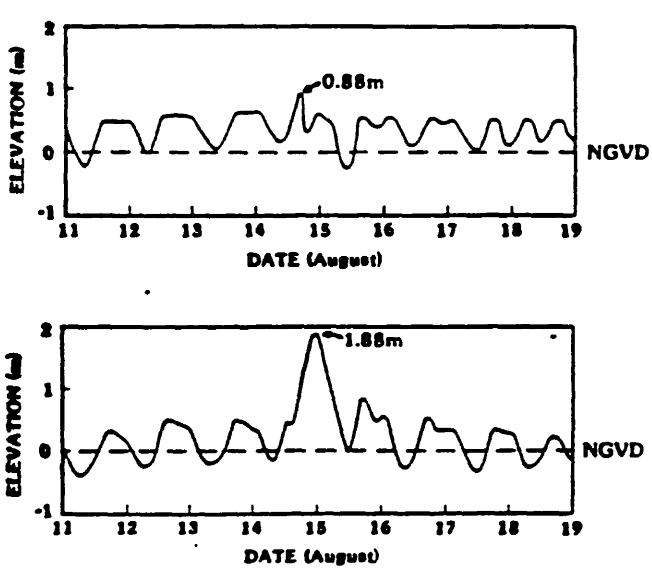

Figure 3. (above) Water-level time series for the passage of Hurricane Danny at the USACE Eugene Island, Louisiana, tide gauge. (below) Water-level time series for the passage of Hurricane Danny at the USACE Cameron, Louisiana, tide gauge.

COASTAL GEOMORPHIC CLASSIFICATION

Classification System

The LGS developed a coastal geomorphologic classification system for shorelines surrounding the Mississippi

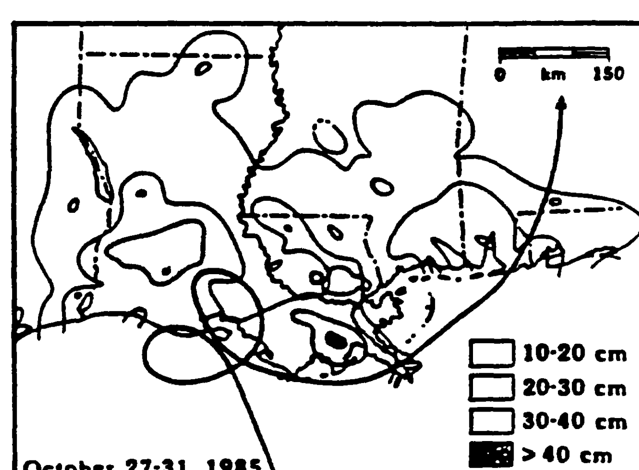

Figure 4. Rainfall distribution during Hurricane Juan. Data from National Oceanic and Atmospheric Administration.

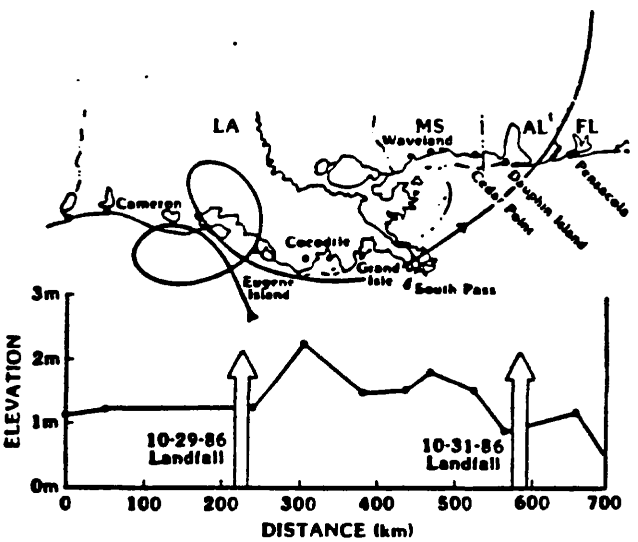

Figure 5. Maximum storm-surge elevations in the Hurricane Juan impact zone.

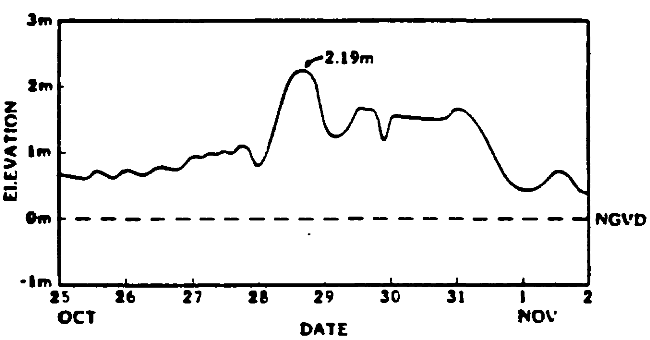

Figure 6. Water-level time series for the passage of Hurricane Juan at the USACE Cocodrie, Louisiana, tide gauge.

River delta and Chenier plains. Based on 10 years of shoreline monitoring, analysis of aerial photography for 1940 - 1985, and numerous field surveys, the classification is used with imagery from low-altitude, high-resolution airborne videotape surveys to describe and quantify the longshore and cross-shore geomorphic, sedimentologic, and vegetative character of Louisiana's shoreline systems. Comparisons of video imagery taken annually and both before and after storms reveal changes in these characteristics. The classification makes it possible to delineate and map detailed geomorphic habitat changes at a resolution higher than that of conventional vertical mapping photography.

The classification system divides shorelines into two broad classes: natural and altered. Each class consists of several genetically linked categories of shorelines. Each category is then subdivided into morphologic types on the basis of landform relief, elevation, habitat type, vegetation density and type, and sediment characteristics (Table 1).

Natural Shorelines

The morphologies of natural shorelines, either bare or vegetated, reflect ongoing coastal processes rather than direct human impacts. The natural shoreline class is made up of five categories: (1) barrier, (2) tidal inlet, (3) storm, (4) erosional, and (5) marsh.

Barrier types are a continuum of landform morphologies that represent the range from a high-erosion, sediment-deficient shoreline to a low-erosion, sediment-abundant shoreline: from intertidal flats through continuous dune fields, respectively. The barrier category includes intertidal flats, washover flats and terraces, dune terraces, continuous dunes, fringing beaches, and perched beaches. Figure 7 illustrates the major washover and dune morphologies mapped in the Isles Dernieres and other barrier shorelines in Louisiana. The aerial photographs of these landforms in Figure 8 show the variations in relief, elevation, and habitat diversity. The *tidal inlets* category includes channels that perpendicularly dissect the barrier shoreline and connect the backbarrier bay with the Gulf of Mexico. These tidal channels remain open, unlike the more ephemeral washover channels. A washover channel that breaches a barrier island will become a tidal inlet if the tidal prism is sufficient to maintain it. The tidal inlet category also includes flood-tidal deltas, which develop landward of

Table 1. Coastal geomorphic classification system

SHORELINE CLASS	CATEGORY		MORPHOLOGIC TYPE
Natural	Barrier		Intertidal flat Washover flat Washover terrace Dune terrace Continuous dune Fringing beach Perched beach
	Tidal inlet		Tidal inlet Flood-tidal delta Ebb-tidal delta
	Storm		Major washover channel Minor washover channel Interdune washover channel
	Erosional		Marsh platform Scarp
	Marsh		Salt marsh
Altered	Protection	"soft"	Barrier restoration Beach nourishment Artificial dune Dune fencing
		"hard"	Seawall Groin
	Habitat disturbance		Spoil bank Pipeline landfall Dredge spoil Industrial structures
	Transportation		Air strip Access canal (open) Access canal (closed) Distributary Piers Jetty Access road

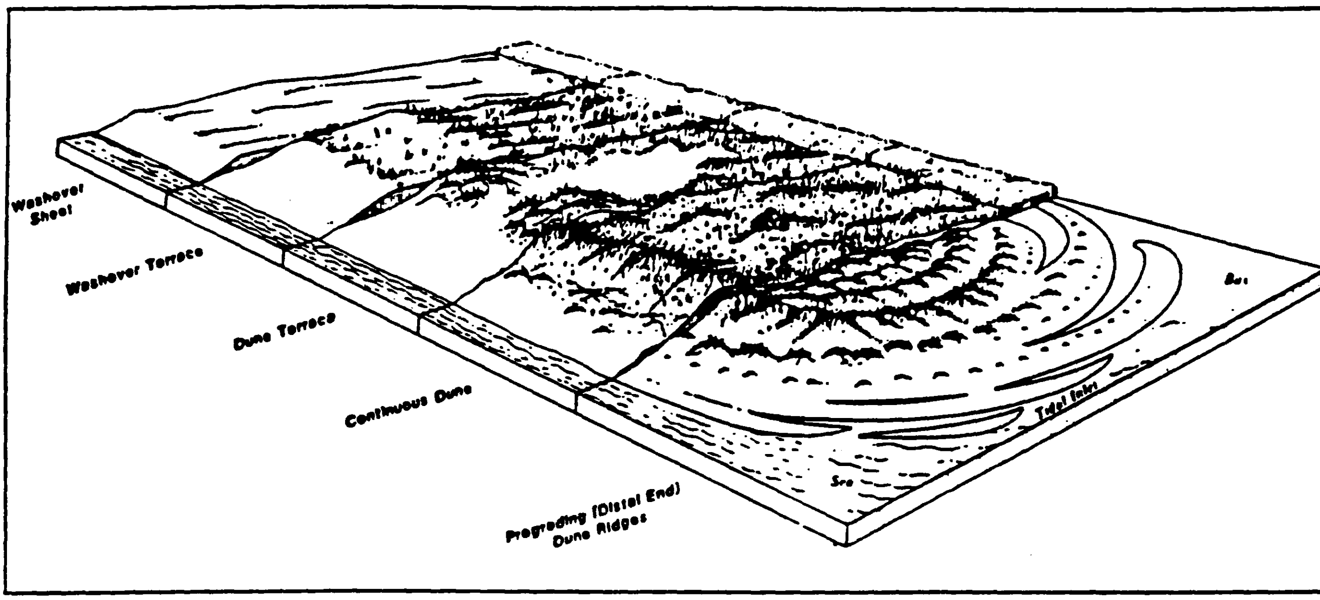

Figure 7. Primary washover and dune morphologic types found in Louisiana's barrier islands. From Ritchie and Penland (1985).

the tidal inlets, and ebb-tidal deltas, which develop on the seaward side.

Three types of *storm* features can be identified: major, minor, and interdune washover channels. A major washover channel is a storm channel cut below sea level that is open during the normal tidal range (Fig. 9-above). A minor washover is a well-defined storm channel cut through a barrier shoreline that is not open throughout the normal tidal range (Fig. 9-below). An interdune washover channel is a small-scale washover channel that penetrates the foreshore terraces and dune types without dissecting the island. In the graphic presentation of the data, the direction of the arrow on the geomorphic maps indicates the predominant direction of storm flow.

Two types of *erosional* morphologic features can be identified. Marsh platforms are erosional outcrops of marsh root mat occurring on a beachface exposed by coastal retreat. An erosional scarp is produced when a retreating shoreline truncates a higher-relief backshore feature. Both of these features are common under normal circumstances; however, storm impacts do produce a greater exposure of marsh platform and erosional scarps per unit length of shoreline.

The *marsh* category comprises areas along the barrier shorelines where salt marsh or fresh marsh forms the shoreline. These features are common in sheltered areas where sandy beaches are nonexistent.

Altered Shorelines

Altered shorelines are sections of coast no longer in a natural state because of human activities ranging from habitat disturbance to erection of seawalls and establishment of barrier island restoration projects. The class includes three categories: (1) transportation, (2) protection, and (3) habitat disturbance (Table 1). The *transportation* category includes jetty systems for maintenance of navigation channels and canals for access and transportation; it also includes access roads to the shoreline, air strips, distributaries, and piers. The coastal *protection* category includes "hard" and "soft" structures (Penland and Suter, 1988). Examples of hard coastal structures are seawalls and groins built to stop coastal erosion and reduce sediment loss. Soft coastal structures include barrier restoration, beach nourishment, dune-building projects (artificial dunes), and dune fencing for coastal erosion control and habitat restoration. The *habitat disturbance* category includes dredge spoil, spoil bank, pipelines, and other industrial structures.

Morphologic Types

Thirty-three coastal morphologic types can be identified in coastal Louisiana, based on landform relief, elevation, habitat type, vegetation density and type, and sediment characteristics. The category *flats*, for example, describes low-elevation, flat-relief landforms less than 1 m (3 ft) above mean tide level (MTL). *Terrace* describes partially and fully vegetated washover and dune surfaces typically 1 – 2 m (3 – 7 ft) above MTL. *Washover flats* are low-elevation, low relief washover surfaces devoid of significant vegetation, maintained or formed by frequent or recent washover events. *Dune terraces* are significantly vegetated washover surfaces where eolian processes have built hummocky and rim dune landforms. *Washover terraces* are washover surfaces with variable elevation, relief and vegetation, and constitute a transition between washover flats and eolian-dominated dune terraces. Therefore, washover terraces can be considered either a low- or high-relief landform depending on and relative to the adjacent shoreline morphology. *Continuous dunes* are the highest-relief and highest-elevation landforms; they are well vegetated and diverse in habitats. Some of the types represent either areas whose morphologies and texture contain engineered coastal structures or areas directly affected or disturbed by human activities. In addition, the texture (sand, shell, concrete, detrital organics, rubble, etc.) and form (straight, undulating, serrate, etc.) of the shoreline help to define its morphological type. These variables are not discussed here, however, because the Isles Dernieres shoreline is predominantly sandy and straight.

All morphologic types identified in the system can be used at any of three descriptor levels; this gives the classification scheme greater flexibility. The three levels are (1) primary morphology, (2) modifier, and (3) variant. The primary morphology descriptor defines the dominant longshore morphologic type per unit length of shoreline and is mappable on a 1:24,000 base map, with the unit being no smaller than 10 m (33 ft). The modifier describes secondary longshore features also mappable at that scale. Variants are important features that can be located and counted but are less than 10 m (33 ft) long.

A morphologic unit consists of a length of shoreline with a uniform morphologic type, texture and form. The length of the morphologic units is mapped from the airborne videotape imagery onto the base maps at a scale of 1:24,000, interpreted from the vertical aerial photography concurrent with the video imagery data. The morphologic units are mapped parallel to the regional shoreline. Figure 10 illustrates the graphic mapping technique. The bottom modifier bars and variants describe features in the surf zone and/or foreshore; the upper bars and variants describe the backshore features. A maximum of three modifiers and two variants, in addition to the primary morphology, are allocated to each unit.

Once each unit is mapped, its length is measured and entered into a physical shore-zone mapping program for quantitative analysis (Reimer, 1988). Measurements are

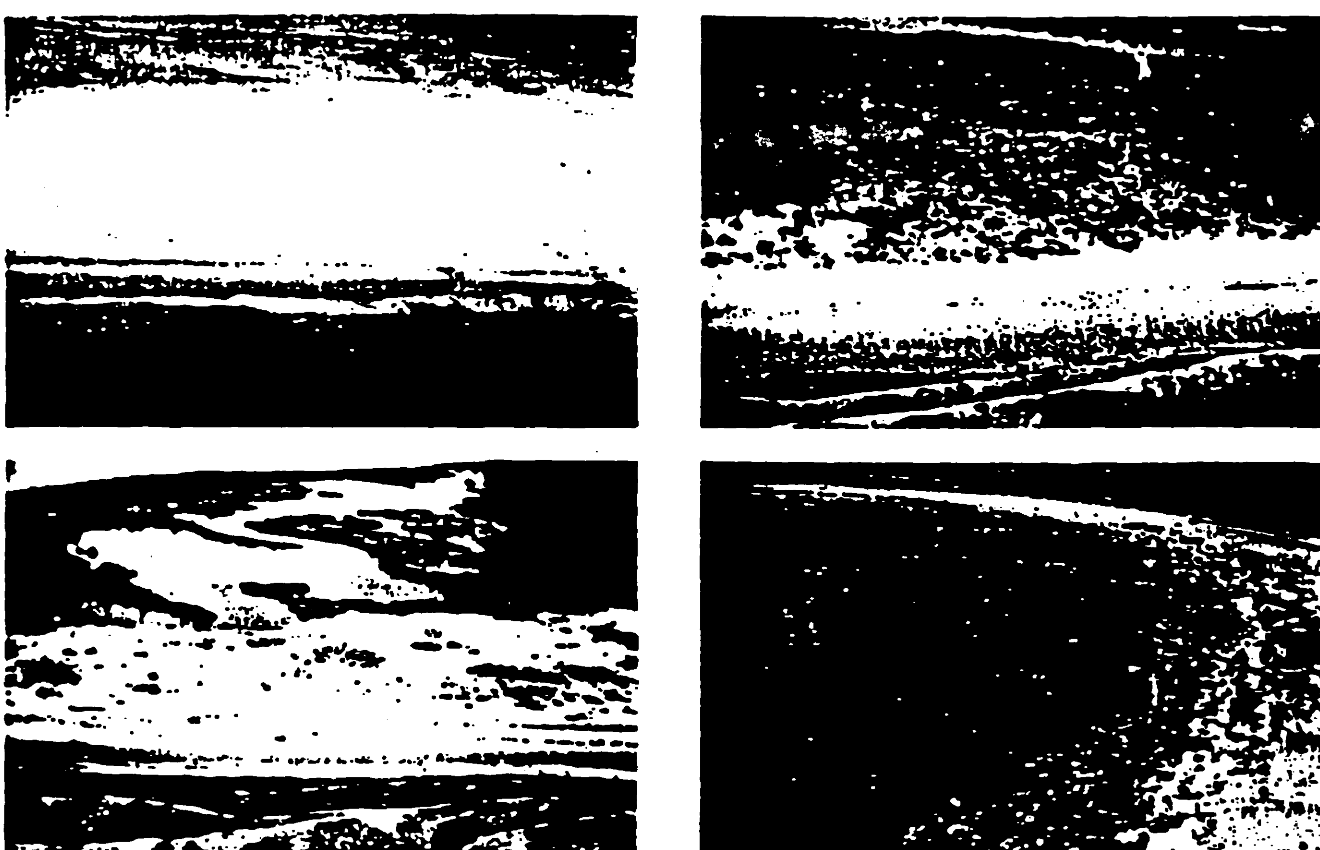

Figure 8. (upper left) Oblique aerial view of a washover flat. (lower left) Oblique aerial view of a washover terrace. (upper right) Oblique aerial view of a dune terrace. (lower right) Oblique aerial view of a continuous dune.

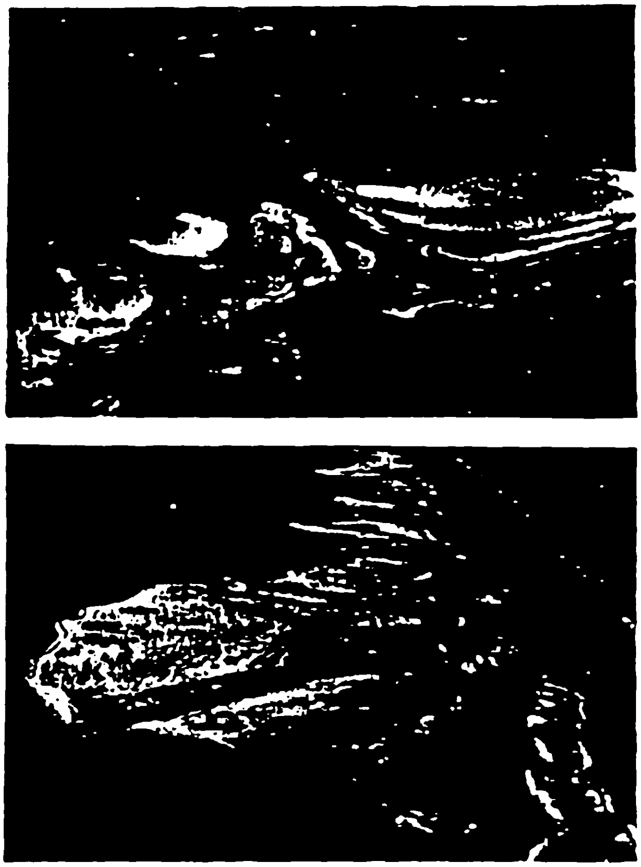

Figure 9. (above) Oblique aerial view of a major washover channel. (below) Oblique aerial view of a minor washover channel.

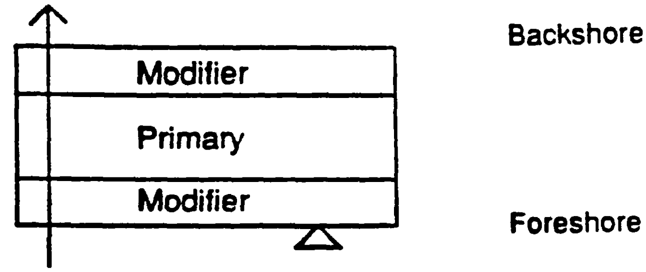

Figure 10. Each descriptor bar is oriented generally parallel to the shoreline and corresponds horizontally in scale and position to its associated map. The dominant longshore morphology of the shore zone is indicated in the larger central primary bar. The bottom modifier bar(s) and variant(s) represent secondary features in the surf zone and foreshore. The upper modifier bar(s) and variant(s) represent the backshore features. The arrow, for example, is a landward-directed washover channel that affects both the foreshore and backshore, and the triangle represents a spoil bank found only in the foreshore at this point.

Table 2. Morphologic types present in the Isles Dernieres

Intertidal flat
Washover flat
Washover terrace
Dune terrace
Continuous dune
Tidal inlet
Major washover channel
Minor washover channel
Marsh platform
Scarp
Barrier restoration
Spoil bank

made shore-normal to the descriptor bars and represent per-unit length of exposed Gulf shoreline. Output is by variable group and consists of the number of units, total unit length, and total unit percentage of shoreline for each of the variables present on the shoreline.

For each airborne video survey year, the geomorphology of the Isles Dernieres is described by total unit length of shoreline. Next, the individual morphologic type is described for each of the four islands in the barrier island arc (Raccoon Island, Whiskey Island, Trinity Island, and East Island). Table 2 shows the morphologic types present on the Isles Dernieres shoreline. Morphologic time series were developed for each island and for the total shoreline length to depict spatial and temporal geomorphic changes.

DISCUSSION AND SUMMARY

Regional Morphology

During non-hurricane years vegetative cover increases and eolian and overwash processes operate under normal shoreline erosion conditions, which allow greater island relief and elevation, as well as greater habitat diversity, to develop (Ritchie and Penland, 1988). The Isles Dernieres had not been affected by hurricanes since 1979, and in 1984 – 85 were characterized by higher-relief morphologies (Table 3; Fig. 11, 12, 13, 14). The data show a slight decrease in percentage of higher-relief forms between these two years as a result of the minor winter storms of 1984 (Fig. 15). The central Isles Dernieres at Whiskey Island and Trinity Island have the lowest relief and are dominated by washover flats and washover terraces. The ends of the Isles Dernieres at Raccoon Island and East Island are higher in relief, diversity, and elevation; the morphologies of these islands are dominated by washover terraces, dune terraces, and

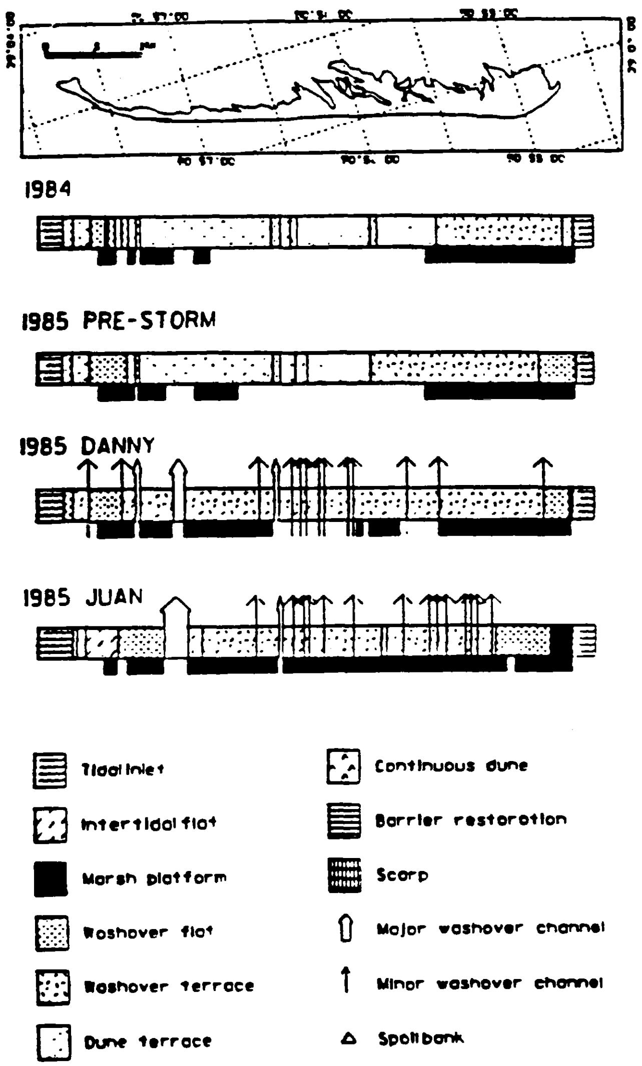

Figure 11. Raccoon Island geomorphic changes, 1984 - 1985.

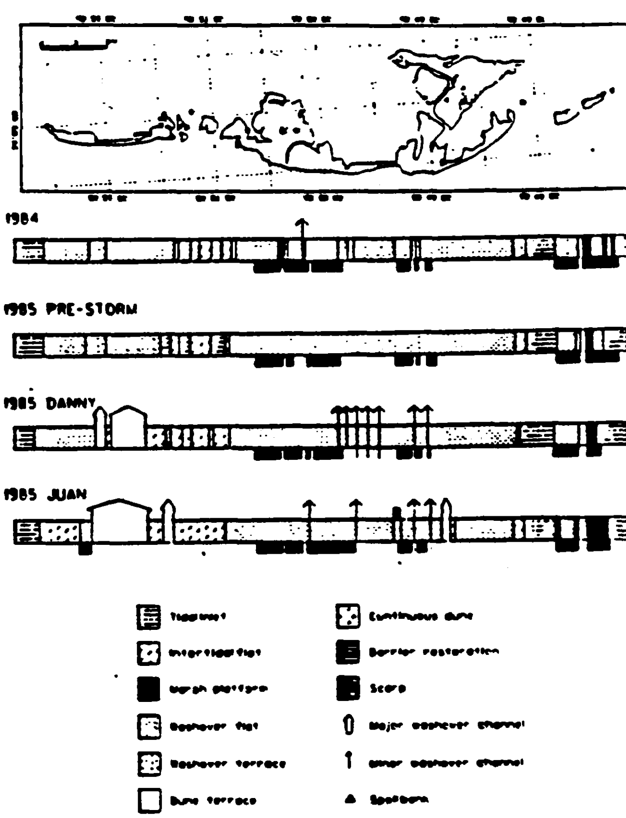

Figure 12. Whiskey Island geomorphic changes, 1984 - 1985.

continuous dunes. The higher and more diverse morphologies of the Isles Dernieres are characterized by well established vegetative cover, slow shoreline retreat rates and an updrift supply of sediment. The lower morphologies are associated with rapidly eroding, poorly vegetated shorelines.

In the central Isles Dernieres, the Whiskey Island and Trinity Island landscape is dominated by the plant species *Spartina patens* (marsh hay cordgrass) and *Panicum amarum* (bitter panicum). The ends of the Isles Dernieres at Raccoon Island and East Island are much more diverse in vegetation and geomorphic habitat types. *Baccharis halimifolia* and *Iva frutescens* are commonly found on the higher dune terraces and continuous dune fields of Raccoon Island, where these woody shrubs appear to be the most effective plants for mitigating overwash. At East Island, *Myrica cerifera* (wax myrtle) and bitter panicum are the important species. Raccoon Island also has the lusnest vegetation in the Isles Dernieres and the west delta barrier shorelines. Vegetation species commonly found on the other islands are much healthier and more robust on Raccoon Island. Seasonally, the vegetation here is consistently better developed. Interestingly, Raccoon Island is the site of the largest marine bird nesting concentration in the barrier islands west of the Mississippi River, if not in Louisiana. This fact provides one possible explanation for the lush vegetation: each year the entire island is fertilized by an extensive layer of guano during the marine birds' nesting season. This same relationship between guano and vegetation appears to hold true for Curlew Island in the Chandeleur Islands, which is the major nesting area in that island chain.

Hurricane Danny Impact

Hurricane Danny resulted in a typical force-1 shore-normal hurricane impact. The greatest changes in primary morphology occurred at Raccoon Island and Trinity Island. Storm-surge overwash reduced the morphology of Trinity Island to predominately washover flats and terraces and resulted in a major increase in exposed marsh platform. At Raccoon Island, the dune terraces were converted to washover terraces and more marsh platform was exposed on the beach

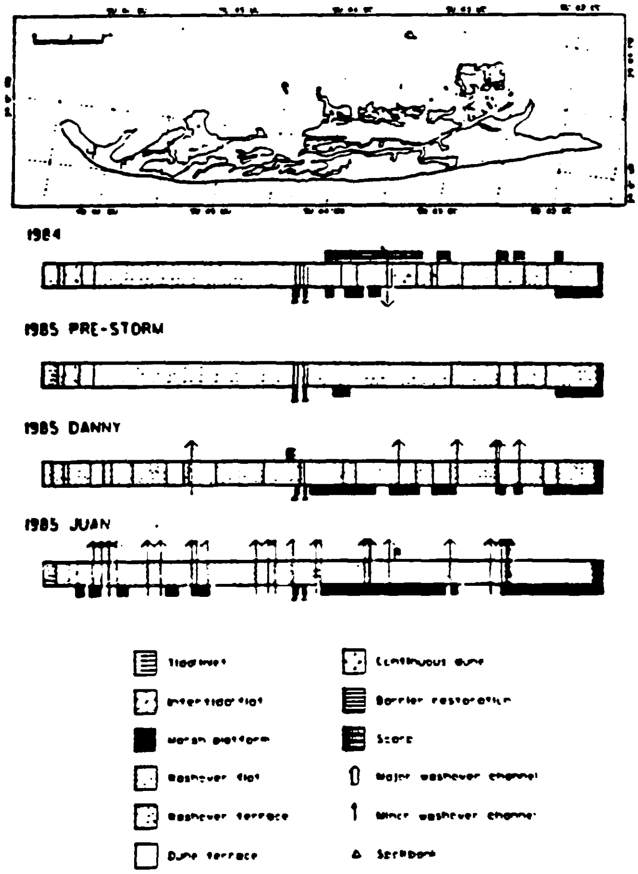

Figure 13. Trinity Island geomorphic changes, 1984 - 1985.

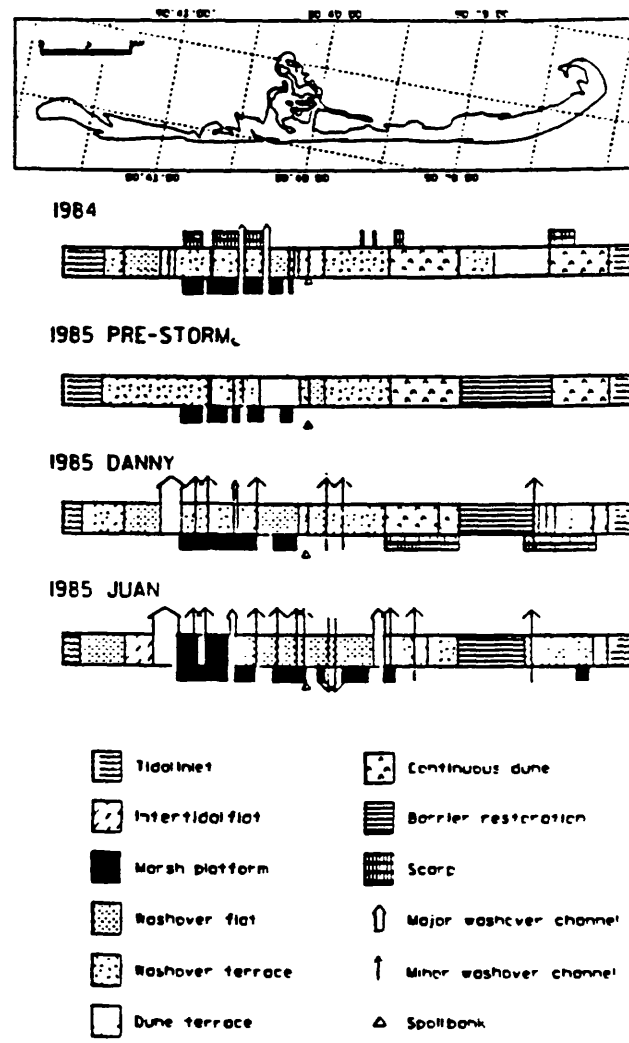

Figure 14. East Island geomorphic changes, 1984 - 1985.

face; however, the overall relief of the island remained relatively high. Whiskey Island and East Island had the fewest changes in primary morphology. Whiskey Island is characterized by lower-relief morphologies, such as washover flats, intertidal flats, and marsh platforms, with washover flats remaining the dominant morphology. Like Raccoon Island, East Island generally lost relief, but the overall relief remained relatively high. The major impact of Hurricane Danny was a general flattening of the island profile and scarping of the higher-relief landforms.

Seven major washover channels were cut through the Isles Dernieres. There was no single preferred area of channelization. All of these major channels were breached at locations where the islands were very narrow, low in profile, and not backed by backbarrier marsh. Hurricane Danny cut 32 minor washover channels through the Isles Dernieres, and, as with the major washover channels, there was no preferred regional zone of development. Minor washover channels generally developed only on the lower-relief morphologies—washover flats and terraces. Erosional scarps were associated with the washover terraces, continuous dunes, and the barrier restoration project on East Island.

Overall, Hurricane Danny was sufficient to dramatically alter the higher-relief landforms of the Isles Dernieres. The dune terraces on Raccoon Island were reduced to washover terraces, and extensive scarps formed on the higher-relief landforms of East Island. However, the overall relief of these islands remained relatively high. The storm surge breached 7 major and 32 minor washover channels associated with the lower-relief landforms. The process-response characteristics of the Isles Dernieres to Hurricane Danny illustrate the effects of a minor hurricane making a rapid shore-normal landfall.

Hurricane Juan Impact

Like Hurricane Danny, Hurricane Juan was a minor storm in terms of wind speed and pressure; however, in terms of storm-surge duration and storm track, this storm was very different. The storm surge lasted three

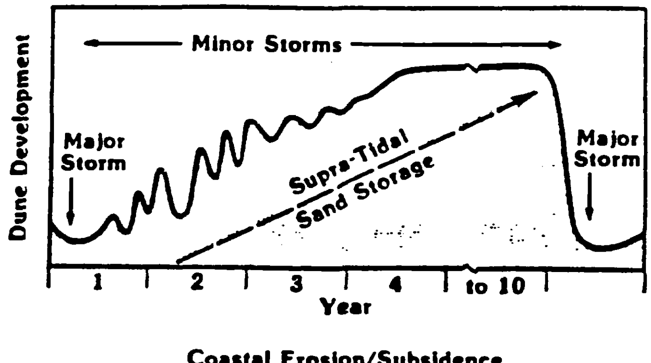

Figure 15. Process-response model of washover and dune development along Louisiana's barrier islands. From Ritchie and Penland (1988).

days instead of several hours as Hurricane Juan wandered across coastal Louisiana. As a consequence, the landscape of the entire Isles Dernieres changed extensively.

The lower-profile and less-vegetated central Isles Dernieres responded dramatically to Hurricane Juan. At Whiskey Island, the washover flat morphology persisted, and many areas were further reduced in profile to intertidal flats. Washover channel breaching continued as new minor channels formed and major channels consolidated. The primary morphology of Trinity Island was reduced from scattered washover terraces and flats to a continuous washover flat. Many new minor washover channels were cut in areas where higher-relief washover terraces were reworked into washover flats.

On the higher-relief areas of the Isles Dernieres, the continuous dunes were extensively eroded. The East Island dunes were converted to dune and washover terraces, washover flats, and marsh platform. The dunes flanking the Terrebonne Parish Barrier Island Restoration Project were converted to dune and washover terraces, but the project itself had only minor washover and localized scarping on the artificial dune front. New major and minor washover channels were breached at East Island. To the west, Raccoon Island underwent the fewest primary morphological changes of the Isles Dernieres. The washover terrace morphology of Raccoon Island remained almost unchanged after Hurricane Juan; the major storm effects were the breaching of more major and minor washover channels and the exposure of more marsh platform along the shoreline.

Hurricane Juan further lowered the already-weakened profile of the Isles Dernieres, enlarged major washover channels, and increased the number of minor washover channels. The geomorphic changes associated with the Hurricane Juan impact reflect more the duration of the storm surge than its magnitude.

Total Geomorphic Change: 1984 - 1985

The cumulative impact of Hurricanes Danny, Elena, and Juan produced dramatic landscape changes in the Isles Dernieres between July 1984 and November 1985 (Fig. 16). The nature of the geomorphic response pattern is a function of the preexisting landscape morphology and the strength, magnitude, and duration of each storm. The net effect of the storms was to transform a relatively high-relief landscape dominated by well vegetated dunes and dune and washover terraces to one dominated by partially vegetated washover terraces and washover sheets with the vegetation stripped away. The entire island chain was breached by 57 minor and 8 major washover channels.

In 1984, the higher-relief continuous dune (6.2%), dune terrace (12.9%), and washover terrace (33.8%) landforms accounted for 52.9% of the primary morphology of the total Isles Dernieres (Table 3; Fig. 17). After Hurricane Juan, these landforms accounted for only 12.2% of the total shoreline length. In contrast, the lower-relief washover flats (22.6%), marsh platform (0.9%), intertidal flats (1.6%), and major washover channels (0.3%) accounted for only 25.4% of the geomorphology of the 1984 Isles Dernieres shoreline length. After Hurricane Juan, the total percentage of these lower-relief landform types dramatically increased to 65.0% of the total Isles Dernieres shoreline length in 1985.

Each individual island of the Isles Dernieres chain had a distinctive geomorphic response to the 1985 hurricane impacts as a function of its pre-storm morphology and the character of each hurricane impact (Fig. 18). Raccoon Island had the largest higher-relief dune terrace system in the Isles Dernieres; this landform accounted for 61.7% of the shoreline in 1984. The lower-relief washover terrace (26.9%) and washover flat (11.4%) accounted for the remaining 38.3% of the shoreline length of Raccoon Island. The 1985 hurricane completely destroyed the extensive dune terrace system and converted it to washover terraces, washover flats, intertidal flats, and major washover channels.

At Whiskey Island the geomorphic changes were not as dramatic because the erosional history of the island is characterized by rapid shoreline retreat and a washover-flat landscape. Between July 1984 and November 1985, the pattern of landscape change was the conversion of washover terraces into marsh platform, intertidal flats, major washover channels, and washover flats. The 1985 hurricanes were also responsible for converting washover flats into other lower-relief morphologies.

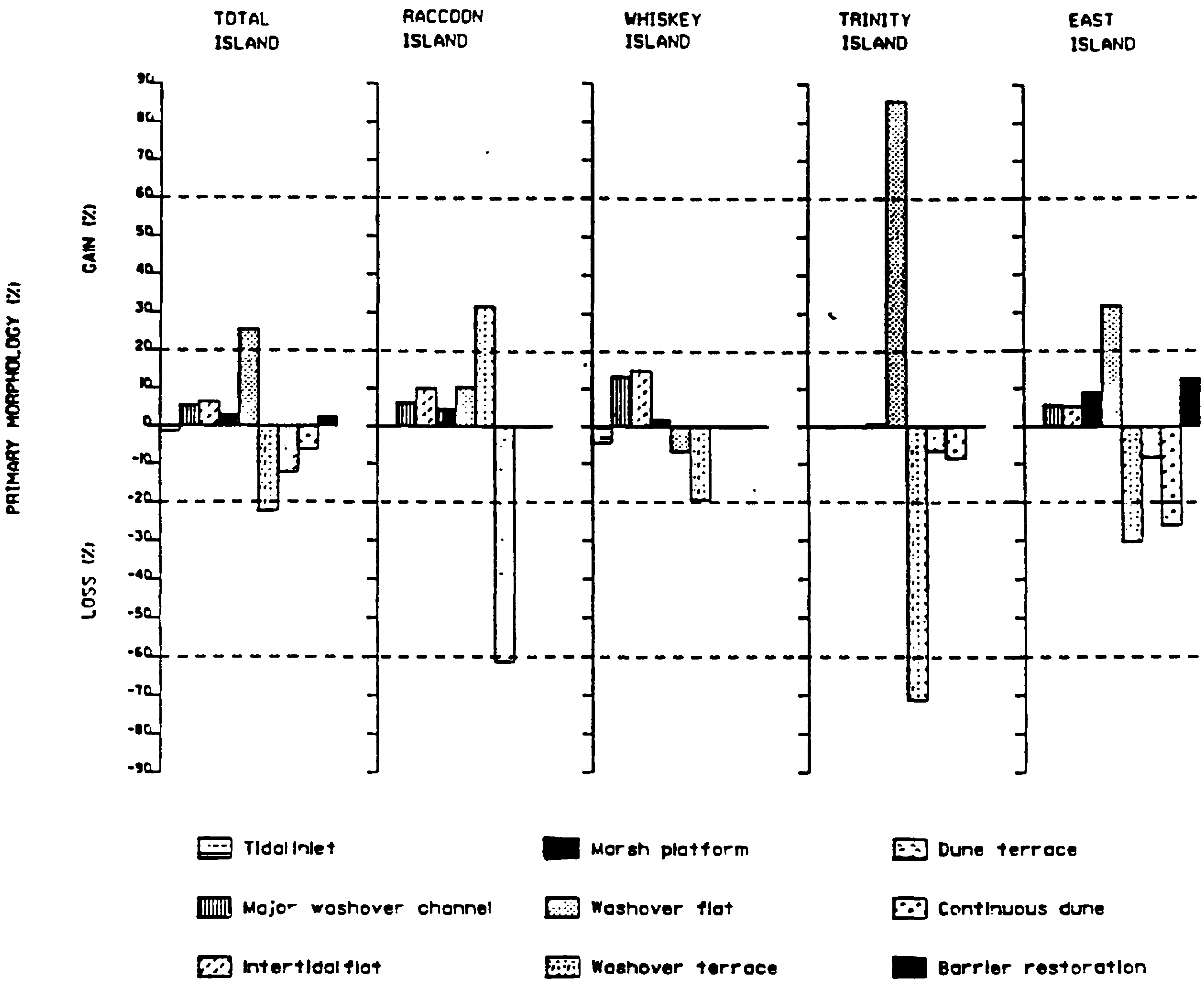

Figure 16. Percentage change of the primary morphology of the Isles Dernieres between 1984 and 1985 post-Juan.

In contrast to Whiskey Island, the higher-relief Trinity Island was almost totally converted to a washover flat. In July 1984, 87.6% of the island shoreline was made up of continuous dunes (8.5%), dune terraces (6.6%), and washover terraces (72.5%). After Hurricane Juan, the geomorphology of Trinity Island was reduced to 97.2% washover flat. This dramatic increase in washover flats reflects the fact that before the hurricanes 76.8% of the Trinity Island shoreline was washover terrace, which is only a slightly higher-relief landform.

East Island was the highest-relief area in the Isles Dernieres. In 1984, 81.2% of this island was made up of continuous dune (25.7%), dune terraces (10.9%), and washover terraces (44.6%). After the Hurricane Juan impact, the landscape of East Island was converted into washover flats (48.5%), marsh platform (8.8%), intertidal flat (5.4%), and major washover channels (7.7%), and washover terraces were reduced to 14.2%.

Comparative Hurricane Processes

The 1984 – 1985 geomorphologic process-response pattern of the Isles Dernieres and each individual island illustrates the differences between Hurricanes Danny and Juan with respect to coastal process variables. Hurricane Danny produced widespread geomorphologic changes in the lower-relief landscape areas as well as breaching through these low areas. The storm surge reduced the higher-level relief landforms but the overall relief remained relatively high. In contrast, Hurricane Juan produced extensive and dramatic geomorphic changes in both high-relief and low-relief landforms. And yet Hurricanes Danny and Juan had similar wind speeds, low pressure, wave heights, and storm-surge

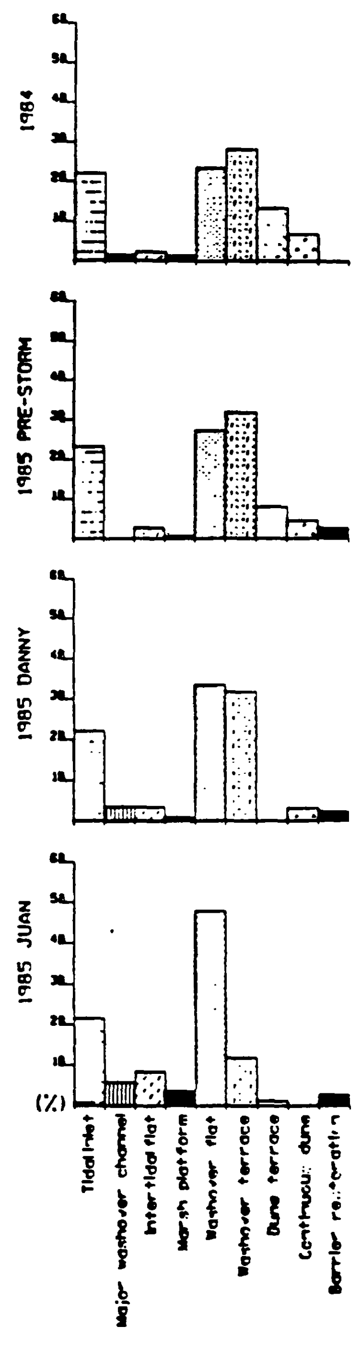

Figure 17. Primary morphology (%) per unit length of the Isles Dernieres shoreline in July 1984, July 1985, August 1985, and November 1985.

levels (Table 4). The major difference between these storms was their duration. Hurricane Danny was classified as hurricane/tropical-storm strength for 60 h, and the storm surge persisted at 50 cm (20 in.) above mean sea level for 18 h. In contrast, Hurricane Juan was classified as hurricane/tropical-storm strength for 108 h, and the storm surge persisted at over 50 cm (20 in.) above mean sea level for 91 h. The geomorphic response of the Isles Dernieres for 1984 - 1985 demonstrates that storm duration is a key variable controlling the response of the islands to these hurricane impacts.

Washover Channel Development

Major washover channels in the Isles Dernieres occurred in low-relief areas of narrow island width without backbarrier marsh, or extensive vegetation on washover surfaces. In this type of low area even minor hurricanes cut major washover channels. Minor washover channels also appeared to be concentrated in the lower-relief coastal landforms. No correlation exists between their location and the width of the islands. This indicates that both island width and relief are major controls in the channelization of overwash flow during hurricane impact. This was observed to be the case in the impacts of Hurricanes Danny and Juan. The areas typically breached by major overwash channels are the recurved spits at Coupe Colin and Coupe Carmen. Washover channel development here initiates a new cycle of tidal inlets and sediment bypassing to the west. Other favorable areas are where the island narrows, loses vegetation, and decreases in relief and elevation.

Barrier Island Restoration

The Barrier Island Restoration Project constructed by Terrebonne Parish prevented East Island from breaching and a new tidal inlet from forming (Fig.19). By raising the elevation of this previous washover and dune terrace area and revegetating it, the project made East Island more storm resistant. If this project had not been in place, this area would have breached, as it was in 1974 after Hurricane Carmen. Some beach erosion and dune scarping occurred in the project area. The amount of change was several orders of magnitude less than that observed on the adjacent natural beaches, where continuous dune systems were converted to washover flat and terrace areas.

Revegetation at the Eastern Isles Dernieres Barrier Island Restoration Project was accomplished through three processes. Initially, plantings were made in parallel shore-normal and shore-parallel rows. However, intense nutria herbivory resulted in a poor survival rate. Therefore, seed was used next instead of live plantings, which are much more expensive. The survival rate for the seed-generated vegetation was much higher than for the live planting. The third revegetation process was by natural recolonization around the project margins. The experience gained with this project indicates that using seeds is the most cost-effective means of maintaining a vegetated island.

Table 3. Morphologic units in the Isles Dernieres, 1984 – 1985, as percentages of total shoreline length

All Islands	Tidal Inlet (%)	Major Washover Channel (%)	Intertidal Flat (%)	Marsh Platform (%)	Washover Flat (%)	Washover Terrace (%)	Dune Terrace (%)	Continuous Dune (%)	Barrier Restoration (%)
1984 July	21.7	0.3	1.6	0.9	22.6	33.8	12.9	6.2	0.0
1985 July	22.5	0.0	2.2	0.5	27.3	31.8	8.0	4.8	3.0
1985 Danny	21.7	3.4	3.3	0.8	33.7	31.6	0.0	2.9	2.5
1985 Juan	20.6	5.6	7.8	3.7	47.9	11.7	0.5	0.0	2.2
Raccoon Island									
1984	0.0	0.0	0.0	0.0	11.4	26.9	61.7	0.0	0.0
1985 Pre-storm	0.0	0.0	0.0	0.0	19.4	34.9	45.7	0.0	0.0
1985 Danny	0.0	4.1	0.0	0.6	13.7	81.6	0.0	0.0	0.0
1985 Juan	0.0	6.0	9.7	4.3	21.9	58.1	0.0	0.0	0.0
Whiskey Island									
1984	12.0	0.0	6.0	2.8	58.8	20.3	0.0	0.0	0.0
1985 Pre-storm	15.1	0.0	8.3	1.1	71.3	4.3	0.0	0.0	0.0
1985 Danny	12.0	8.2	12.9	1.4	65.5	0.0	0.0	0.0	0.0
1985 Juan	7.9	13.3	21.0	4.7	52.1	1.1	0.0	0.0	0.0
Trinity Island									
1984	0.0	0.0	0.0	0.8	11.6	72.5	6.6	8.5	0.0
1985 Pre-storm	0.0	0.0	0.0	1.0	15.3	76.8	4.3	2.6	0.0
1985 Danny	0.0	0.0	0.0	1.3	49.3	49.3	0.0	0.0	0.0
1985 Juan	0.0	0.0	0.0	1.6	97.2	1.2	0.0	0.0	0.0
East Island									
1984	0.0	2.1	0.0	0.0	16.9	44.6	10.9	25.7	0.0
1985 Pre-storm	0.0	0.0	0.0	0.0	13.4	43.5	0.0	25.2	17.9
1985 Danny	0.0	4.2	0.0	0.0	18.8	45.3	0.0	17.1	14.6
1985 Juan	0.0	7.7	5.4	8.8	48.5	14.2	2.7	0.0	12.6

Table 4. Comparison of Hurricanes Danny and Juan

Process	Hurricane Danny	Hurricane Juan
WIND		
Maximum speed (kn)	80 kn[1]	75[2]
Hours classified as hurricane	24[1]	42[2]
Hours classified as tropical storm	36[1]	66[2]
Maximum low pressure (mb)	987[1]	971[2]
WAVES		
Significant wave height (m)	6.74[3]	11.89[3]
Maximum offshore wave height (m)	9.67[3]	13.05[3]
TIDES		
Maximum surge height (m)	2.4[4]	22[4]
Hours surge height >50 cm	18[4]	91[4]

[1]National Hurricane Center (1985a)
[2]National Hurricane Center (1985b)
[3]Coastal Studies Institute, Louisiana State University
[4]U.S. Army Corps of Engineers, New Orleans District

CONCLUSIONS

1) The central Isles Dernieres, Whiskey Island and Trinity Island, typically have lower relief and elevation and less habitat diversity than islands at the ends of the chain, Raccoon Island and East Island.

2) The morphology of Raccoon Island is predominately washover and dune terraces under non-hurricane conditions and predominately washover terraces and flats after hurricane impacts.

3) The morphology of Whiskey Island is predominately washover flats under non-hurricane and hurricane-impact conditions.

4) The morphology of Trinity Island is predominately dune and washover terraces under non-hurricane

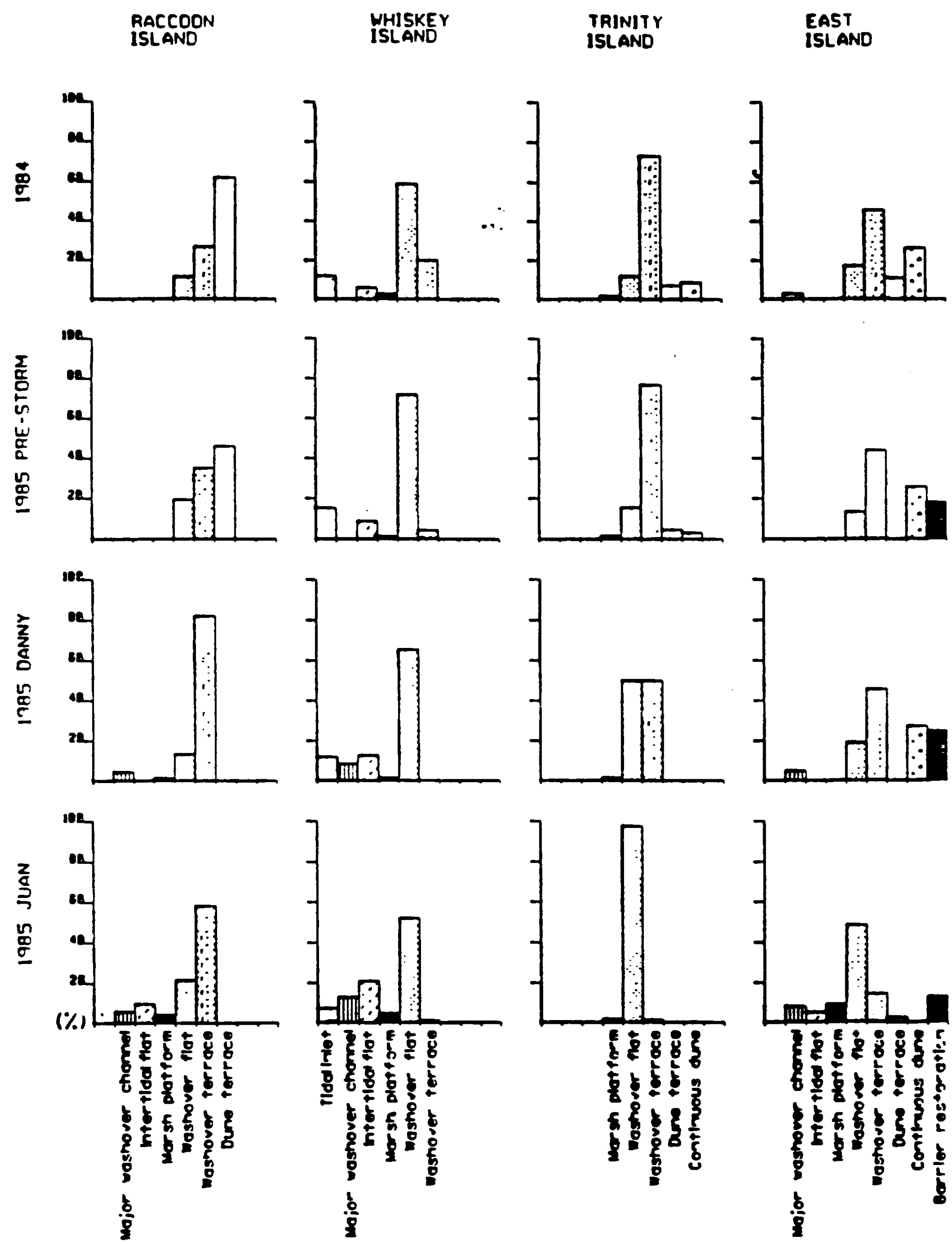

Figure 18. Primary morphology (%) per unit length of shoreline on each island of the Isles Dernieres for July 1984, July 1985, August 1985, and November 1985.

Figure 19. Oblique aerial view of the Terrebonne Parish barrier island restoration project in the eastern Isles Dernieres.

5) The morphology of East Island is predominately a mixture of washover terrace, dune terrace, and continuous dune under non-hurricane conditions and predominately washover flats and terraces after hurricane impacts.

6) The rate of shoreline change and sediment supply controls the spatial morphologic variability.

7) The frequency, magnitude, and duration of hurricane impacts controls the temporal morphologic variability.

8) The lower-profile, rapidly eroding coastal areas are more sensitive to variations in high-energy wave and overwash conditions than are the higher-profile and slower-eroding coastal areas.

9) Major washover channels were concentrated in low-profile, narrow-width areas that lacked vegetation and backbarrier marsh.

10) Vegetation plays an important role in stabilizing barrier islands and reducing the effects of hurricane impact.

11) The barrier island restoration technique used in the Isles Dernieres proved successful in preventing overwash and reducing coastal erosion.

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SEQUENCE STRATIGRAPHY OF THE MISSISSIPPI DELTA

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ABSTRACT

One method of testing the concept of sequence stratigraphy is to compare it to Quaternary sediments in which chronology, stratigraphic relations and facies geometry are more clearly understood than in older rocks. Rapid deposition rates during Quaternary glacial-eustatic cycles in large deltaic depocenters generate sequences comparable to those in the ancient stratigraphic record. In the northern Gulf of Mexico, the late Wisconsinan-Holocene Mississippi River has deposited a Type 1 sequence which includes lowstand, transgressive, and highstand systems tracts. Characteristics of modern Mississippi River sedimentary environments support the methodology used in sequence analysis but the short time taken for sequence generation here raises important questions about sequence timescales, correlation, and driving mechanisms.

INTRODUCTION

The development of seismic and sequence stratigraphy at Exxon Production Research (Vail et al, 1977; Haq et al, 1987) and elsewhere (e.g., Brown and Fisher, 1980) provided a new view of the relations between relative sea level and sedimentation and demonstrated the genetic link between them. The interpretation of ancient sediments has traditionally relied on comparison with modern depositional environments and the application of facies models and Walther's Law (e.g., Walker, 1984). There have been few attempts to integrate or compare the results obtained from modern depositional environments with those from the seismic-sequence stratigraphic approach (Vail, 1987). This is largely due to a perceived difference in scale between the two approaches and the long time span apparently required for sequences to develop.

Here we compare a classic set of Quaternary sedimentary environments deposited by the Mississippi River in the northern Gulf of Mexico with the depositional sequences predicted from the Exxon Production Research (EPR) approach (Posamentier and Vail, 1988), concentrating on transgressive and highstand systems tracts. This comparison is used to test the EPR method in modern sedimentary environments where more data are available and relations are much clearer than in subsurface or outcrop studies of ancient rocks. The late Pleistocene-Holocene Mississippi delta and fan are among the most intensively studied and documented modern sedimentary environments (e.g. Walker, 1984). The chronology of sea level, sequence development and the time occupied by a single sequence are accurately constrained by techniques such as radiometric and isotope dating (e.g. Frazier, 1967; 1974). In addition, modern depositional environments such as deltas and submarine fans are readily identified from their geomorphology and location, and do not require an extra interpretation step necessary for sequence and systems tract determination in ancient rocks. Because both the EPR seismic/sequence stratigraphy approach and marine sediments derived from the Mississippi River are extensively described elsewhere (see below), only a brief summary of each is presented here.

SEQUENCE STRATIGRAPHY

A sequence is a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Mitchum, 1977). Sequence stratigraphy is the study of rock relationships within a chronostratigraphic framework of repetitive, genetically related strata bounded by surfaces of erosion or nondeposition, or their correlative conformities (Van Wagoner et al, 1987). A key concept of sequence stratigraphy is the interplay between relative sea level, subsidence, and sediment supply. If sediment supply is held constant, differing rates of sea level change and subsidence will produce a rise or fall of relative sea level (RSL). This change in RSL produces transgressions and regressions which shift the sediment depocenter between the deep sea floor (lowstand systems tract) and alluvial plain/continental shelf (highstand systems tract), with several intermediate positions occupied by transgressive and shelf margin wedge systems tracts (Fig. 1). When RSL falls below the shelf break, a Type 1 unconformity is generated. The overlying Type 1 sequence consists of a lowstand followed by transgressive and highstand systems tracts (Van Wagoner et al, 1987). Sequences are thought to be generated by varying global sea level (Vail et al, 1977; Posamentier and Vail, 1988). Many sequences have been stratigraphically correlated to a set of global cycle charts (Haq et al, 1987). The sequence stratigraphy concept thus consists of two distinct parts. One

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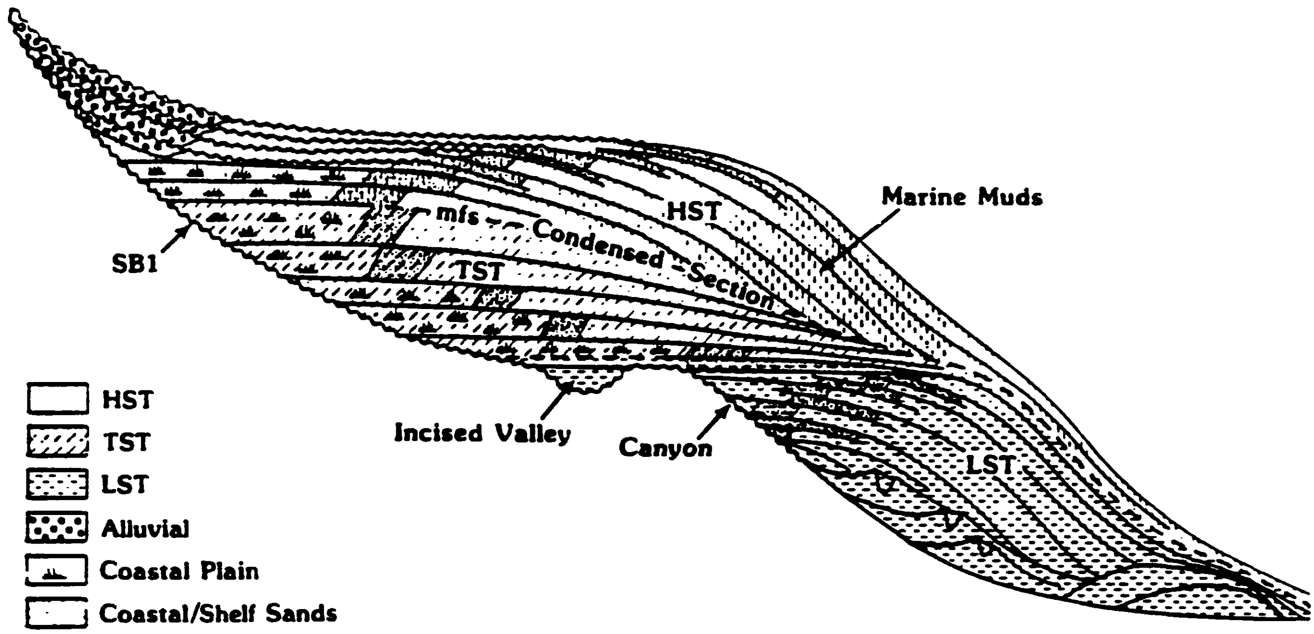

Figure 1. Major features of a sequence and associated systems tracts. LST = lowstand systems tract, TST = transgressive systems tract, HST = highstand systems tract, SB1 = type 1 sequence boundary, mfs = maximum flooding surface. Boundaries within systems tracts define parasequences. Each of these features can be identified in Quaternary sediments deposited in Gulf of Mexico by Mississippi River. Figure modified from Vail, (1987; his Fig. 4a).

is concerned with the generation of sequences and systems tracts by changes in RSL. The second covers global correlation of the sequences and the mechanism of sequence formation.

MISSISSIPPI DELTA STRATIGRAPHY

Quaternary marine sediments deposited by the Mississippi River accumulated mainly in submarine fan (e.g., Bouma et al. 1985) and deltaic (e.g. Frazier, 1967) environments. Each lobe of the Mississippi Fan (Fig. 2) results from sediment supplied during a Quaternary sea level lowstand (Bouma et al, 1986). The youngest fan lobe was supplied by Mississippi River sediments (Mazzulo. 1986) during the late Wisconsinan lowstand between 10-12 ka and 22-25 ka (Coleman et al, 1983). Sediments were delivered to the fan through a submarine canyon primarily by mass-movement processes (Coleman et al, 1983). RSL in the northern Gulf of Mexico during the late Wisconsinan lowstand fell to depths of -430 ft (-130 m) (Berryhill, 1986a), exposing the continental shelf and producing a set of shelf-margin deltas (Berryhill and Suter. 1986). A detailed sequence analysis of Mississippi Canyon and Fan sedimentation is not available. but the presence of coarse grained sediments, channels. and channel-levee-overbank complexes (Bouma et al. 1986) suggests that the deposits conform in general to a lowstand systems tract. Between 18 and 9 ka RSL rose from 200-430 ft (60-130 m) below present sea level (bsl) to around 65 ft (20 m) bsl. During the 18 ka lowstand, the Mississippi River had incised a trench across the continental shelf and, together with tributary

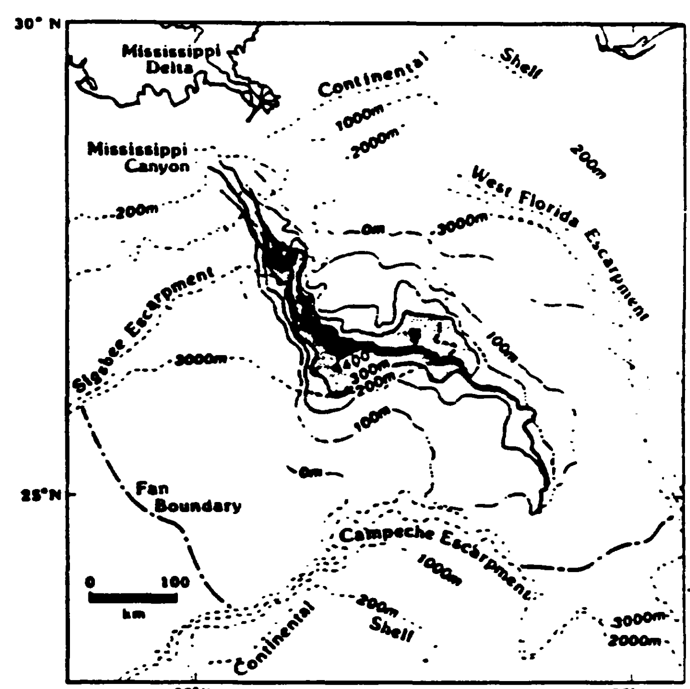

Figure 2. Location of Mississippi Canyon and Fan (modified from Bouma et al, 1986 p. 438-9). Fan boundary, isopach of youngest fan lobe (contours in meters), canyon and channel pattern shown. The 200-m (650-ft) isobath corresponds to the shelf break.

streams and subaerial weathering processes, produced an erosional unconformity on the Pleistocene Prairie terrace marked by a widespread oxidation surface (Fisk and McFarlan, 1955). This incised lowstand surface conforms with a Type 1 unconformity in EPR terminology. Sediments infilled and were largely restricted to the Mississippi Canyon (Fig. 2) during the period 18-9 ka.

Between 9 and 3.5 ka the Mississippi River was no longer totally confined to the canyon and proceeded to develop a number of progressively more shoal-water deltas (Fig. 3, numbers 1-3) on the outer to mid continental shelf (Fisk and McClelland, 1959; Frazier, 1967). This backstepping of individual shelf-phase delta complexes indicates that sediment volume supplied by the river was unable to keep pace with the overall eustatically driven transgression. The ability of delta plains to establish during this transgression indicates the existence of several periods in which the rate of RSL rise slowed or achieved a stillstand. As rates of RSL rise increased again these earlier phase deltas were themselves transgressed and reworked (Frazier, 1967; 1974; Penland et al, 1988). Shelf-phase delta complexes onlap the Pleistocene Type 1 unconformity with Holocene coastal sedimentary facies. This constitutes coastal onlap in EPR models. An example of the shelf-phase deltas is the Teche-Maringouin delta plain (Figs. 3 and 4) which was initiated between 6 and 7.5 ka when sea level was 19-26 ft (6-8 m) lower than present. The facies consist (Fig. 5) of a progradational component comprising clay underlying and seaward of delta front sands. The second component of this delta sequence was deposited during transgression and consists of a lagoonal deposit overlain by a shelf sand body (e.g., Ship Shoal) derived from flooding and reworking of the delta front. Each shelf-phase delta

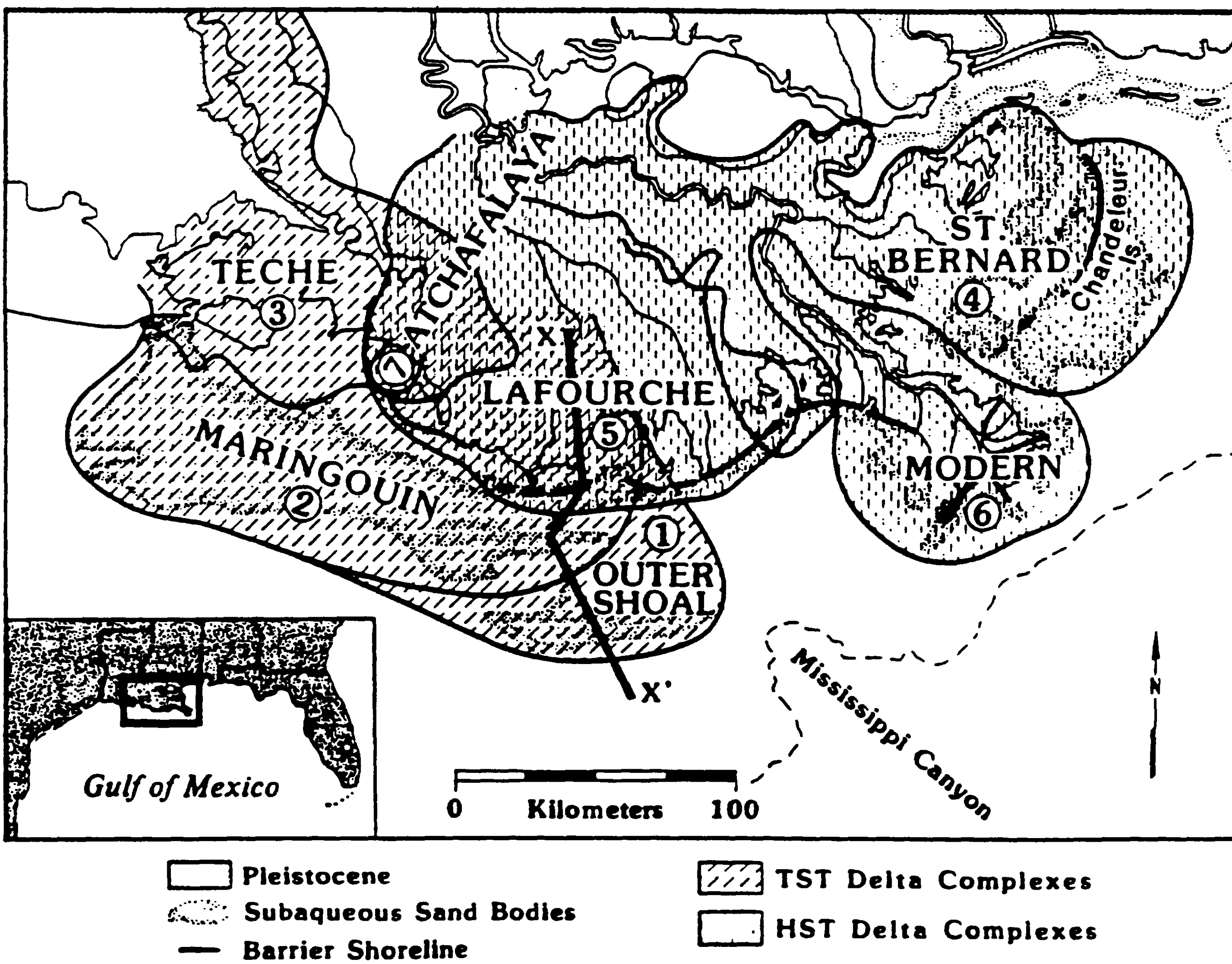

Figure 3. Holocene Mississippi River delta plain is composed of seven delta complexes occupying transgressive systems tract (1-3) and highstand systems tract (4-7). Location of geological cross section in Figure 2 is shown as X-X'. Figure modified from Frazier (1967), and Penland et al (1988).

complex is interpreted to represent an EPR parasequence. Stacking of the Teche, Maringouin, and Outer Shoal delta complexes (Figs. 3 and 4) between 9 and 3.5 ka resulted in the formation of a retrogradational parasequence set and defines a transgressive systems tract (Van Wagoner et al, 1987). The outer shelf region seaward of the Teche-Maringouin delta complex (Fig. 3) received little sediment supply after transgression and constitutes a condensed section in EPR models.

The culmination of the eustatic rise occurred around 3-4 ka in the Mississippi delta and resulted in the retreat of the coastline to the mouth of the Mississippi alluvial valley. The exact timing of the eustatic stillstand is debatable and may not have begun until at least 3.6 ka. Here, we assume the St. Bernard represents the first of the highstand delta complexes (Fig. 3). It began to establish a significant delta plain around 4 ka at the terminus of the alluvial valley, 30 mi (50 km) landward of the Teche-Maringouin shoreline. This position at the close of the eustatic transgression represents the EPR time of maximum flooding (Fig. 1).

The subsequent development of the Holocene Mississippi delta consists of a series of prograding delta complexes that began at the early St. Bernard shoreline and advanced more than 90 mi (150 km) southeast (Frazier, 1967) to the position of the currently active Modern or Balize delta (Fig. 6). In between, the Mississippi River continued to develop the St. Bernard delta complex (active 4.6-1.8 ka) and initiated two new delta complexes, the Lafourche (active 3.5-0.4 ka, Fig. 3) and the Plaquemines-Modern (active 1 ka to present). The central region of the Mississippi River delta plain contains the transgressive systems tract of the Teche-Maringouin delta overlain by the highstand systems tract of the Lafourche delta. The transgressive systems tract is separated from the highstand systems tract by a ravinement surface. Details of the stratigraphic relationships and sedimentary facies developed across a transgressive/highstand systems tract boundary are shown in Fig. 7. During the highstand, sediment volume supplied by the river has easily outstripped regional subsidence and any minor eustatic rise. Stacking of the St. Bernard, Lafourche and Modern delta complexes has produced a progradational parasequence set (cf. Van Wagoner et al, 1987). Together they make up a highstand systems tract which is still forming. The presence of lowstand, transgressive and highstand systems tract above a Type 1 sequence boundary (Fig. 4) indicates that late Wisconsinan-Holocene Mississippi River sedimentation is producing a Type 1 sequence (terminology from Van Wagoner et al, 1987).

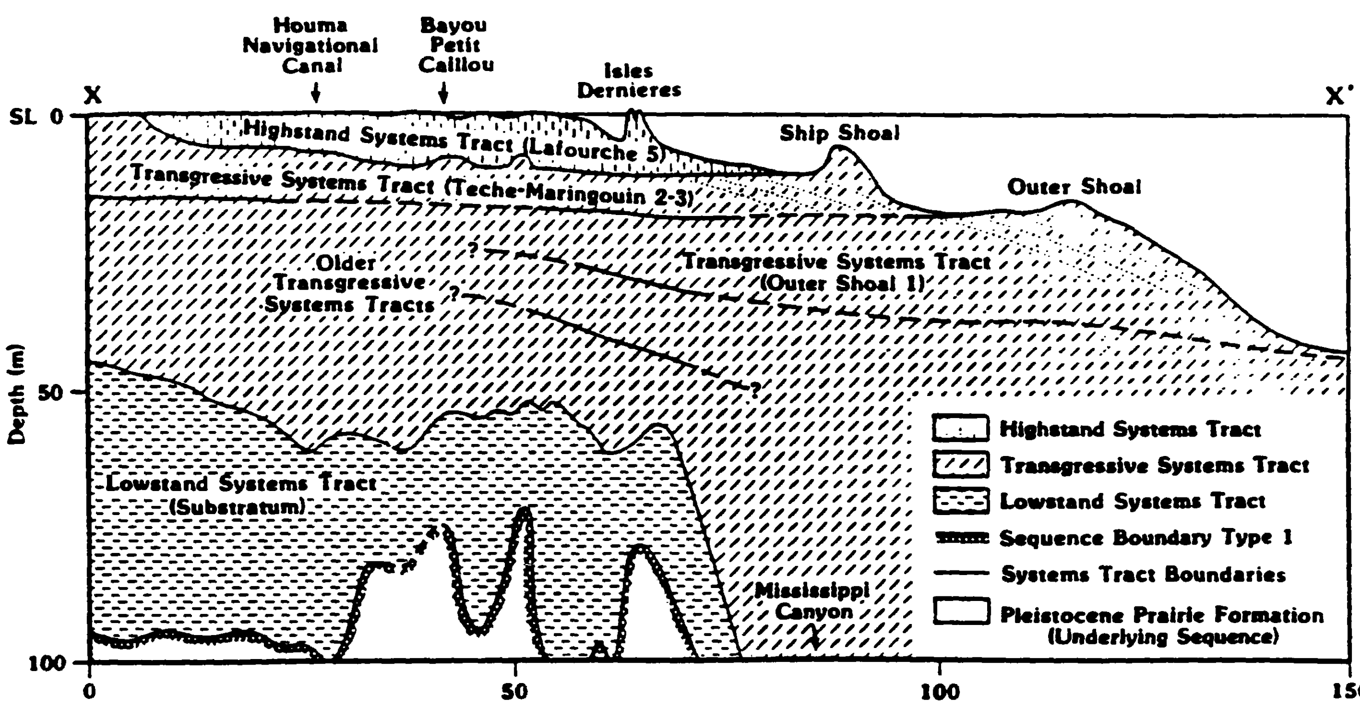

Figure 4. Mississippi delta cross section X-X' showing stratigraphic relations between Type 1 sequence boundary and lowstand, transgressive, and highstand systems tracts. Parasequence boundaries occur within and between systems tracts. Dotted lines within transgressive systems tracts represent progradational foresets identified from high resolution seismic data. Figure based on original data syntheses of high resolution seismic and vibracore data together with U.S. Army Corps of Engineers boreholes (see Penland et al, 1988 for summary).

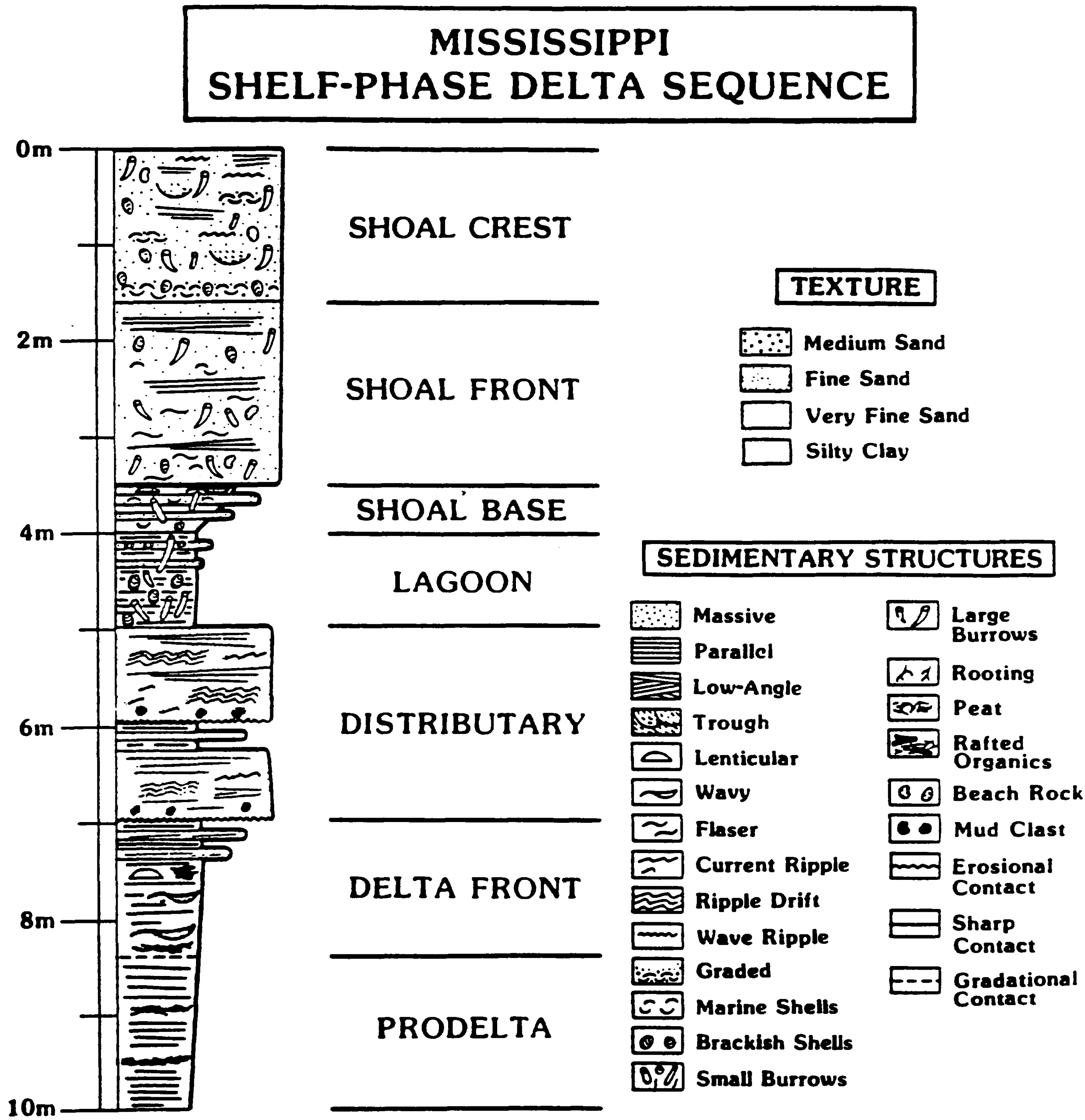

Figure 5. Mississippi shelf phase delta constitutes a parasequence and averages from 10 to 50 m thick. This parasequence consists of progradational and transgressive components, each of which may contain a sand body. Parasequences such as this may develop in either the transgressive or highstand systems tract and result in a vertical section which differs considerably in thickness and facies distribution from the traditional Mississippi delta model (from Penland et al, 1988).

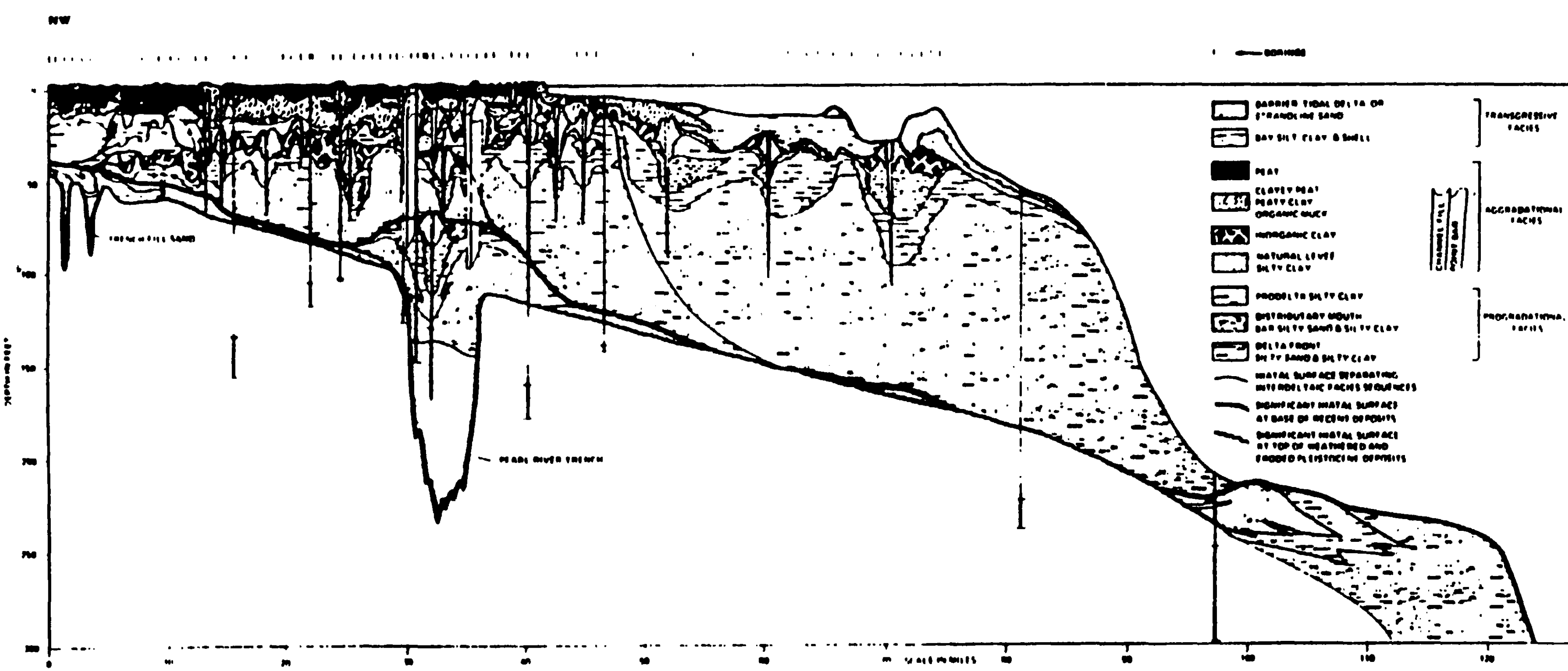

Figure 6. Cross section from New Orleans south-east to the shelf break. Here highstand systems tract of the St. Bernard delta progrades over lowstand and transgressive systems tract and almost reaches the shelf break. Highstand systems tract is underlain by transgressive sand body which occurs along a ravinement surface dated as older than 5350 years before present (modified from Frazier, 1967).

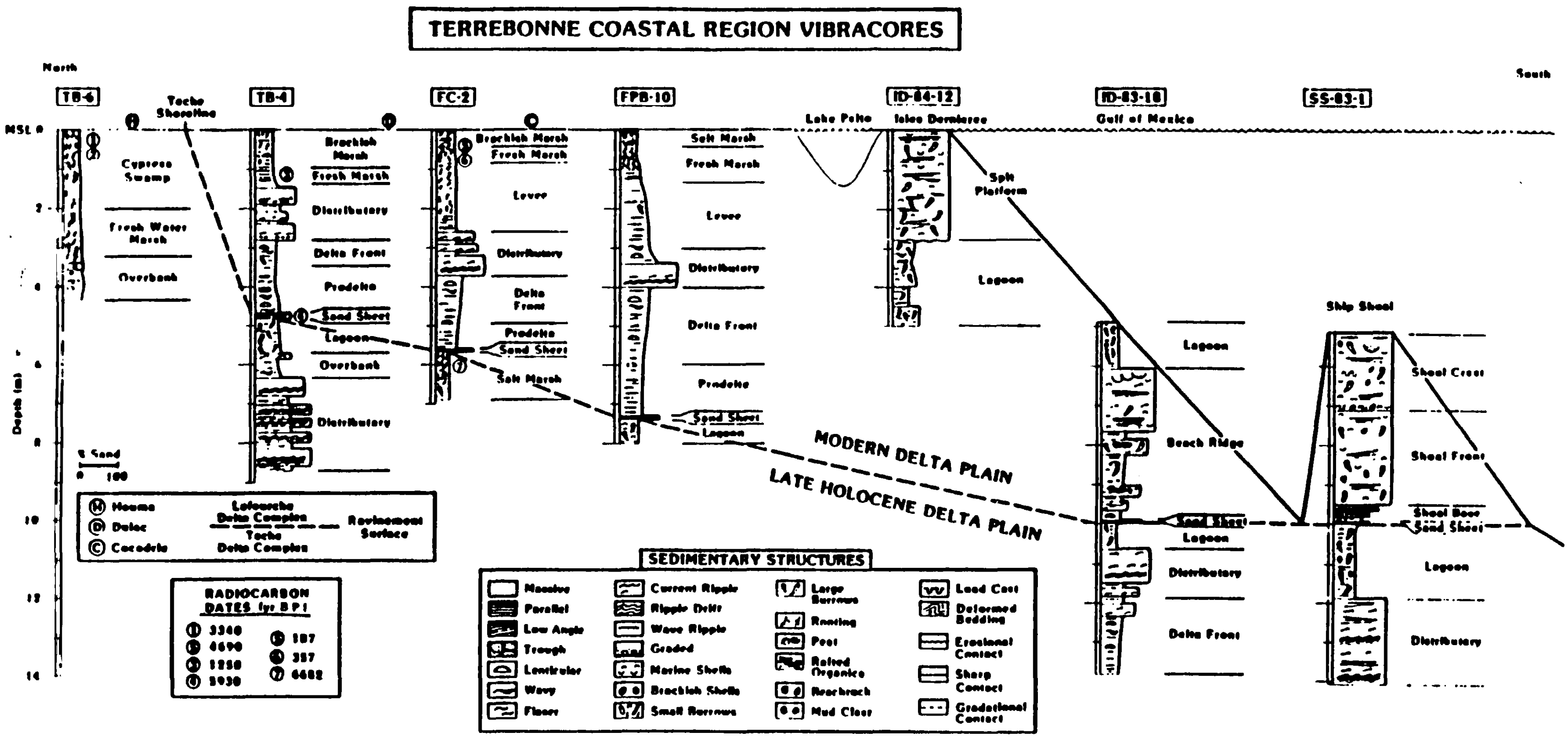

Figure 7. Vibracore dip section from the Central Mississippi River delta plain where the Lafourche delta of the highstand systems tract (modern delta plain) overlies the transgressive systems tract of the Teche-Maringouin delta (late Holocene delta plain). The two systems tracts are separated by a ravinement surface which is often associated with a transgressive sand sheet. This figure (from Penland et al, 1988) illustrates the detailed stratigraphy and facies distribution found along the boundary of transgressive and highstand systems tracts (figure located at the northern end of cross section in Fig. 4).

DISCUSSION

Many discussions of the Mississippi River delta emphasize the most recent. deep water Modern delta complex (e.g. Walker, 1984) and use it as a model for the complete Mississippi delta or for deltas in general. Comparisons with sequence stratigraphy correctly identify the Modern delta complex as a parasequence forming at the culmination of the highstand systems tract. Sedimentation in the Holocene Mississippi delta began once canyon infilling was complete around 9 ka and has continued throughout the subsequent transgressive and highstand systems tracts. Comparison of Mississippi River deltaic sedimentation with sequence stratigraphy enables a clearer understanding of the distribution and variability of deltaic sedimentary environments and facies. Sequence stratigraphy discriminates the early Holocene deltas of the transgressive systems tract (now located on the continental shelf) from the highstand deltas of the middle to late Holocene at the end of the Mississippi alluvial valley and the currently-active deepwater Modern delta located at the shelf break (Fig. 3, 6). The complex Mississippi depositional system is given added coherence by sequence stratigraphy. Each component of the Mississippi sequence can be classified into systems tracts and linked together by the sequence stratigraphy approach.

Previous determination of sequences and systems tracts has been limited to outcrop (Haq et al, 1987) and subsurface studies, particularly in ancient rocks (e.g., Vail et al, 1984). Testing the sequence stratigraphy approach in modern sedimentary environments enables comparison at much higher stratigraphic resolution and produces a higher degree of confidence in the result. The sequence/seismic stratigraphy methodology of EPR (Vail et al. 1977; Posamentier and Vail, 1988) functions well when applied to Quaternary Mississippi River sediments in the northern Gulf of Mexico. The generation of sequences and systems tracts by changes in RSL (the first part of the sequence stratigraphy concept) appears to be confirmed by this comparison. The Type 1 sequence being generated by the Mississippi River is underlain by a Type 1 unconformity and contains stacked parasequence sets in lowstand, transgressive, and highstand systems tracts. Modern sedimentary facies geometry within the systems tracts also conforms well to general EPR model predictions (Posamentier et al, 1988). The conformity of the Mississippi River sequence to EPR models is not a trivial correlation. Although short-lived. the Mississippi River sequence contains a large volume of sediments and would be identifiable on exploration seismic and well log data. Lowstand systems tract deposits in the youngest Mississippi Fan lobe (Fig. 2) are more than 1300 ft (400 m) thick and extend downslope more than 300 mi (500 km) (Bouma et al, 1985). Sediments deposited in the Mississippi Canyon during the latest Wisconsinan sea level lowstand are more than 1970 ft (600 m) thick (Coleman et al, 1983). Individual delta complexes that make up parasequences in the transgressive and highstand systems tracts average 30-165 ft (10-50 m) in thickness (Frazier, 1967; Penland et al, 1988) and extend 125 mi (200 km) down dip and more than 250 mi (400 km) along strike. Holocene sediment beneath the Modern delta is over 575 ft (175 m) thick at the present shelf edge (Fisk and McFarlan, 1955). A large percentage of ancient clastic sequences can be expected to form in tectonic settings similar to the Quaternary in the northern Gulf of Mexico where passive margin depocenters are infilled by major rivers (Burke, 1977).

Confirmation of the EPR methodology for sequence analysis by comparison with modern sedimentary sequences raises serious problems for the second part of sequence stratigraphy-global cycle chart construction. If sea level cycles are formed by a glacial-eustatic mechanism throughout the geologic record, as proposed by Vail et al (1977) and Haq et al (1987), then some ancient sequences must resemble the Mississippi delta and other sequences of the late Quaternary (Beard et al, 1982; Berryhill, 1986b) in the northern Gulf of Mexico. Likely intervals for glacially formed sequences include the Quaternary-Neogene and the Permian-Carboniferous (Frakes, 1979). The recurrence period of glacial cycles is controlled by earth's orbital properties throughout geological time and averages less than 100 k.y. (Hays et al, 1976). Quaternary glacial sequences in the northern Gulf of Mexico (such as the Mississippi delta/fan) developed during relative sea level cycles that lasted less than 30 k.y. Biostratigraphic resolution is incapable of globally correlating such short-lived cycles (Miller and Kent, 1987). Although early EPR charts gave average durations for "third order cycles" of 2.5 m.y. in the Cenozoic, and 10 m.y. in the Jurassic (Vail et al, 1977), there is no age limitation for either a sequence or a cycle (Van Wagoner et al, 1987). Many cycles on the most recent EPR charts have durations of only 1 m.y. (Haq et al, 1987). This is approximately the limit of resolution for a biostratigraphic zone and represents the lower limit of global cycle correlation (Miller and Kent, 1987). The increase in cycle number and decrease in cycle duration in recent global charts suggests that many cycles have real durations of less than 1 m.y. Under glacial conditions, thick sequences with high deposition rates could accumulate one order of magnitude faster than they could be resolved by biostratigraphy, making it impossible to demonstrate simultaneous formation on a global scale.

If ancient cycles are not formed by a glacial-eustatic mechanism, then there is no other known process capable of forming globally synchronous rapid changes in sea level (Donovan and Jones, 1979). Without any glacial process for global cycle formation, particularly in times that appear ice-free such as the Mesozoic (Frakes, 1979). it may prove more appropriate to interpret changes in RSL at such times as resulting mainly from tectonic processes operating within individual or adjacent basins (as suggested by Hubbard, 1988) or from other controls as yet undiscovered. Such an interpretation has far-reaching implications for sedimentary basin analysis. Nonglacial processes operate at different rates and scales than glacial processes. Sequence stratigraphic interpretation relies on a subtle interplay between sea level, sediment supply, and subsidence. Any change in RSL behavior caused by alternation between or combination of glacial and tectonic driving mechanisms would result in a globally nonuniform stratigraphic record containing variable continental margin geometry and sedimentary environment distribution.

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MASSIVE SEDIMENT BYPASSING OF A WIDE TIDAL INLET; CAT ISLAND PASS, LOUISIANA

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ABSTRACT

The Isles Dernieres is a rapidly eroding transgressive barrier arc located in central Louisiana about 90 mi (150 km) west of the Mississippi River. Much of the islands' Gulf shoreline has retreated over 0.6 mi (1 km) during the past 100 years. Today, the island area is less than 25 percent of what it was 100 years ago. To study the erosion of the arc, we used surface-modeling software to represent historical surveys of the region.

Comparisons of three combined bathymetric/topographic surveys taken of the Isles Dernieres barrier-island arc during the past 100 years show many expected features, such as shoreface retreat, inlet development and migration, and downdrift spit growth. An unexpected feature was a large volume of sediment that began bypassing a 6 mi (9 km) wide inlet system to the east of the Isles Dernieres sometime between 1934 and 1986.

Sediment bypassed the inlet at 13 to 26 ft (4 to 8 m) depths, depositing a 2.5 mi (4 km) by 11 mi (18 km) shore-parallel lobe of sediment along the path of transport. The volume of sediment in the lobe was 1.5 billion cubic feet (44 million cubic meters), more sediment than was deposited by longshore transport near the islands during the same period. Sediment supplied by the bypassing nourished the eastern Isles Dernieres, resulting in a decrease in both shoreface and shoreline erosion. The average shoreline erosion rate in the area supplied by the bypassing decreased from 36 ft/yr (11 m/yr) between 1890 and 1934 to 16 ft/yr (5 m/yr) between 1934 and 1986. If the bypassing continues, the rate of erosion of the eastern Isles Dernieres will be mitigated and the life of the arc prolonged. This decrease in the erosion rate will only lessen the rate of destruction of the islands; the trend of area loss in the Isles Dernieres is not likely to be reversed.

INTRODUCTION

Louisiana's barrier islands are eroding rapidly, with nearly 40 percent of the total island area lost since the 1890's (Penland and Boyd, 1981). In a cooperative effort, the U.S. Geological Survey and the Louisiana Geological Survey are studying the processes causing erosion of barrier islands in Louisiana to improve our ability to predict future erosion (Sallenger et al, 1987). One phase of the project uses historical maps of Louisiana's barrier islands and inner shelf to quantify changes and transport pathways of the transgressive barrier systems.

Historical maps document the rapid erosion of the Isles Dernieres barrier arc in central Louisiana. The island area decreased from 13.0 mi^2 (33.6 km^2) in 1890 to 3.1 mi^2 (8.1 km^2) in 1986, a 76 percent loss at an average rate of 0.10 mi^2/yr (0.27 km^2/yr) (Fig. 1). If this rate of loss continues, the islands will vanish by the year 2020. Unfortunately, the system is too complex to predict the arc's future by assuming that land loss will continue at the same rate. The dynamics of the barrier system is changing as it matures. An understanding of the evolution of these dynamics is necessary to accurately predict the future of the Isles Dernieres, as well as that of other similar transgressive barrier systems.

Historical maps of the Isles Dernieres area also show the response of the seafloor, which helps identify the processes causing the arc's evolution. An unexpected finding of the map comparisons was that the Isles Dernieres arc was not a closed system— a large quantity of sediment bypassed a 6 mi (9 km) wide tidal inlet to the east of the arc at depths below the upper shoreface. The transport pathway for that sediment was delineated by a large depositional lobe that now reaches the eastern Isles Dernieres and is nourishing the island, resulting in a decrease of shoreline erosion. In this paper we document the inlet bypassing at depths below the upper shoreface and its impact on the eastern Isles Dernieres, and discuss possible mechanisms for driving the bypassing.

STUDY AREA MORPHOLOGY AND EVOLUTION

The study area centers on a transgressive barrier-island arc, the Isles Dernieres in south-central Louisiana, located about 90 mi (150 km) west of the Mississippi River (Fig. 2). Also included in the 680 mi^2 (1750 km^2) area is the western end of the next barrier island to the east, Timbalier Island.

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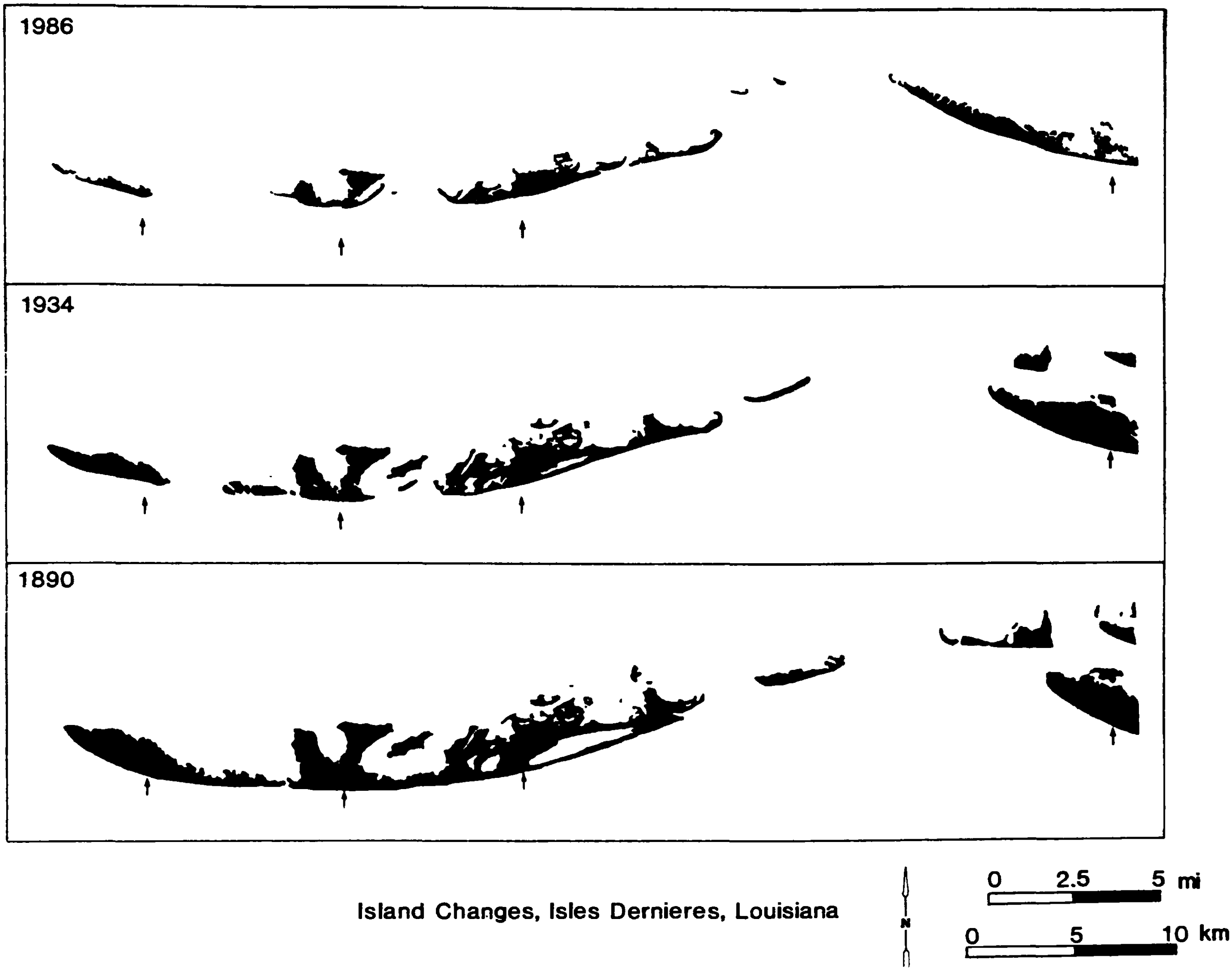

Figure 1. Historical shoreline changes from 1890 to 1986 of the Isles Dernieres and west Timbalier, Louisiana. The Gulf of Mexico is to the south and the mainland (not shown) is to the north of the Isles Dernieres. The tips of the arrows are fixed to the 1890 shoreline. Note the erosion of the Gulf shoreline, the decrease in island area of the Isles Dernieres, and the westward (downdrift) spit growth of Timbalier Island.

The Isles Dernieres arc is older than Timbalier Island. The Isles Dernieres began forming about 420 years B.P. when the Mississippi River abandoned the Bayou Petite Caillou delta, a subdelta of the LaFourche delta complex (Penland et al, 1988). A symmetrical island arc evolved as relative sea level rise detached the erosional headland and flanking barriers from the mainland [stages 1 and 2 of Penland et al's (1988) transgressive Mississippi delta barrier model]. Timbalier Island is part of the younger Bayou LaFourche delta complex and is presently actively building to the west by downdrift spit accretion using sediment supplied by headlong erosion to the east (Penland et al, 1988). The portion of Timbalier Island in the study area is less than two hundred years old.

The Isles Denieres arc is 20 mi (32 km) long, with typical island widths of 0.9 to 1.2 mi (1.5 to 2 km) in the central arc and 0.3 to 0.6 mi (0.5 to 1 km) in the flanks. The islands are low lying, with small sand dunes developed in isolated regions. The Gulf side of the island is typically a sandy beach about 330 ft (100 m) wide composed of very fine-grained sand (Dingler and Reiss, 1989). Landward of the narrow strip of sand, the islands are salt-water marsh.

The seafloor offshore of the islands has a steep shoreface that extends to a water depth of about 10 to 16 ft (3 to 5 m; 1:200 average slope in the east-central Isles Dernieres) and a gentler sloping (about 1:1000 to 1:2000) inner shelf portion (Fig. 3). Contours tend to parallel the shoreline, but this trend is disrupted by inlets and an offshore shoal, Ship Shoal.

Ship Shoal, thought to be a transgressive remnant of

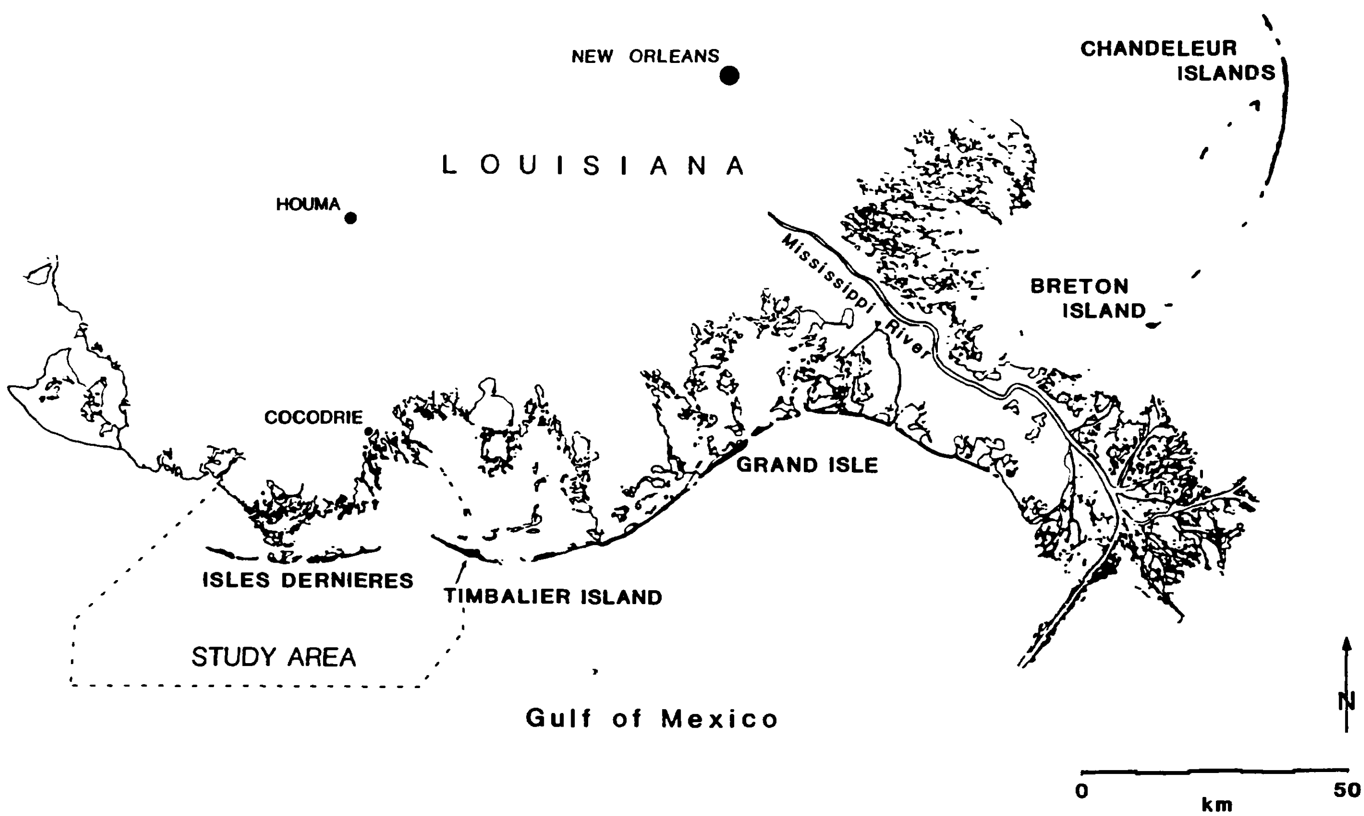

Figure 2. Location of the study area in south-central Louisiana

the Maringouin delta complex which was abandoned about 6000 years B.P. (e.g., Frazier, 1967; Penland et al, 1986), lies about 9 mi (15 km) offshore of the islands and spans the entire length of the arc. The shoal rises from a depth of about 33 ft (10 m), and is shallowest (10 ft or 3 m below sea level) to the west. The shoal narrows and deepens to the east, its crest reaching only 26 ft (8 m) below sea level. This east-west asymmetry could influence the evolution of the Isles Dernieres by redistributing wave energy reaching different portions of the islands through shielding and refraction of waves. In the east, the shoal ends about 11 mi (17 km) seaward of the inlet between the Isles Dernieres and Timbalier.

Inlets have played a major role in the arc's evolution. Surveys show that in 1890 the arc was a single continuous island, except for a breach by a narrow (330 ft, or 100 m, wide) inlet several miles west of the central arc (Fig. 1). Since 1890, inlet formation has contributed to erosion of the arc through channel cutting, widening, and migration. By 1986, tidal inlets fragmented the arc into four groups of islands (Fig. 1.) Within the arc, tidal inlets range in width from several tenths of miles to 4 mi (several hundred meters to 6 km) and have cut away a total of 5 mi (8 km) of the 20 mi (32 km) long arc (25 percent of the length).

Two large tidal inlets, Cat Island Pass and Wine Island Pass, separate the Isles Dernieres from the next barrier island to the east, Timbalier Island (Fig. 3). In 1934, the passes were separated by a small island, Wine Island, and the distance between Timbalier and Isles Dernieres was 8 mi (13 km). By 1974, these passes coalesced into a single inlet and the westward growth of Timbalier reduced the width of the inlet to 6 mi (9 km) (Suter and Penland, 1987). Although the passes joined, the inlet had two distinct channels that were separated by a shallower section where Wine Island was once located before it migrated northward. In 1986, the channel of Cat Island Pass was 26 ft (8 m) deep, while Wine Island Pass's channel was 52 ft (16 m) deep. These deep, wide passes constitute a formidable barrier to longshore transport.

METHODS OF STUDY

The U.S. Coast and Geodetic Survey (USCGS) and the U.S. Geological Survey have collected a large quantity of bathymetric and topographic survey data in the study area during the past 100 years. For example, a 1986 data set, gathered by the U. S. Geological Survey, consists of bathymetry including over 100,000 soundings and aerial photography of the islands at a 1:4800 scale. Due to the massive amounts of data, the survey data were processed using computer techniques, including software for modeling three-dimensional surfaces.

The first step in processing was to convert survey information to a digital format. For earlier hydrographic charts, soundings were digitized from stable-base copies of the original unpublished USCGS smooth sheets (Jaffe et al, 1988). The 1934 hydrographic data were already digitized by the National Ocean Survey and were obtained on computer tapes. Soundings were digitally recorded in the 1986 survey, so no conversion was necessary (Williams et al, 1989). Shorelines were digitized from large-scale USCGS topographic maps for the early surveys and from aerial photographs for the most recent survey.

The digital data were then translated to a common reference system (datum) in preparation for the comparison of maps. A common reference system eliminates unreal changes that would be introduced by a changing datum. Positions were shifted to the 1927 North American Datum, a horizontal datum. Elevations, such as sounding depths and mean high water line (shoreline), were originally referenced to sea level at the time of the survey. Because the rate of sea level rise was rapid in the area (Penland et al, 1988), the vertical datum change between surveys was large. To bring the data into a common reference all elevations were shifted to the 1986 hydrographic survey vertical datum. The amount of shift was determined by assuming that the vertical datum change was equal to the average vertical change between surveys in a large stable offshore region (Jaffe et al, in prep.). This scheme was necessary because there was no direct measurement of vertical datum change in the study area spanning the entire period of surveying. The rates of vertical datum change calculated using this scheme were consistent with relative sea level rise rates determined from measurements over the past 40 years, using tide gauges near the area.

After converting survey information to a common datum, the morphology of the seafloor and islands was modeled using surface modeling software. A computer calculated a best-fit minimum tension surface to the survey data for each of the three survey periods. The average absolute deviation of the surface from the original data was less than 6 in. (15 cm) for all survey periods. The average net deviation of the surface from the original data was less than 1.6 in. (4 cm) for all survey periods.

In order to determine the amount of erosion or accretion to the islands and adjacent seafloor, the bathymetry/topography of the 1934 surface was subtracted from the 1986 surface. Likewise, the bathymetry/topography of the 1890 surface was subtracted from that of the 1934 surface. The amounts of erosion/accretion derived from these comparisons form the basis of this study.

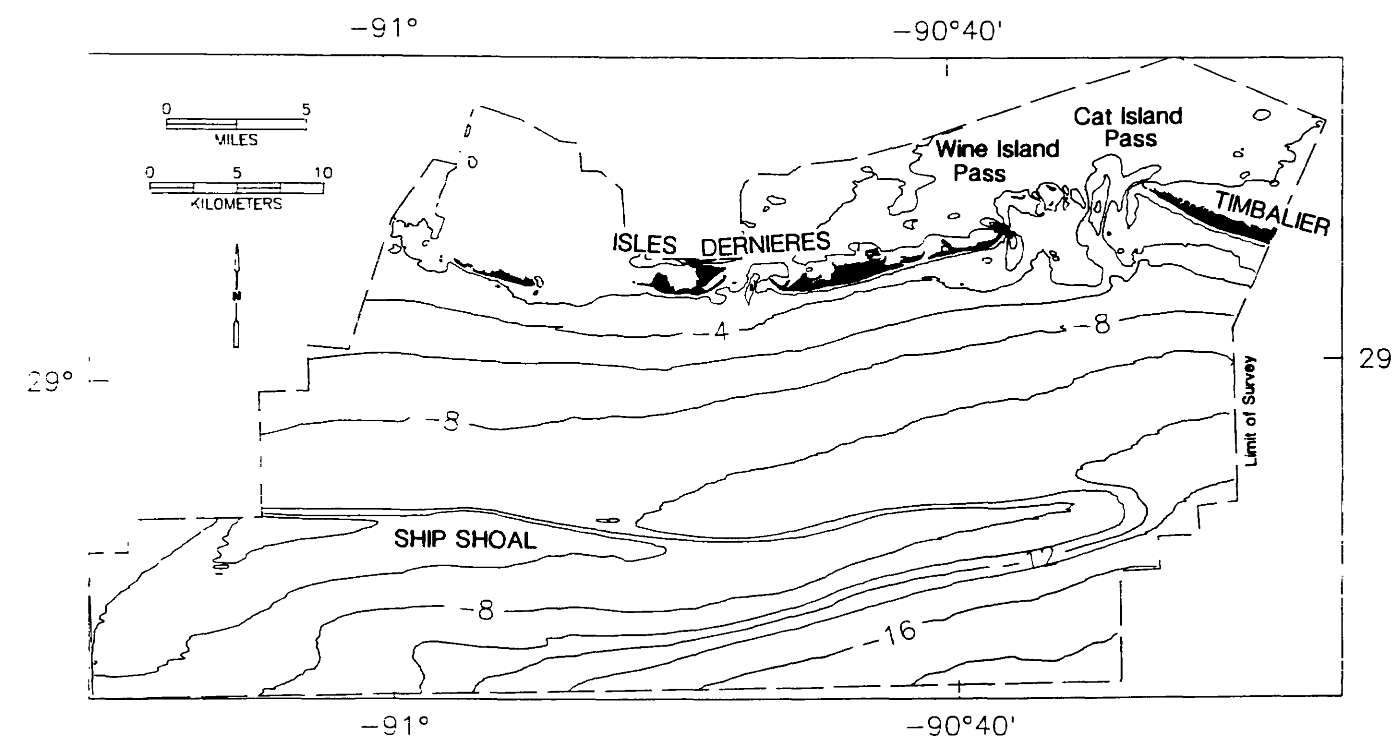

Figure 3. Map of 1986 bathymetry in the study area. Contour interval is 2 meters.

Seafloor and Island Changes, Isles Dernieres and West Timbalier, Louisiana

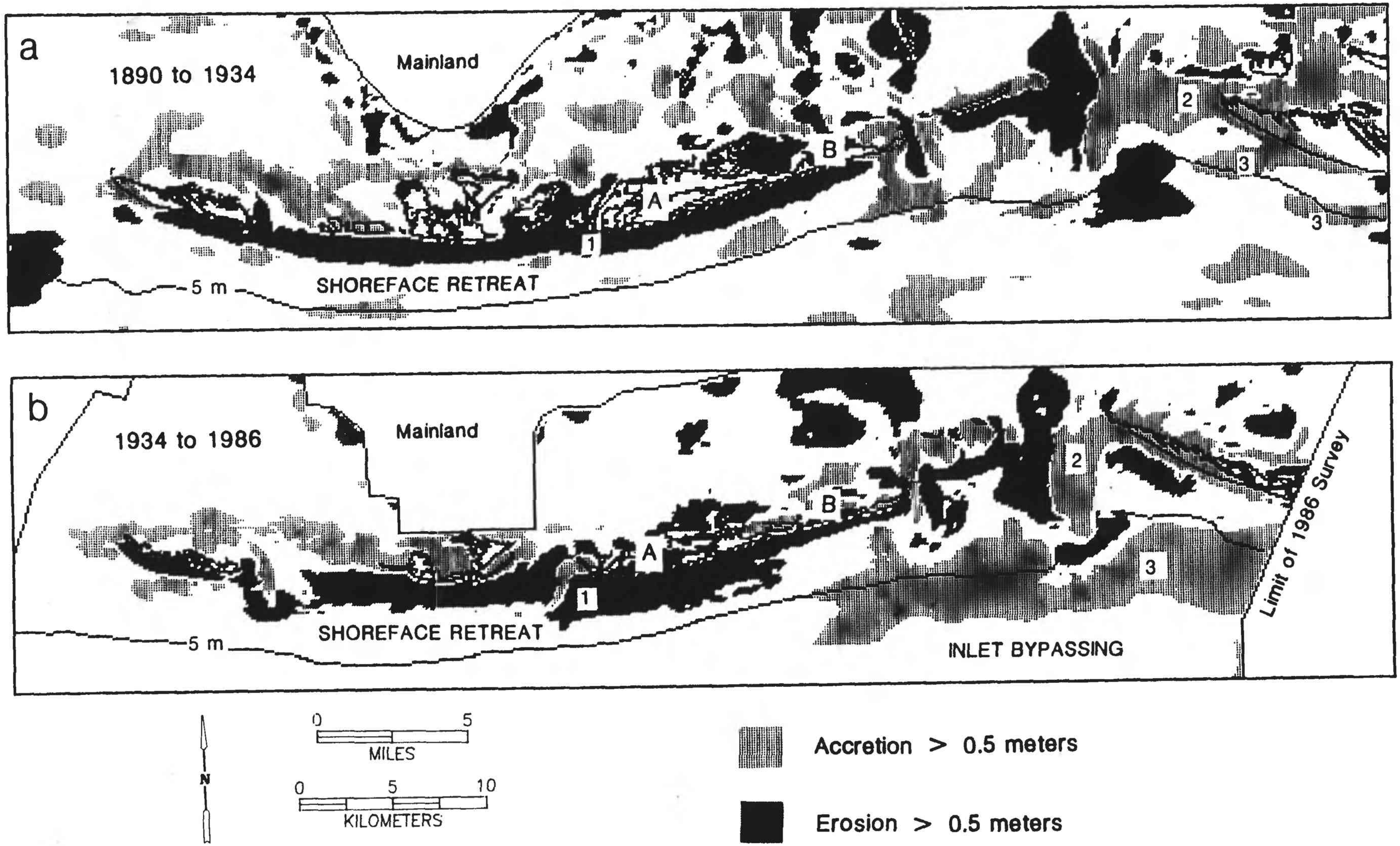

Figure 4. Seafloor and island changes in the study area north of 29° latitude. Figure 4a shows changes from 1890 to 1934. Figure 4b shows changes from 1934 to 1986. Areas with vertical accretion greater than 1.6 feet (0.5 meters) are shaded in a light pattern, while areas with vertical erosion greater than 1.6 feet (0.5 meters) are shaded in a darker pattern. Areas discussed in the text are numbered as follows: 1—shoreface erosion, 2—sediment deposited from longshore transport in shallow water close to Timbalier Island, 3—sediment deposited from longshore transport offshore of Timbalier Island. The letters A and B refer to locations where shoreline and shoreface erosion rates are compared in the text. Also shown are island shorelines and the 5 meter depth contour from the latter year of the comparison.

RESULTS

Three surveys (1890, 1934, 1986) were processed using surface modeling software. This paper focuses on shoreface erosion and on deposition caused by longshore transport in the eastern portion of the study area during two time periods: 1890 to 1934, and 1934 to 1986. Figure 4 (a, b) shows parts of the study area north of 29° latitude with more than 2 ft (0.5 m) of accretion or erosion for the two periods. Also shown are the 16.4 ft (5 m) depth contour and island shorelines from the latter survey of each comparison.

Changes from 1890 to 1934

During 1890 to 1934, the shoreface retreated in response to sea level rise, hurricanes, and storms. The retreat of the shoreface over the 44 years between surveys resulted in a band of erosion offshore of the islands (marked by 1 in Fig. 4a). The seaward limit of the erosion was picked as the line where the shoreface profiles for the two surveys were within 2 ft (0.5 m) of each other. The zone of shoreface erosion was about 0.6 mi (1 km) wide and extended the length of the arc, except for several miles (several kilometers) at the flanks where longshore transport caused spit growth. Note that the band of erosion was of roughly consistent width.

The predominant direction of longshore transport in the area is from east to west (Peyronnin, 1962). Longshore transport pathways into the study area from the east were marked by east-west elongate depositional bodies at the west end and offshore of Timbalier Island. Three pathways appeared in the comparison of surveys from 1890 and 1934 (Fig. 4a). These pathways are discussed below.

Sediment transported along Timbalier Island caused spit growth and westward migration of the tidal inlet channel (marked 2 in Fig. 4a) (Suter and Penland, 1987). Spit growth is shown in Figure 4a by accretion within the 1934 shoreline of Timbalier. Inlet migration is shown by filling on the inlet's east side and erosion on its west side. The volume of sediment transported alongshore that was deposited in the new section of spit and the channel was 1.4 billion cubic feet (39 million cubic meters), an average longshore transport rate of about 31 million ft^3/yr (890,000 m^3/yr). Downdrift spit growth and inlet migration are commonly observed features of transgressive barrier systems (e.g. Hayes et al, 1973; FitzGerald and FitzGerald, 1977). The two other pathways for longshore transport that occurred between 1890 and 1934 have not been previously recognized (3 in Fig. 4a).

Sediment was transported alongshore into the study area along two offshore routes. One pathway was delineated by a depositional lobe that was attached to Timbalier in the east and extended to a depth of about 16 ft (5 m) in the west (3 in Fig. 4a). In the 44 years between surveys, this 0.9 mi (1.5 km) wide lobe grew about 3 mi (5 km) to the west. The volume of sediment in the lobe was 109 million cubic feet (3.1 million cubic meters), substantially less than the volume of sediment deposited near Timbalier Island.

The other offshore pathway for longshore transport was marked by a 0.6 mi by 2.5 mi (1 km by 4 km) shore-parallel lobe deposited in 13 to 23 ft (4 to 7 m) depths (also 3 in Fig. 4a). The east end of this lobe is outside of the study area. The volume of sediment in the lobe within the study area was 102 million cubic feet (2.9 million cubic meters).

Changes from 1934 to 1986

Seafloor and island changes from 1934 to 1986 are shown in Figure 4b. Again, shoreface retreat resulted in a band of erosion offshore of the arc (1 in Fig. 4b). The pattern of shoreface erosion was discontinuous. Shoreface erosion was lessened near inlets because of ebb-tide delta formation and deposition of sediment brought in by longshore transport processes. The width of the shoreface erosion zone varied along the length of the arc from 0.3 to 2 mi (0.5 to 2.0 km). The greatest width of erosion was near the center of the Isles Dernieres and the narrowest was on the eastern end of Isles Dernieres.

Sediment was transported alongshore into the study area along two routes. Sediment moving along Timbalier Island caused continued spit growth and tidal inlet channel migration (2 in Fig. 4b). New spit growth and channel deposition from 1934 to 1986 amounted to 1.3 billion cubic feet (36 million cubic meters) of sediment, an average longshore transport rate of 24 million ft^3/yr (690,000 m^3/yr). The other pathway for longshore transport into the study area was in deeper water.

A large depositional lobe marks a longshore transport pathway in 13 to 26 ft (4 to 8 m) depths (3 in Fig. 4b). The lobe measured 11 mi by 2.5 mi (18 km by 4 km) and was thickest in the east (about 5 ft or 1.5 m). The volume of sediment deposited in this lobe was 1.6 billion cubic feet (44 million cubic meters), more than the volume of sediment associated with spit growth and inlet migration. For the 52-year period between surveys, this is an average deposition rate of about 30 million ft^3/yr (850,000 m^3/yr). The lobe extends outside the study area to the east, so the lobe volume and average deposition rate are low estimates. Although most of the material deposited appears to be from a longshore source, the irregular shape near the tidal channels suggests that the inlets supplied or reworked a small portion of the material deposited. The lobe crosses the entire inlet system between Timbalier and the Isles Dernieres.

Inlet Bypassing at and Below Lower Shoreface Depths

Sediment started bypassing the Wine Island Pass/Cat Island Pass inlet system to the east of the Isles Dernieres some time between 1934 and 1986. The path of bypassing was marked by a depositional lobe offshore of the inlet which crossed the inlet and reached the eastern Isles Dernieres (3 in Fig. 4b). Although offshore lobes were deposited between 1890 and 1934, the lobes were too small to bypass the inlet. Evidently, these lobes represented the initial stages of massive bypassing that occurred later.

The sediment bypassing the inlet reached the eastern Isles Dernieres and reduced shoreface erosion. The width of the band of erosion marking shoreface retreat in the eastern Isles Dernieres was 0.3 mi (500 m) for the period 1934 to 1986, in contrast to 0.6 mi (1 km) for the period 1890 to 1934. The narrowing of this zone in the later time period was not caused by an overall reduction in the width of the shoreface erosion zone along the length of the arc, but was associated with inlet bypassing. Away from the eastern part of the islands, the width of the shoreface erosion zone increased for the period 1934 to 1986.

The shoreline erosion rates, averaged over the period between surveys, also decreased in the nourished area in the eastern Isles Dernieres (location B in Fig. 4). The erosion rate at B from 1890 to 1934 was 36 ft/yr (11 m/yr), compared to 16 ft/yr (5 m/yr) for 1934 to 1986. The average erosion rate for the period when bypassing occurred was less than half the rate before the bypassing. The stretch of shoreline with decreased erosion is directly onshore from the depositional lobe which formed as a result of the bypassing. At location A in Figure 4, west of the area affected by bypassing, the average erosion rate was 36 ft/yr (11 m/yr) both before and after the bypassing.

If this bypassing continues, the eastern Isles Dernieres will be supplied with sediment and the rate of erosion of the islands will be affected. To predict whether the bypassing will continue, the processes causing the bypassing must be understood and an assessment made as to whether these processes will continue to be active in the future.

DISCUSSION

Although the processes forcing the bypassing of the Cat Island Pass/Wine Island Pass inlet system are still not known, measurements of updrift shoreline erosion, bathymetric comparisons in the study area, and field measurements of flow offshore from other Louisiana barrier islands suggest possible mechanisms for the bypassing. Inlet bypassing below the upper shoreface requires a sediment source, a way to get the sediment to deeper water if the source is in shallow water, and a way of moving the sediment alongshore. Each of these requirements is addressed below.

Penland et al (1988) used patterns of shoreline erosion near Timbalier Island to determine the source of sediment for its westward spit growth. They found that eroding headlands to the east (updrift) were the source for the spit accretion. Similarly, longshore transport from east to west is driving the inlet bypassing, indicating that the source of sediment is also to the east. Although updrift headland erosion is the most likely source for sediment bypassing the inlet, it remains to be proved whether that headland erosion can supply the large volume of sediment bypassing the inlet.

Bathymetric comparisons can be used to determine possible pathways for transporting sediment from a shallow water source to deeper water. Comparisons show depositional or erosional areas (regions where transport has occurred) that delineate pathways of sediment transport. Although inlet bypassing did not occur from 1890 to 1934, a transport pathway to deeper water is marked by an east-west elongate depositional lobe that was attached to Timbalier Island in the east and extended to a water depth of 16 ft (5 m) in the west (labeled 3 in Fig. 4a). To create this lobe, sediment transported along the island from east to west continued in a straight path while the shoreline curved towards the north.

The smaller lobe located farther offshore that was deposited from 1890 to 1934 originated outside of the study area, so the pathway that delivered its sediment is not shown in Figure 4a. Because the depositional lobe that formed from 1934 to 1986 is an extension of this offshore lobe, it is worthwhile discussing possible pathways for transport of sediment to the lobe. If the lobe is extrapolated to the east, it would intersect near the eastern end of Timbalier because the island extends farther south outside the study area (Fig. 2). A bifurcation of transport along a section of the island where shoreline orientation had a favorable curvature, similar to the shoreline curvature seen for the more onshore lobe discussed above, could be responsible for delivering sediment to this offshore depositional lobe. Another possibility is that sediment reached deeper water through inlet processes, because an inlet has been present since 1890 near where the lobe would intersect the island. Work in progress, which extends the area of study to the east, should shed light on the pathway of sediment transport from shallow water to this offshore lobe.

Once the sediment travels from its source area to deeper water, coastal currents could continue the forcing of alongshore transport. Murray and Lugo-Fernadez (1988) found strong contour-parallel mean currents in 23 to 43 ft (7 to 13 m) of water during winter storms at Fourchon, about 30 mi (50 km) east of the study area. Mean longshore currents reached 2 ft/sec (60 cm/sec), easily strong enough to cause alongshore transport of sand (Yalin, 1977).

Although currents generated during winter storms are capable of forcing the bypassing, it is still not known whether the bulk of the transport occurs during frequent small events or large infrequent events, such as hurricanes. Taking sediment cores of the lobes could elucidate the periodicity of transport through examination of the thickness, number, sediment size, grading, and vertical sequence of laminae. More work on the flow field at a wide inlet also needs to be done to determine the potency of small storms in driving the offshore bypassing.

The processes causing the bypassing are still unknown. Sediment did bypass a 6 mi (9 km) wide inlet in 13 to 26 ft (4 to 8 m) water depths, and was an unexpected source for the Isles Dernieres arc. Bypassing below the upper shoreface raises questions about the interchange of sediment between barrier islands separated by wide tidal inlets and about the interaction of barrier systems during their evolution.

SUMMARY

1) Comparisons of historical maps show that a large volume of sediment bypassed offshore from a 6 mi (9 km) wide inlet to the east of the Isles Dernieres in 13 to 26 ft (4 to 8) water depths.

2) This bypassing occurred during the period 1934 to 1986. There is some evidence that it began during the previous 44 years from 1890 to 1934.

3) In an area nourished by the bypassed sediment in the eastern Isles Dernieres, the shoreline erosion rate was less than half that prior to bypassing.

4) If the bypassing continues, the supply of sediment could lessen the rate of erosion of the Isles Dernieres.

5) The exact processes driving the bypassing are not known; however, recent measurements by Murray and Lugo-Fernadez (1988) show that contour-parallel coastal currents during winter storms in Louisiana are capable of driving alongshore transport at the depth of bypassing.

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DISTRIBUTION AND TEXTURAL CHARACTER OF SURFICIAL SEDIMENTS, ISLES DERNIERES TO SHIP SHOAL REGION, LOUISIANA

S. Jeffress Williams[1], Shea Penland[2], and Ronald C. Circé[1]

ABSTRACT

Since 1986, the U.S. Geological Survey and the Louisiana Geological Survey have undertaken field studies of the physical processes responsible for the widespread and extremely rapid coastal erosion of Louisiana's barriers along the Mississippi River delta plain coast. The study area encompasses the coastal and inner shelf region from Raccoon Point to Sandy Point and includes a data base of 40 ft (12 m) long vibracores, surface grab samples, sidescan sonar, high-resolution seismic reflection profiles, and precision hydrographic profiles.

This paper presents results from detailed grab sample surveys in the coastal-shelf sector that includes the Isles Dernieres barrier island chain seaward almost 19 mi (30 km), to include Ship Shoal. The surface and near surface sediments of the region reflect fluvial, deltaic and nearshore marine origins with evidence of winnowing and reworking by waves and currents associated with frequent tropical storms and winter cold fronts.

Beach sediments on the four islands are remarkably uniform in grain size (fine quartz sand), except for often abundant beach rock and carbonate shell debris, and are generally moderately to very well-sorted. The shoreface and inner shelf are mantled with muddy sands and sandy muds, whereas Ship Shoal is almost wholly fine quartz sand, similar in many sedimentologic respects to the Isles Dernieres. These findings are consistent with the model of coastal evolution presented by Penland et al (1988) in which Ship Shoal was described as the prototypical example of a drowned coastal barrier undergoing submarine reworking and migrating landward in pace with the rapid rates of eustatic sea-level rise and basin subsidence.

INTRODUCTION

Since 1986, the U.S. Geological Survey, working in cooperation with the Louisiana Geological Survey (LGS) and the Coastal Studies Institute at Louisiana State University, has conducted a program of coastal research in Louisiana. The studies have focused on quantifying the extent of erosion and land loss and understanding the geologic conditions and sedimentary processes causing widespread and rapid erosion of the barrier islands that front the delta plain coast.

The study area encompasses the coast and continental shelf region west of the modern Mississippi River delta from the Isles Dernieres east to Sandy Point, as well as the Chandeleur Islands region east of the delta (Fig. 1). The objectives and tasks of the program are described in Sallenger et al (1987, 1989); we have completed 4 years of a planned 5-year effort.

This paper presents provisional results from several surveys carried out over the past several years to map and characterize the surficial sediments in the nearshore region west to the delta. The sampling effort is continuing this year and the results presented here will be combined with the new information and included in the final reports.

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STUDY AREA SETTING

The study area described in this paper includes the delta plain region of south-central Louisiana in the vicinity of the Isles Dernieres and Timbalier barrier islands and Ship Shoal off the coast of Terrebonne Parish (Fig. 2). The general limits of the area are from longitudes 91° 01′ to 90° 28′W and from latitudes 29° 05′ to 28° 48′N.

The Isles Dernieres as well as the other coastal barriers of the delta plain have responded to the Holocene transgression by undergoing dramatic loss of land area and rapid landward migration. The barriers are dominated by frequent storm washover, resulting in topographic relief of generally less than 3 ft (1 m). These barriers are separated by fairly wide and deep tidal-inlet troughs, several exceeding 26 ft (8 m) in water depth, which connect the back-barrier bays to the Gulf of Mexico. The shoreface region seaward of the islands to 16 ft (5 m) depths generally has irregular morphology marked by broad and seaward-protruding ebb-tide platforms at the major tidal inlets.

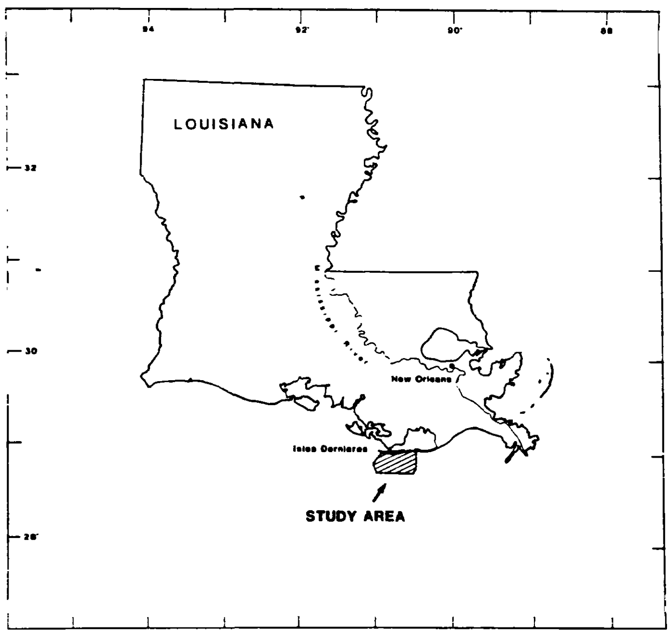

Figure 1. Index map of the Louisiana coast showing the study area at the western end of the delta plain province. The area includes the Isles Dernieres barrier island arc and the inner shelf including Ship Shoal.

Ship Shoal is the largest and most prominent and distinctive of several such sand bodies in the Gulf of Mexico. It is clearly defined by its shore parallel orientation, tapered shape toward the east, and asymmetrical longitudinal profile. The maximum dimensions of the shoal body are 27 nautical miles (nm) (50 km) long and 6.5 nm (12 km) wide, with 10 to 26 ft (3 to 8 m) of relief.

The Louisiana delta plain, extending 217 statute miles (mi) (350 km) along the shoreline and covering an area of nearly 11,200 mi^2 (29,000 km^2), is an extremely low relief region consisting of thick stacked sequences of unconsolidated sands and muddy sediments deposited by the Mississippi River in a subsiding basin during the past 7,500 years. In classic papers by van Andel (1960), van Andel and Poole (1960), Frazier, (1967), Coleman, (1988), and Penland et al (1988), the depositional history and evolutionary development of the delta region were discussed, based on careful analysis of geophysical data, deep core holes, and mapping surficial landforms. Their work showed that the Mississippi River has shifted its channel position at least six times during the Holocene since sea level approached its present elevation. Once a deltaic complex is fully developed, abandonment and switching of the river channel occurs; the fluvial sediment supply is cut off and the delta then evolves through a three-stage cycle of transgression. The Isles Dernieres represent Stage 2 of the Lafourche delta in which the barrier island arc detaches from the delta headland while continued subsidence and storm activity reduce the subaerial island area and enlarge the tide inlets. The next evolutionary step, Stage 3, is represented by Ship Shoal, which marks the distal margin of the Maringouin delta complex. Once tidal inlets segment the barriers and washover events are frequent, the beach and dune sands are widely dispersed to adjacent areas and the barrier is transformed to an inner shelf sand body. With continued rise in relative sea level, nearshore waves and currents winnow and rework the shoal, forming a marine sand body with none of the stratigraphic or structural characteristics of the former barrier island (Krawiec, 1966; Cuomo, 1984; Neese, 1984, and Penland et al, 1988.

FIELD AND LABORATORY METHODS

During the sediment sampling and sidescan sonar survey aboard the RV *Acadiana* in May 1987, 217 surficial grab samples and 186 line-miles (300 line-kilometers) of sidescan sonar (Klein 500 kHz equipment) were collected simultaneously within a 4-day period. Approximately the top 2 in. (5 cm) of the seabed was sampled at each station using a towed underway bed-material sampling device (BM-54) designed and built by the U.S. Army Corps of Engineers. Navigation positioning during the cruise was done by LORAN-C using a Northstar 6000 receiver and a TI silent 700 data logger. As shown in Figure 2, the samples and sidescan data were collected in a grid-rectangular pattern, with sample spacing approximately 1 nm (1.8 km) apart at selected LORAN line intersections.

Also during May 1987, a suite of 42 sediment samples was collected along 21 transects on the Isles Dernieres (Fig. 3). The transects were oriented shore-normal and samples were taken from the primary beach environments (foreshore, backshore, berm, washover fan). Samples were generally evenly spaced at 0.6 nm (1 km) intervals from the eastern end at Wine Island Pass (Fig. 3) to the western end at Raccoon Point. Only results from the 21 beach samples are discussed in this paper. Interpretations of all 42 samples are in progress and will be the subject of a separate report that is in preparation.

Textural analyses of the beach and offshore sediment samples were performed in the U.S. Geological Survey Sedimentology Laboratory at Woods Hole, Massachusetts, using a combination of a settling tube for the sand-size fraction and a Coulter Counter (model TA II) instrument for the silt and clay fractions. Each grain-size component was computed as a percentage of the total dry weight of the sample. Following the textural analyses, the grain-size data and visual descriptions were used with Folk's (1974) grain-size statistics and classification system to derive the sediment classifications shown in Figures 2 and 3. The sidescan data were analyzed and

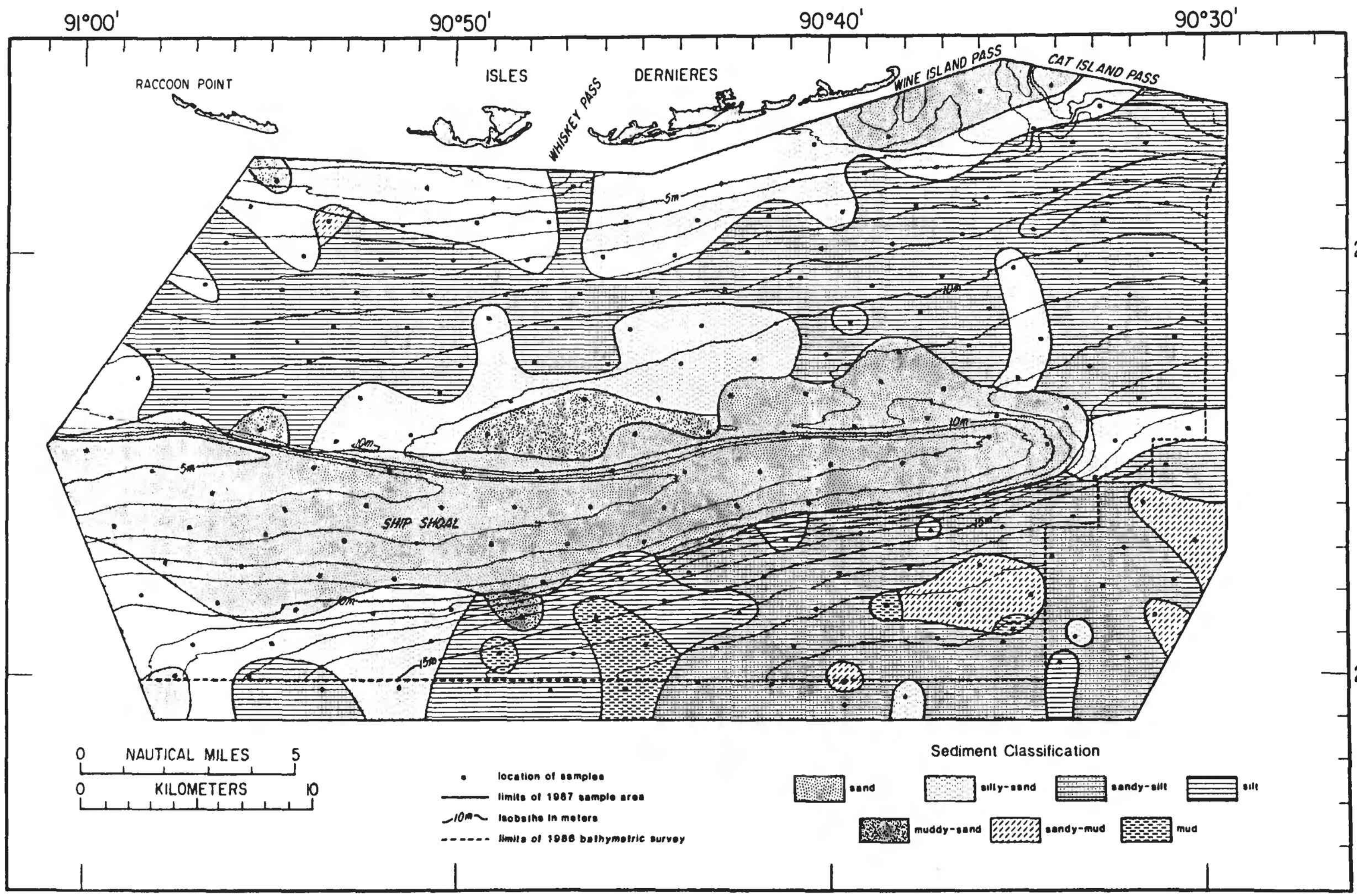

Figure 2. Map of the inner shelf off south-central Louisiana showing the distribution of seven major sediment facies. Bathymetry is from a 1986 survey described in Williams et al (1989); the sediment textural interpretations are from Circé et al (1988, 1989).

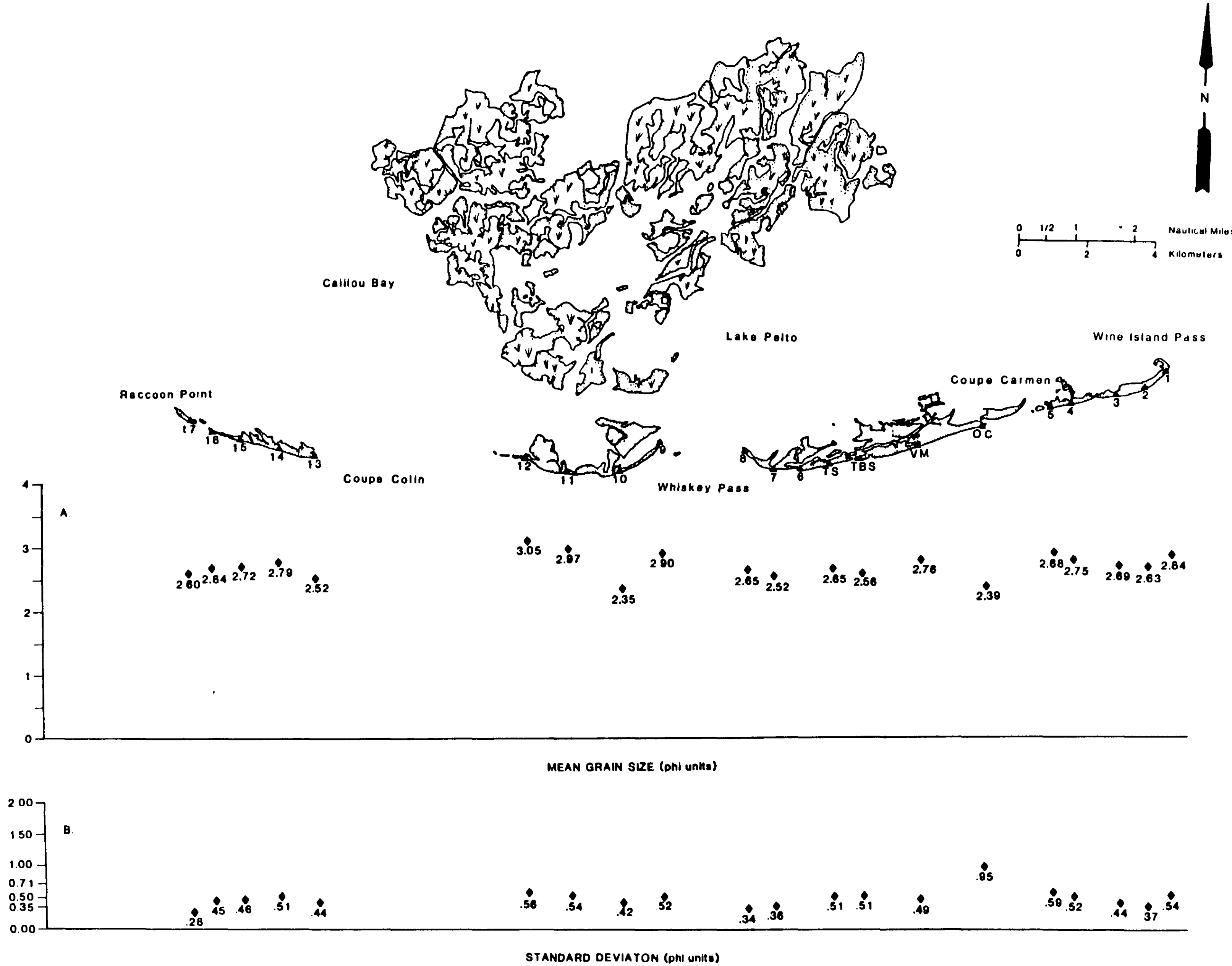

Figure 3. Isles Dernieres barrier islands showing the 21 transect locations where beach sediment samples were collected. Plots show the extremely uniform grain size (fine sand) and sorting (moderately to very well-sorted) of the beach sediments.

interpreted using standard techniques described in Williams (1982) to characterize the sea floor and extrapolate sediment texture information between the sample stations.

RESULTS

Isles Dernieres Barrier Sand Facies

The four islands of the Isles Dernieres (Fig. 2) are erosional remnants of a once continuous island that has undergone significant landward migration, loss of land area, and disintegration. Since the mid-19th century, the Isles Dernieres have migrated more than 0.6 mi (1 km) landward and lost more than one-half of their area due to in-place narrowing by erosion on both the bay and gulf sides of the islands. The normal coastal processes, dominated by storms, have planed off the beach berm and dune features from the islands, leaving mostly washover sand flats and terraces and small incipient dunes. Especially on the foreshore, broken and whole shells (primarily *Crassostrea virginica*, *Mulinia lateralis*, *Rangia*, and *Mercenaria mercenaria*) are abundant and armor the beach surface against wind and water erosion.

The sediment texture data plotted in Figure 3 show the mean grain size and sorting for the four islands. The beaches are greater than 99 percent quartzose sand with mean grain size ranging from 2.35 to 3.05 phi (fine sand), and sorting from 0.28 to 0.95 (moderately to very well-sorted). These grain size statistics indicate the evolutionary history of the barrier islands: the sands are derived from a single source, the actively eroding deltaic margin, and represent well-winnowed lag deposits.

Inner Shelf Surficial Sediments

The shoreface and inner shelf from Raccoon Point to Cat Island Pass (Fig. 2) have an even, gently seaward sloping surface to the 39 ft (12 m) isobath at the base of Ship Shoal. Seaward of Ship Shoal the regional slope continues to depths of 59 ft (18 m) in the southeast corner of the study area, about 13.5 nm (25 km) from the Isles Dernieres coast.

The shelf samples were divided into seven categories based on their sand content. Consistent with the findings of Mazzullo (1986), quartz sand was found to be a major component of the surficial sediments. The samples contain an average sand content of 54 percent, but this varies widely. The minimum sand content is 0.5 percent while many samples in nearshore areas, Cat Island and Wine Islands Passes, and most of Ship Shoal are 90 to 99 percent sand (Circé et al, 1989).

The percentages of silt and mud vary widely across the shoreface and shelf as a result of the many depositional and erosional processes acting on the older deltaic and shoreline and nearshore deposits. Circé et al (1989) pointed out that the percentages of clay-size sediment are generally low throughout the region. Slightly more than 70 percent of the samples contain less than 10 percent clay. The low mud content reflects the winnowed and reworked nature of the shelf surface.

SUMMARY

Analyses of a suite of surficial sediment samples from the Isles Dernieres barrier islands and the adjacent inner shelf demonstrate that the evolutionary development of the region is the product of complex transgressive sedimentary processes that have recently been described by Penland et al (1988).

The storm and washover-dominated beaches have sandy sediments with extremely uniform mean grain size and sorting, and beach rock clasts and shell debris commonly armor the beach surface. The low-gradient shelf is mantled with muddy sands and sandy muds with the exception of Ship Shoal, which is composed of clean fine-grained sand similar in many respects to the Isles Dernieres.

ACKNOWLEDGEMENTS

This work is part of the Louisiana Barrier Island Erosion Study being carried out by the U.S. Geological Survey and Louisiana Geological Survey. The assistance of staff from both organizations for conducting the field studies and analyzing the samples is appreciated. Also, Steven Underwood and Mark Byrne from the Coastal Engineering Research Center provided technical help critical to the success of the sidescan and sampling surveys. The use of trade names in this publication is for descriptive purposes only and does not imply endorsement by the USGS or the LGS. Technical reviews by P. Teleki, M. Ierardi and E. Winget are appreciated.

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INNER SHELF DEPOSITS OF THE LOUISIANA-MISSISSIPPI-ALABAMA REGION, GULF OF MEXICO

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ABSTRACT

The late Quaternary morphology, shallow stratigraphy and sediment distribution of the Louisiana-Mississippi-Alabama inner shelf region are the product of transgressive and regressive sedimentary processes. Shelf sedimentary facies were deposited by deltaic progradation, followed by shoreface erosion and submergence. This information is based on interpretations and synthesis of more than 4,160 mi (6,700 km) of high resolution seismic profiles, 75 grab samples, and 77 vibracores.

The shelf can be divided into two main depositional regions. The southwestern region, east and south of the Mississippi River plain, was formed by early Holocene delta complexes, overlying a late Wisconsinan delta. Deposits of the late Wisconsinan delta consist of well-defined coarsening-upward sequences and represent deltaic progradation during low sea level stands. The relatively recent Mississippi delta complexes have deposits which consist of fine-grained sands, silt and clay. With the late Holocene rise in sea level, asymmetrical sand ridges (16 ft, or 5 m, relief) have formed due to marine reworking of shoreline features.

The northeastern region, offshore of the Mississippi-Alabama barrier islands, was formed by Pleistocene fluvial systems and Recent shoreface erosion and ravinement. Underlying the relatively thin Holocene sediment cover are relict fluvial sands which were deposited during the late Wisconsinan lowstand. Subsequent sea level rise allowed marine processes to rework and redistribute sediments forming the nearshore fine-grained facies and shelf sands sheet.

INTRODUCTION

Late Pleistocene and Holocene morphology of the Louisiana-Mississippi-Alabama inner shelf region is the product of transgressive and regressive sedimentary processes. Shelf and inner shelf morphology has been strongly influenced by subsidence and glacio-eustatic flucuations in sea level, which resulted in repeated rises and falls during the Quaternary (Ludwick, 1964; Frazier, 1974; Beard et al, 1982; Kindinger, 1988). Outbuilding of the shelf resulted primarily from coastal-plain extension during sea withdrawal across the shelf.

A broad shelf has formed east of the Mississipi River delta in Louisiana offshore of Mississippi-Alabama. The bathymetry and subsurface characteristics of the Louisiana-Mississippi-Alabama shelf are the result of deltaic deposition and intervening periods of erosion during lowstands. Typically, the progradational sediments overlie sediments deposited during transgression. Little evidence of structural deformation, such as faults or diapirs, is present on this shelf.

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According to Frazier (1974), late Quaternary surficial sediments across the shelf relate to several different depositional episodes. The surficial and shallow subsurface sediments of the shelf are generally sandy as evidenced by grab samples, vibracores, and the presence of buried stream channel bedforms inferred from seismic profiles.

The inner shelf of Louisiana-Mississippi-Alabama is bordered on the west by the oldest and largest barrier island system in the Mississippi River delta plain (Fig. 1), the Chandeleur Islands arc (Penland et al, 1985). To the north is the Mississippi-Alabama barrier island chain lying parallel to the northern Gulf of Mexico coast. The basic shelf morphology was described by Ludwick (1964) and Frazier (1967). These studies and others used grab samples and shallow cores to characterize the local geology (Fisk, 1944, 1956; Curray, 1960; Coleman and Gagliano, 1964; Lehner, 1969; Frazier, 1974; Coleman, 1976; Beard et al, 1982). Generally, these studies discussed the cyclic sedimentation of the Mississippi River delta complex which includes the St. Bernard delta.

The surge in research towards understanding coastal processes and erosion has sparked new regional investigations into the geologic framework of the coastline and

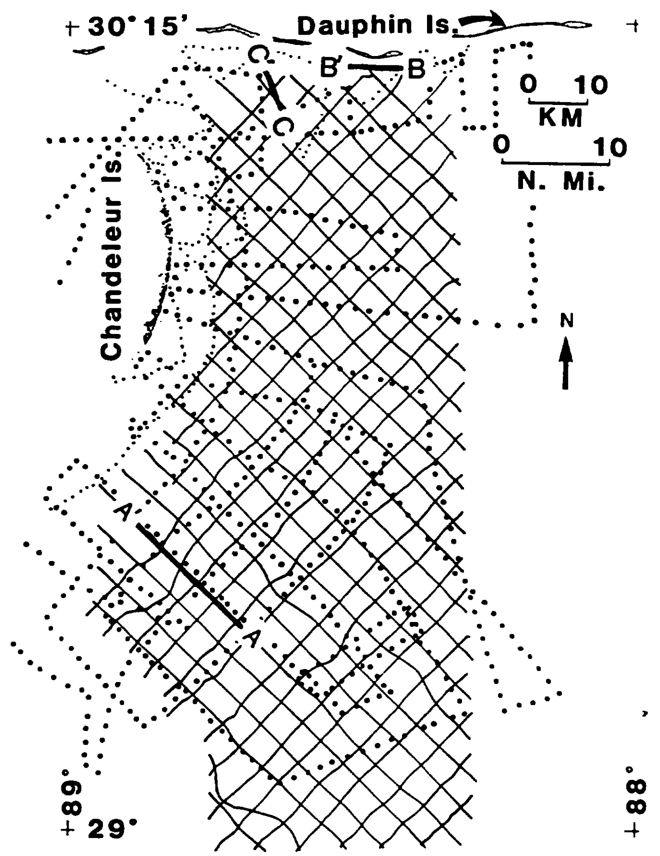

Figure 1. Location of high resolution single channel seismic reflection tracklines collected in 1981 and 1987.

continental shelf. The purpose of this paper is to describe the geologic framework and lithology of the Louisiana-Mississippi-Alabama inner shelf region.

DATA BASE

The Louisiana-Mississippi-Alabama inner shelf was surveyed in 1981 and in 1987-88 using high-resolution, single-channel seismic-profiling techniques as part of a cooperative project between the Louisiana Geological Survey and the U.S. Geological Survey. More than 4160 line-miles (6,700 line-kilometers) of reflection profiles were collected (Fig. 1). A variety of seismic equipment was used: a 400-Joule minisparker, 3.5- and 12-kHz transducers, 40- and 5-cubic-inch airguns, and a Geopulse Boomer system. During the 1981 cruises 75 surficial grab samples were collected across the area (Fig. 2). These data, along with 77 vibracores 40 ft (12 m) long taken in 1987 (Fig. 2) are currently being analyzed. Results are expected to be available in late 1989.

SURFICIAL SEDIMENTS

The Louisiana-Mississippi-Alabama shelf is a broad, smooth, gently sloping (<0.1°) sea-floor ranging from 0 (barrier island shoreface) to 246 ft (0 to 75 m) water depth where the shelf break has formed. Large areas of the shelf are covered by sandy sediments with smaller areas of prodelta and transitional facies (Fig. 3). The inner shelf sand-silt-clay percentages averaged from grab samples were 56, 26, and 18, respectively (Kindinger et al, 1982). Shoreline migration (regressive and transgressive) and coastal processes, such as delta building, longshore transport, shoreface erosion, submergence, and storms, have reworked the sediments and winnowed out much of the finer sediments.

Ludwick (1964) divided the Louisiana-Mississippi-Alabama shelf into six facies, including transition zones, based on surficial sediments. Mazzullo and Bates (1985) divided the present shelf into two distinct regions on the basis of surfical grain morphology and age. East of the Mississippi River delta plain, the shelf is covered by the Eastern Sand Deposit, a thin layer of relict well-sorted fine to medium quartzose sand of late Pleistocene and early Holocene age deposited by rivers of the southeastern United States. The westernmost part of the shelf, which includes the St. Bernard and modern delta complexes, is covered by Holocene sand, silt, and clay depo-

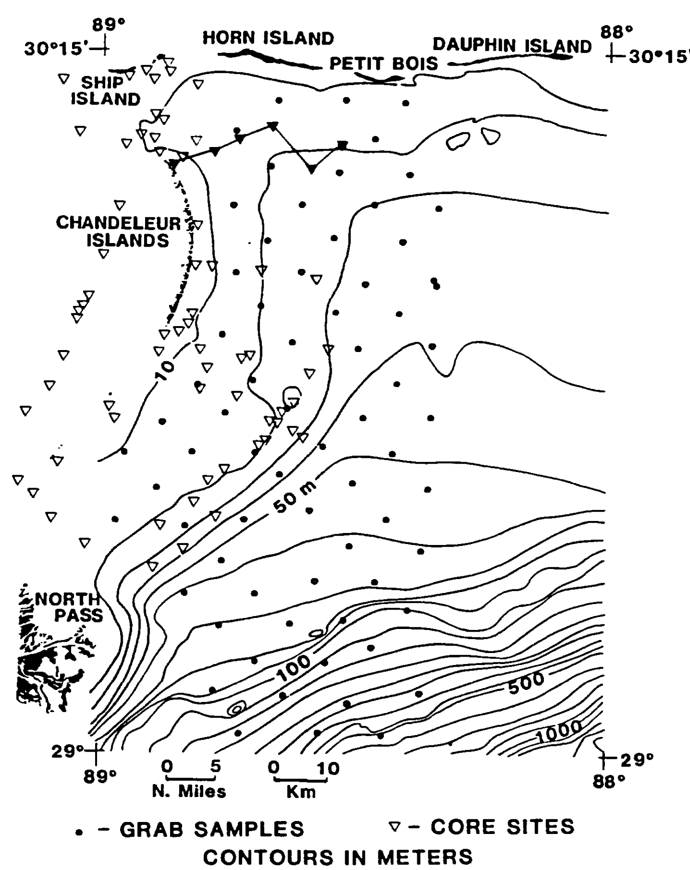

Figure 2. Bathymetry map of study area, including locations of 75 surficial grab samples and 77 vibracores. The linked vibracores are the samples used in the cross section in Figure 7.

sited in association with the Mississippi River (Ludwick, 1964; Mazzullo and Bates, 1985).

The distribution of the surficial sediments is the product of fluctuating sea level during the late Quaternary. The sands on the southeast side and in the northeast corner are the oldest sediments in this area (Fig. 4-A,C,D). These orthoquartzite sands were derived from the Cretaceous and younger sedimentary mantle of the Appalachians (van Andel and Poole, 1960) and were emplaced as fluvial and/or beach deposits during the last major lowstand 18,000 yrs B.P. (Ludwick, 1964; Frazier, 1974). The clayey silts extending across the central region are St. Bernard prodelta muds (Fig. 3). These muddy sediments are the approximate basinward limit of clay deposition during recent times (Frazier, 1974). The silty sand, sand-silt-clay and clayey sand to the north, east, and south of the clayey silt occur in a transition zone where the prodelta muds and eastern sands have mixed laterally and vertically. The southern end of the clayey-silt salient is a mixture of St. Bernard deposits and sediment presently being deposited from the Modern birdfoot delta (Fig. 5 — Balize) of the Mississippi River.

The sand in the southwest corner below the Chandeleur Islands has been produced by reworking of the distributary mouth bar sands in a landward direction by wave erosion on the subsiding delta. Sand from the coalescing sand bars formed the Chandeleur Islands, and Chandeleur and Breton Sounds behind the island chain (Penland and Suter, 1983). Sand ridges found in this area formed during the most recent temporary stillstand (Kindinger, 1988). The silty sand and sandy silt located north, within, and to the south of the Chandeleur Islands sand salient represent reworking of the St. Bernard delta lobe as well as modern sedimentation processes. Murray (1976) reported that ebb-directed tidal flushing of the turbid Chandeleur-Breton Sounds estuary water flows to the north and south of the Chandeleur Island chain. The tongue of silty sand extending into the Chandeleur Island sand salient either represents settling of this finer-grained sediment into a naturally occurring depression, or may possibly be reworked lagoonal/tidal flat sediments deposited behind an earlier barrier ridge.

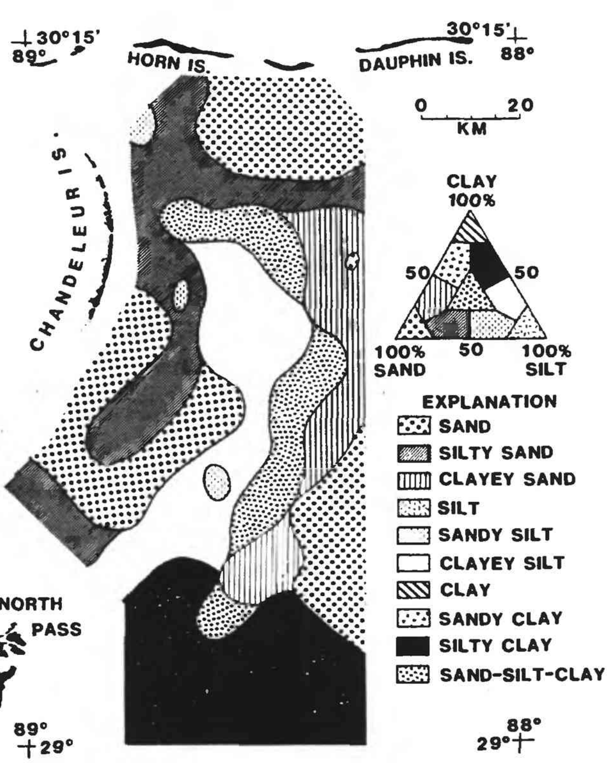

Figure 3. Surficial sediment distribution showing extent of sandy sediments covering the shelf. From Kindinger et al (1982).

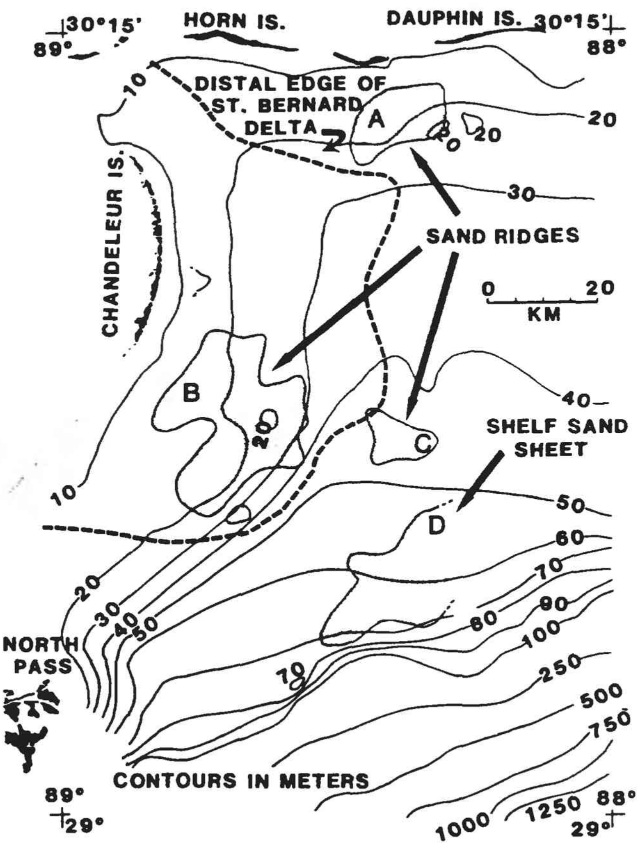

Figure 4. The sand ridges and sheet shown are evident on seismic profiles and have topographic relief, with some areas 16 ft (5 m). Sand Ridges A, B, and C are asymmetrical in cross section and Sheet D is relatively lens-shaped. A, C, and D are part of the Eastern Sand Sheet which covers much of the shelf. B is part of the St. Bernard delta complex.

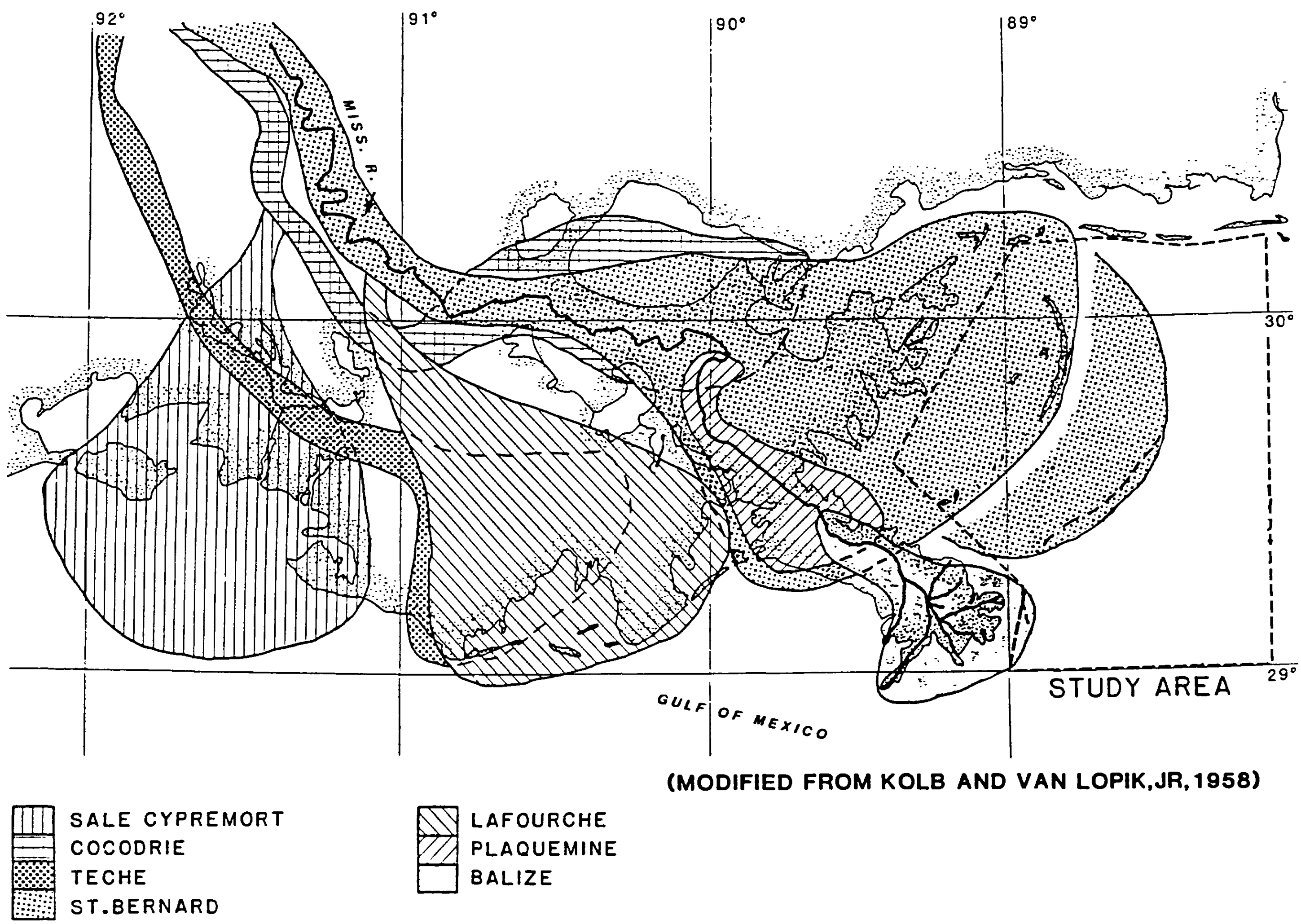

Figure 5. Recent delta complexes of the Mississippi River and the relative location of the study area. Modified from Kolb and van Lopik (1958).

STRATIGRAPHY AND LITHOLOGY

Stratigraphic units have been defined by utilizing unconformities and correlatable conformities identified from seismic profiles. These units were identified by superposition of sequences and seismic character of the sequences within the data (Fig. 6). The lower boundary of the oldest sequence is a prominent shelf-wide erosional unconformity identified as early Wisconsinan. The erosional surface was buried by thin parallel beds during the subsequent sea-level rise and by thicker deposits of a progradational delta, termed the Lagniappe delta by Kindinger (in press). Stratigraphic evidence indicates that this delta was deposited during the last major lowstand, the late Wisconsinan (Kindinger, 1988). Data from wellsite borings presented by Coleman and Roberts (1988) agree with this interpretation. The younger sequence deposited above the Lagniappe delta has a prominent shelf-wide erosional unconformity as its base which is also the upper boundary of the Lagniappe delta. The stratigraphy of the younger sequence is the erosional unconformity overlain by transgressive deposits and deltaic sediments of the St. Bernard Delta complex. The St. Bernard ceased prograding ~1,200 yrs B.P. (Frazier, 1967). The Chandeleur Islands are remnants of the St. Bernard delta; the retreat path and processes have been described by Penland et al (1985).

Southwestern Region—Louisiana Chandeleur Islands and St. Bernard Delta

The progradation of the St. Bernard delta complex was the most recent major geologic event in the area and covered the west-southwest region of the inner shelf with an average of 13 ft (4 m) of sediment (Kindinger, 1988). This delta thins evenly from west to east and has very little internal structure seen in seismic profile, except for obscure high-angle clinoforms near the pinchout on the shelf (Fig. 6). Frazier (1974) divided the formation of the lobe into six smaller units produced by six depositional episodes; only two of these units enter the Mississippi-Alabama inner shelf area. On the other hand, Coleman

(1976) considered the St. Bernard complex as the product of basically one event rather than delineating smaller units produced by each episode. This delta is cited as the classic example of a delta's destructive phase once abandoned by its river. Marine reworking of the unconsolidated mass of deltaic sediment immediately begins destroying it (Penland et al, 1988). The seaward margin of the delta consists of thin sedimentary beds in which

Figure 6. Seismic profile with line-drawn interpretation. The late Wisconsinan delta is bound below by an early Wisconsinan shelf-wide erosional unconformity and above by a Pleistocene-Holocene shelf-wide erosional unconformity. The St. Bernard overlies these deposits and thins to pinch at mid-shelf (Figure 4). Location of A-A' is shown in Figure 1.

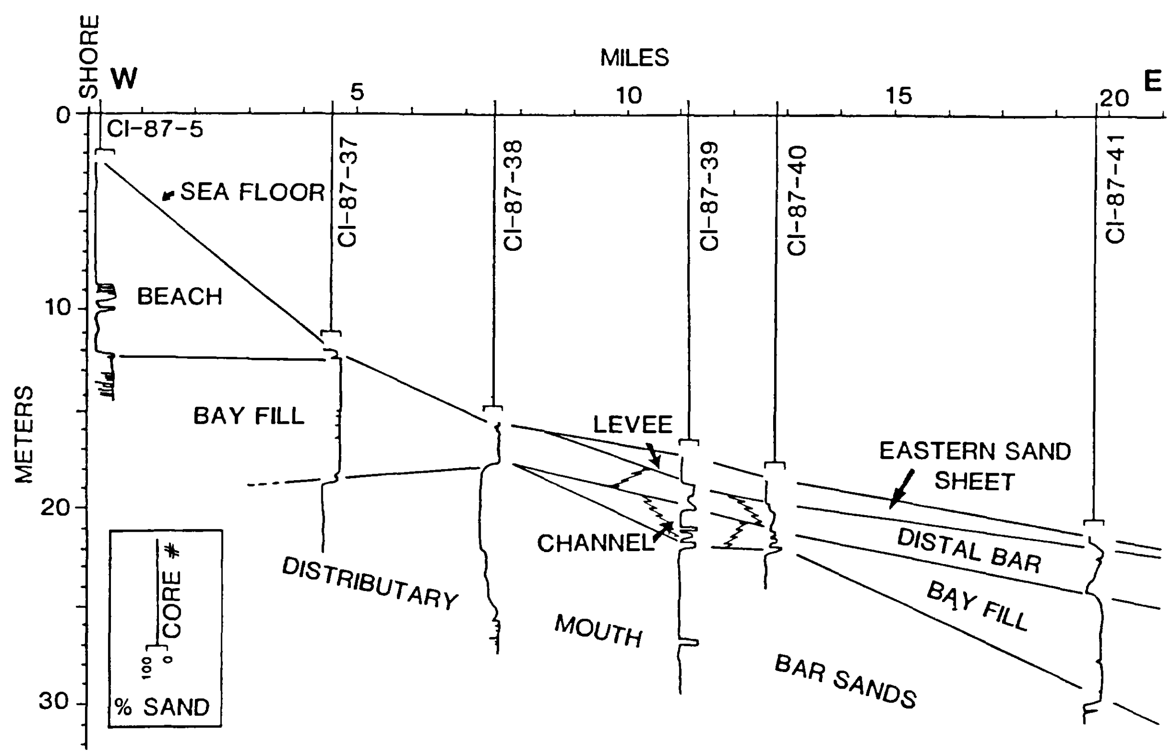

Figure 7. Cross section interpretated from lithologic descriptions of a vibracore transect. This cross section is from the northern flank of the St. Bernard delta with the western end located on the shoreface of the northern Chandeleur Islands. The log shown is percent sand visually described from each core. Location of cores is shown in Figure 2.

most of the progradational foresets have been reworked and destroyed.

In cross section typical delta facies are found within the St. Bernard delta complex; Figure 7 is an example from a series of vibracores on the northern delta flank adjacent to the northern extent of the Chandeleur Islands. It should be stressed that this is a preliminary interpretation of these vibracores. In core CI-87-5, nearest shore, a shoreface/beach sand (Chandeleur sand facies) overlies bay fill composed of clayey-silt to silty-clay with sand stringers. In the mid-section, core CI-87-39, channel and levee deposits overlay distributary mouth bar sands. The channel was confirmed by seismic profile interpretation. The shoreward extent of the Eastern Sand Sheet is visible in this core. Core CI-87-41 is a more complete sequence with similar facies including distal bar facies.

The sand ridges (Fig. 4-B) discussed above are a major feature of the southwestern region, which includes the Chandeleur sand deposit. A core taken on the crest through one ridge shows a 13 foot (4 meter) section of fairly clean sand over alternating beds of silt and silty-sand, topped by bay fill with silt and lenticular sands. An adjacent core taken in the trough contains a shell hash layer capping the corresponding bay fill section in the adjacent shoal crest core.

Northeastern Region—Mississippi-Alabama Nearshore Deposits

Several depositional processes have also affected the nearshore inner shelf. As discussed above, shoreline migration and coastal processes have reworked the sediments and winnowed out much of the finer material. Profile B-B′ (Fig. 8) shows a buried sand ridge whose superstructure has been truncated by a ravinement surface. Also truncated by this ravinement surface are shingled reflectors that may be associated with the sand ridge. The buried sand ridge is found at the east end of Petit Bois Island and is probably the remnant of the westerly migration of Petit Bois Island. The channels shown on the profile may have been stream or tidal channels. The most recent sea withdrawal left the inner shelf subaerially exposed, allowing streams to become entrenched in the area (Fig. 9). Cross section C-C′ shows stream incisions with channel deposits that are examples of the numerous channel incisions and deposits found throughout the inner shelf area. In general, the channel deposits consist of one or more of the following: coarse-grained sand, medium-grained sand, or poorly sorted medium- to silty fine sand. Much of the nearshore area is covered by the Eastern Sand Deposit. A typical example is Core CI-87-40 (Fig. 7). The sands are greenish-gray with high shell content including whole shells and hash.

CONCLUSIONS

The evolution of the Louisiana-Mississippi-Alabama shelf region is the product of transgressive and regressive sedimentary processes. Shelf sedimentary facies were deposited by deltaic progradation followed by shoreface erosion and submergence. The shelf can be divided into two main depositional regions, southwestern and northeastern. The southwestern region formed by the overlap of two ancestral Mississippi River delta complexes on a late Wisconsinan delta. Deposits of the late Wisconsinan delta consist of well-defined coarsening-upward sequences and represent deltaic progradation during low sea level. The relatively recent Mississippi delta complex deposits consist of fine-grained sands, silt and clay. With the late Holocene rise in sea level, marine reworking of an ancient shoreline produced asymmetrical sand ridges (16 ft or 5 m relief). The sand ridges were created by the winnowing of deltaic sediments deposited as distributary mouth bar sands by the St. Bernard delta.

The northeastern region offshore from the barrier islands of Mississippi-Alabama has formed by Pleistocene fluvial systems and shoreface erosion and ravinement. Relict fluvial sands, deposited during the late Wisconsinan lowstand and transgression, underlie the relatively thin Holocene sediment cover. Subsequent sea level rise allowed marine processes to rework and redistribute sediments to produce the nearshore fine-grained facies and shelf sands sheet.

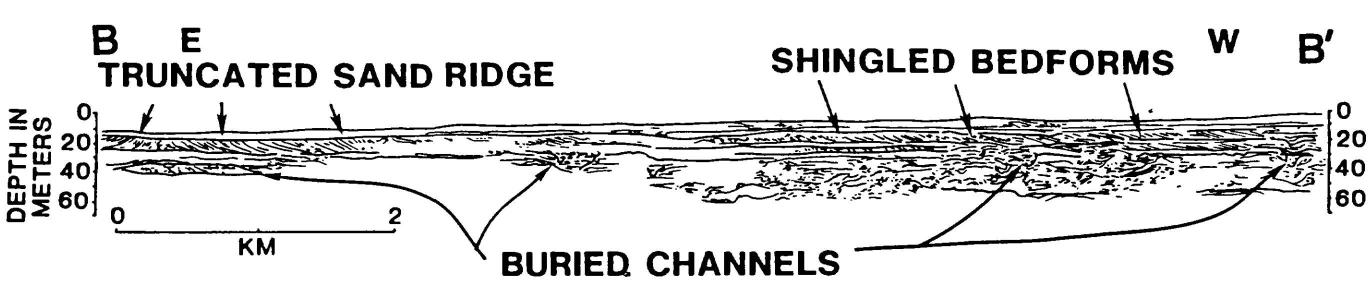

Figure 8. Line drawing of seismic profile. The truncated sand ridge shown to the east is the most eastern remnant of Petit Bois Island. Location of profile B-B′ is shown in Figure 1.

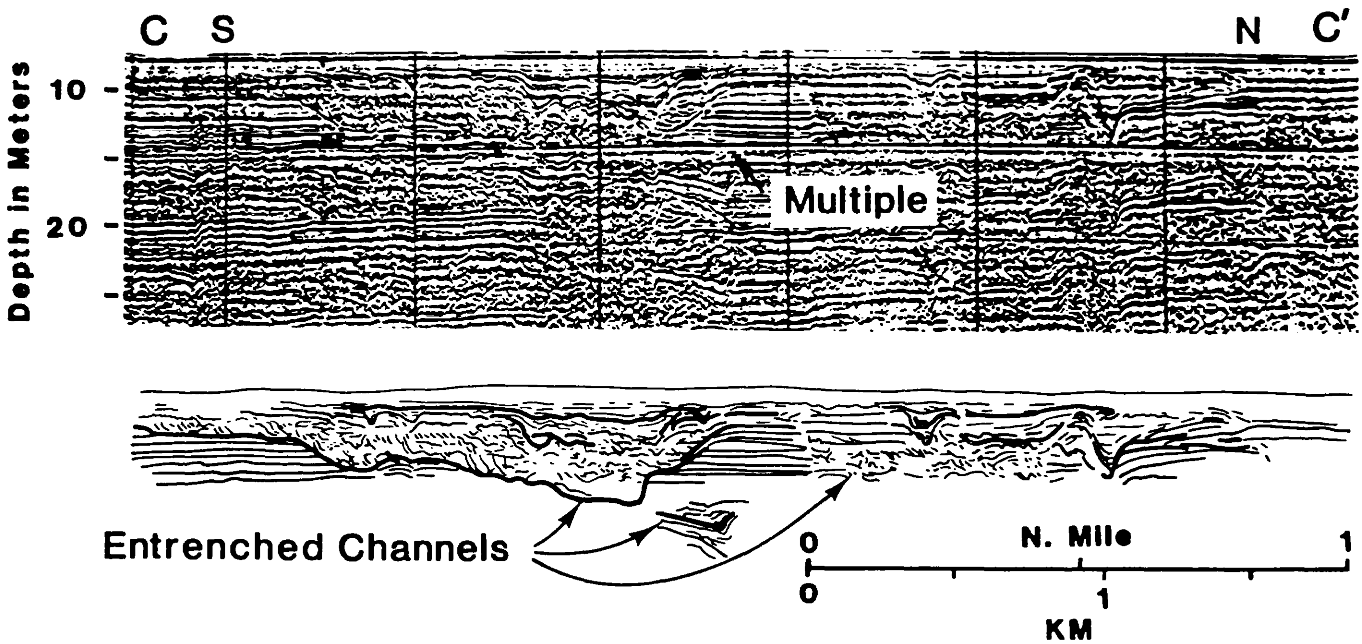

Figure 9. Seismic profile with schematic interpretation. This profile demonstrates the most recent entrenchment of the inner shelf during lower sea level. Much of the nearshore has been incised by similar channels. Location of profile C-C' is shown in Figure 1.

ACKNOWLEDGEMENTS

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Offshore and Onshore Sediment Resource Delineation and Usage for Coastal Erosion Control in Louisiana: the Isles Dernieres and Plaquemines Barrier Systems

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Abstract

The restoration and preservation of Louisiana's barrier shorelines requires a knowledge of onshore and offshore sources of construction aggregate for coastal erosion control. This paper is the result of years 3 and 4 of the Continental Margins Program of the Minerals Management Service (MMS), which focused on the distribution, quality, and environmental concerns surrounding the usage of sand resources for coastal erosion control in the Isles Dernieres and Plaquemines barrier island systems. Data from high-resolution seismic profiles and vibracores were used to locate potential offshore borrow areas for barrier island restoration and beach nourishment. Research concerns that need to be addressed during the decision-making process of sand resource usage are (1) the amount of sediment that can be removed without adversely impacting shoreline stability and project performance, (2) the source area economics of distance, quality, and material performance, and (3) the development of the suitable technology for low-cost shallow water dredging.

Introduction

Louisiana contains 40% of the coastal wetlands in the United States and experiences 80% of this nation's wetland loss (Turner and Cahoon, 1987). Coastal erosion rates range from 5 to 20 m/yr and are as high as 40 to 50 m/yr during years with hurricane impacts. The protection of Louisiana's barrier shorelines is essential to the preservation of extensive estuarine systems and will require a maintenance program of regularly scheduled barrier restoration, beach and shoreface nourishment, and vegetation projects (Penland and Suter, 1988). There are three major components in planning a coastal erosion control and restoration project. The first component is to determine sources of sediment available for construction. Transportation is the second concern when selecting a potential borrow site. A choice must be made between the expense to dredge and transport high-quality material from offshore areas or the less expensive option to transport poor-quality material from a closer onshore source. The third major concern is the environmental effects from dredging. Which source areas are the best to use, offshore or onshore? Will the dredged hole affect the nearshore wave regime, causing zones of accelerated erosion or poor project performance? In years 3 and 4 of the Continental Margins Program, the Coastal Geology Section of the Louisiana Geological Survey focused research on the delineation and utilization of sediment resources in the Isles Dernieres and Plaquemines barrier shoreline systems (Fig. 1). The specific objectives are to describe the coastal erosion and land loss problem in these areas with special attention placed on describing the sediment resources and discussing

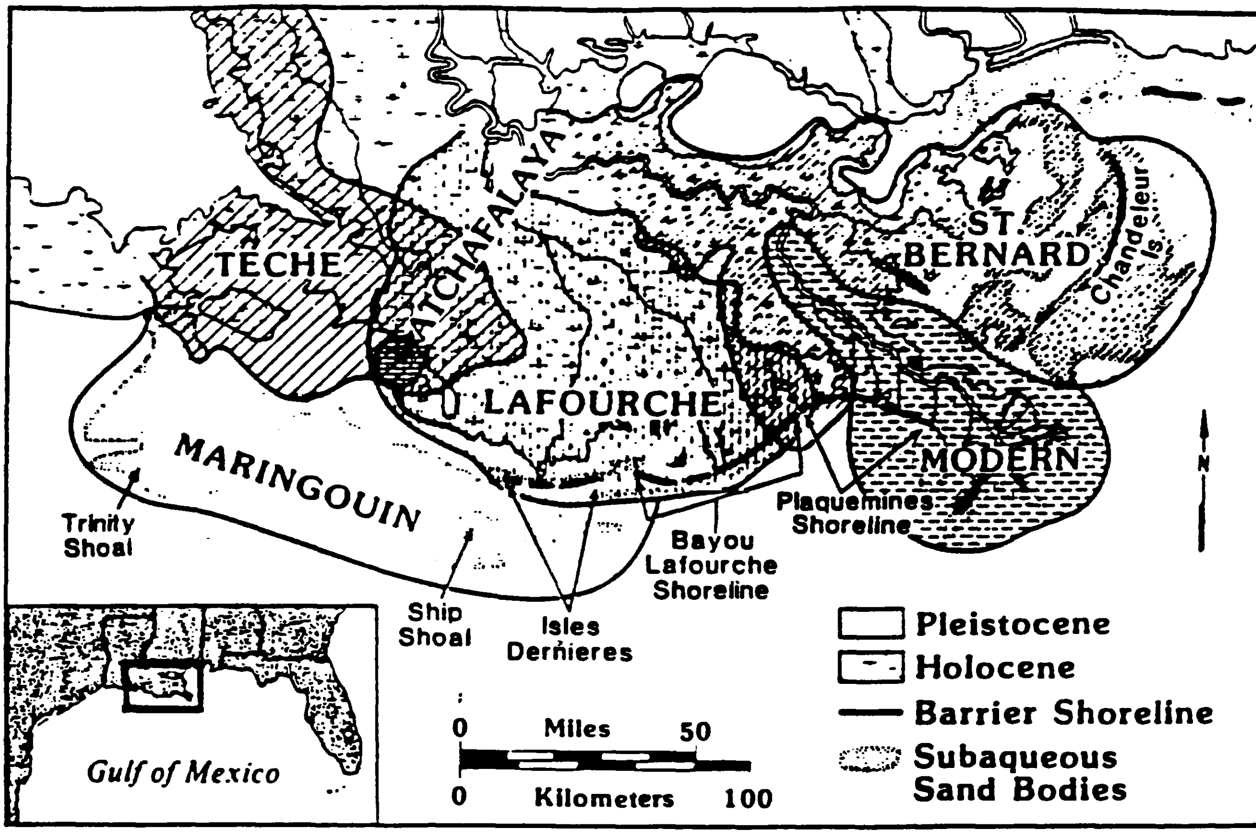

Fig. 1. Location diagram of the Plaquemines and Isles Dernieres shorelines.

the utilization of offshore versus onshore sources for coastal erosion control.

Geologic setting

The barrier island and mainland shorelines constitute the protective geologic framework of Louisiana's estuaries and vegetated wetlands within the Mississippi River delta plain. The highest rates of coastal erosion in Louisiana occur along the barrier islands (Penland and Boyd, 1981). Louisiana's barrier islands protect the Terrebonne, Barataria, and Chandeleur estuarine systems from the wave energy of the open Gulf of Mexico, regulate salinities, and lessen the effects of storms. Disappearance of these shorelines will result in the destruction of Louisiana's barrier-built estuaries and accelerated marsh deterioration. Between 1880 and 1978, Louisiana's barrier islands decreased in area by 41%. At these rates, the life expectancy of the individual barrier island systems ranges between 10 years for the Isles Dernieres and 225 years for the Chandeleur Islands. Such destruction will severely impact the fishery, fur, and waterfowl industries, valued at an estimated $1 billion per year, whose harvests depend on the habitat provided by these fragile estuaries (Turner and Cahoon, 1987).

Isles Dernieres system

The Isles Dernieres barrier shoreline originated from the transgression and submergence of the Caillou headland distributaries and beach ridges that were abandoned 600–800 yr B.P. (Penland et al., 1985, 1987). The Isles Dernieres barrier island arc encloses Caillou Bay, Terrebonne Bay, and Lake Pelto and consists of the Caillou headland, with a flanking spit to the west and a small spit to the east (Penland et al., 1989). In 1853, Pelto and Big Pelto bays separated the Caillou headland and flanking barriers from the mainland by a narrow tidal channel less than 500 m wide. By 1978, these bays had increased threefold in size and coalesced to form Lake Pelto. The Isles Dernieres are now located 6–8 km offshore from the retreating mainland. During this time the Gulf shoreline of the Caillou headland also retreated landward more than 1 km and segmented to form the four small islands of the Isles Dernieres barrier shoreline.

The Louisiana Geological Survey, in cooperation with the U.S. Geological Survey, has performed a

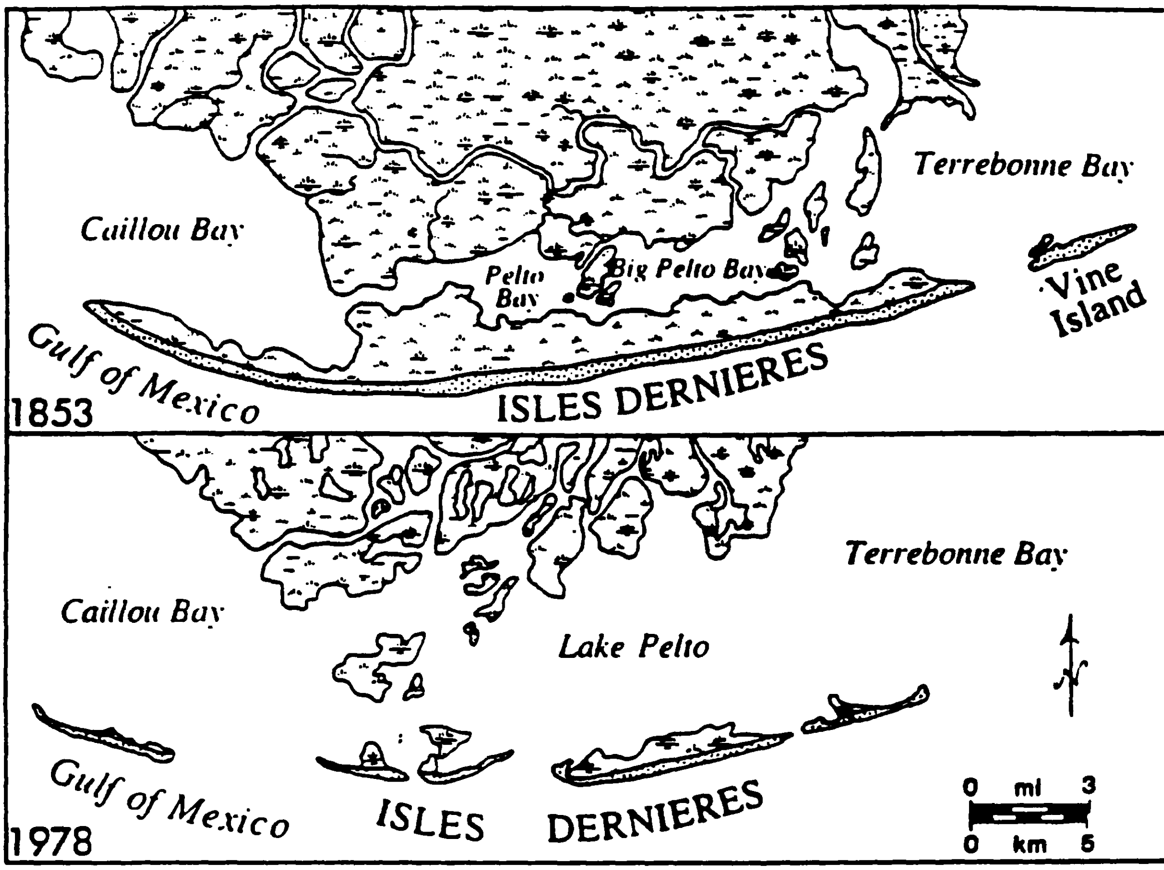

Fig. 2. A comparison of historical maps of the Isles Dernieres barrier island arc in Terrebonne Parish, Louisiana. Note the rapid land loss and retreat of the coastal zone (Penland and Boyd, 1981).

detailed analysis of coastal erosion in the Isles Dernieres. The results concluded that between 1890 and 1988 portions of the Isles Dernieres shoreline experienced 1,805 m of erosion at an average rate of 18.4 m/yr (McBride et al., 1989). The area of the Isles Dernieres decreased significantly from 3,360 to 771 hectares between 1890 and 1988 (Fig. 2). The total loss was 2,589 hectares at an average rate of 26.4 ha/yr for the past 98 years. Assuming rates of coastal land loss are linear, the entire Isles Dernieres will most likely become submerged and evolve into a subaqueous inner-shelf sand shoal by the year 2007. The Isles Dernieres have experienced both gulfside and bayside erosion. Shoreline change rates along the entire Isles Dernieres bayside shoreline ranged from 10.2 m/yr in a landward direction to 4.8 m/yr in a seaward direction during the interval 1890 to 1988.

Plaquemines system

The Plaquemines barrier shoreline consists of three headlands that were abandoned approximately 350 yr B.P. (Boyd and Penland, 1988). Because of the shoreline orientation, southeasterly waves transport available sediment to the west, as evidenced by the geomorphology of barrier islands and spits. Because little sand is available, erosion occurs throughout this area and ranges from 5–15 m/yr (Adams et al., 1976). The largest flanking barrier islands include Shell Island and Grand Terre. Shell Island is a recurved spit composed primarily of reworked oyster shells and sand. The Empire Waterway and jetties were constructed on the updrift end of Shell Island where it attached to the Dry Cypress Bayou headland. Prior to jetty construction, Shell Island had retreated landward and attached itself to the Dry Cypress Bayou headland by 1930. During this period, Shell Island migrated onshore, maintaining its width by equal amounts of shoreline erosion and back-barrier washover deposition. With jetty construction came a disruption of the longshore sediment transport that was being eroded from the Dry Cypress Bayou headland and transported northwestward towards Shell Island. Shell Island began to narrow owing to increased shoreline erosion and decreased washover deposition. To further

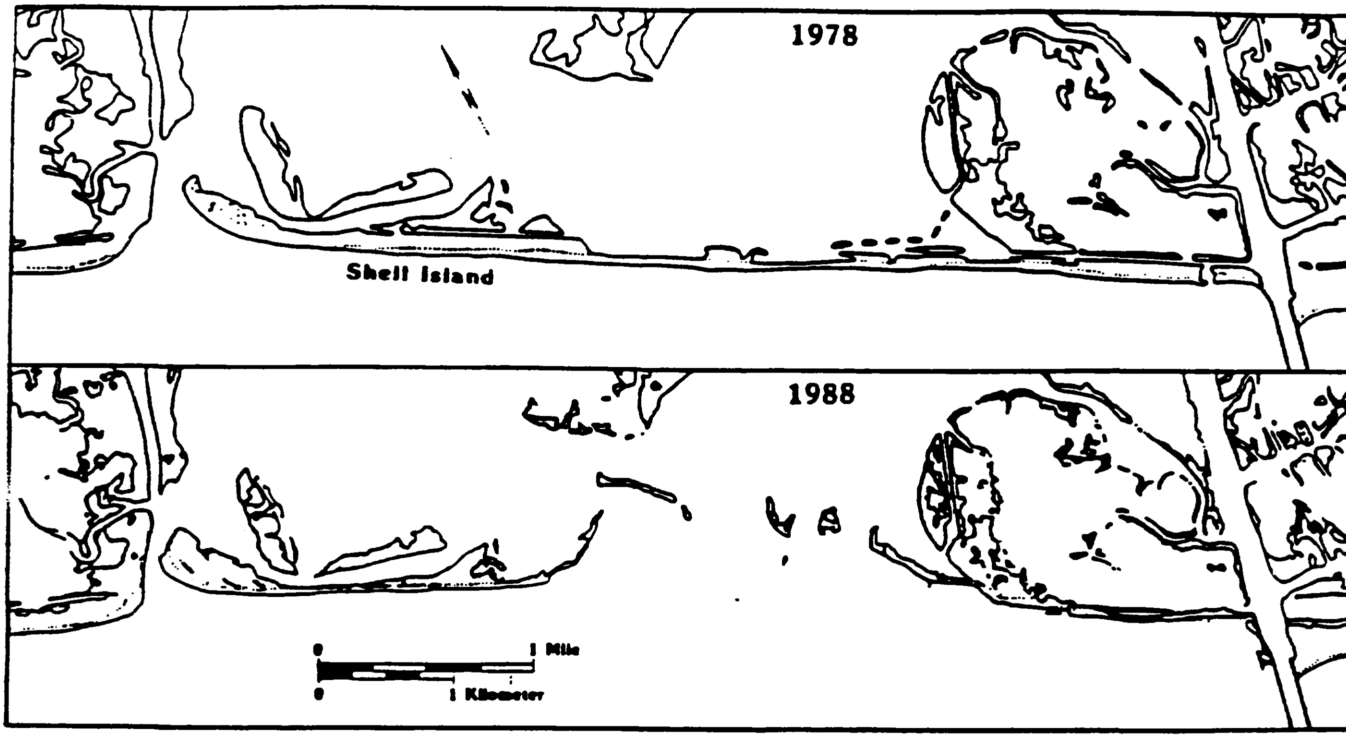

Fig. 3. Coastal changes for Shell Island illustrating the impact of the Empire jetty system between 1978 and 1988.

decrease the stability of Shell Island, two parallel pipelines were dredged along the shoreline axis of the island. The double pipeline created a sink to longshore and overwash-dispersed sands, whereas at other locations the elevation of the spoil banks prevented backbarrier washover deposition. By 1979, the island width had decreased to such a point owing to the combined effects of the Empire Waterway jetties and the shore-parallel double pipeline that Hurricane Bob breached Shell Island (Penland and Suter, 1988). Since 1979, the breach in Shell Island has grown in width greater than 2 km (Fig. 3).

Methods

The exploration for onshore and offshore sand resources delineated potential sand deposits using high-resolution seismic profiling systems (a Datasonics 3.5 kHz subbottom profiler and an ORE Geopulse). After the potential sand deposits were identified with seismic profiles, vibracores were taken to obtain samples of sediments for textural analysis and to confirm seismic interpretations. Wave refraction analysis was conducted using the Wave energy model developed by May (1974) in order to estimate the potential impact of dredging a large hole in the subbottom nearshore (Mossa, 1988). Output was generated for waves from the southeast, south, and southwest with heights of 2 and 4 m and periods of 5 and 7 seconds. These are typical wave conditions during extratropical and tropical cyclones or hurricanes, when most of the erosion along the shoreline occurs. Refraction diagrams and numerical findings were generated for these 12 scenarios in both actual situations and hypothetical situations where several dredge hole configurations were used.

Results

Sand resource delineation

Isles Dernieres

Twenty-five potential borrow areas for coastal erosion control were identified in the Terrebonne Parish waters (Fig. 4). Distributary, beach ridge, ebb-tidal delta, flood-tidal delta, recurved spit, and inner-shelf shoal deposits make up these borrow areas. The total volume of sand in these areas is estimated at 5,167,000,000 m³ (Penland et al., 1988). Sufficient sediment of suitable grain size occurs in the Terrebonne Parish coastal waters to restore and nourish the Isles Dernieres and Timbalier Island for the near future. Of the 25 potential borrow areas identified, only 6 will be

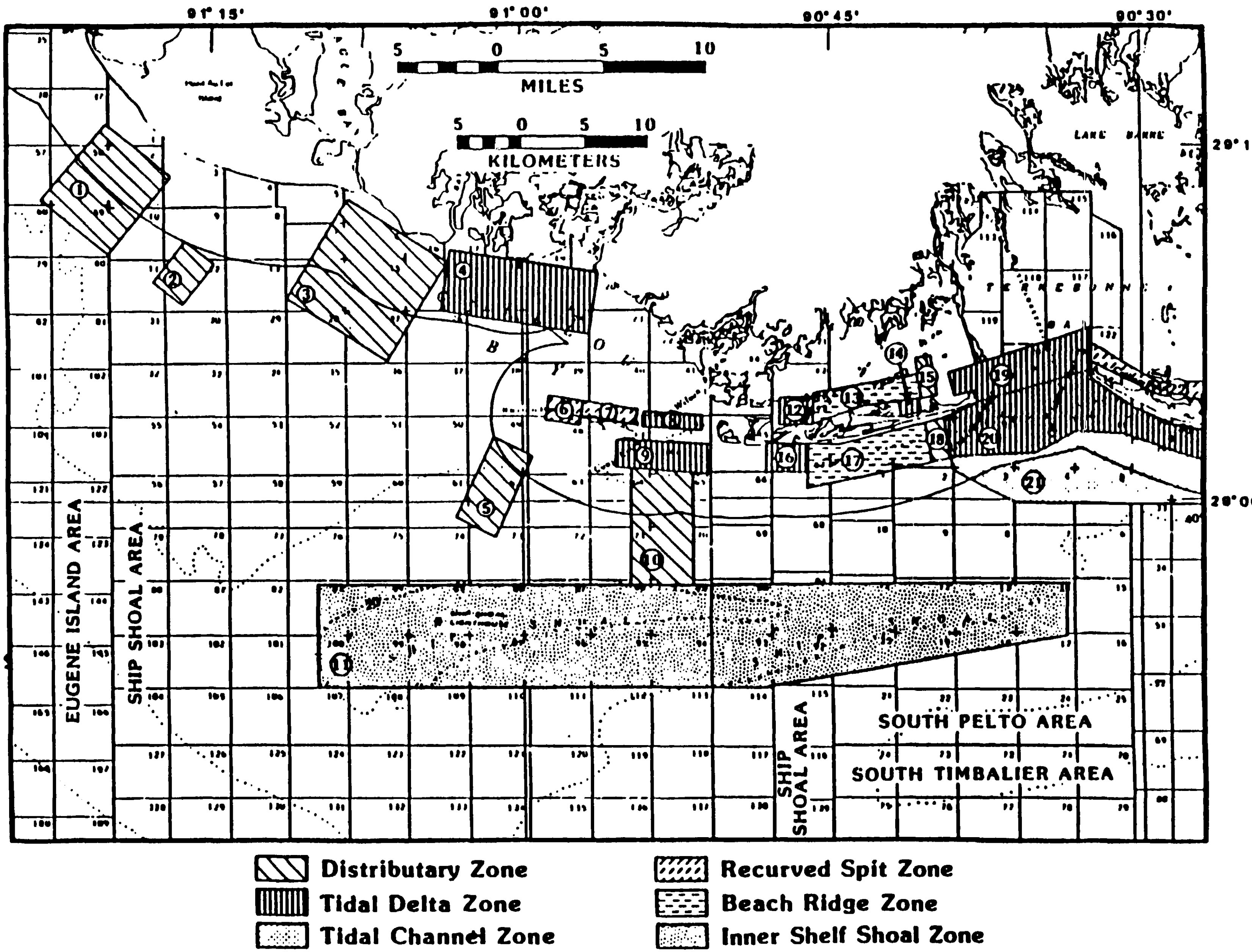

Fig. 4. Location of potential sand resource areas in the western Terrebonne Parish region.

TABLE 1

Selected potential borrow area grain-size composite standards

Location	ϕ84	ϕ50	ϕ16	Sorting	% Sand	Deposit
11	3.05	2.80	2.10	0.45	>90	Inner shelf shoal
17	4.17	3.66	3.16	0.90	27-95	Beach ridge plain
18	4.42	3.27	3.14	0.68	76-96	Distributary channels
19	3.41	2.75	1.68	1.08	86-92	Flood tidal delta
20	3.99	3.26	2.68	0.64	77-99	Ebb-tidal delta
21	3.85	3.35	2.83	0.50	20-40	Tidal inlet channel

presented in detail. Of these, Ship Shoal and Cat Island Pass are the largest and best-quality sand bodies offshore of Terrebonne Parish for barrier island restoration and beach nourishment in the Isles Dernieres (Table 1).

Ship Shoal is 15 km offshore of the Isles Dernieres. It is the largest and highest quality sand body in the Terrebonne Parish coastal waters (no. 11 in Fig. 4). Ship Shoal is a shore-parallel sand body, 50 km long and 8–12 km wide, lying in 10 m of water; it has a relief above the surrounding shelf of 3–7 m east to west along its crest axis (Fig. 5). Four major sand facies were delineated within the Ship Shoal: (1) shoal crest, (2) shoal front, (3) shoal base, and (4) sand sheet. Ship Shoal contains >1,278,830,000 m^3 of sand in

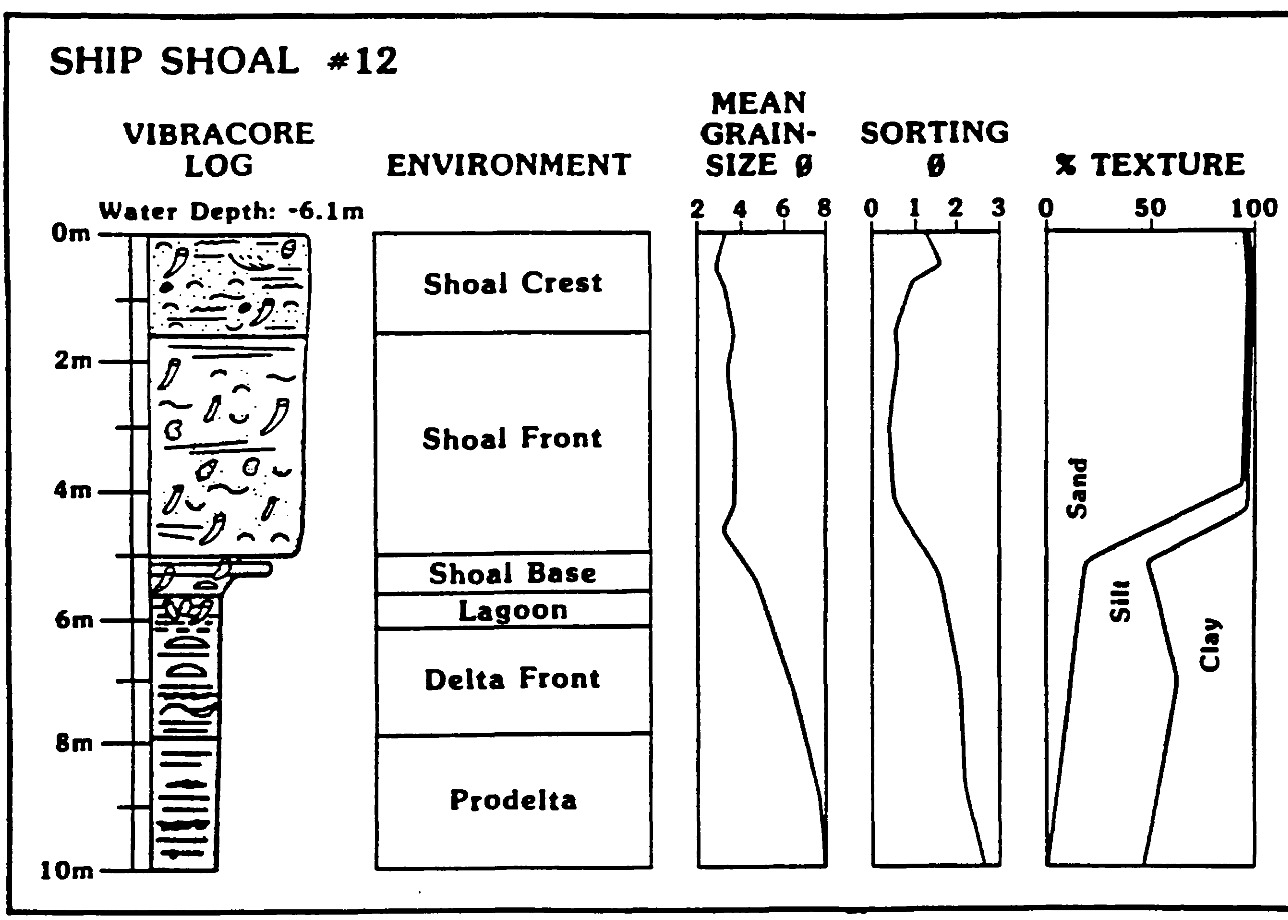

Fig. 5. Isopach map of Ship Shoal (Penland et al., 1986).

the range of 2–3ϕ, which is similar in texture to that of both the Isles Dernieres and Timbalier Islands beach sands. The western portion of the shoal is the thickest and is underlain by the sandy fill of the distributary channel. A sedimentary sequence from the central shoal is represented by vibracore SS-83-12. The shoal-crest deposits average 1.5 m thick. The shoal-front deposits are thickest in the central region, averaging 3–4 m; the shoal-base deposits are 0.5–1.0 m thick. The sedimentary sequence in vibracore SS-83-12 represents the eastern margin of the underlying deltaic section in the western shoal region defined by the presence of interbedded delta-front sand, silt, and clay. Farther east, the regressive deltaic sequence is composed entirely of prodelta muds.

The Cat Island Pass sand body is made up of three distinct sedimentary facies: (1) flood tidal delta, (2) tidal channel, and (3) ebb-tidal delta (Suter and Penland, 1987). Located immediately north of the Cat Island Pass tidal channel is a poorly developed flood-tidal delta sand body. The thickness of the flood-tidal delta averages approximately 1 m with a sand content of 97%, a mean grain size of 2.87ϕ, and an average sorting coefficient of 0.45ϕ. The estimated volume is about 30,070,000 m^3 with no overburden (Penland et al., 1988). Located seaward of the inlet throat of Cat Island Pass is an area composed of ebb-tidal delta, spit platform, and tidal channel deposits (no. 20 in Fig. 4B). Mean grain size is 2.85ϕ, the average sorting coefficient is 0.52ϕ, the percent sand is 93.71, and the estimated volume is 610,080,000 m^3. Located seaward of the Cat Island Pass ebb-tidal delta and the 8-m isobath is an area composed of tidal inlet channel deposits (no. 21 in Fig. 4B). Seismic profiles show these deposits to be characterized by high-angle clinoformal reflectors produced by the westward migration of Cat Island Pass (Suter and Penland, 1987). Vibracores document a shell-rich, sandy sequence within the buried channel, which is generally coarser grained than the overlying deposit. This deposit reaches a maximum thickness of 12 m in the thalweg of the channel system offshore and extends from the shoreline to some 7 km offshore. The tidal channel sand body covers an area of about 150 km^2 with a volume of >648,902,028 m^3, assuming an average thickness of 4 m. The sand content of this deposit ranges from 20–92%; the mean grain-size is 2.85ϕ with a sorting coefficient of 0.52ϕ. Approximately 1–4 m of sandy ebb-tidal delta overburden blankets the tidal inlet channel deposits.

Table 2 lists the results of the overfill factor calculations for the six borrow areas. Composite borrow samples were compared with composite native samples for the Isles Dernieres and Timbalier Island as well as each composite dune, terrace, and beach sample for these island systems. Overall, Ship Shoal (11) has the best overfill factor

TABLE 2
Overfill factors for selected borrow areas in Terrebonne Parish coastal waters

Location	ID-Composite Factor	Beach Factor	Terrace Factor	Dune Factor
		Isle Dernieres		
11	1.16	1.03	1.26	1.22
17	>10.00	>10.00	>10.00	>10.00
18	>10.00	10.00	>10.00	>10.00
19	1.39	1.31	1.46	1.48
20	4.55	3.75	5.00	4.91
21	9.00	7.00	>10.00	>10.00
		Timbalier Island		
11	1.05	1.04	1.03	1.08
17	>10.00	>10.00	>10.00	>10.00
18	9.90	9.90	9.90	>10.00
19	1.28	1.28	1.24	1.33
20	3.40	2.96	2.78	3.48
21	4.85	4.50	4.20	6.00

of 1.16 for the Isles Dernieres and 1.05 for Timbalier Island, followed by the Cat Island pass flood-tidal delta (19) with 1.39 and 1.28, respectively; Cat Island pass ebb-tidal delta area (20) with 4.55 and 3.40; Caillou distributary (18) with >10.00 and 9.90; Cat Island Pass tidal channel (21) with 9.00 and 4.85; and Cheniere Caillou beach ridge shoreface (17) with >10.00 for both (Fig. 4).

Shell Island

Nine potential borrow areas for barrier island restoration and beach nourishment fill were identified onshore and offshore of Jefferson and Plaquemines parishes (Fig. 6). Distributary, beach ridge, and ebb-tidal delta deposits make up these borrow areas. The total volume of sand in these areas is estimated at 397,000,000 m³ (Maciasz et al., 1988). Sufficient sediment occurs in the Plaquemines Parish coastal waters to restore barrier shorelines in the Shell Island region. The potential borrow areas are designated as numbers 49 through 55 in Fig. 6.

The Grand Bayou distributary channel area is designated number 49 in Fig. 6. Thickness of channel fill deposits averaged about 9 m throughout the area, which is estimated to contain about 32,000,000 m³ of borrow material. Overburden amount and lithology will be variable. The Grand Bayou Pass ebb-tidal delta target was delineated on the basis of geomorphology (no. 50 in Fig. 6). The average thickness of this small ebb-tidal delta is about 1.5 m, which translates to an estimated borrow material volume of about 6,000,000 m³. Textural characteristics can be expected to be similar to Cat Island Pass. There is little or no overburden. The Shell Island distributary channels are shown in Fig. 6 (no. 51). As with the other distributary areas, amount and lithology of both the sand deposits and the overburden within the site are variable. Based upon an average channel fill thickness of 9 m measured from seismic profiles, there is an estimated 56,000,000 m³ of borrow material within this target. The eastern, western, and central Scofield Bay distributary channel sand resource targets appear to be part of the same distributary system but were sufficiently spaced to warrant designation as three separate targets (no. 52, 53, and 54 in Fig. 6). Textural characteristics of these deposits are probably similar to those found for the vibracore shown in Fig. 6, taken from distributary deposits south of the target. Based upon the average thickness of the distributary channels as measured from seismic profile, an estimated 130,000,000 m³ of borrow material are contained within these sites. The overburden is silty clay, the amount ranging up to several meters. Textural characteristics of the sand bodies will be quite variable. The Dry Cypress Bayou distributary channel is the last target offshore of Shell Island. The average thickness of channel deposits within this area reaches about 9 m, resulting in an estimated volume of borrow material of some 131,000,000 m³. Sands within this deposit range from 1.99 to 3.37ϕ, with overburden ranging from 3 to 4 m of silty clays. Textural characteristics of the sand bodies will be quite variable.

Sand resource usage

Utilization of onshore and offshore sand resources for coastal erosion control, particularly dredge holes, can impact shoreline stability and project performance. Dredge holes in the barrier island shoreface have produced zones of accelerated coastal erosion, impacting project performance of the restored beach adjacent to the borrow sites (Combe and Soileau, 1987). The following section on Grand Isle examines the impact of dredging in shoreface and ebb-tidal barrier island environments in order to provide insight into shallow water sand usage. The Isles Dernieres section examines the results of dredging impact wave refraction analysis as well as the history of the dredging activities at Cat Island Pass.

Grande Isle

Grand Isle is a relatively stable barrier island located on the eastern part of the Bayou Lafourche headland. Because it is the only commercially and residentially developed island on the Louisiana coast, there have been numerous coastal engineering project attempts to protect Grand Isle. The most recent major construction project for beach erosion control and hurricane protection on Grand Isle was a dune line having a crest elevation of 3.5 m NGVD (Combe and Soileau, 1987). Construction began in 1983, was completed in 1984, and used 2,150,000 m³ of sand, of which about twice this volume was dredged from the onshore borrow pits approximately 800 m from the beach (Combe and Soileau, 1987). The borrow area located on the barrier island shoreface was parallel to the shoreline and measured nearly 2,750 by 450 m with excavations of 6 m at both ends and 3 m near the center of the pit below the adjacent sea floor (Fig. 7). Shoreface water depths surrounding the dredge hole are 4–6 m, making the maximum depths in the borrow site 7–12 m. The configuration of the shoreface borrow site was that of two pits connected by a narrower dredged area (Fig. 7). The dredging of these double pits was followed by

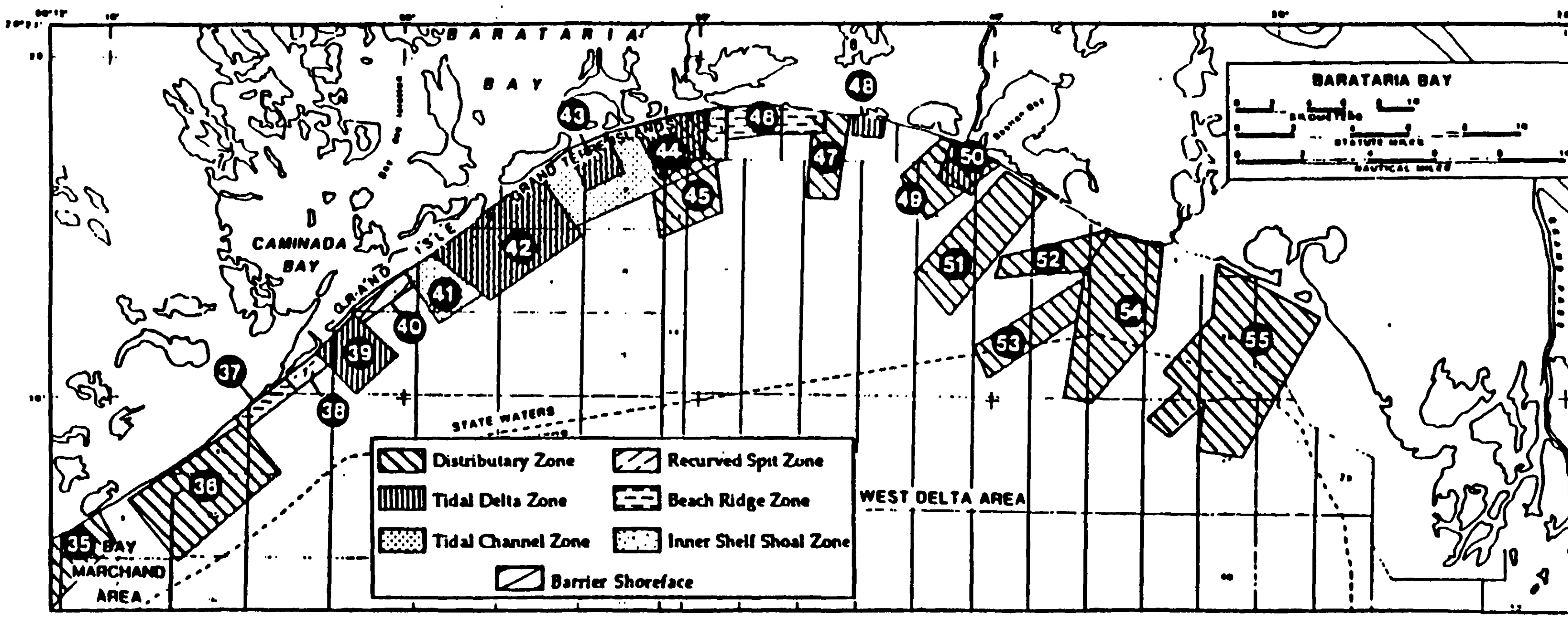

Fig. 6. Location of sand resource targets in the Barataria Bay and Approaches area (NOS Charts 11358 and 11361).

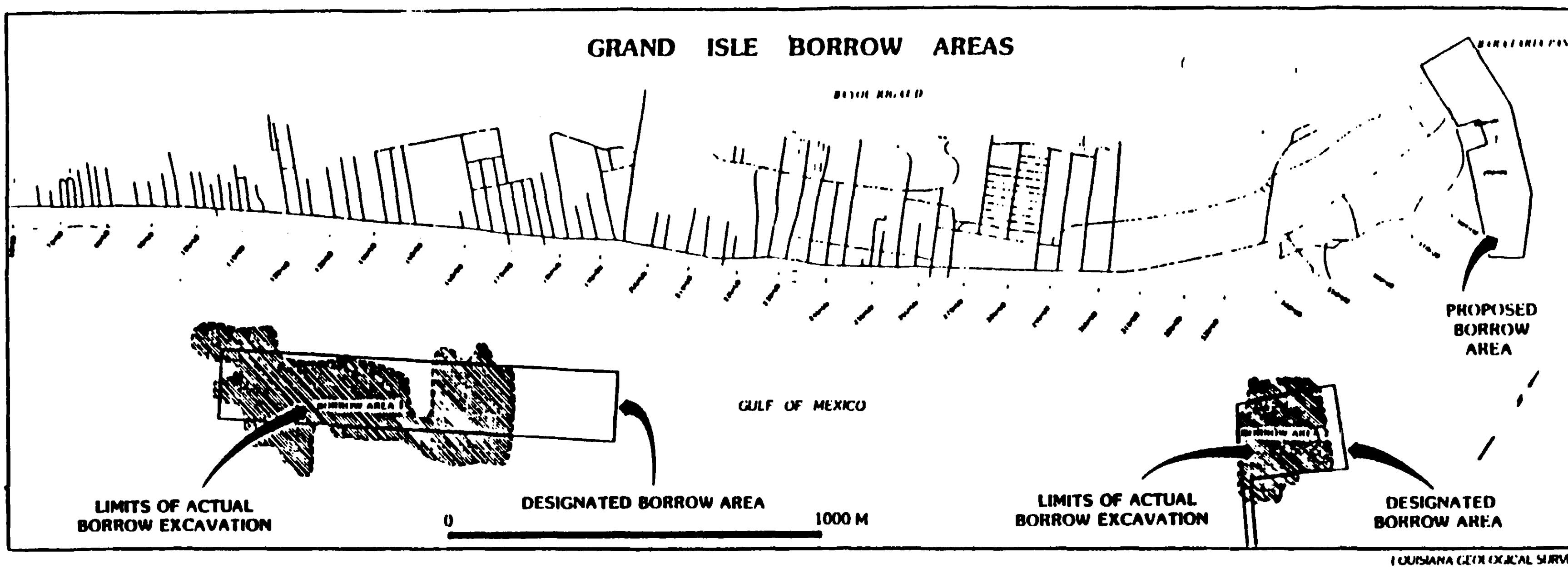

Fig. 7. Actual and proposed borrow areas for construction of hurricane protection dune line and beach nourishment at Grand Isle.

the development of a double set of cuspate bars located immediately landward on the beach. Each cuspate bar was separated by zones of accelerated beach erosion that impinged against the base of the protective dune destroying more than 50 m of new beach. In contrast, the apex of each cuspate bar extends seaward of the original design shoreline owing to accretionary ridge and runnel processes supplied by the adjacent zones of beach erosion.

A second borrow site was used on the swash platform of the western margin of Barataria Pass ebb-tidal delta adjacent to the Grand Isle state park. This dredge site is located 450 m offshore in water depths of 4–5 m. About 600,000 m^3 of sand was removed, producing a single hole 7–8 m deep. Soon after the dredging of this hole, a similar pattern of accelerated beach erosion zones separated by cuspate bar formation took place. Much speculation has focused on the relationship between the dredge holes, the process of cuspate bar formation, and the performance of the Grand Isle project. The exact process is unknown; however, the effect of dredging deep holes in shallow water shoreface and swash platform environment is established.

The only routine dredging activity in the Grand Isle area is associated with the Barataria Waterway where a navigation channel is maintained through the terminal lobe of the Barataria Pass ebb-tidal delta. In contrast to the shallow water sites used for construction aggregate, there has been no documented relationship between the dredging activities and beach erosion on the adjacent shoreline. Even though located in similar water depths, the dredging is located 3–5 km offshore on the terminal lobe compared with 400–500 m offshore for the onshore sites. The channel is maintained to a depth of 4.6 m.

Ship Shoal

The Isles Dernieres represent the most rapidly eroding barrier island in Louisiana, and current predictions suggest this barrier island arc will be converted into an inner shelf shoal by the year 2007. Island destruction will lead to the severe degradation of the Terrebonne estuary. As a consequence, the need for barrier island restoration exists. Offshore, Ship Shoal represents the largest and highest quality sand source in the north Gulf of Mexico and is a likely target of construction aggregate for coastal erosion control.

With the concerns over nearshore, shallow water dredging raised by the Grand Isle project experience, the Louisiana Geological Survey investigated the potential impact of dredging at Ship Shoal by use of wave refraction techniques (Mossa 1988; Suter et al., 1989). Results show that the longer wave periods and larger waves converge and break over the shoal sand body (Fig. 8). These incident waves subsequently redevelop as secondary waves with shortened periods and lower wave heights. In particular, the western shoal crest provided the most protection to Raccoon Island in the western Isles Dernieres because of the 3–4 m shallow water depths. In the wave refraction analysis, the bathymetry was altered to represent the removal of the eastern, central, and western portions of Ship Shoal—approximately one-third of the sand body volume. The wave refraction analysis of the modified bathymetric terrain indicated that removing volumes in excess of 400,000,000 m^3 resulted in increased wave energy being transmitted to the Isles Dernieres shoreline and reduced storm protection. This wave refraction analysis was geared towards assessing large-scale changes in order to determine if it was reasonable to pursue higher resolution wave refraction analysis. Removing 400,000,000 m^3 of sand for a coastal erosion control project is unrealistic; typical volumes are less than 10,000,000 m^3. The next level of analysis should be to assess the impact of 5–10,000,000-m^3-sized dredge holes on the wave refraction pattern. This work may show that the removal of small amounts of construction aggregate is acceptable.

The only experience with dredging in the Ship Shoal and Isles Dernieres region is at the Houma navigation channel through Cat Island Pass ebb-tidal delta. The navigation channel is 6 m deep and 100 m wide and is located 3–4 km from shore. The average annual maintenance dredging was 276,143.7 m^3 per year between 1966 and 1980. As in the case at the Barataria Pass Waterway, dredging the terminal lobe of Cat Island Pass appears to have no determined effects on the adjacent beaches of the Isles Dernieres and Timbalier Island.

Conclusions

The seismic and vibracore data from the Isles Dernieres and Shell Island surveys indicate sufficient sand resources exist to maintain these barrier islands for the foreseeable future. Ship Shoal is by far the largest and highest quality aggregate for coastal erosion control in Louisiana. Ship Shoal contains enough high-quality sand for more than 500 Grand Isle-sized beach nourishment projects.

Coastal erosion control efforts at the Isles Dernieres and Shell Island are faced with poorer

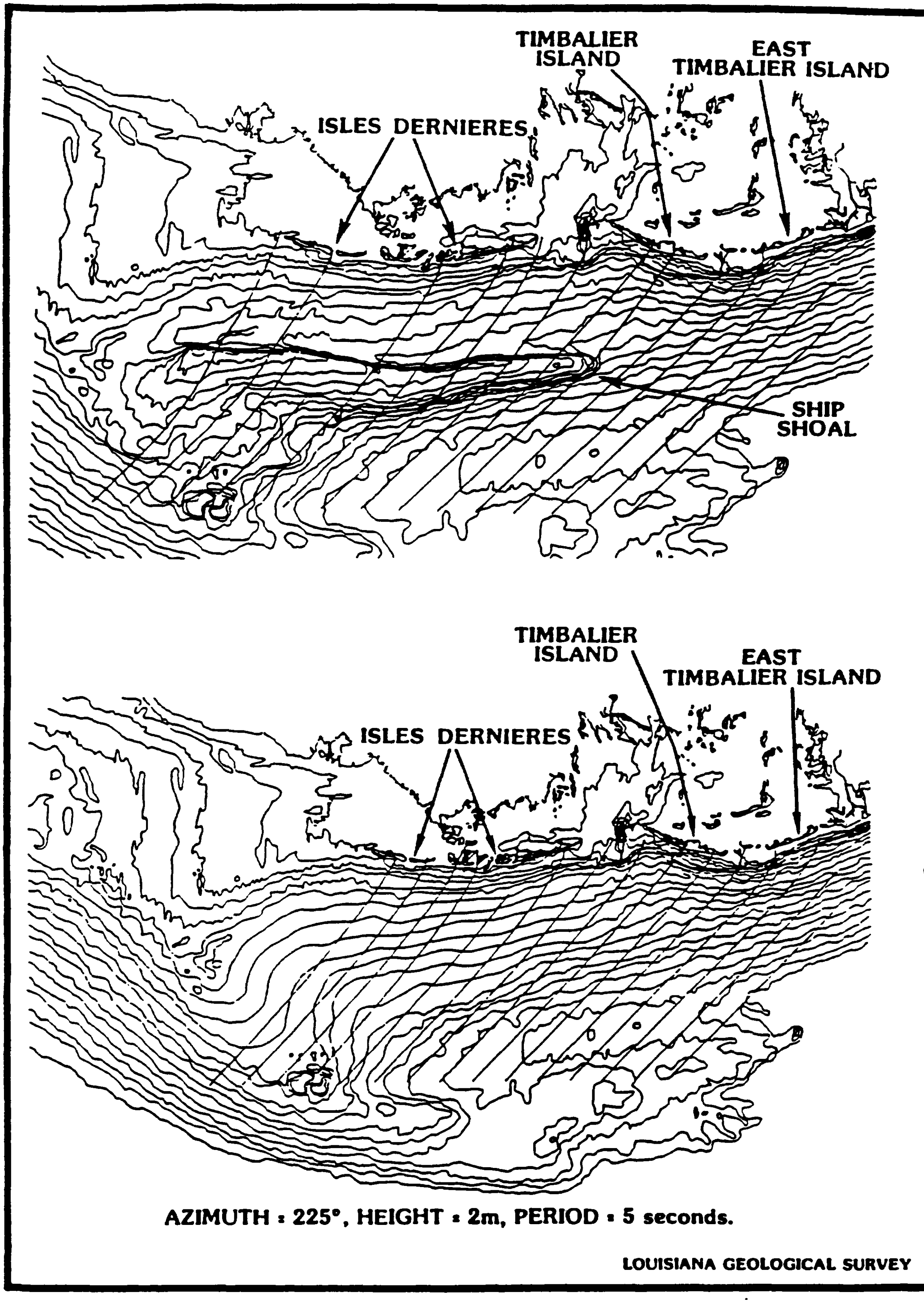

Fig. 8. Wave refraction diagrams for the Ship Shoal area using existing bathymetric data (upper) and hypothetical bathymetric data with Ship Shoal removed (lower). Azimuth is 225°, wave height is 2 m, and wave period is 5 s. Under these conditions, some wave orthogonals break over Ship Shoal, but not if it were removed.

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quality aggregate near the potential project areas and high-quality material located at a distance. At Shell Island, the nearshore distributary deposits have an overfill value of 8–10. In the Isles Dernieres, the nearshore tidal inlet deposits have an overfill value of 6–9. In contrast, the Ship Shoal sand body located further offshore has a superior overfill factor of 1.16. Our dredging experiences for coastal erosion control at Grand Isle suggest that usage of deposits on the shoreface and ebb-tidal delta areas immediately adjacent to the shoreline produces erosion and poor project performance. However, the maintenance dredging associated with the Houma navigation channel and the Barataria Waterway through the terminal lobe of Cat Island Pass and Barataria Pass, respectively, appears to have no effect on the stability of the adjacent shorelines.

The delineation of the available sand resources and review of the environmental concern over usage indicate the major research question facing the planning process is this: Which coastal erosion control project is the most cost-effective and performs the best—one that dredges and transports large amounts of poor-quality material a short distance or one that dredges and transports small amounts of high-quality material a long distance? Answering this important coastal design question will require thorough review of dredging economics, dredging technology, and the performance and handling of different types of material.

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COASTAL LAND LOSS IN LOUISIANA

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ABSTRACT

The Mississippi River delta and chenier plains in Louisiana are experiencing catastrophic coastal land loss rates exceeding 100 km^2/yr. Louisiana's coastal zone contains 40 percent of the U.S. wetlands and 80 percent of the Nation's loss occurs here. The origin and stability of these coastal environments is tied to the sediments discharged by the Mississippi River throught the delta cycle process. Sediments accumulate in well-defined delta complexes at approximately 800-1000 year intervals followed by abandonment and barrier island formation. The delta-cycle process, that bulds new delta complexes, barrier islands, and cheniers is curently stopped by flood and navigation control structures. These structures harness the flow of the Mississippi River within a massive levee system, channeling most of the sediments off the continental shelf. Deprived of sediments and subsiding rapidly, Louisiana's wetlands are vanishing. Researchers have long recognized the catastrophic coastal land loss conditions occurring and speculated on the causes. The chronic problem of wetland loss is well documented, but poorly understood. Over the last decade, two schools of thought have developed in the coastal research community concerning the relative roles of the causal factors driving the extreme rates of land loss and change. One school of thought emphasizes the natural processes of the delta cycle process and human activities are ranked as secondary in importance. In contrast, the other school of thought places primary importance on human activities and of secondary importance are the natural processes. A review of previous coastal land loss research indicates the only way to accurately determine the relative roles of different types and processes of land loss is to develop a classification suitable for quantitatively mapping the spatial distribution and contribution of each geomorphic loss type to the total amount of land loss in a given interval of time.

INTRODUCTION

Coastal erosion and wetland loss are serious and widespread problems of national importance with long-term economic and social consequences. Louisiana is experiencing the highest rates of coastal erosion and wetland loss in the United States and possibly the world. Rates of coastal loss have increased from 10 km^2/yr to more than 100 km^2/yr over the last century (Morgan and Larimore, 1957; Craig et al., 1980; Gosselink et al., 1979; Wicker, 1980; Gagliano et al., 1981; Sasser et al., 1986; Adams et al., 1978; Walker et al., 1987; Coleman and Roberts, 1989; Britsch and Kemp 1990). Louisiana's barrier islands, whose presence creates and maintains an extensive barrier-built estuarine system, protect the marshes and bays from offshore wave conditions and saltwater intrusion from the Gulf of Mexico. These islands are vanishing, decreasing in area and eroding at very rapid rates (Peyronnin, 1967; Penland and Boyd, 1981, 1982; Morgan and Morgan, 1983; McBride et al., 1989). The disappearance of Louisiana's barrier islands will result in the destruction of the large estuarine bay systems and the acceleration of wetland loss. Coastal land loss severly impacts the fur, fish, and waterfowl industries, valued at an estimated $1 billion per year, as well as the environmental quality and public safety of south Louisiana's sea level citizens (Gagliano and van Beek, 1970; Gosselink, 1984; Turner and Cahoon, 1987; Chabreck, 1988; Davis, 1983, 1989). The region's renewable resource base depends on the habitat provided by these fragile estuarine ecosystems. Understanding the coastal geomorphological processes, both natural and human-induced (Table 1) that control barrier island erosion, estuarine deterioration, and wetland loss in Louisiana is essential in evaluating the performance of the various restoration, protection, and management methods currently envisioned or employed (Table 2).

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Table 1. Louisiana Coastal Land Loss Processes

Natural	Human
Delta-Cycle Process	Flood Control
Subsidence	Canals
Eustacy	Pipelines
Storm Impact	Subsurface Withdrawal
Geosynclinal Downwarping	Water Pollution

Table 2. Solutions to Louisiana's Coastal Land Loss Problem

Tactics	Relative Costs
Strategic Management and Retreat	$$$$
Sediment Diversions	$$$
Marsh Management	$$
Coastal Erosion Control	$
Research and Development	¢

Coastal erosion and wetland loss are posing a growing challenge to Louisiana and other Gulf Coast states as our population becomes increasingly concentrated in and dependent upon coastal areas. The Environmental Protection Agency (EPA) and National Research Council (NRC) forecast the rates of sea level rise will increase over the next century. This increase will dramatically accelerate coastal land loss in the future (Barth and Titus, 1984; National Research Council, 1987). Because of its geologic setting, the severe coastal land loss conditions found in Louisiana today provides a worse-case scenario for the future coastal conditons forecast by the EPA and NRC. More importantly, Louisiana's coastal problems document the importance of understanding the processes driving coastal land loss. The U.S. Geological Survey (USGS) and Louisiana Geological Survey (LGS) cooperative coastal research program strives to improve our knowledge and understanding of the processes and patterns of coastal land loss and of the forecast of adverse impacts on people and resources in the coastal zone (Sallenger and Williams, 1989). Many solutions to most coastal land loss problems caused by geologic processes overly emphasize stopping the result of the process and do not give adequate consideration to the process itself. This approach results in many engineering solutions that rely on costly brute force rather than more sophisticated, less expensive approaches that are in concert with natural processes defined by scientific study (Penland and Suter, 1988). The lack of understanding the processes also leads to oversimplified concepts producing false hope that simple solutions exist. The key objectives of the USGS and LGS cooperative coastal research program are to provide good scientific information on coastal erosion and wetland loss suitable for developing a strategy to conserve and restore coastal Louisiana and to improve communication among scientists, engineers, and decision makers. This paper summarizes the geologic framework in which coastal erosion and wetland loss occurs in Louisiana. In addition, this paper discusses the controversy surrounding the causes of coastal land loss and the relative roles of natural processes and human activities.

REGIONAL GEOLOGY

Delta Plain

The coastline of the northern Gulf of Mexico is dominated by the Mississippi River. Since about 7,000 yr B.P., the Mississippi River has built a deltaic platform comprising numerous individual delta lobes and groups of related lobes known as delta complexes (Russell, 1936; Risk 1944; Kolb and Van Lopik, 1958, Scruton, 1960; Frazier, 1967; Coleman, 1988). The delta-building process consists of prodelta platform establishment, followed by distributary progradation and bifurcation, that results in delta plain consolidation (Figure 1). This process continues until the distributary course is no longer hydraulically efficient. Abandonment occurs, initiating the transgressive phase of the delta cycle. The abandoned delta subsides, and coastal processes rework the seaward margin, generating a sandy barrier shoreline backed by bays and lagoons (Kwon, 1969; Penland et al., 1981). Coastal land loss occurs naturally during this stage. Transgressions occur repeatedly, both for delta complexes and delta lobes.

The contemporary delta plain can be subdivided into two distinct categories, active deltas and abandoned deltas. Delta building occurs in 20 percent of the delta plain and is restricted to the Modern complex and the newly active Atchafalaya complex. The Plaquemines delta of the Modern complex is abandoned. The four remaining complexes, the Maringouin, Teche, St. Bernard, and Lafourche are all abandoned and have some type of transgressive shoreline or shoal sand body developing. The Balize lobe of the Modern delta complex is represented by the familiar "bird-foot" delta model. The delta has prograded into deep water near the shelf margin and the greater accommodation space results in the accumulation of hundred of meters of sediments in one deltaic cycle. Mass movement of sediments is extremely important in building the deltaic sequence. The Atchafalaya delta complex emerged as a subaerial feature after the 1973 flood (van Heerden and Roberts, 1988). According to Fisk (1952), the Atchafalaya has been a distributary of the Mississippi River since the mid-1500s and by the 1950s had captured about 30 percent of the flow of the Mississippi River. Because the route of the Atchafalaya River to the Gulf is some 300 km shorter than the current course of the Mississippi River, Fisk (1952) predicted a relocation of the main distributary to the Atchafalaya course. As a result, a series of large control structures have been built north of Baton Rouge to hold the Mississippi River in its present position. Were it not for these structures, the Balize delta would probably have been abandoned by now and have entered the transgressive phase.

As a delta is abandoned, marine processes begin to dominate the system. Coastal land loss occurs and deltaic sand bodies supply coarse sediment to the nearshore current field. An erosional headland with flanking barrier spits develops, and an evolutionary process of barrier island formation begin (Penland et al., 1988). The abandoned Bayou Lafourche delta headland is the most recent example of this landform. Erosion rates on the central headland average as much as 20 m annually, reaching over 50 m in hurricane years (Ritchie and Penland, 1988). The Timbalier Islands to the west of the Bayou Lafourche headland and Grand Isle to the east, represent a Stage 1 barrier system (Figure 2). The Plaquemines barrier shoreline

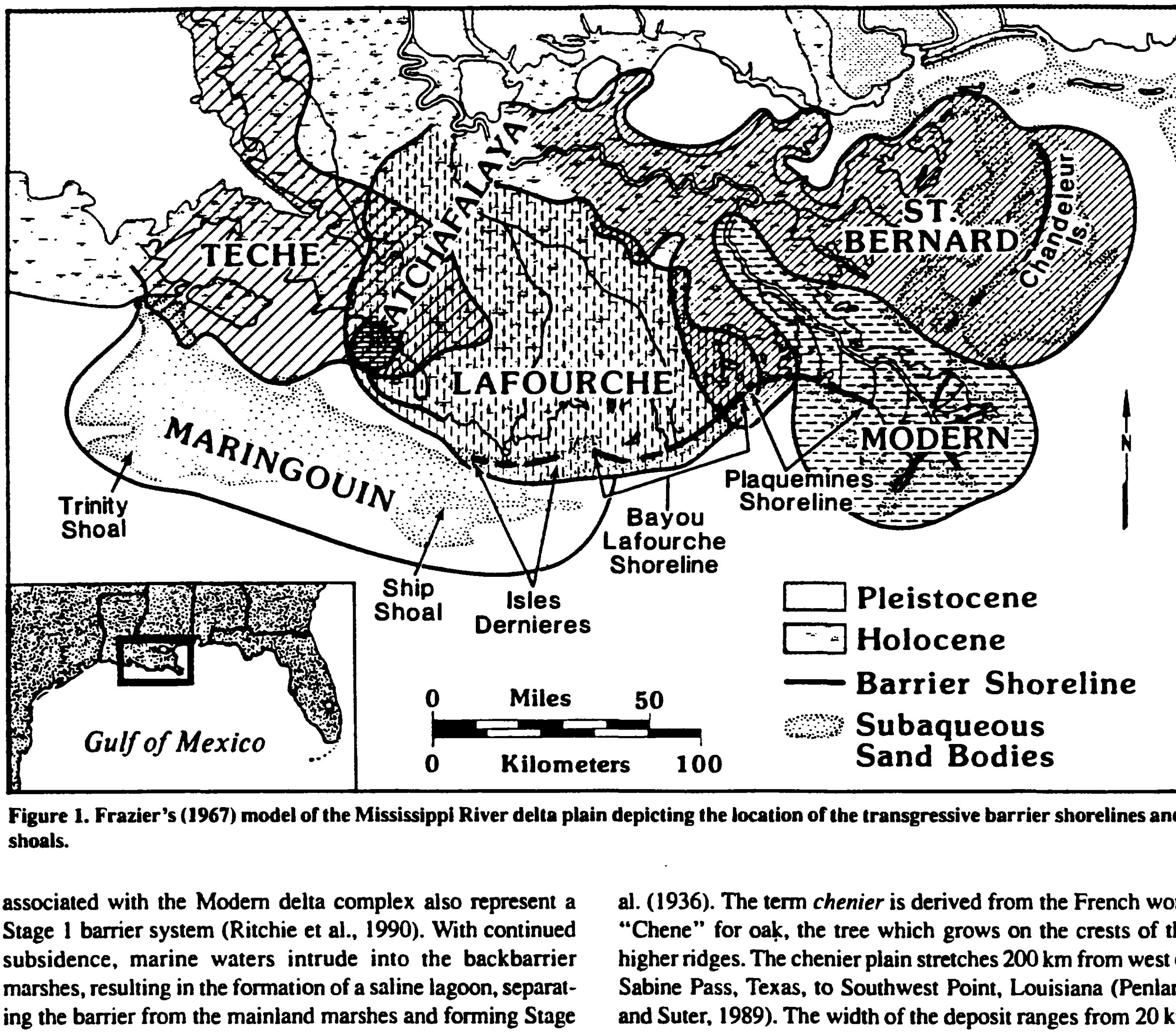

Figure 1. Frazier's (1967) model of the Mississippi River delta plain depicting the location of the transgressive barrier shorelines and shoals.

associated with the Modern delta complex also represent a Stage 1 barrier system (Ritchie et al., 1990). With continued subsidence, marine waters intrude into the backbarrier marshes, resulting in the formation of a saline lagoon, separating the barrier from the mainland marshes and forming Stage 2, the barrier island arc. The best examples of this are the Isles Dernieres derived from the Lafourche delta complex and the Chandeleur Islands derived from the St. Bernard delta complex (Penland et al., 1985; Ritchie et al., 1989).Further subsidence removes the coarser-grained distributary mouth bar and channel deposits from the nearshore wave field, resulting in a cessation of sediment supply to the barrier islands. At this point, continued reworking by waves and storms begins the degradation of the barrier islands. The subaerial island area decreases greatly as sands are lost seaward to an inner shelf sand sheet, landward by overwash, and captured in tidal-inlet sinks. This process is well illustrated by the evolution of the Isles Dernieres. Ultimately the barrier system loses its subaerial integrity and forms Stage 3, and inner-shelf shoal (Penland et al., 1989a).

Chenier Plain

The chenier plain is a series of alternating ridges and mud flats, first described by Russell and Howe (1935) and Howe et al. (1936). The term *chenier* is derived from the French word "Chene" for oak, the tree which grows on the crests of the higher ridges. The chenier plain stretches 200 km from west of Sabine Pass, Texas, to Southwest Point, Louisiana (Penland and Suter, 1989). The width of the deposit ranges from 20 km to 30 km, with elevations of the ridges varying from 2 m to 6 m (Figure 3). Gould and McFarland (1959) used shallow borings and radiocarbon dates to interpret the sedimentary facies and stratigraphic history of the chenier plain. Transgressive and regressive wedges overlie a soil zone that is also the Pleistocene-Holocene unconformity. The wedge thickens from 3 m to 6 m and is progressively younger seaward. Vertical sequences consist of basal and upper layers of marsh or bay mud separated by intermediate layers of shoreface sand and mud. Shoreface deposits either grade upward into chenier sand shell or are overlain by bay and tidal-flat sand and mud. A thin but extensive layer of organic-rich marsh sediments caps the sequence.

Shoreline composition and rate of seaward progradation of the chenier plain were determined by proximity of the Mississippi River outlet. Shallow-water mudflats were rapidly deposited when the main distributaries of the river lay in the southwest portion of the delta plain. When those deltas were abandoned, marine processes reworked the mudflats concentrating the coarsest material into chenier ridges. Periodic repe-

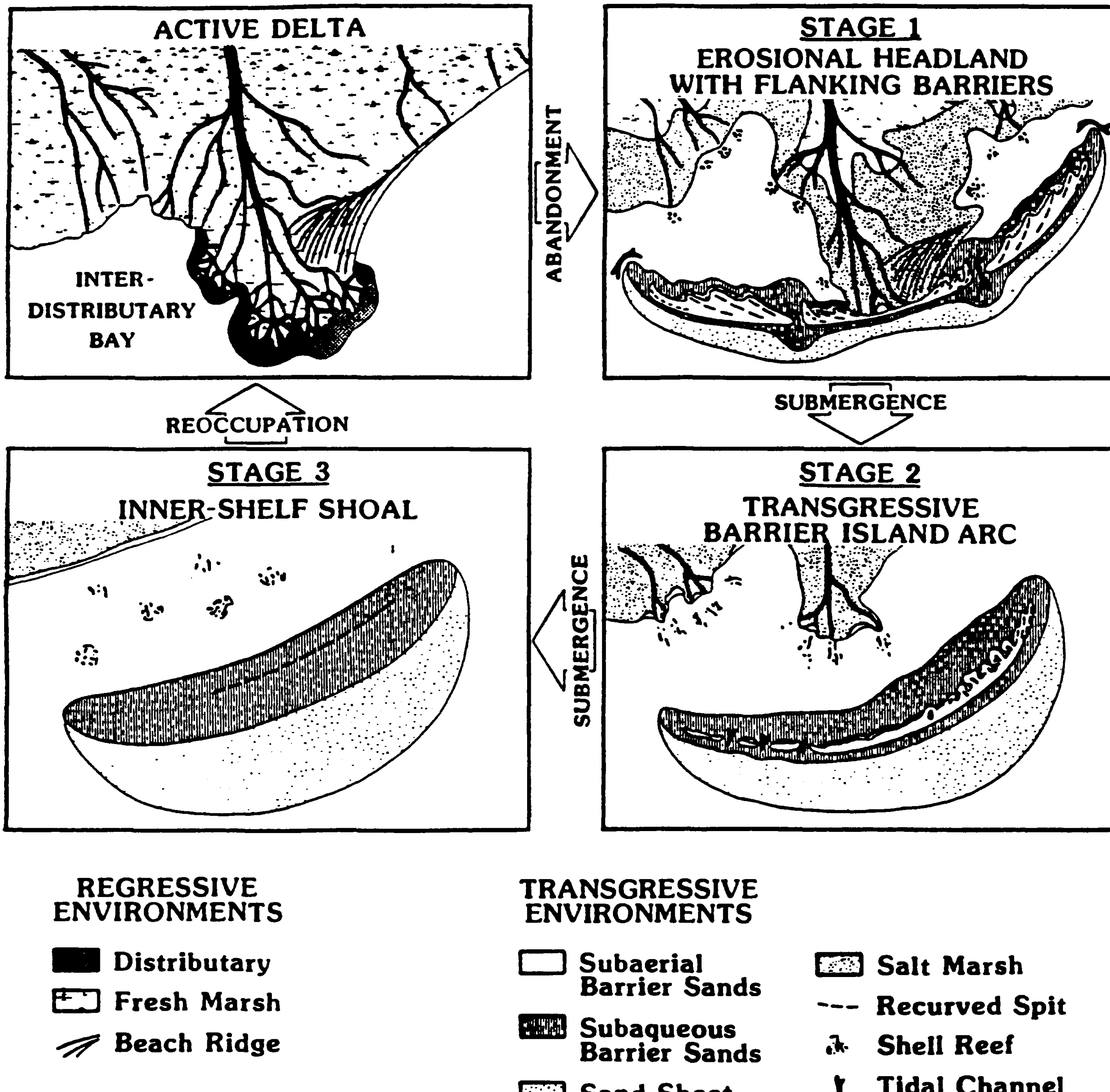

Figure 2. The genesis and evolution of the transgressive depositional systems in the Mississippi River delta plain are best summarized within the framework of a three-stage geomorphic model (Penland et al. 1988).

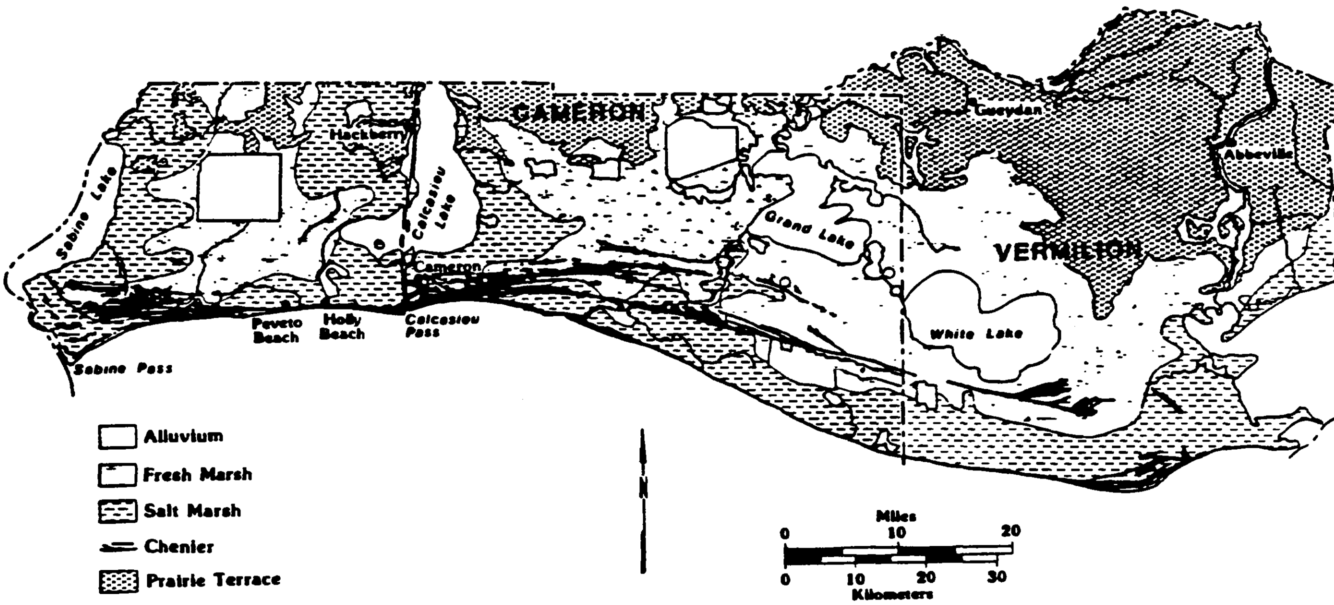

Figure 3. The regional geomorphology of the Mississippi River chenier plain.

tition of these processes produced the alternating chenier ridge and mudflat topography. Recent work on mud-flat progradation associated with the development of the Atchafalaya delta (Wells and Roberts, 1981) has shed some new light on the processes of chenier formation (Wells and Kemp, 1981; Wells, 1986, Kemp, 1986). With the position of the Atchafalaya River delta complex at the western margin of the deltaic plain, significant mudflat progradation is occurring in the area west of Freshwater Bayou and in the Cameron-Calcasieu area. Major mud-flat progradation appears to be linked to the passage of cold fronts and hurricanes.

COASTAL LAND LOSS

Behind the protective barrier islands are extensive estuaries that are rapidly disintegrating by pond development, bay expansion, coastal erosion, and human impacts (Morgan, 1967). The chronic problem of wetland loss in Louisiana is well-documented, but poorly understood (Wicker 1980; Galiano et al., 1981; Britsch and Kemp, 1990). Previous studies show coastal land loss has persisted and accelerated since the 1900s. Much speculation and debate in the research, government, and environmental communities surrounds the issue of coastal land loss, the processes driving coastal change (Table 1), and the strategy of coastal protection and restoration (Table 2).

Coastal land loss refers to the set of processes that convert land to water. *Coastal change* is a more complex concept. It describes the set of processes driving the conversion of one geomorphic habitat type into another geomorphic habitat type. The process of coastal land loss and change typically follows the conversion of vegetated wetlands to an estuarine water body, followed by barrier island destruction and the conversion of estuarine water bodies to less productive open Gulf of Mexico conditions. The coastal land loss process can be subdivided into two major types: coastal erosion and wetland loss. Coastal erosion describes the retreat of the shoreline along the exposed coasts of large lakes, bays, and the Gulf of Mexico. In contrast, wetland loss is used to describe the development of ponds and lakes within the interior wetlands and the expansion of large coastal bays behind the barrier islands and mainland shoreline.

Coastal Erosion

Louisiana is experiencing the highest coastal erosion rates in the United States (Morgan and Larimore, 1957; Adams et al., 1978; Penland and Boyd, 1981, van Beek and Meyer-Arendt, 1981; Morgan and Morgan, 1983; McBride et al., 1989). In the U.S. Geological Survey's *National Atlas of the United States of America* (1988), Louisiana appears on the coastal erosion and accretion plate as the nation's erosion hot spot (Figure 4). Coastal erosion rates in Louisiana average -4.2 m/yr with a standard devision of 3.3. The coastal erosion rates ranged between +3.4 m/yr and -15.3 m/yr (Table 3). The average Gulf of Mexico shoreline change rate is -1.8 m/yr, the highest in the U.S. By comparison, the Atlantic erodes at an average rate of -0.8 m/yr, while the Pacific coast is relatively stable at an average rate of ± 0.00 m/yr. In Louisiana, the majority of the coastal erosion is concentrated in the barrier shorelines that front the Mississippi River delta plain. The average coastal erosion rate of -4.2 m/yr represents the long-term conditions exceeding 50 years averaged together by per unit length of shoreline for 600 km of coast. This number is not representative of the individual storm events that drive the long-term average as well as the coastal erosion hot spots. Coastal erosion is not a constant 365-day-a-year process; bursts of erosion are associated with the passage of major cold fronts, tropical storms, and hurricanes (Harper, 1977; Penland and Ritchie, 1979; Boyd and Penland, 1981; Dingler and Reiss, 1988; Ritchie and Penland, 1988; Dingler and Reiss, 1990). Field measurements have documented 20-30 m of coastal erosion during a single storm event lasting 3-4 days. These major storm events produce energetic overwash conditions that erode the beach and reduce the barrier landscape into lower relief landforms (Penland et al., 1989b). In addition to beach erosion, the total area of Louisiana's barrier shorelines is decreasing rapidly. In 1880, the total barrier island area in Louisiana was measured at 98.6 km^2 and by 1980 the total area had decreased to 57.8 km^2. This represents a 41% decrease in area at a rate of 0.41 km^2/yr (Penland and Boyd, 1982).

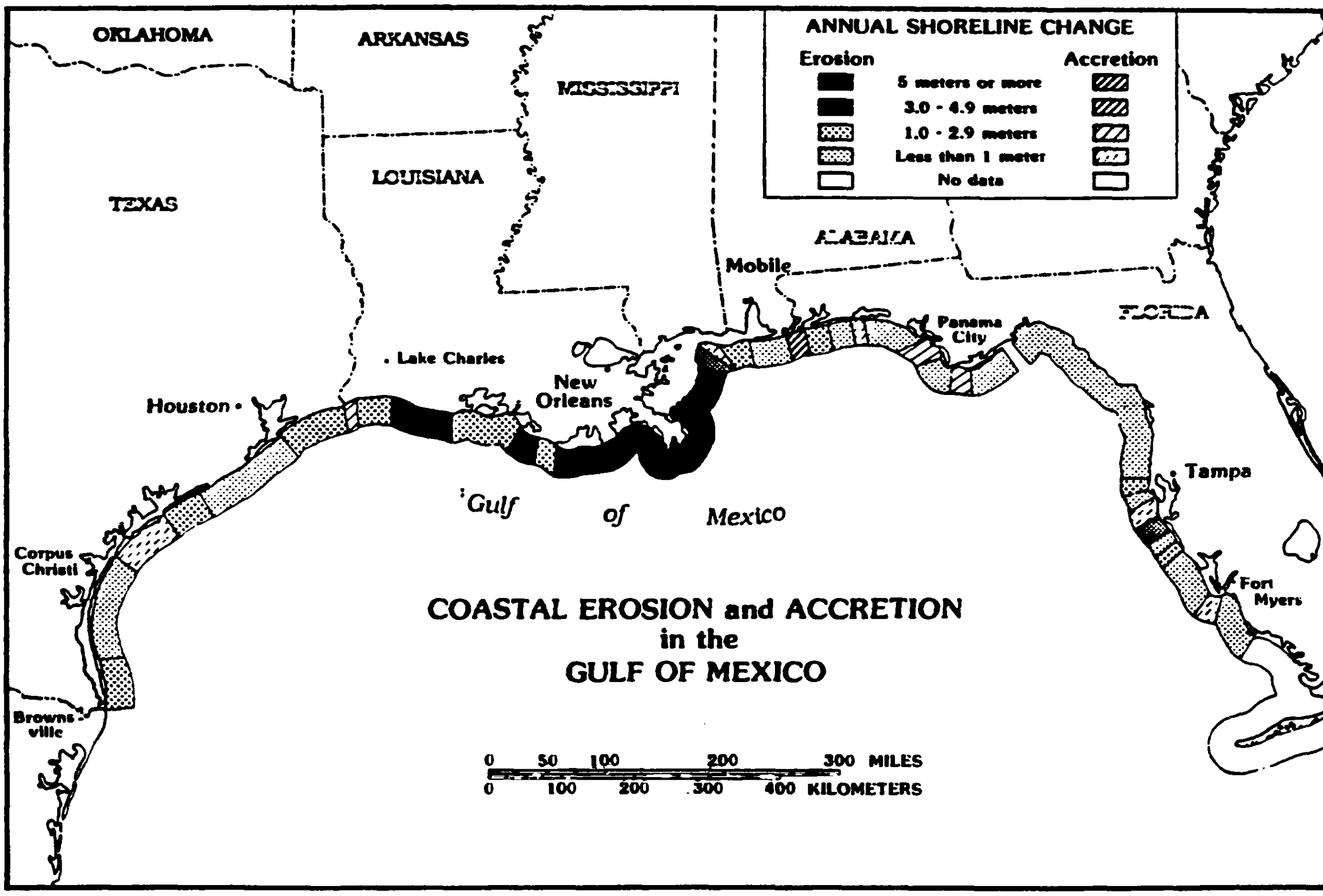

Figure 4. The distribution of coastal erosion in the Gulf of Mexico (U.S. Geological Survey 1988).

Table 3. Rate of Shoreline Change for U.S. Coastal States and Regions[1].

Region	Mean, m/yr[2, 3]	Standard Deviation	Total Range	N[4]
Atlantic Coast	–0.8	3.2	25.5/24.6	510
Maine	–0.4	0.6	1.9/–0.5	16
New Hampshire	–0.5	—	–0.5/–0.5	4
Massachusetts	–0.9	1.9	4.5/–4.5	48
Rhode Island	–0.5	0.1	–0.3/–0.7	17
New York	0.1	3.2	18.8/–2.2	42
New Jersey	–1.0	5.4	25.5/–15.0	39
Delaware	0.1	2.4	5.0/–2.3	7
Maryland	–1.5	3.0	1.3/–8.8	9
Virginia	–4.2	5.5	0.9/–24.6	34
North Carolina	–0.6	2.1	9.4/–6.0	101
South Carolina	–2.0	3.8	5.9/–17.7	57
Georgia	0.7	2.8	5.0/–4.0	31
Florida	–0.1	1.2	5.0/–2.9	105

Table 3. Continued

Region	Mean, m/yr[2, 3]	Standard Deviation	Total Range	N[4]
Gulf of Mexico	-1.8	2.7	8.8/-15.3	358
Florida	-0.4	1.6	8.8/-4.5	118
Alabama	-1.1	0.6	0.8/-3.1	16
Mississippi	-0.6	2.0	0.6/-6.4	12
Louisiana	-4.2	3.3	3.4/-15.3	106
Texas	-1.2	1.4	0.8/-5.0	106
Pacific Coast	-0.0	1.5	10.0/-5.0	305
California	-0.1	1.3	10.0/-4.2	164
Oregon	-0.1	1.3	5.0/-5.0	86
Washington	-0.5	2.2	5.0/-3.9	46
Alaska	-2.4	2.0	2.9/-6.0	69

[1] U.S. Geological Survey, 1988.
[2] Negative values indicate erosion; positive values indicate accretion.
[3] Meter = 0.3048 ft.
[4] Total number of 3-min grid cells over which the statistics are calculated.

The barrier shoreline system, with the highest rate of coastal erosion in Louisiana is the Isles Dernieres located in Terrebonne Parish (Penland and Boyd 1981; McBride et al., 1989). From 1890 to 1988, the Isles Dernieres shoreline experienced an average of 1644 m of beach erosion at a rate of -12.2 m/yr (Figure 5). The greatest amount of beach erosion was measured in the central barrier island arc at Whiskey Island where a total of 2573 m of beach retreat took place at an average rate of -19.1 m/yr. In 1890, the total area of the Isles Dernieres was measured at 3360 ha, and by 1988 the island area was measured at 771 ha, a total decrease of 2589 ha or 77% in area over 135 years, at a rate of 26.4 ha/yr. The first island in the Isles Dernieres barrier island arc forecasted to be destroyed by coastal erosion is East Island in 1998 and the last is Trinity Island by 2007. Of immediate threat to Louisiana, particularly Terrebonne and Lafourche parishes, is the predicted loss of the Isles Dernieres by the early 21st century. The destruction of the Isles Dernieres will dramatically impact the stability and quality of the Terrebonne Bay barrier-built estuary and the associated coastal wetlands.

Wetlands Loss

Louisiana contains at least 40% of the United States coastal wetlands and is suffering 80% of the wetland loss (Figure 6). Nationwide, outside of Alaska, Hawaii, and the Great Lake regions, coastal marshes occupy an area of 46,971,000 ha, most occur in the Gulf of Mexico and south Atlantic region of the United States (Table 4). The northern Gulf of Mexico contains 21,510,000 ha of coastal wetlands or 45.8% of our nation's total (Alexander et al., 1986; Reyer et al., 1988). The Atlantic coast accounts of 24,773,000 ha or 52.7%, and while only 1.5% or 688,000 ha are located along the Pacific coast, Louisiana's 11,928,000 ha of coastal wetlands is equivalent to 48% of all the coastal wetland found in the 14 U.S. Atlantic states. Within the northern Gulf of Mexico, Louisiana contains 55.5% of the coastal wetlands occurring there, or 11,928,000 ha out of a total of 21,510,000 ha. Within Louisiana, the Mississippi River delta plain contains 995,694 ha of salt marsh, fresh marsh, and swamp representing 74% of the state's coastal wetlands (Table 5). To the west, the chenier plain contains 347,593 ha of coastal wetlands, accounting for the remaining 26%. Cameron Parish on the chenier plain, encompasses the largest expanse of salt and fresh marsh by a single parish, a total of 302,033 ha. On the delta plain, the 233,711 ha within Terrebonne Parish is the region's largest expanse of coastal wetlands, followed by Plaquemines Parish at 167,980 ha, Lafourche Parish at 118,224 ha and St. Bernard at 104,906 ha. Louisiana's wetland parishes constitute the single largest concentration of coastal marshes in the contiguous United States.

Table 4. Distribution of Coastal Wetlands in the United States[1]

Region and State	Wetland Area in Hectares[2, 3]				Total
	Salt March	Fresh Marsh	Tidal Flats	Swamp	
Northeast					
Maine	69	107	343	104	521
New Hampshire	39	0	N/A	N/A	31
Massachusetts	200	63	172	103	538

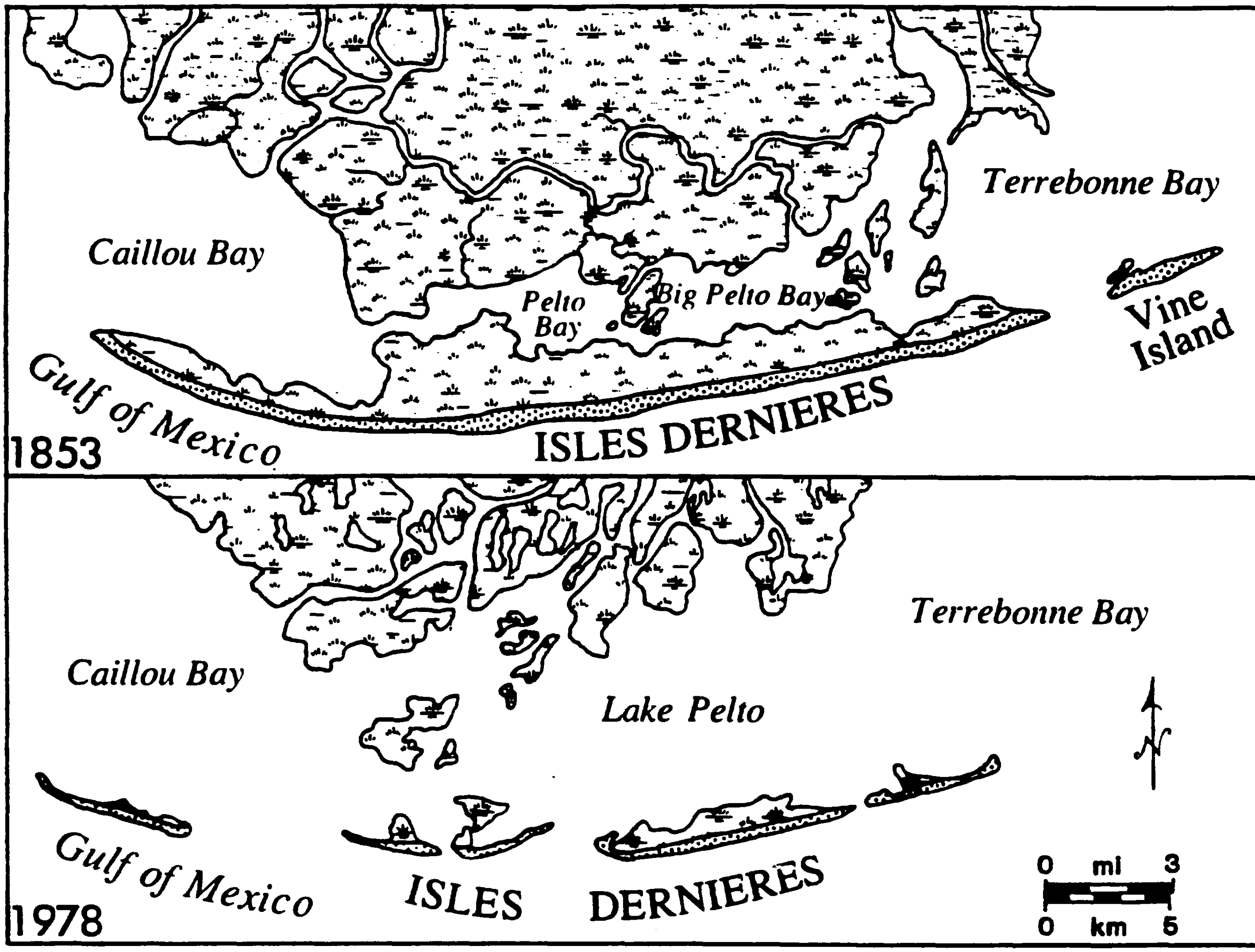

Figure 5. Coastal erosion in the Isles Dernieres between 1853 and 1978 (Penland et al. 1981).

Table 4. Continued

Region and State	Wetland Area in Hectares[2, 3]				Total
	Salt March	Fresh Marsh	Tidal Flats	Swamp	
Rhode Island	33	N/A	N/A	237	270
Connecticut	69	N/A	N/A	N/A	69
New York	111	14	N/A	N/A	125
Pennsylvania	N/A	3	N/A	N/A	3
New Jersey	902	90	202	1,960	3,154
Delaware	324	29	47	512	912
Maryland	679	107	7	80	873
Virginia	632	83	N/A	N/A	715
Subtotal	3,049	496	670	2,996	7,211
Southeast					
North Carolina	659	381	N/A	8,745	9,788
South Carolina	1,533	268	N/A	N/A	1,801
Georgia	1,553	131	39	1,187	2,910
Florida (Atl)	398	1,591	N/A	1,075	3,063
Subtotal	4,143	2,371	39	11,006	17,562

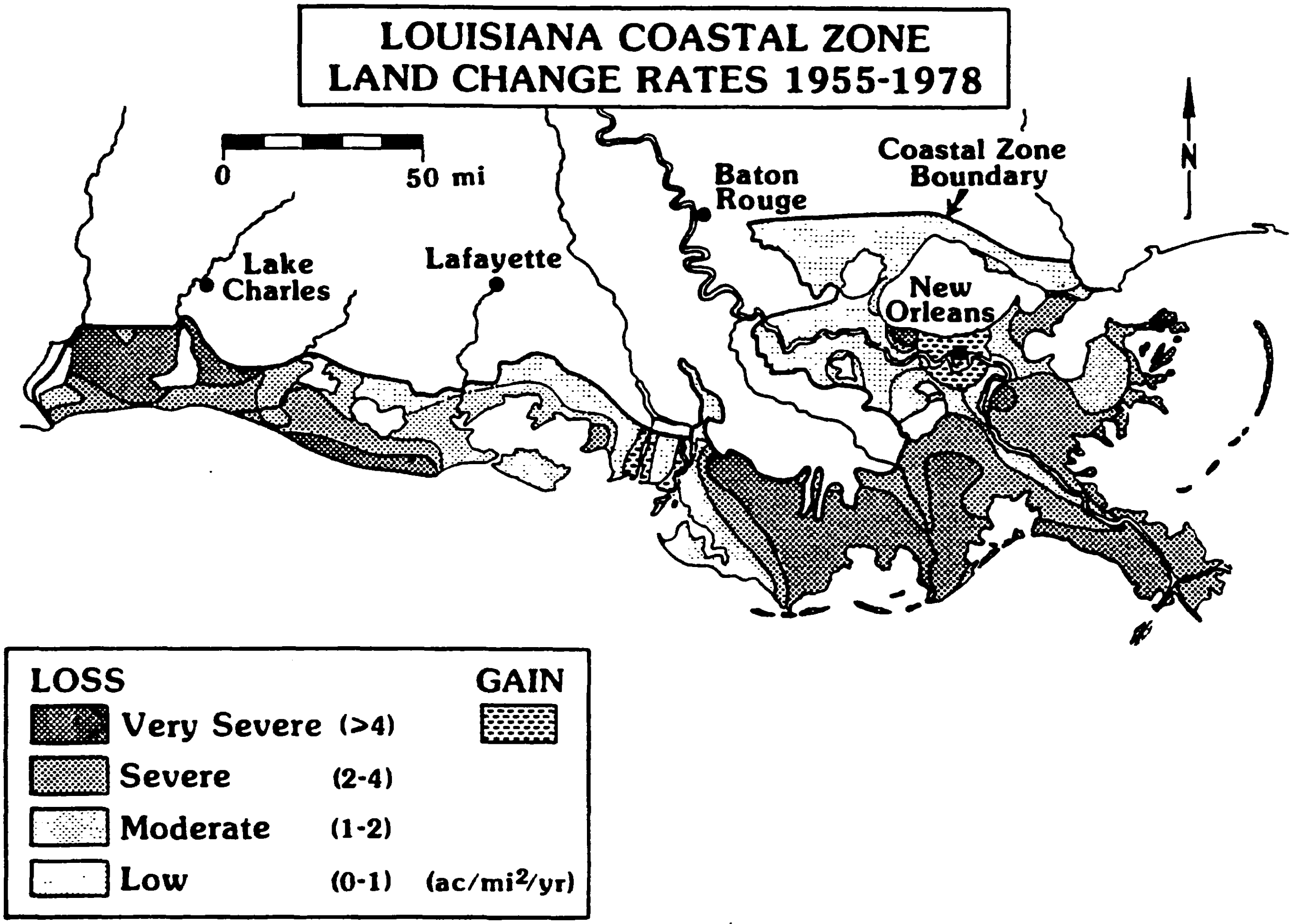

Figure 6. The distribution of coastal land loss in Louisiana (van Beeck and Meyer-Arendt, 1982).

Table 4. Continued

Region and State	Wetland Area in Hectares[2,3] Salt March	Fresh Marsh	Tidal Flats	Swamp	Total
Gulf of Mexico					
Florida (Gulf)	1,790	321	N/A	4,028	6,139
Alabama	61	44	N/A	628	732
Mississippi	266	17	N/A	315	598
Louisiana	7,256	2,858	N/A	1,814	11,928
Texas	1,620	327	N/A	167	2,114
Subtotal	10,991	3,567	N/A	6,952	21,510
West Coast					
California	90	18	56	14	178
Oregon	78	3	3	N/A	209
Washington	98	74	9	121	302
Subtotal	266	118	169	135	688
Total	18,449	6,551	879	21,087	46,971
(% of Total)	(39)	(14)	(2)	(45)	(100)

[1] Alexander et al., 1986
[2] Hectare = 2.4 acres
[3] x 1000
N/A = Not Available

Table 5. Distribution of U.S. Coastal Wetlands in the Gulf of Mexico[1]

Region and State	County	Westland Area in Hectares[2]				Total
		Salt March	Fresh Marsh	Flats	Swamp	
Gulf of Mexico						
Florida (GOM)	Bay	3092	383	—	20,023	23,506
	Charlotte	5,685	—	—	7,889	13,574
	Citrus	14,319	—	—	7,192	21,511
	Collier	19,501	—	—	38,282	57,784
	Dixie	10,996	—	—	19,115	30,112
	Escambia	1,271	—	—	6,202	7,473
	Franklin	9,420	1,073	—	67,615	78,276
	Gulf	296	3,071	—	55,380	58,747
	Hernando	5,266		—	11,289	16,555
	Hillsborough	1,145	269	—	4,315	5,729
	Jefferson	2,132	—	—	8,149	10,281
	Lee	6,636	—	—	20,174	26,810
	Levy	18,323	99	—	6,136	24,558
	Manatee	505	129	—	2,786	3,420
	Monroe	74,551	30,349	—	103,721	208,621
	Okaloos	305	—	—	12,554	12,859
	Pasco	1,731	—	—	1,554	3,285
	Pinellas	—	—	—	2,792	2,792
	Santa Rosa	3,711	21	—	18,574	22,306
	Sarasota	418	—	—	438	857
	Taylor	11,176	—	—	21,490	32,666
	Wakulla	9,157	834	—	3,986	13,977
	Walton	1,716	—	—	13,921	15,637
Total Florida (GOM)		201,526	36,227	0	453,593	691,346
Alabama	Baldwin	1,847	3,299	—	49,023	45,555
	Mobile	4,993	1,650	—	21,675	36,931
Total Alabama		6,840	4,948	0	24,532	82,487
Mississippi	Hancock	10,280	701	—	8,411	19,392
	Harrison	3,738	234	—	2,570	6,542
	Jackson	15,882	935	—	24,532	41,355
Total Mississippi		29,907	1,869	0	35,514	67289
Louisiana	Assumption					
	Cameron	169,689	132,848	—	96	302,033
	Iberia	43,224	4,907	—	2,570	50,700
	Jefferson	32,944	8,645	—	13,317	54,906
	Lafourche	99,299	10,981	—	7,943	118,224
	Livingston	—	—	700	700	—
	Orleans	20,093	701	—	3,738	24,532
	Plaquemines	135,047	21,262	—	11,682	167,980

Table 5. Continued

Region and State	County	Westland Area in Hectares[2]				Total
		Salt March	Fresh Marsh	Flats	Swamp	
	St. Bernard	100,234	—	—	4,672	104,906
	St. Charles	9,346	7,944	—	7,469	25,700
	St. James	17,842	20,093	—	—	—
	St. John the Baptist	3,037	2,103	—	26,349	34,813
	St. Mary	9,112	45,093	—	37,759	96,728
	St. Tammany	14,953	6,308	—	9,579	30,841
	Tangipahoa	—	5,841	—	25,700	31,542
	Terrebonne	139,720	73,131	—	20,560	233,711
	Vermilion	40,421	2,103	—	3,037	45,560
Total Louisiana		817,119	321,866	0	204,301	1,343,287
Texas	Aransas	4,187	2,093	—	—	6,280
	Brazoria	19,738	2,692	—	1,495	23,925
	Calhoun	10,766	7,645	—	—	17,943
	Chambers	29,009	—	—	—	29,308
	Galveston	20,636	—	—	—	20,635
	Harris	897	299	—	5,383	6,579
	Jackson	1,495	1,495	—	—	2,990
	Jefferson	63,102	5,084	—	1,794	69,981
	Kleberg	—	5,383	—	—	5,383
	Matagorda	15,252	1,196	—	897	17,345
	Nueces	—	1,196	—	—	1,196
	Orange	11,962	4,186	—	8,373	24,523
	Refugio	1,794	1,794	—	—	3,588
	San Patricio	2,390	2,990	—	598	5,682
	Victoria	797	1,196	—	—	2,691
Total Texas		182,429	36,785	0	18,799	238,056
Total Gulf of Mexico		1,237,821	401,695	0	782,950	2,422,467

[1] Alexander et al., 1986
[2] Hectare = 2.41 acres

The current coastal land loss rate estimate is in excess of 12,000 ha/yr for the Mississippi River delta and chenier plains in south Louisiana (Figure 6). Of this total, 80% of the loss occurs in the delta plain and 20% in the chenier plain (Gosselink et al., 1979; Gagliano et al., 1981). Previous studies indicate that the rate of coastal land loss has accelerated over the last 75 years. Rates of loss within the delta plain alone have accelerated from 1735 ha/yr in 1913, 4092 ha/yr in 1946, to 7278 ha/yr in 1967 followed by 10,205 ha/yr in 1980 (Figure 7). Forecasts were made that Lafourche Parish would be destroyed in 205 years, St. Bernard Parish in 152 years, Terrebonne Parish in 102 years, and Plaquemines Parish in 52 years from 1978 due to accelerating coastal land loss conditions (Gagliano et al., 1981).

New research results indicate coastal land loss persists at levels below those measured in the 1970s and below the rates predicted to accelerate into the future. Britsch and Kemp (1990) conducted a mapping study of coastal land loss using 50 15′ USGS topographic quadrangle maps from the Mississippi River delta plain. Coastal land loss rate curves were developed for each quadrangle and the delta plain. The 1932-33 U.S. Coast and Geodetic Survey T-Sheets served as the base for aerial photography interpreted for the years 1956-58, 1974 and 1983. The results showed coastal land loss rates increased after the 1930s from 3339 ha/yr (12.89 mi^2/yr) in 1956-58 to 7257 ha/yr (28.01 mi^2/yr) in 1974. After 1974, the coastal land loss rates decreased to 5949 ha/yr (22.97 mi^2/yr) in 1983 (Figure 8). The numbers compared well with those measured by Gagliano et al. (1981) through 1967; however, the maximum rate of land loss mapped in 1978 exceeded the maximum rate mapped by Britsch and Kemp (1990) for 1974. The Britsch and Kemp (1990) study again substantiated the catastrophic nature of the coastal land loss problem in Louisiana.

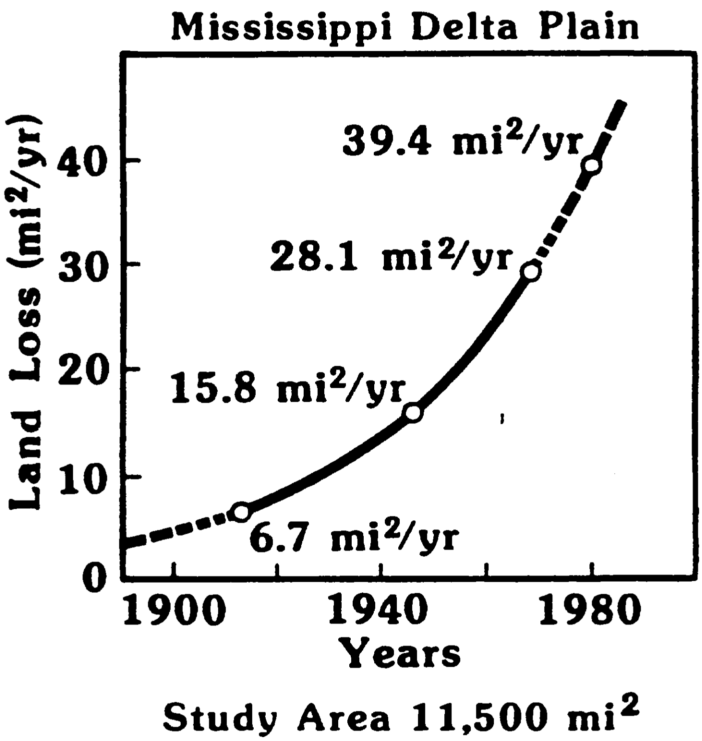

Figure 7. Coastal land loss curve for the Mississippi River delta plain by Gagliano et al. (1981).

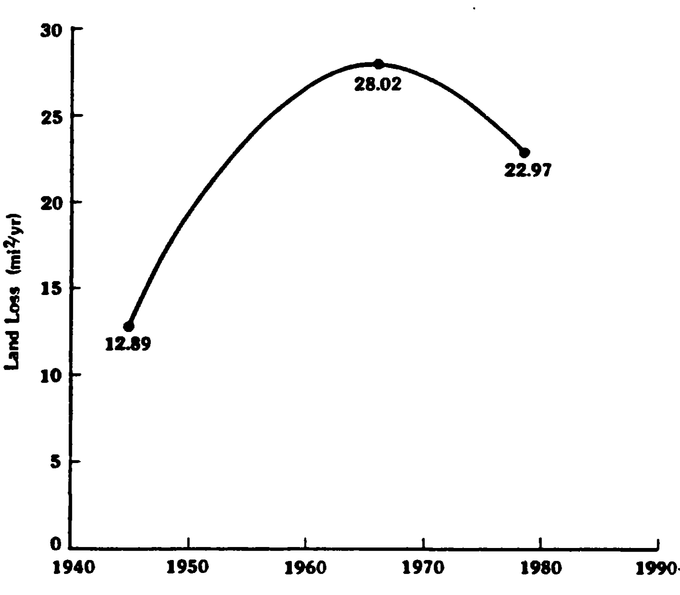

Figure 8. Coastal land loss curve for the Mississippi River delta plain by Britsch and Kemp, (1990).

COASTAL LAND LOSS PROCESSES

Researchers have long recognized the catastrophic coastal land loss conditions in Louisiana, measured the rate, and speculated on the causes (Gosselink et al., 1979; Craig et al., 1980; Wicker 1980; Gagliano et al., 1981; Scaife et al., 1983; David, 1986; Coleman et al., 1986; Walker et al., 1987; Coleman and Roberts, 1989). In the process of trying to understand the mechanism of coastal land loss, much emphasis has been placed on identifying and ranking the causative factors driving change. It is important to be able to understand the processes driving coastal land loss in order to design effective management and restoration systems. It is also important to understand the spatial distribution of land loss and the contribution of each loss type to the total loss occurring in coastal Louisiana in order to formulate an efficient environmental strategy to address the problem.

Numerous causes, both natural and human-induced have been identified for the death of marsh vegetation and subsequent deterioration of expansive tracts of interdistributary wetlands in Louisiana (Turner and Cahoon, 1987). Some of the causes are related to biological activity such as animal eat-outs. But most of the causes are related to hydrologic and/or sedimentologic imbalances brought about by high rates of relative sea level rise (Penland and Ramsey, 1990), intrusion of salt water into areas of lower salinity (Wang, 1987), reduced sediment supply (Meade and Parker, 1985; Kesel, 1989), and man's modification of regional and local hydrology and sediment distribution for purposes of flood control, navigation, or mineral extraction (Swenson and Turner, 1987; Turner and Cahoon, 1987). Natural causes for these imbalances include stage in the delta cycle, compaction and differential subsidence, sea level changes, episodic catastrophic storm events, geosynclinal down warping, and long-term climate changes. Human-induced causes for these imbalances include elimination of annual spring floods by leveeing and damming distributaries for flood control, dredging of navigation and oil/gas canals, and sub-surface fluid withdrawal. The interaction of the many causes has led to the current high rates of inland marsh deterioration. Although we have identified these causes, we still lack an understanding of the processes behind these causes and how they interact. To what degree do human activities such as pipeline construction influence hydrologic and sediment imbalances and therefore marsh loss in interior marshes? Hence we are unable to quantify what percentage of the loss is attributable to most of these causes. Development of effective management policies and procedures will be hindered until we acquire such knowledge.

Over the last decade, two schools of thought have developed in the coastal research community concerning the relative roles of the causal factors driving the extreme rates of land loss and change. One school of thought emphasizes the natural processes of the delta cycle; coastal erosion, bay expansion, and subsidence are viewed as some of the primary factors controlling land loss and human activities are ranked as secondary in importance. In contrast, the other school of thought places primary importance on human activities such as flood structures and pipeline canals, while recognizing that the natural processes are also important. Today, the environmental groups in Louisiana are leading an ongoing campaign to identify the oil and gas industry as the primary coastal land loss culprit who should pay for the restoration of the Mississippi River delta plain. Many of the beliefs, perceptions, and concepts held by the scientific, industrial, and environmental communities are based on limited technical information, professional bias, statistical inference, and public misinformation. No study to date has successfully delineated and ranked the different contributions to the total amount of land loss that has occurred in Louisiana over the last five decades. Baumann et al. (1987) represents the first study to delineate and map the direct impact of pipeline canals. This study determined canals directly contributed 6% to the total amount of coastal land loss between 1954 and 1978, the remaining 94% is unknown. A review of previously coastal land loss research indicates the only way to accurately determine the relative roles of different types and processes of land loss is to develop a classification suitable for quantitative mapping the spatial distribution and contribution of each geomorphic loss type to the total amount of land loss in a given interval of time.

SUMMARY

Louisiana is experiencing catastrophic coastal land loss conditions due to the complex interaction of natural and human-induced causes. Controversy surrounds the issues of coastal land loss and coastal restoration. State- and federal-supported research on coastal land loss as well as our experience in Louisiana has documented that the most cost-effective methods for restoring Louisiana's coastal environments are ones that work with or enhance coastal geomorphological processes. Sediment and vegetation are the only tools that will be effective in restoring Louisiana's coastal zone. The protection and restoration of barrier islands, estuaries, and wetlands must be placed on the same priority as navigation and flood control in order to ensure the future of these important National coastal resources, the delta and chenier plains of the Mississippi River.

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Paper No. 140

Coastal land loss: using barrier island techniques in Louisiana to protect estuarine environments

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1.0 INTRODUCTION

Louisiana has the highest rates of coastal erosion and wetland loss in the United States (Figure 1). Rates of coastal land loss have been estimated to exceed 100 km^2/yr (39 mi^2) in the Mississippi River delta plain (Gagliano et al., 1981). The destruction of valuable estuarine environments by submergence of barrier islands, large bay system expansion, and acceleration of salt marsh deterioration has reached national importance, because it severely impacts the fur, fish, and waterfowl industries, valued at an estimated $1 billion per year (Chabreck, 1988; Turner and Cahoon, 1987).

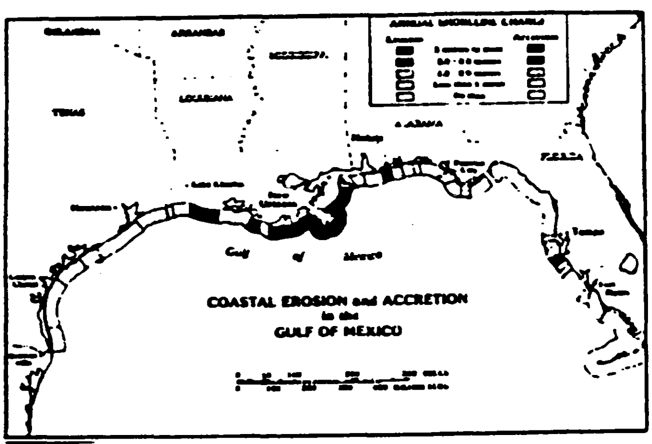

Figure 1. Annual shoreline change in Louisiana (after U.S. Geological Survey, 1989).

Louisiana barriers, which protect the extensive barrier-built estuarine system, decreased in area from 95.8 km^2 (37.36 mi^2) to 56.98 km^2 (22.22 mi^2) (41%) between 1853 and 1978 (Figure 2). Forecasts by the U.S. Environmental Protection Agency (Barth and Titus, 1984) and National Academy of Sciences (National Research Council, 1987) predict increasing rates of sea-level rise, accelerating coastal land loss and beach erosion in the future. Analysis of water stages from tidal stations in Louisiana and the Gulf of Mexico indicates that Louisiana already experiences the National Research Council (1987) predicted rates for the entire United States (Penland et al., 1989; Ramsey and Penland, 1989).

Current rates of barrier island erosion and wetland loss provide the only modern analog to these predicted conditions. Increasing rates of coastal land loss raise serious potential problems that require careful study and well-planned management techniques. Speculation and debate in the research, government, and environmental communities surrounds the issue of coastal land loss, and the strategy of coastal protection and restoration. This paper is designed to illustrate one of the more efficient techniques to protect valuable estuarine environments. Understanding the coastal geomorphological processes, both natural and human-induced, is the first essential step in evaluating the performance of various coastal protection methods currently envisioned or being employed (Penland and Suter, 1988).

2.0 COASTAL LAND LOSS

Previous studies show that coastal land loss has persisted and accelerated since the 1900s. The coastal land loss process can be subdivided into two processes: coastal erosion and wetland loss. Coastal erosion is the retreat

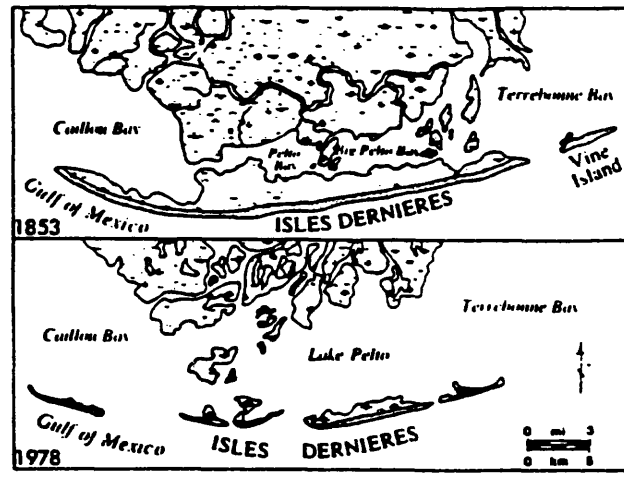

Figure 2. Shoreline changes from historical maps in the Isles Dernieres barrier island arc system between 1853 and 1978. Note the rapid land loss and retreat of the coastal zone. (Redrawn from Penland and Boyd 1981).

of the shoreline along the exposed coasts of large lakes, bays, and the Gulf of Mexico. In contrast, wetland loss is the development of ponds and lakes within the interior wetlands and the expansion of large coastal bays behind the barrier islands and mainland shoreline. The chronic problem of wetland loss in Louisiana is well-documented, but poorly understood (Craig et al., 1979; Gagliano et al., 1981).

2.1 Coastal Erosion

Coastal erosion rates in Louisiana average - 4.2 m/yr. This average represents only long-term conditions (exceeding 50 years), and is not representative of the individual storms that drive the long-term average. Coastal erosion is not a constant 365-day-a-year process. Impacts of major cold fronts, tropical storms, and hurricanes are associated with surges of erosion (Ritchie and Penland 1988). Field measurements have documented 20-30 m of coastal erosion during a storm lasting 3-4 days. This amount is equivalent to several years of erosion at the average rate (Dingler and Reiss, 1989). These major storms produce energetic overwash conditions which erode the beach and reduce the barrier landscape to lower-relief landforms.

2.2 Wetland Loss

Louisiana contains 40% of the coastal wetlands of the United States and 80% of its wetland loss. Nationwide (outside of Alaska, Hawaii, and the Great Lakes region) (Alexander, 1985), coastal marshes occupy 24,544 km^2 (9,440 mi^2). Most of which occur in the Gulf of Mexico and the south Atlantic region of the United States. Louisiana contains 9,880 km^2 (3,800 mi^2) of coastal wetlands -- an area equal to that found in the 14 Atlantic coast states, and 69% of the coastal wetlands occurring in the Gulf of Mexico region.

The current rate of coastal land loss is estimated about 100 km^2/yr for the Mississippi River delta and chenier plains in south Louisiana. Of this total, 80% of the loss occurs in the delta plain and 20% in the chenier plain. Previous studies show that the rate of coastal land loss has accelerated over the last 75 years. Gagliano et al. (1981) documented an increase in rates of coastal land loss in the Mississippi delta plain from 17.42 km^2/yr (6.7

mi²/yr) in 1913, 41.08 km^2/yr (15.8 mi^2/yr) in 1946, to 73.06 km^2/yr (28.1 mi^2/yr) in 1967 followed by 102.44 km^2 (39.4 mi^2) in 1980. If forecast rates prove correct, Lafourche Parish would be destroyed in 205 years, St. Bernard Parish in 152, Terrebonne parish in 102, and Plaquemines Parish 52 years from 1981.

Controversy surrounds the issue of whether Louisiana's coastal wetlands can be sustained into the next century if the current levels of land loss continue. Of immediate threat to Louisiana, particularly Terrebonne and Lafourche parishes, is the forecasted loss of the Isles Dernieres by the turn of the century, which will dramatically impact the stability and quality of the Terrebonne Bay barrier-built estuary and the vegetated wetlands of lower Terrebonne basin.

3.0 PROTECTION STRATEGY

3.1 Strategy

Barrier island erosion and land loss are primarily a function of sediment loss, relative sea-level rise, and devegetation. Human impacts are secondary, but they often drastically increase coastal deterioration. In Louisiana, two management options have been applied. One is to build coastal structures to combat natural processes and hold the remaining habitats in place; the other option is to replace the material lost from the barrier island system and hold it in place by planting dune and backbarrier marsh habitats. Of the two options, the latter has proven most cost-effective and capable of preserving and restoring Louisiana barrier shoreline habitats. As a consequence, any comprehensive plan to preserve Louisiana's barrier shorelines must pursue sediment and vegetation projects as well as mitigation projects to reverse human impacts. The tactics of this strategy should include beach nourishment, barrier restoration, shoreface nourishment, vegetation, and coastal structure modification. For this approach to be successful, a regularly scheduled maintenance program mush be developed for each barrier-built estuary.

3.2 Barrier Restoration

This is a new technique developed in Louisiana to restore transgressive barrier island habitats and prevent the island from breaching during storms. As described previously, Terrebonne Parish built a barrier island restoration pilot project in the eastern Isles Dernieres which restored the island (Jones and Edmonson, 1987). This technique involves placement of fill material directly on the crest and backbarrier areas. This requires less fill per linear foot of shoreline than a beach nourishment project. The restoration cost per linear foot was $263 ($801.62 per meter). This project restored the dunes, vegetated backbarrier terraces and salt marsh, and prevented the island from breaching during the 1985 hurricane impacts (Figure 3).

Figure 3. Oblique aerial photograph of the Terrebonne Parish - Eastern Isles Dernieres barrier island restoration project.

3.3. Beach Nourishment

Beach nourishment projects require large volumes of high quality sand for construction, resulting in reduced construction cost per meter of beach. The average per meter construction cost for the USACOE 1985 Grand Isle project was $710.18 ($233 per meter of beach; this is less than the cost of the Terrebonne Parish barrier island restoration project, which required 10 times less material. The average cost was $2.23 per m^3 (2.94 per yd^3) of fill. Nationwide, the typical cost of beach nourishment is $1.06 - 9.18 per m^3 ($1.40 - $12.08 per yd^3) of fill (National Research Council, 1987).

3.4 Shoreface Nourishment

Shoreface nourishment is a new technique which has been tested in Australia, Denmark, and at Hilton Head Island, South Carolina (Bruun, 1988a). This technique builds a beach-shore face profile in equilibrium with its process environment; as a consequence construction and maintenance costs are lower, and the rapid beach erosion that typically follows the construction of beach nourishment projects does not occur. The advantage of the shoreface nourishment technique is the ease of dumping and the minimal earth-moving equipment required. A cost comparison in Queensland, Australia (1986) indicated the average beach nourishment costs are $2.66 m^3 ($3.50 yd^3) for beach fill and $1.14 m^3 ($1.50 yd^3) for shoreface fill (Bruun, 1988b).

3.5. Vegetation

Building dunes and backbarrier habitats using vegetation on natural island surfaces or on dredged material is the most inexpensive method of protection (Mendelssohn, 1987). Vegetation programs cost significantly less than the various dredged material techniques. Furthermore, hurricane impact research has shown that dune and marsh vegetation are extremely effective at retarding coastal erosion. When vegetation is used in combination with nourishment or restoration projects, new and diverse barrier habitats can be built. The cost for a typical dune building project is $15-30 per meter ($5-10 per linear foot) of barrier island.

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Relative Sea-Level Rise in Louisiana and the Gulf of Mexico: 1908–1988

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ABSTRACT

PENLAND, S. and RAMSEY, K.E., 1990. Relative sea-level rise in Louisiana and the Gulf of Mexico: 1908–1988. *Journal of Coastal Research*, 6(2), 323–342. Fort Lauderdale (Florida). ISSN 0749-0208.

Louisiana is experiencing the most severe wetland loss and barrier island erosion in North America. Rates of land loss exceed 100 square kilometers per year in the Mississippi River delta and chenier plains. Rapid sea-level rise induced by delta-plain subsidence and a deficit of terrigenous wetland sediment are the primary factors driving the rapid deterioration of the Louisiana coastal zone.

Within the Mississippi River delta plain, the Houma tide gage documented a relative sea level rise rate of 1.09 cm/yr from 1946 to 1988, based on U.S. Army Corps of Engineers tide gauge records. On the coast, the Eugene Island tide gage documented a slightly higher relative sea level rise rate of 1.19 cm/yr. When other tide gages in Louisiana with 30-year records or more are compared to the record of the Houma tide gage station, relative sea level appears to rise faster in the Terrebonne Parish area than anywhere else in Louisiana. Representative water level histories from the Chenier plain, Teche basin, Terrebonne delta plain, Barataria basin, Balize delta plain, St. Bernard delta plain, and Pontchartrain basin indicate the regional rates of relative sea level rise decrease to the east and the west from the Terrebonne coastal area.

In comparison with other National Ocean Survey tide gage records throughout the U.S. Gulf Coast, Louisiana is experiencing the highest relative sea level rise rate at 1.04 cm/yr for Grand Isle, the rates decrease from 0.63 cm/yr at Galveston, Texas to 0.15 cm/yr at Biloxi, Mississippi. Mean relative sea-level rise in Louisiana is more than five times the Gulf of Mexico average. A comparison of the Grand Island relative sea level rise rate (1.04 cm/yr) with the global relative sea level rise rate (0.12 cm/yr) indicates that, on the average, relative sea level is rising 10 times faster in Louisiana than in the much of the rest of the world.

The rapid rate of relative sea level rise observed in Louisiana can be attributed to subsidence of the Mississippi River delta plain due to sediment compaction. Louisiana directly overlies the entrenched Pleistocene valley of the Mississippi River, which is filled with Holocene deltaic sediments more than 150 m thick.

ADDITIONAL INDEX WORDS: *Sea-level rise, tide gauge, coastal zone, land loss, coastal erosion, Louisiana, Gulf of Mexico.*

INTRODUCTION

Louisiana is faced with a catastrophic land loss problem, a rapid rise in relative sea level is one of the primary processes driving barrier island erosion, the loss of valuable marshes, and the potential destruction of a vast estuarine resource base. Louisiana contains 40% of this nation's coastal wetlands and 80% of the coastal wetland erosion is occurring here. In order to understand the rate and magnitude of relative sea level rise, two tide gauge networks in Louisiana and the northern Gulf of Mexico were analyzed to determine temporal and spatial trends of relative change. The U.S. Army Corps of Engineers (USACE) maintains a network of 83 tide gauge stations throughout coastal Louisiana, which were used to determine the local and regional character of relative sea level rise in Louisiana. The National Ocean Survey (NOS) maintains nine tide gauge stations throughout the northern Gulf of Mexico in Texas, Louisiana, Mississippi, Alabama, and Florida and these were used to determine the character of relative sea level rise throughout the region (LYLES *et al.*, 1987).

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Coastal Erosion in Louisiana

Louisiana is experiencing the most severe land loss and barrier island erosion in North America (Figures 1, 2). Land loss rates in the

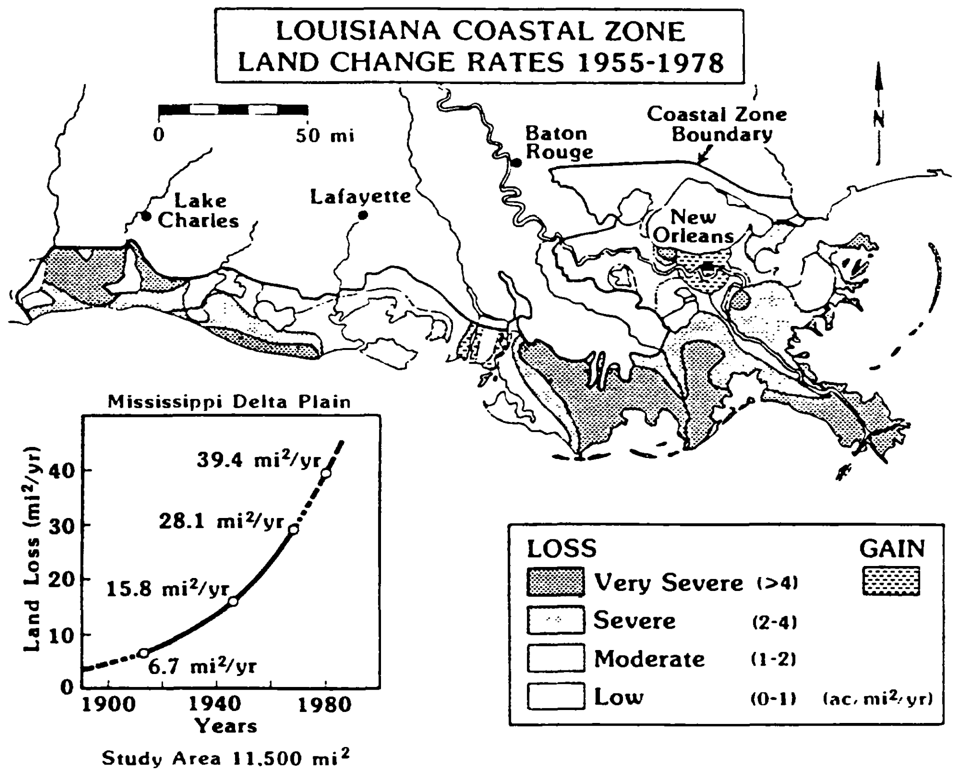


Figure 1. Diagram illustrates the pattern of coastal land loss in Louisiana (van Beek and Meyer-Arendt, 1982).

Mississippi River delta plain exceed 102 square kilometers per year (GAGLIANO *et al.*, 1981). Louisiana experienced a decrease in total barrier island area of about 37%, from 92.4 km^2/yr to 57.8 km^2, between 1880 and 1979 (PENLAND and BOYD, 1981). Current predictions based on a land loss rate of 27.7 km^2/yr indicate that Terrebonne Parish will be converted into open water within 102 years (GAGLIANO *et al.*, 1981). Between 1887 and 1979, the Terrebonne Parish barrier islands decreased in area from 48.3 km^2 to 18.3 km^2 (PENLAND and BOYD, 1981). At a loss rate of 0.326 km^2/yr, these islands will be converted to submerged sand shoals in 56 years. Rapid relative sea level rise induced by delta-plain subsidence and a deficit of terrigenous wetland sedimentation are the primary factors driving the rapid deterioration of the Louisiana coastal zone.

Previous Sea-Level Rise Studies

Previous investigations have documented that the analysis of tide gauge records is a valid technique for measuring relative sea level rise in Louisiana and the Gulf region (GORNITZ *et al.*, 1982; HICKS *et al.*, 1983; MARMER 1954; PIRAZZOLI 1986; GORNITZ and LEBEDEFF 1987; HICKS and HICKMAN 1988; PENLAND *et al.*, 1988a). An early comparison of relative sea level rise rates for Louisiana revealed rates as high as 4.3 cm/yr (SWANSON and THURLOW 1973). That study used 11 years (1959–1970) of tide gauge records from the Mississippi River delta plain. A comparison of the SWANSON and THURLOW (1973) data set with other, more recent data sets (BOESCH *et al.*, 1983; BYRNE *et al.*, 1976, 1977; DELAUNE *et al.*, 1985; PENLAND *et al.*, 1988a; PIRAZZOLI 1986) suggests that the 4.3 cm/yr rate of relative sea level rise is anomalous because the short period of record (1959 to 1970). Typically, the longer the period of record for a tide gauge station, the lower the rate of relative sea level rise calculated from the data. HICKS (1968) suggests that the period of record should exceed two lunar nodal tide cycles to yield accurate results. A nodal tide cycle is the 18.6-year period that it takes for the moon to complete its nodal cycle. Using tide gauge records of 20-year

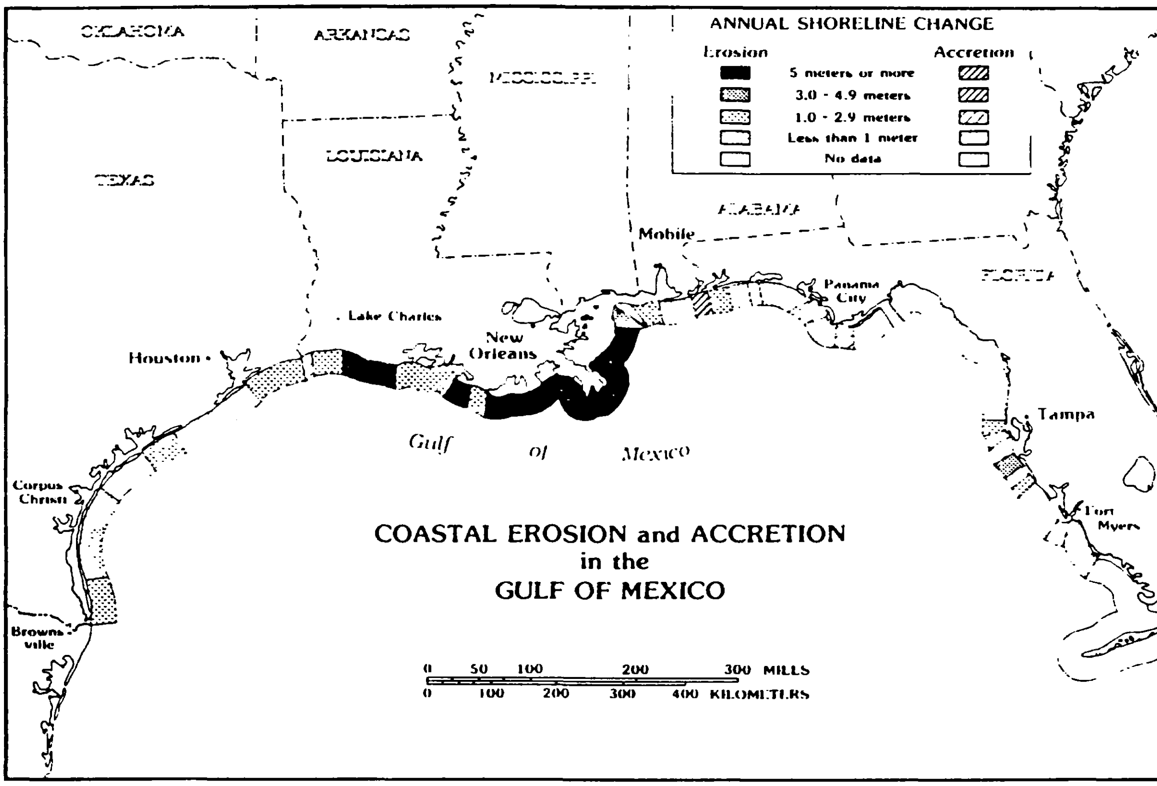


Figure 2. Annual shoreline change rates in the northern Gulf of Mexico (after U.S. Geological Survey 1989).

periods or more accounts for any water level variations resulting from this astronomical phenomenon as well as nontidal effects such as wind, direct atmospheric pressure, river discharge, currents, water temperature, and salinity (HICKS 1968).

TIDE GAUGE DATA ANALYSIS

Database and Analysis

Two tide gauge networks exist in the Gulf of Mexico region. Both of these were analyzed to determine the rates of relative sea level rise affecting Louisiana (Figure 3). The USACE has maintained tide gauges in Louisiana since 1933, when it established the first station at Morgan City on the Intracoastal Waterway. Today, the USACE maintains 83 tide gauges in coastal Louisiana; however, only 20 of these have records that exceed two lunar node tidal cycles. The oldest NOS tide gauge station in Louisiana is the Eugene Island station, which was established in 1939. The other NOS station in Louisiana is at Grand Isle. The oldest NOS tide gauge station in the Gulf of Mexico is located at Galveston, TX and was established in 1908. The NOS network provides a comparative data set for the U.S. Gulf coast while the USACE network provides readings only for Louisiana.

The NOS tide gauge stations at Grand Isle and Eugene Island are considered to have the best resolution of all Louisiana stations. These tide gauges record water levels every six minutes, 24 hours a day at locations with direct tidal exchange with the Gulf of Mexico. The Eugene Island station has a period of record from 1939 to 1974. In 1974 NOS stopped maintaining the station and the USACE began keeping the records. The Grand Isle station at Bayou Rigaud has 40 years of records (1947–1987). NOS maintains this station and sends the 8:00 a.m. readings to the USACE for their records. The NOS provided summaries of daily mean, high and low water levels at each station (HICKS *et al.*, 1983). These data were averaged

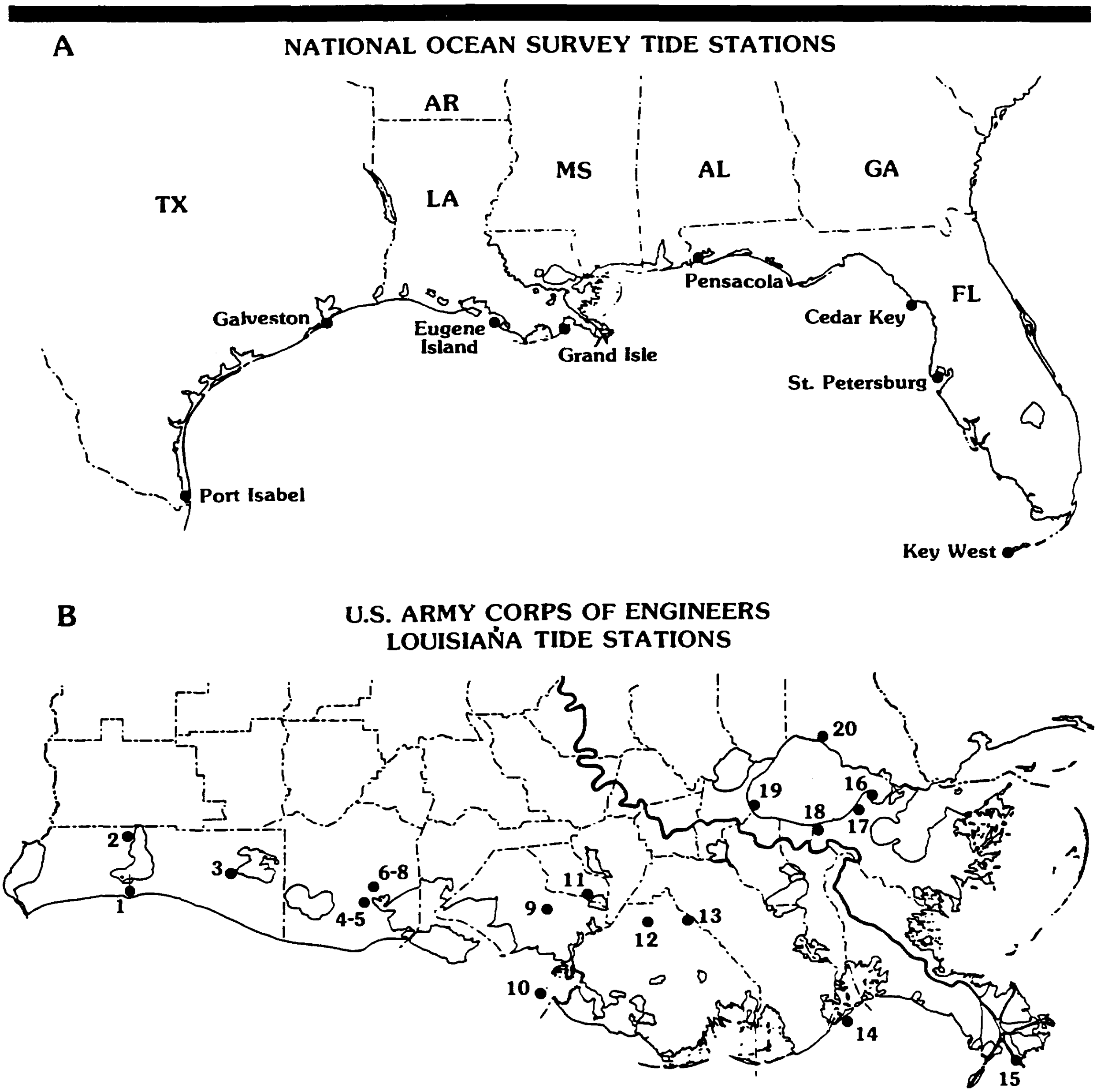


Figure 3. (A) Location of the National Ocean Survey tide gage stations in the Gulf of Mexico (Lyles *et al.*, 1987). (B) Location of the U.S. Army Corps of Engineers tide gauge stations in Louisiana (U.S. Army Corps of Engineers, 1931–1988).

into monthly summaries of mean monthly and annual water levels. For each station, a time-series plot of annual water levels was constructed. A linear regression was performed on the complete data set in order to produce a best-fit straight line with a slope equal to the rate of relative sea-level rise. In this way, a relative sea-level rise rate based on the entire record was obtained. The maintenance history for each station was reviewed to remove any errors in the data that may have resulted from re-positioning or damage to the station. This same procedure was performed for the NOS tide gauge stations in Texas, Mississippi, and Florida. The tide gauge stations with sufficient record included Port Isabel and Galveston in Texas and Pensacola, Cedar Key, St. Petersburg, and Key West in Florida. USACE maintains a station in Biloxi, Mississippi which was used with the NOS stations to complete the comparison in the Gulf of Mexico.

Data from 20 U.S. Army Corps of Engineers tide gauge stations in the Louisiana coastal region were analyzed for this study. Daily USACE water level measurements were averaged and summarized in mean monthly and mean annual tables. The mean annual water-level history was then plotted against time. A linear regression was performed to produce a best-fit straight line with a slope equal to the rate of change in sea-level. This analysis was performed for the entire record. The maintenance record for each tide gauge was examined to identify errors in the data set. The USACE stations were grouped into seven geomorphic regions: (1) the Chenier plain, (2) the Teche basin, (3) the Terrebonne delta plain, (4) the Barataria Basin, (5) the Balize delta, (6) the St. Bernard delta plain, and (7) the Pontchartrain Basin (Figure 4).

NOS Tide Gauge Results—Gulf of Mexico

Louisiana. The Eugene Island station lies on the Point au Fer shell reef system 8 km south of the prograding Atchafalaya River delta (Figure 3A). This station has a good maintenance record, but recently has become more and more affected by Atchafalaya River flooding, notably the spring floods of 1972 and 1973. An analysis of the entire record (1939–1974) indicates a relative sea-level rise rate at Eugene Island of 1.19 cm/yr (Table 1). The Bayou Rigaud tide gauge station at Grand Isle lies behind the barrier island on the Exxon Dock adjacent to Barataria Pass (Figure 3A). After the Bayou Rigaud station was destroyed, NOS established a new station at the U.S. Coast Guard station and renamed it East Point. The records show that, between 1947 and 1987, relative sea-level rose steadily at a rate of 1.04 cm/yr (Table 1, Figure 5). The water-level time series appears to have been contaminated very little by Mississippi River flooding.

Texas. The Galveston tide gauge station is located at the east end of Galveston Island on the Texas coast (Figure 3A). This site is connected to the Gulf of Mexico by the Houston Ship Channel. The period of record ran from 1908 to 1986 and the rate of relative sea-level rise was analyzed to be 0.63 cm/yr (Table 1, Figure 6).

The Port Isabel tide gauge station lies on the mainland shoreline of Laguana Madre at the south end of Padre Island (Figure 3A). Relative sea-level rise was 0.31 cm/yr between 1944 and 1986 (Table 1, Figure 6).

Florida. The Pensacola tide gauge station

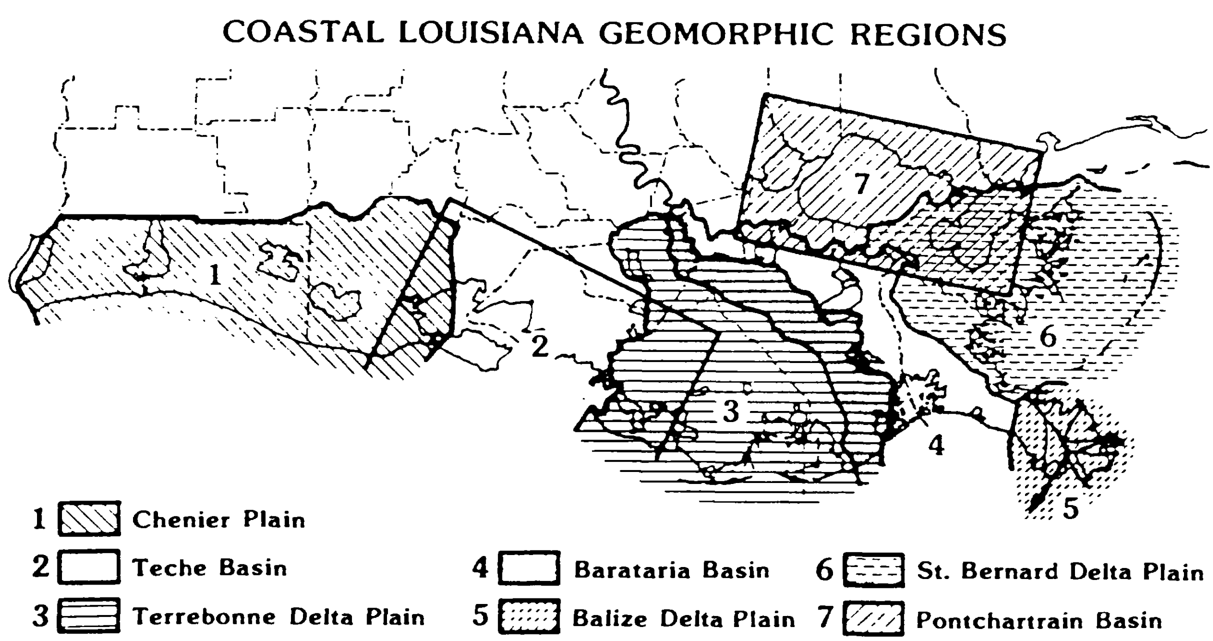


Figure 4. Geomorphic regions in coastal Louisiana.

Table 1. *National Ocean Survey (NOS), Gulf of Mexico Tide Gage Stations.*

Station Name	Station Location	Record Period	RSL (cm/yr)
Eugene Island	Louisiana	1934–1974	1.19
Grand Isle	Louisiana	1947–1987	1.04
Galveston	Texas	1908–1988	0.63
Port Isabel	Texas	1944–1979	0.31
Pensacola	Florida	1923–1988	0.23
Cedar Key	Florida	1914–1986	0.17
St. Petersburg	Florida	1947–1986	0.24
Key West	Florida	1913–1986	0.22

lies on the mainland shoreline of Escambia Bay near the west end of Santa Rosa Island (Figure 3A). The station is connected to the Gulf of Mexico by Perdido Pass. An analysis of the entire period of record, 1923 to 1986, reveals a rate of relative sea-level rise of 0.23 cm/yr (Table 1, Figure 7).

The Key West tide gauge station lies at the extreme western end of the Florida Keys in the southeastern Gulf of Mexico (Figure 3A). The relative sea-level rise rate for the period of record, 1913 to 1986, was calculated to be 0.22 cm/yr (Table 1, Figure 7).

The St. Petersburg tide gauge station is on the western shore of Tampa Bay and the locale is connected to the Gulf of Mexico by a series of tidal inlets along the Tampa Bay barrier shoreline (Figure 3A). Its period of record runs from 1947 to 1986 and yielded a relative sea-level rise rate of 0.24 cm/yr (Table 1, Figure 8).

The Cedar Key tide gauge station lies on a

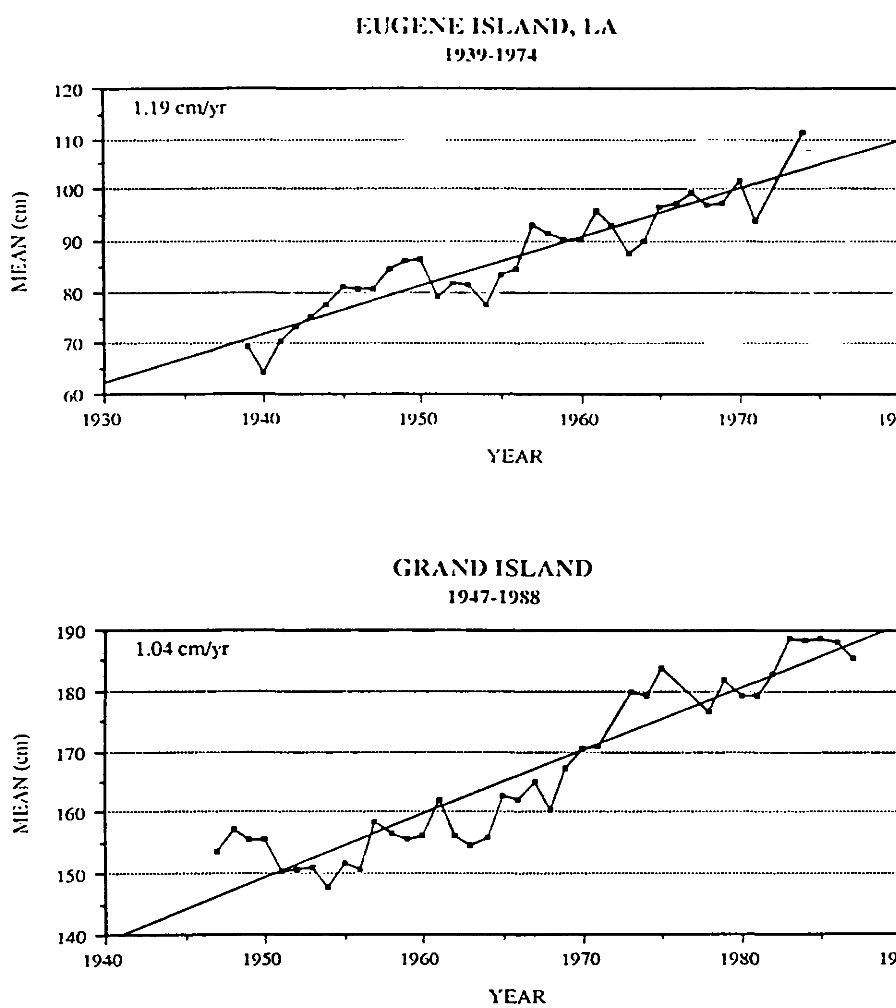


Figure 5. Water level time-series for the NOS Louisiana tide gauge stations.

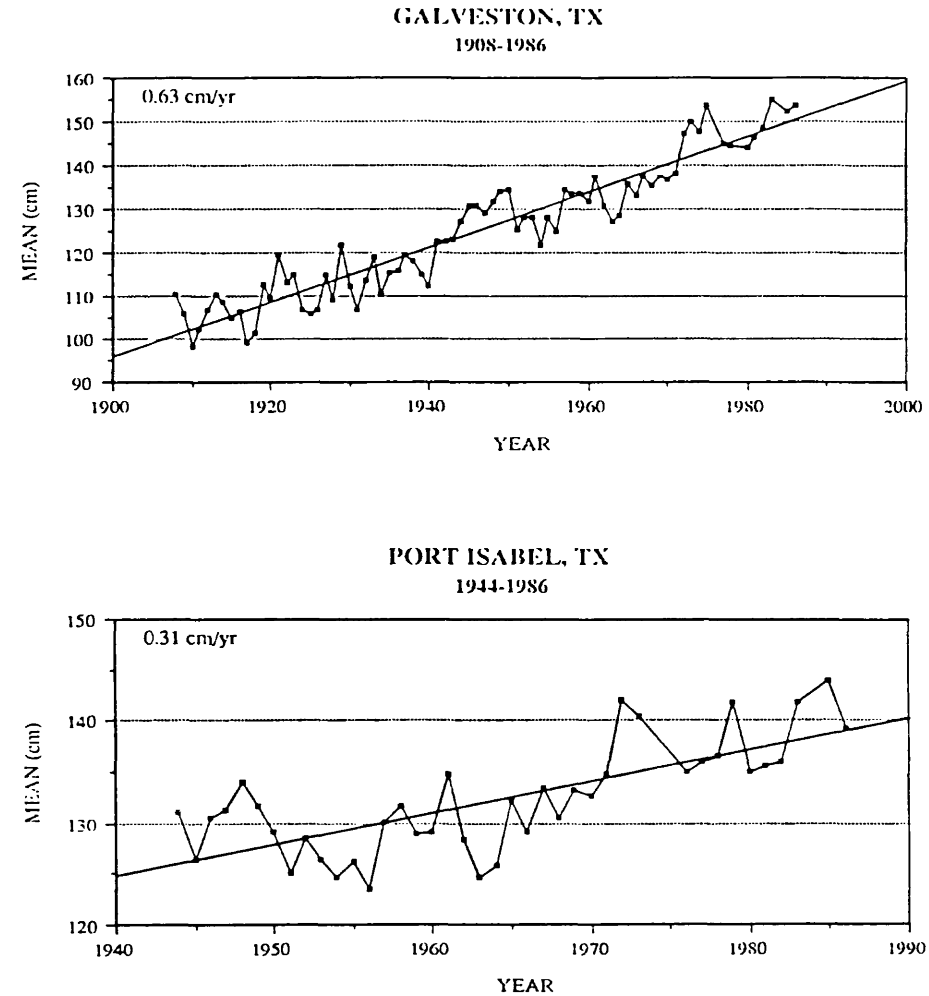


Figure 6. Water level time-series for the NOS Texas tide gauge stations.

coastal island between Suwannee Sound and Waccassa Bay in the Big Bend region of Florida (Figure 3A), directly on the Gulf of Mexico. A relative sea-level rise rate of 0.17 cm/yr was calculated for the period of record 1914 to 1986 (Table 1, Figure 8).

USACE Tide Gauge Results—Louisiana

Chenier Plain. The Chenier Plain in western Louisiana is a marginal delta plain composed of a series of transgressive shell or sand ridges separated by regressive mud flats (Figure 4). The Chenier Plain is about 2,500 years old (GOULD and McFARLAN 1959; PENLAND and SUTER, 1990). It began prograding seaward when sea-level rise slowed at the approximate end of the Wisconsinan glacial period. This coastal deposit pinches out landward about 49 km inland on the Pleistocene Prairie terrace and reaches a maximum thickness of about 10 m along the shoreline. The USACE maintains 12 tide gauge stations on the Chenier Plain. A review of these water-level time series indicate that only eight of the tide gauge stations have periods of record sufficient for analysis (Table 2).

The Calcasieu Pass tide gauge station lies about 3 km from the coast near Cameron which is connected to the Gulf of Mexico via Calcasieu Pass (Figure 3B). Of the Chenier Plain stations, it is most directly connected to the Gulf of Mexico and thus should have the most accurate measurements (Figure 9). The rate of relative sea-level rise for the station's entire period of record is 0.57 cm/yr (Table 2).

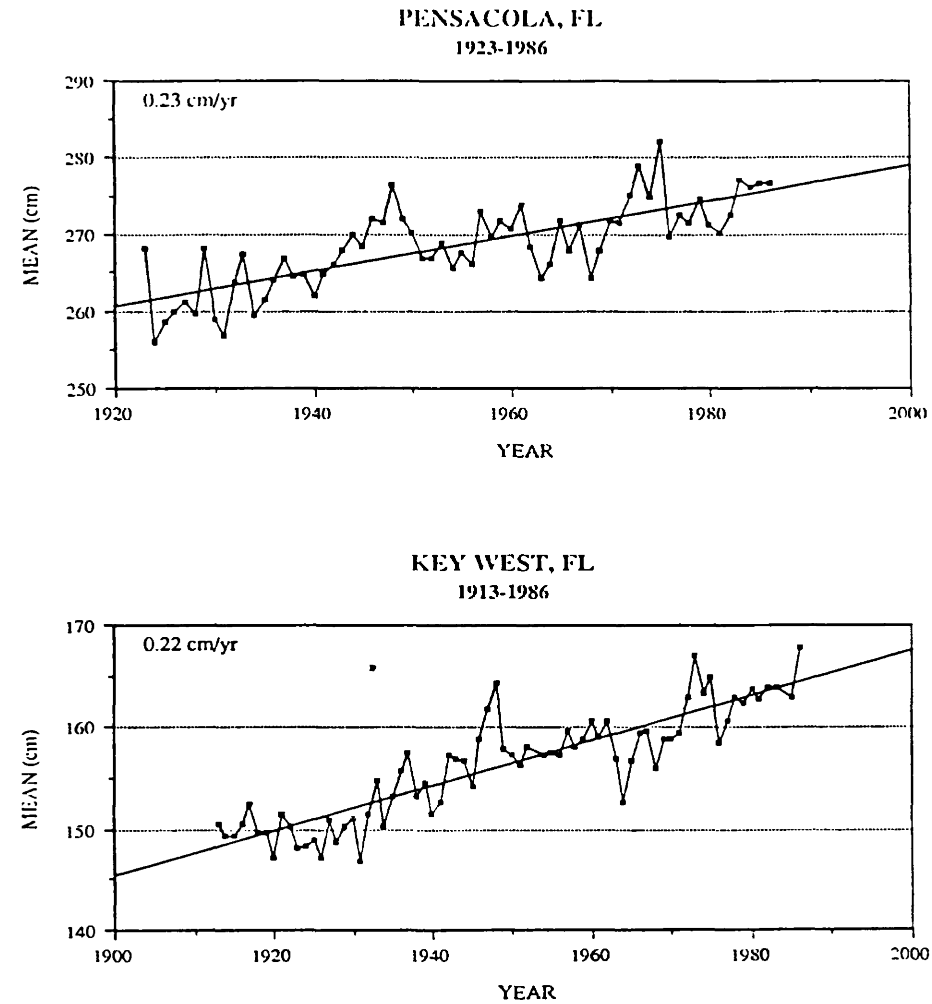


Figure 7. Water level time-series for the NOS Pensacola and Key West, Florida tidal stations.

The rates of relative sea-level rise for the Chenier Plain stations with complete records range between 0.34 cm/yr and 0.69 cm/yr for the period of record (Table 2). The average rate of relative sea-level rise, based on all eight Chenier Plain tide gauge stations, is 0.57 cm/yr.

Teche Basin. The Teche Basin is a marginal deltaic basin that developed within the erosional remnants of the Teche delta complex in the late Holocene delta plain when sea-level stood 4-6 m below present (Figure 4). Submergence of this delta complex over the last 4,000 years has generated a series of interconnected bays between the old Teche distributaries (PENLAND *et al.*, 1987). These bays are partially separated from the Gulf of Mexico by Marsh Island, Atchafalaya Bay shell reefs, and Point au Fer Island. The thickness of the Holocene section increases from west to east in the Teche basin because it overlies the western wall of the infilled Pleistocene valley of the Mississippi River (KOLB and VAN LOPIK 1958). Holocene sequences range from 10–15 m thick near Chenier au Tigre to over 100 m thick near Morgan City. Vermilion Bay, West Cote Blanche Bay, East Cote Blanche Bay, and Atchafalaya Bay make up the Teche Basin.

The water-level regime in the Teche Basin is complicated by the growth of the Atchafalaya River delta complex into the basin. Increasing seasonal flooding combined with high rates of sedimentation associated with delta growth tend to amplify the effects of relative sea-level rise. The tide gauge stations in the Teche basin measure the combined effects of eustatic

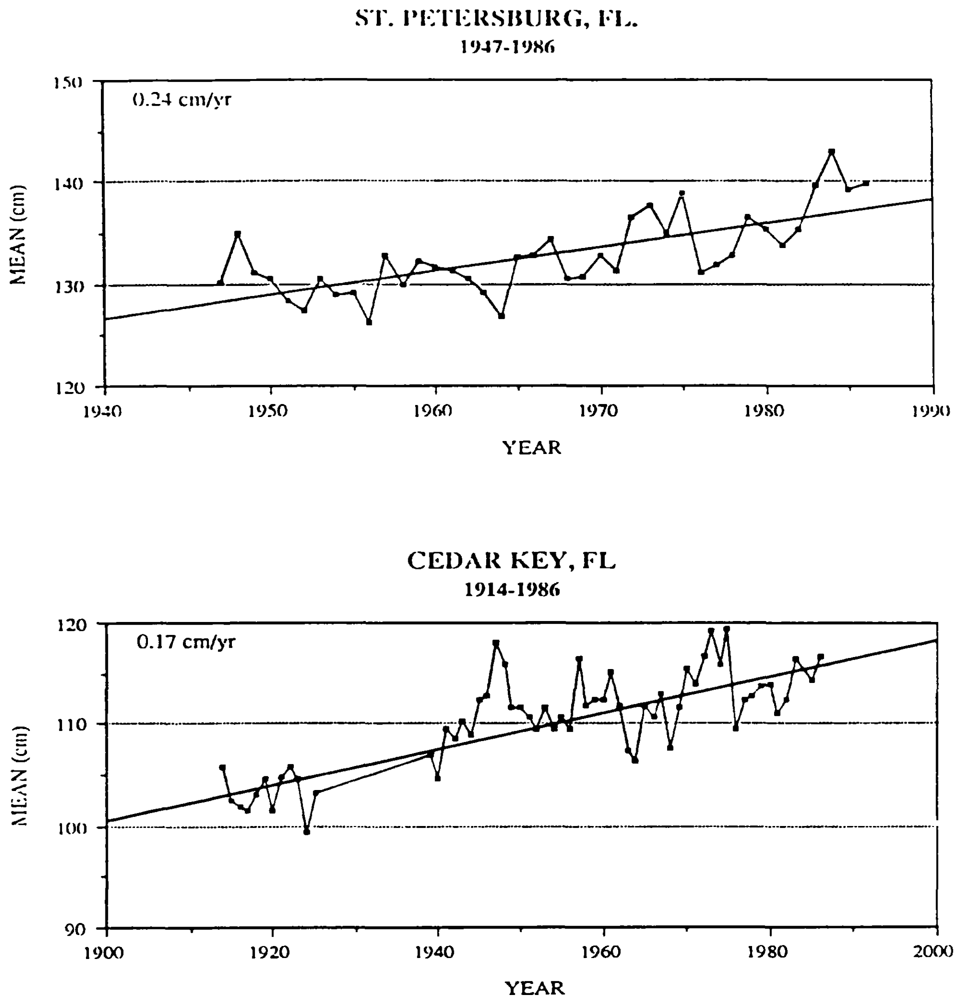


Figure 8. Water level time-series for the NOS St. Petersburg and Cedar Key, Florida tidal stations.

changes and subsidence with the added effect of rising Atchafalaya River stages.

The USACE maintains 23 tide gauge stations throughout the Teche Basin. A review of their water level histories indicates that only three of these stations have sufficient periods of record or clean enough records to make them suitable for analysis (Table 2). These stations are Calumet, Eugene Island, and Morgan City. The rates of relative sea-level rise were measured at 1.77 cm/yr, 1.17 cm/yr, and 1.26 cm, respectively, for the periods of 1942–1988, 1942–1988 and 1933–1987, respectively (Figure 10). The average relative sea-level rise rate for the entire period of record for all three Teche Basin stations is 1.40 cm/yr. It is important to note the variable and erratic character of these tide gauge records as compared to records from other stations in Louisiana. These erratic, and rapid water level changes can be attributed to several years of flooding associated with the growth of the Atchafalaya River delta (Table 2).

Terrebonne Delta Plain. The Terrebonne delta plain represents the depositional surface of the Teche and Lafourche delta complexes of the Mississippi River delta plain (Figure 4). This delta plain consists of several small deltas that are truncated by a series of transgressive barrier shorelines generated by multiple episodes of distributary switching (PENLAND *et al.*, 1987; PENLAND *et al.*, 1988c). The Terrebonne delta plain directly overlies the infilled Pleistocene valley of the Mississippi River. The thickness of the Holocene section in this region ranges between 100 m and 200 m. The western

Table 2. *U.S. Army Corps of Engineers, Louisiana Tide Gage Stations.*

Station Name	Parish Location	Record Period	RSL (cm/yr)
Chenier Plain			
Cameron	Cameron	1942–1988	0.57
Hackberry	Cameron	1943–1988	0.34
Mermentau River	Cameron	1949–1988	0.69
Schooner Bayou-East Auto	Vermilion	1942–1988	0.61
Schooner Bayou-East Staff	Vermilion	1942–1988	0.58
Vermilion Lock-East Auto	Vermilion	1942–1988	0.53
Vermilion Lock-East Staff	Vermilion	1943–1988	0.54
Vermilion Lock-West	Vermilion	1942–1988	0.68
Teche Basin			
Calumet	St. Mary's	1942–1988	1.77
Eugene Island	St. Mary's	1942–1988	1.17
Morgan City	St. Mary's	1933–1987	1.26
Terrebonne Delta Plain			
Greenwood	Terrebonne	1942–1986	0.98
Houma	Terrebonne	1946–1988	1.09
Barataria Basin			
Grand Isle	Jefferson	1949–1986	1.11
Balize Delta Plain			
Port Eads	Plaquemines	1944–1988	0.94
St. Bernard Delta Plain			
South Shore	Orleans	1949–1986	1.01
Little Woods	Orleans	1931–1977	1.09
Pontchartrain Basin			
West End	Jefferson	1931–1987	0.40
Frenier	St. John the Baptist	1931–1984	0.36
Mandeville	St. Tamany	1931–1988	0.45

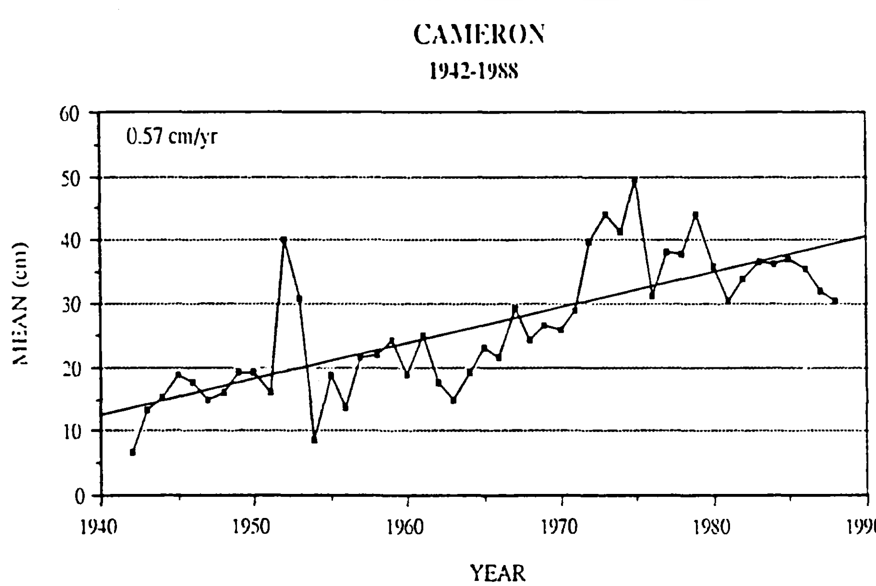


Figure 9. Water level time-series for U.S. Army Corps of Engineers Chenier plain.

margin of the Terrebonne delta plain is adjacent to the prograding Atchafalaya River delta and is experiencing higher and higher river stages as a result. In contrast, the eastern portions of the Terrebonne delta plain are not affected by the Atchafalaya River.

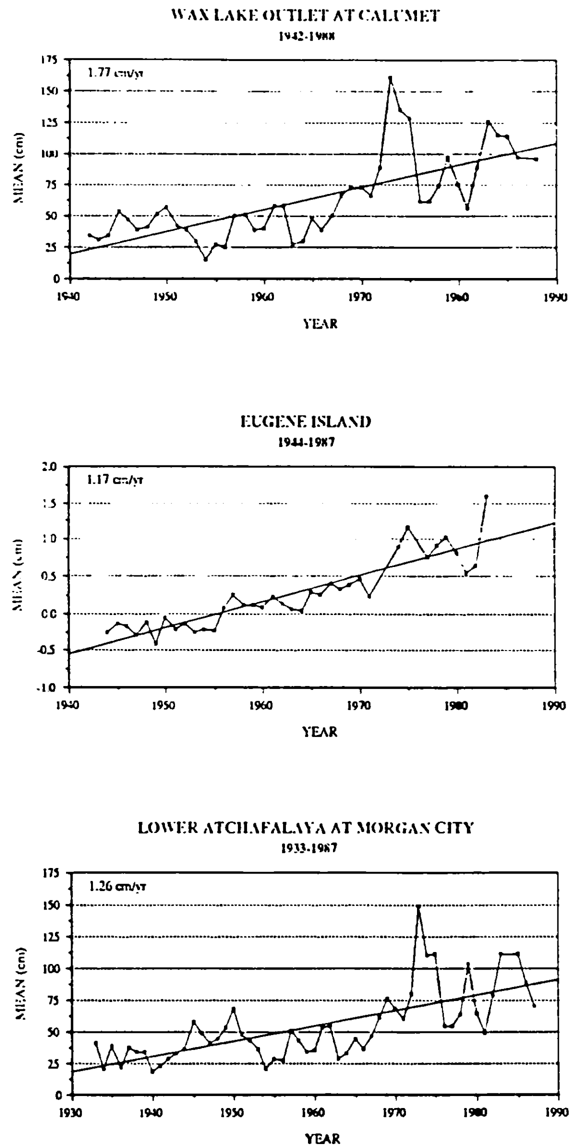
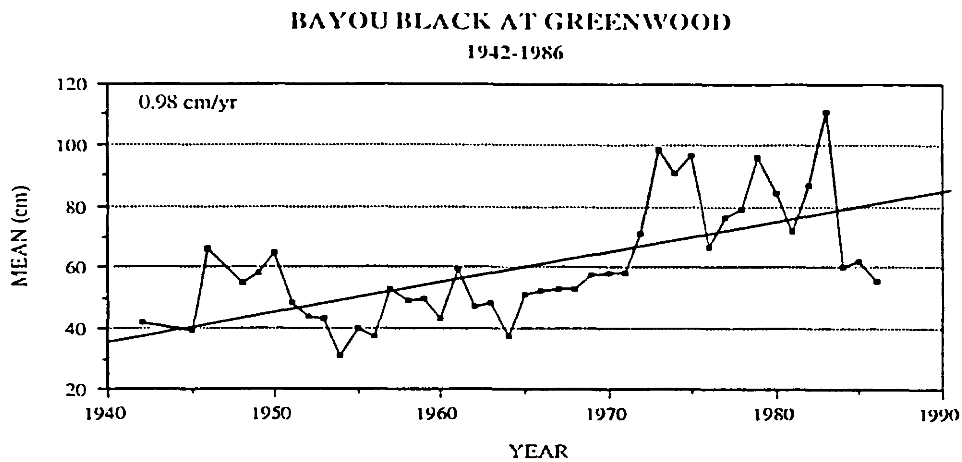


Figure 10. Water level time-series for U.S. Army Corps of Engineers Teche basin.

The USACE maintains eight tide gauge stations in the Terrebonne delta plain. A review of the water-level histories from these stations indicates that only two locations had periods of record suitable for analysis. The Greenwood tide gauge station is located in the western portion of the Terrebonne delta plain in the zone influenced by Atchafalaya River flooding (Figure 3B). The Houma tide gauge station lies in the central portion of the Terrebonne delta plain (Figure 3B).

The Greenwood tide gauge station is in Bayou Black 25 km east of the Atchafalaya River. The period of record analyzed for this station ran from 1942 to 1986. The analysis indicated a relative sea-level rise rate of 0.98 cm/yr (Table 2, Figure 11).

The Houma tide gauge station lies 70 km inland on the Intracoastal Waterway and is connected to the Gulf of Mexico by the Houma Navigation Channel. The period of record analyzed was from 1946 to 1988. The rate of relative sea-level rise was calculated to be 1.09 cm/yr during this interval (Figure 11). The average



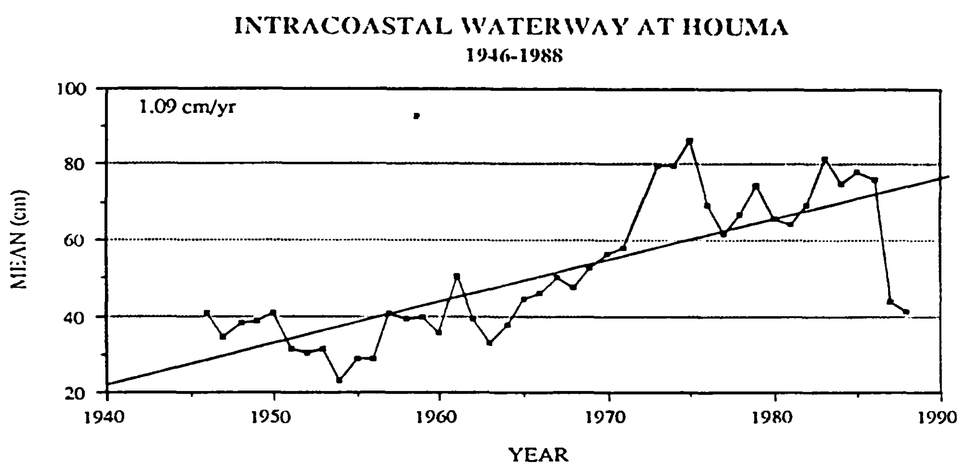


Figure 11. Water level time-series for U.S. Army Corps of Engineers Terrebonne delta plain.

relative sea-level rise rate for the two Terrebonne delta plain tide gauge stations is 1.04 cm/yr.

Barataria Basin. The Barataria Basin is an interdistributary wetland system located between the abandoned Lafourche and Plaquemines delta complexes (Figure 4). The basin consists of Lac Des Allemands, Lake Salvador, Little Lake, Caminada Bay, and Barataria Bay. The seaward margin of this deltaic estuary is formed by the Caminada-Moreau coast, Grand Isle, Grand Terre Islands, and Cheniere Ronquille. Caminada Bay and Barataria Bay are connected to the Gulf of Mexico via Caminada Pass, Barataria Pass, Pass Abel, Quatre Bayoux Pass, and Pass Ronquille. The Barataria Basin lies over the eastern wall of the infilled Pleistocene valley of the Mississippi River. The thickness of the Holocene section in the Barataria Basin increases from 10–15 m in the upper basin to over 100 m at Grand Isle (KOLB and VAN LOPIK 1958).

The USACE maintains seven tide gauge stations in the Barataria Basin. A review of the water level histories for these tide gauge stations revealed that only one site has a record suitable for analysis. The Grand Isle tide gauge station is located at the U.S. Coast Guard station on Bayou Rigaud, less than 1 km from the Gulf of Mexico via Barataria Pass. The period of record analyzed ran from 1947 to 1986. The analysis of the entire record yielded a relative sea-level rise of 1.11 cm/yr (Table 2, Figure 12).

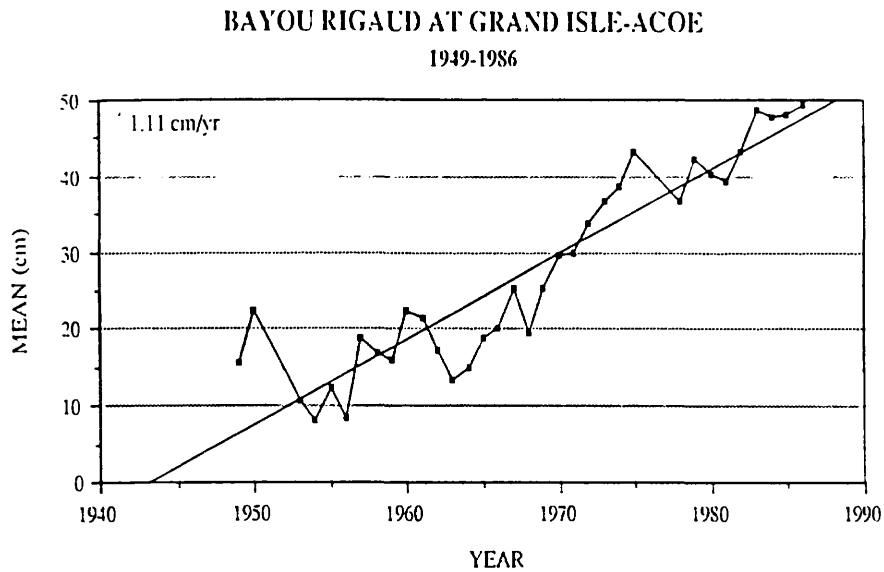


Figure 12. Water level time-series for U.S. Army Corps of Engineers Barataria basin.

Balize Delta Plain. The Balize delta plain is a smaller, active deepwater delta of the larger Modern delta complex (Figure 4). This delta lies south of Venice and consists of seven major distributaries. The delta has been building toward the edge of the continental shelf for approximately 400 years (COLEMAN, 1988). Termed the "bird-foot," the Balize delta consists of a sequence of subdeltas that have overlapped to form the depositional surface. The thickness of the Holocene section exceeds 100 m. The main distributaries of the Balize delta are Southwest Pass, South Pass, Southeast Pass, Northeast Pass, North Pass, Pass a Loutre, and Main Pass. The tidal regime in this coastal region is heavily influenced by the stages of the Mississippi River.

The USACE maintains 10 tide gauge stations in the Balize delta plain and adjacent Mississippi River. A review of these stations indicated that only one station has records of sufficient quality and duration for analysis. The Port Eads tide gauge station is located at South Pass about 4–5 km north of the Gulf of Mexico. The erratic character of the records reflects repeated flooding. The period of record analyzed was between 1944 and 1988. The analysis indicated a relative sea-level rise rate of 0.94 cm/yr (Table 2, Figure 13).

St. Bernard Delta Plain. The St. Bernard delta plain represents the depositional surface of the abandoned St. Bernard delta complex, which is more than 3,000 years old (Figure 4). The transgressive submergence of this delta complex over the last 2,000 years has generated the Chandeleur barrier island arc, which is separated from the mainland by Chandeleur Sound (PENLAND *et al.*, 1985). Numerous large passes and tidal inlets connect the St. Bernard wetlands and Chandeleur Sound with the Gulf of Mexico. The Holocene section in this area increases in thickness from 15–20 m near Little Woods to over 100 m near Breton Island.

The USACE maintains 10 tide gauge stations in the St. Bernard delta plain. Only two of these stations had records suitable for analysis, these stations are South Shore and Little Woods, located on the Bayou Sauvage delta of the St. Bernard delta complex, which separates Lake Pontchartrain and Lake Borgne. The Rigolets connects Lake Pontchartrain with the Gulf of Mexico.

The South Shore tide gauge station lies immediately west of Point aux Herbes. Its period of record runs from 1949 to 1986. The analysis of the entire water-level history yielded a relative sea-level rise rate of 1.01 cm/yr (Table 2, Figure 14).

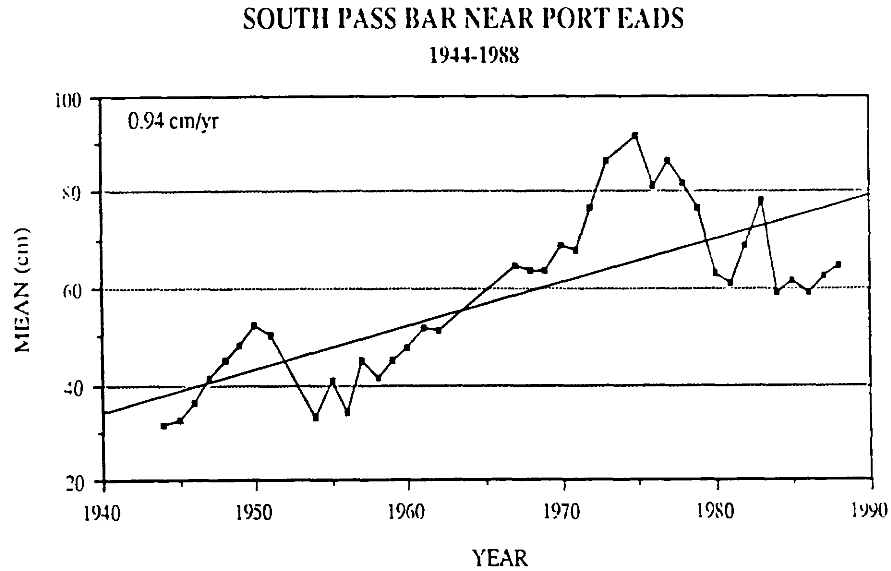


Figure 13. Water level time-series for U.S. Army Corps of Engineers Balize delta plain.

The Little Woods tide gauge station is 10 km southwest of the South Shore station. It has records dating from 1931 to 1977. A relative sea-level rise rate of 1.09 cm/yr was calculated for the entire period of record (Table 2, Figure 14).

Pontchartrain Basin. The Pontchartrain Basin is a marginal deltaic basin located between the Pleistocene terraces in the Florida Parishes and the St. Bernard delta complex (Figure 4). The progradation of the St. Bernard delta complex 2,500 years ago along the eastern side of the Mississippi River delta plain enclosed the Pontchartrain Basin, which consists of Lake Maurepas connected to Lake Pontchartrain by Pass Manchac, Lake Pontchartrain connected to Lake Borgne by The Rigolets, and Lake Borgne connected to the Gulf of Mexico by Mississippi Sound. The Holocene section of the basin pinches out against the Pleistocene terraces to the north and thickens to 10–15 m toward the south adjacent to the St. Bernard delta plain. The USACE maintains 11 tide gauge stations in the Pontchartrain Basin. Of these only three have records suitable for analysis: the West End, Frenier,and Mandeville tide gauge stations.

The West End tide gauge station lies at the western end of Lake Pontchartrain (Figure 3B). Its records date back to 1931 and continue to 1987. The analysis of the West End water-level history revealed a relative sea-level rise rate of 0.40 cm/yr (Table 2, Figure 15).

The Frenier tide gauge station is located south of the West End station on the southwest shore of Lake Pontchartrain (Figure 3B). Its period of record runs from 1931 to 1984. The water-level history analysis yielded an average relative sea-level rise rate of 0.36 cm/yr (Table 2, Figure 15).

The Mandeville tide gauge station, located on the north shore of Lake Pontchartrain (Figure 3B), has a period of record from 1931 to 1988. The analysis of its water-level history indicates a relative sea-level rise rate of 0.45 cm/yr for the entire record (Table 2, Figure 15).

REGIONAL COMPARISON

Gulf of Mexico—NOS Tide Gauge Stations

Louisiana is experiencing a higher rate of sea-level rise than any other state on the Gulf Coast. The zones of highest sea-level rise are associated with the Mississippi River delta plain, while the rates along the Chenier Plain to the west and the Pontchartrain Basin to the east decrease to levels comparable to those of adjacent coastal states (Figure 16). The highest rate of relative sea-level rise in Louisiana,

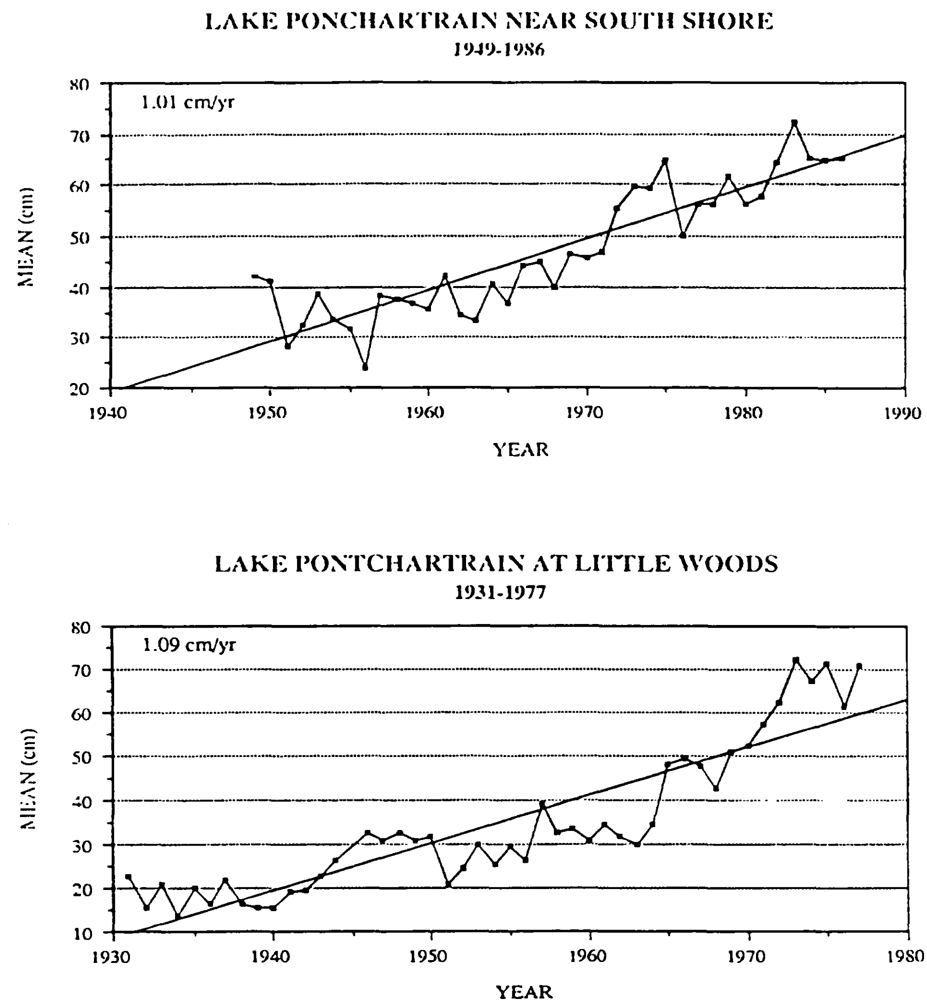


Figure 14. Water level time-series for U.S. Army Corps of Engineers St. Bernard delta plain.

according to NOS tide gauge data, is at Eugene Island, where the average rate for the period 1939–1974 has been calculated to be 1.19 cm/yr.

In Texas, the rate of relative sea-level rise ranges from 0.31 cm/yr in Port Isabel to 0.62 cm/yr at Galveston. The Galveston rate is nearly identical to the rate for the Chenier Plain in western Louisiana. In the eastern Gulf of Mexico, the Mississippi, Alabama, and Florida tide gauges recorded the lowest rates of relative sea-level rise. For Florida, the relative sea-level rise rates averaged between 0.17 cm/yr at Cedar Key and 0.23 cm/yr at Pensacola. Biloxi recorded the lowest relative sea-level rise rates in the Gulf of Mexico with an average of 0.15 cm/yr for the entire period of record.

Louisiana—USACE Tide Gauge Stations

Of the seven geomorphic regions identified in Louisiana, the Teche Basin is experiencing the highest rate of relative sea-level rise based on the USACE tide gauges (Figure 17). The average rate of relative sea-level rise recorded from the three tide gauge stations indicate a rate of 1.31 cm/yr in the Teche Basin. The Calumet tide gauge station had the highest relative sea-level rise rate, 1.77 cm/yr. However, the rapid apparent relative sea-level rise rate in the Teche Basin is anomalous due to the impact of Atchafalaya River flooding and delta building. When the measurements that were taken during the years of major flooding are omitted from the analysis, the rate of relative sea-level rise

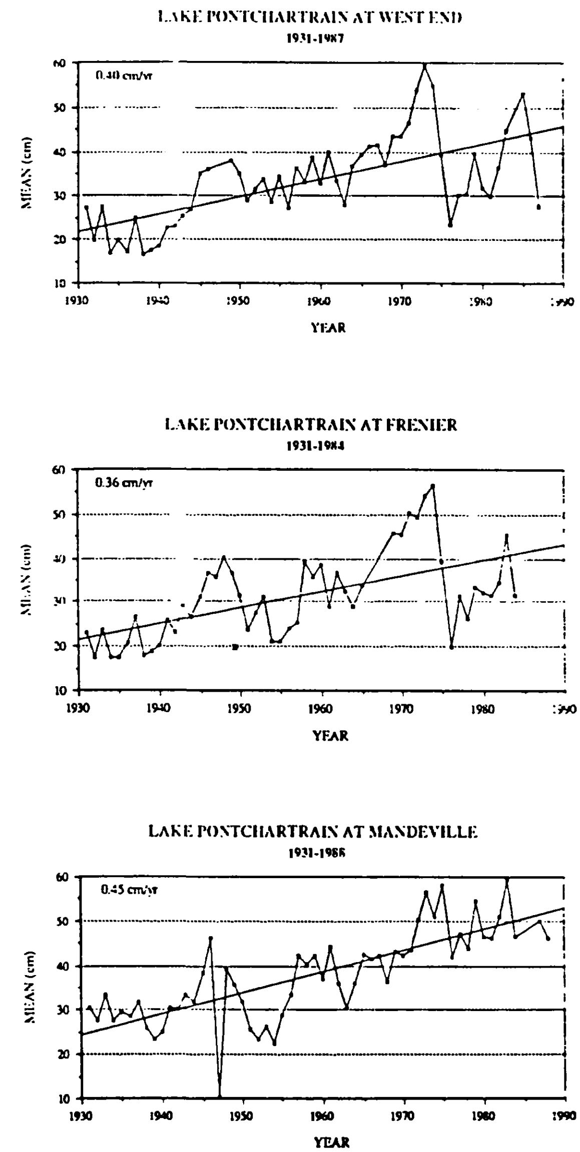


Figure 15. Water level time-series for U.S. Army Corps of Engineers Pontchartrain basin.

is reduced. For example, when this procedure was followed for the Eugene Island tide gauge station records, the overall rate of relative sea-level rise at that station fell from 1.61 cm/yr to 0.81 cm/yr. High rates of relative sea-level rise are to be expected in the Teche Basin because of the thick underlying sequence of Holocene valley fill. Even so, the Teche Basin records do not accurately depict the effects of subsidence and eustatic changes because of the Atchafalaya River flooding. Similarly, Mississippi River floods contaminate the Balize delta plain tide gauge station readings.

The second-highest rate of average relative sea-level rise, 1.04 cm/yr, is found in the Terrebonne delta plain and is based on an average of the Greenwood and Houma stations. These high rates of relative sea-level rise are to be expected because the Terrebonne delta plain directly overlies the thickest portion of the Mississippi River delta plain where the Holocene section is more than 250 m thick. Because there is minimal contamination from the Atchafalaya River, the Terrebonne delta plain measurements should represent accurately the combined effects of eustatic change and compac-

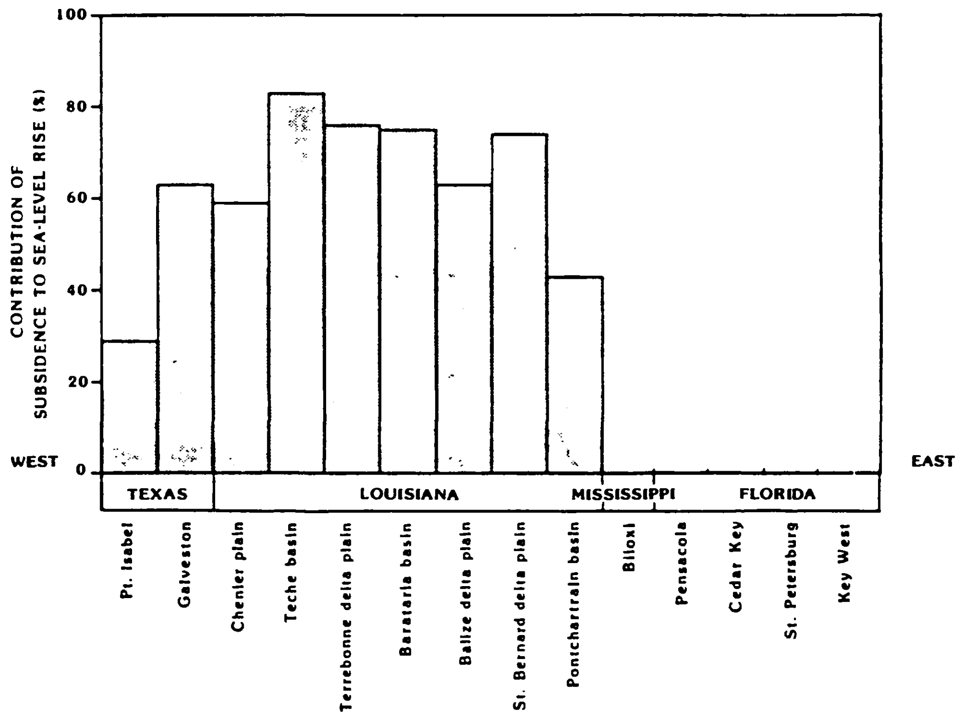


Figure 16. Relative sea-level rise histogram for the NOS Gulf of Mexico.

tional subsidence. On either side of the Teche Basin and Terrebonne delta plain the average rates of relative sea-level rise decrease. Eastward lie the Barataria Basin, the Balize delta plain, the St. Bernard delta plain, and the Pontchartrain Basin, with rates of 1.11cm/yr, 0.94 cm/yr, 1.05 cm/yr, and 0.41 cm/yr, respectively. To the west of the Teche Basin lies the Chenier plain, which is experiencing an average relative sea-level rise rate of 0.57 cm/yr. This pattern of relative sea-level rise is the result of impaction, which related to the varying thickness of the underlying Holocene Mississippi River delta plain (ROBERTS 1985; PENLAND *et al.*, 1988b).

Compactional Subsidence

In the Louisiana coastal zone, the natural compaction of Holocene deltaic sediments is viewed as the primary factor driving relative sea-level rise. Contour maps of the Pleistocene/Holocene boundary associated with the Mississippi River delta and chenier plains were constructed by FISK (1948) and KOLB and VAN LOPIK (1958) showing the entrenched Pleistocene valley filled with more than 150 m of Holocene sediments. We compared the thickness of the Holocene sequence and the rate of relative sea-level rise at each tide gauge station. Figure 18 illustrates this relationship between relative sea-level rise and Holocene sequence thicknesses for the Mississippi River delta and chenier plains. For the chenier plain, where the Holocene sediment thickness is less than 10 m, the lowest relative sea-level rise rates are observed. For the delta plain, where the Holocene sediment thickness is greater than 50 m, the highest relative sea-level rise rates are found. This relationship indicates that the rapid rate of sea-level rise observed in Louisiana can be attributed to the natural compaction found in the Mississippi River delta plain.

CONCLUSIONS

(1) The analysis of National Ocean Survey tide gauge records from nine stations along the U.S. Gulf Coast indicates that Louisiana is experiencing the highest rates of relative sea-level rise in the Gulf of Mexico. Maximum relative sea-level rise rates in Louisiana ranged

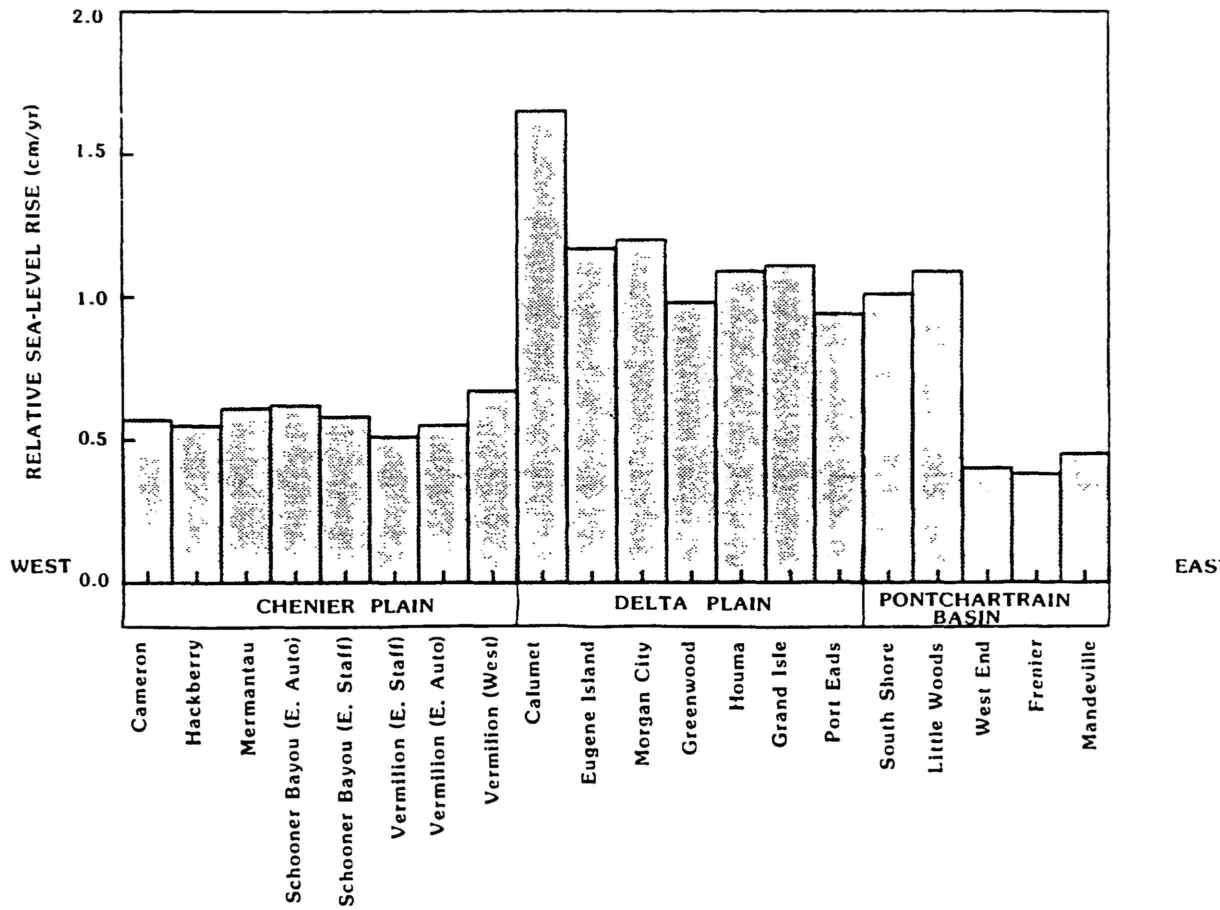


Figure 17. Relative sea-level rise histogram for the U.S. Army Corps of Engineers Louisiana stations.

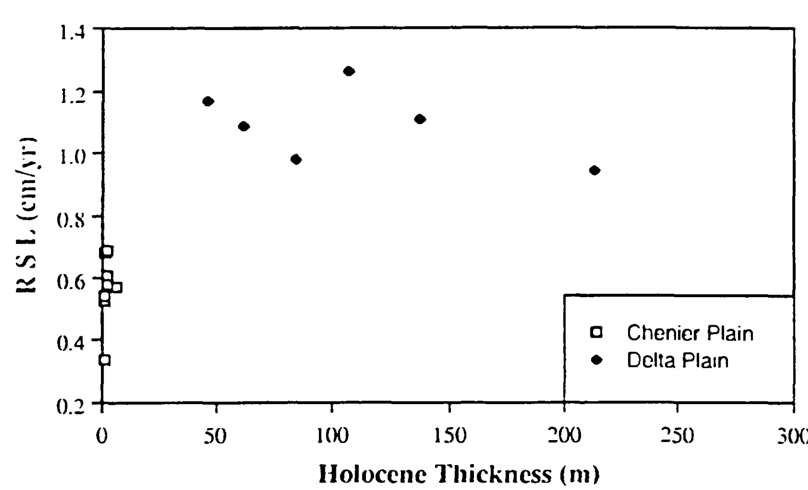


Figure 18. Relationship between relative sea-level rise and the thickness of the Holocene sediments in the Mississippi River delta and chenier plains.

between 1.04 cm/yr and 1.19 cm/yr. Texas ranks second with rates ranging between 0.31 cm/yr and 0.63 cm/yr, followed by Florida with rates from 0.17 cm/yr to 0.24 cm/yr, and Mississippi-Alabama with a rate of 0.15 cm/yr.

(2) An analysis of U.S. Army Corps of Engineers tide gauge records from 20 stations in coastal Louisiana indicates that the highest rate of relative sea-level rise not *contaminated* by the discharge of the Mississippi River is 1.11 cm/yr at Grand Isle within the Barataria Basin. Relative sea-level rise rates up to 1.77 cm/yr can be found within the Teche Basin, but the average rates from these stations have been artificially elevated by readings taken during the flood stages of the Atchafalaya River. Relative sea-level rise rates decrease east and west away from the Terrebonne delta plain. East of the delta plain lies the Pontchartrain Basin where relative sea-level rise rates range from 0.36 cm/yr to 0.45 cm/yr. West of the delta plain, the rates range between 0.34 cm/yr and 0.69 cm/yr.

(3) The regional pattern of rapid relative sea-level rise observed for Louisiana is related to the thickness of the underlying Holocene sediments. The greatest rates of relative sea-level rise are associated with the Mississippi River delta plain where the underlying Holocene section reaches a maximum thickness of about 150–200 m. East and west of the delta plain, the thickness of the Holocene section decreases to less than 20 m. In some cases the Holocene section pinched out completely as it does in Florida. The rates of both relative sea-level rise and subsidence decrease east and west of Louisiana.

ACKNOWLEDGMENTS

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□ RÉSUMÉ □

La Louisiane connait actuellement les plus sérieuses pertes de sables et érosions rencontrées sur les îles barrières d'Amérique du Nord. Ces pertes affectent plus de 102km^2 par an dans le delta du Mississippi, et 0,326km^2 par an de la surface des îles barrières. Les facteurs essentiels conduisant à la déterioration de la frange côtière de Louisiane sont: la rapide montée du niveau de la mer induite par la subsidence du delta, et un déficit des apports terrigènes sur les zones humides.

La montée moyenne du niveau de la mer entre 1946 et 1988 est de 1,09cm par an dans la plaine du Mississippi à Houma; sur le littoral, à l'île Eugène, elle atteint 1,19cm par an. La comparaison de l'ensemble des données montre que le niveau de la mer monte plus vite dans la zone de Terrebonne Parish que partout ailleurs en Louisiane. Les faits historiques concrétisant cette montée du niveau de la mer (plaine de Chénier, bassins de Teche, Baratavia et Ponchartrain, deltas de Terrebonne, Balize et St. Bernard) indiquent que la hausse moyenne du niveau de la mer décroît d'est en ouest à partir de la zone littorale de Terrebonne.

Comparées à celles du golfe, ces données montrent que la Louisiane connait une montée relative de 1,04 cm par an à Grand Isle, que ce chiffre décroît à 0,62cm par an à Galveston (Texas), pour atteindre 0,15cm par an à Biloxi (Mississippi). La montée moyenne du niveau de la mer en Louisiane est plus de 5 fois supérieure à celle du golfe du Mexique. Comparée à la montée globale du niveau de la mer (0,12cm par an), celle qui est enregistrée à Grand Isle (1,04cm par an) montre que la mer monte dix fois plus vite en Louisiane que dans les autres parties du monde.

La rapidité de cette montée peut être attribuée à la subsidence du delta du Mississippi par compaction sédimentaire. En effet, la Louisiane s'étend sur la vallée pléistocène du Mississippi, recouverte par les sédiments du delta holocène de plus de 150m d'épaisseur.—*Catherine Bressolier (Géomorphologie EPHE, Montrouge, France).*

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PRELIMINARY ASSESSMENTS OF THE OCCURRENCE AND EFFECTS OF UTILIZATION OF SAND AND AGGREGATE RESOURCES OF THE LOUISIANA INNER SHELF

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Abstract

Suter, J.R., Mossa, J. and Penland S., 1989. Preliminary assessments of the occurrence and effects of utilization of sand and aggregate resources of the Louisiana inner shelf. In: M.C. Hunt and S.V. Doenges (Editors), Studies Related to Continental Margins. Mar. Geol., 90: 31–37.

Louisiana is experiencing the most critical coastal erosion and land loss problem in the United States. Shoreline erosion rates exceed 6 m/yr in more than 80% of the Louisiana coastal zone and can be up to 50 m/yr in areas impacted by hurricanes. The barrier islands have decreased in area by some 40% since 1880. Land loss from coastal marshlands and ridgelands from both natural and human-induced processes is estimated to exceed 100 km^2/yr. In response, a two-phase plan has been established, calling for barrier-island restoration and beach nourishment, both requiring large amounts of sand. The plan will be cost-effective only if sand can be found offshore in sufficient quantities close to project sites. To locate such deposits, the Louisiana Geological Survey is conducting an inventory of nearshore sand resources on the Louisiana continental shelf. Exploration for offshore sand deposits is conducted in two phases, with high-resolution seismic reflection profiling to locate potential sand bodies followed by vibracoring to confirm seismic intepretations and obtain samples for textural characterization. As part of the initial stages of the program, reconnaissance high-resolution seismic investigations of three areas of the continental shelf representing different stages in the evolutionary sequence of barrier shorelines were carried out. The Timbalier Islands, flanking barriers of the eroding Caminada–Moreau headland, contain potential sand resources associated with buried tidal and distributary channels. The Chandeleur Islands, a barrier-island arc, have potential offshore sands in the form of truncated spit and tidal inlet deposits, submerged beach ridges, and distributary channels. Trinity Shoal, an inner shelf shoal, is an offshore feature containing up to 2×10^9 m^3 of material, most of which is probably fine sand.

These reconnaissance surveys have demonstrated the occurrence of sand resources on the Louisiana continental shelf. Utilization of such deposits for island restoration or beach nourishment raises the question of potential adverse effects on the shoreline due to alteration of the inner shelf bathymetry by removing material or deposition of spoil in the process of dredging. Wave refraction analysis models provide a means by which hypothetical wave energy distribution can be determined and possible changes due to resource utilization assessed. A preliminary assessment of the consequences of using sand from Ship Shoal, a large shore-parallel feature, as borrow material for beach nourishment was conducted. Initial results indicate that the shoal serves to attenuate storm waves, and removal of this feature would result in increased erosion and overwash on the adjacent Isles Dernieres barrier-island shoreline. These findings illustrate the need to determine optimum dredging configurations if environmentally deleterious effects of utilization of offshore sand and aggregate resources are to be minimized.

Introduction

Louisiana is experiencing the most critical coastal erosion and land loss in the United States. Shoreline erosion rates exceed 6 m/yr in more than 80% of the Louisiana coastal zone and can be up to 50 m/yr in areas impacted by hurricanes. Land loss from coastal marshlands

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and ridgelands, resulting from both natural and human-induced processes, is accelerating and now exceeds 100 km^2/yr (Gagliano et al., 1981). The barrier islands have decreased in area from 105 km^2 (1880) to 64 km^2 (1979), a total reduction of approximately 40% (Penland and Boyd, 1981). Decreased delivery of sediments resulting from artificial stabilization and confinement of the Mississippi River and human activities related to hydrocarbon production, coupled with natural processes such as compactional subsidence and saltwater intrusion, have produced the current coastal erosion and land-loss problem. In response to this condition, Act 41 of the 1981 Extraordinary Session of the Louisiana Legislature created the Coastal Environment Trust Fund. The Louisiana Coastal Protection Master Plan, developed by the Louisiana Geological Survey Department of Natural Resources to implement this mandate, was approved in 1985. Phase I of the Master Plan calls for restoration of the eroding barrier shorelines, and Phase II provides for beach nourishment using sand dredged from the Gulf of Mexico.

The large amount of sand required for these projects can be obtained cost-effectively only if sand can be found offshore in sufficient quantities. To locate sand for beach nourishment and restoration projects, the Coastal Geology Section of the Louisiana Geological Survey is conducting a state-wide nearshore sand-resource inventory on the Louisiana continental shelf. Exploration for offshore sand deposits is conducted in two phases. Potential sand bodies are first located through high-resolution seismic reflection profiling; vibracoring is then conducted to confirm seismic interpretations and obtain samples for textural characterization. In the initial stages of the program, funding from the U.S. Minerals Management Service was used for high-resolution seismic investigations of three areas of the inner continental shelf representing different stages in the evolutionary sequence of barrier shorelines (Fig.1). The Timbalier Islands, flanking barriers of the eroding Caminada-Moreau headland, contain potential sand resources associated with buried tidal and distributary channels (Fig.2). The Chandeleur Islands, a barrier-island arc, have potential offshore sands in the form of truncated spit and tidal-inlet deposits, submerged beach ridges, and distributary channels. Trinity Shoal, an inner-shelf shoal, is an offshore feature containing up to 2×10^9 m^3 of material, most of which is probably fine sand. A total of 2000 line km of high-resolution seismic profiles were obtained in these areas (Suter and Penland, 1987). Statewide, more than 10,000 line km have been acquired to date.

Utilization of offshore sand deposits for island restoration or beach nourishment raises the question of whether the shoreline could be adversely affected by the removal of material or deposition of spoil during dredging and the resulting alteration of innershelf bathymetry. Models of wave-refraction analysis provide a means by which hypothetical wave-energy distributions can be determined and possible changes due to resource utilization assessed. U.S. Minerals Management Service funding was used to conduct a preliminary assessment of the consequences of using borrow material from Ship Shoal, a large shore-parallel feature located offshore of the Isles Dernieres, a barrier-island chain to be restored as part of the Coastal Protection Master Plan (Fig.3). Computer plots were generated using available bathymetric data and five hypothetical bathymetric scenarios of sand-resource extraction for twelve wave-climate conditions; in total, 72 plots and corresponding energy-flux parameters were produced (Mossa, 1986).

Methods

High-resolution seismic reflection profiling

Exploration for offshore sand and aggregate resources was generally carried out in two phases. First, potential deposits must be identified and their distribution mapped. This is accomplished through use of high-resolution seismic-profiling techniques. Sound sources are towed by a research vessel along preplotted

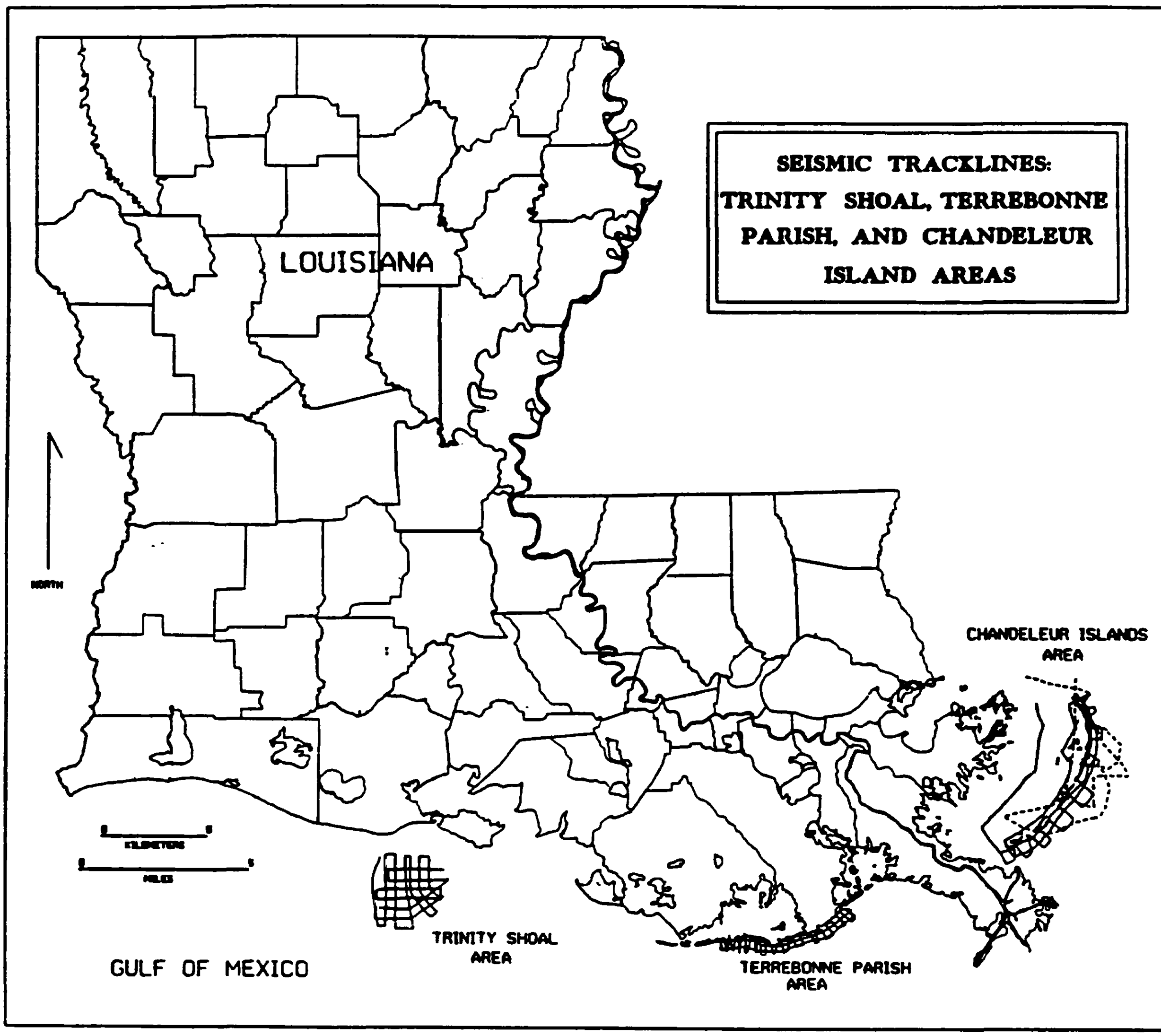

Fig.1. Locations of the three areas of the Louisiana inner continental shelf surveyed using Minerals Management Service funds (from Suter and Penland, 1987).

tracklines through the area being explored. Among other variables, the type and intensity of reflections of the sound signals from the subbottom are functions of the lithology of the seabed and submerged strata. Other factors influencing seismic reflection profiles include the type of seismic source used, sea state, water depth, geometry of the tow, vessel speed, type of receiver, filtration of the signal, scale of display, and chart speed of the recorder (Suter and Penland, 1987).

Throughout most of the sand-resource inventory, a Datasonics 3.5-kHz subbottom profiler was used as the high-frequency tool, and an ORE Geopulse, a Uniboom-type system, was used to provide greater penetration. Vertical resolution of these two tools is about 0.5 and 1.5 m, respectively. Penetration averaged about 20 m for the 3.5-kHz device and exceeded 100 m for the Geopulse near the Trinity Shoal area and in some parts of the Chandeleur Islands area. The returning signals were split traced on an EPC 3200 recorder at sweep rates of $\frac{1}{8}$ s for each channel, resulting in an effective

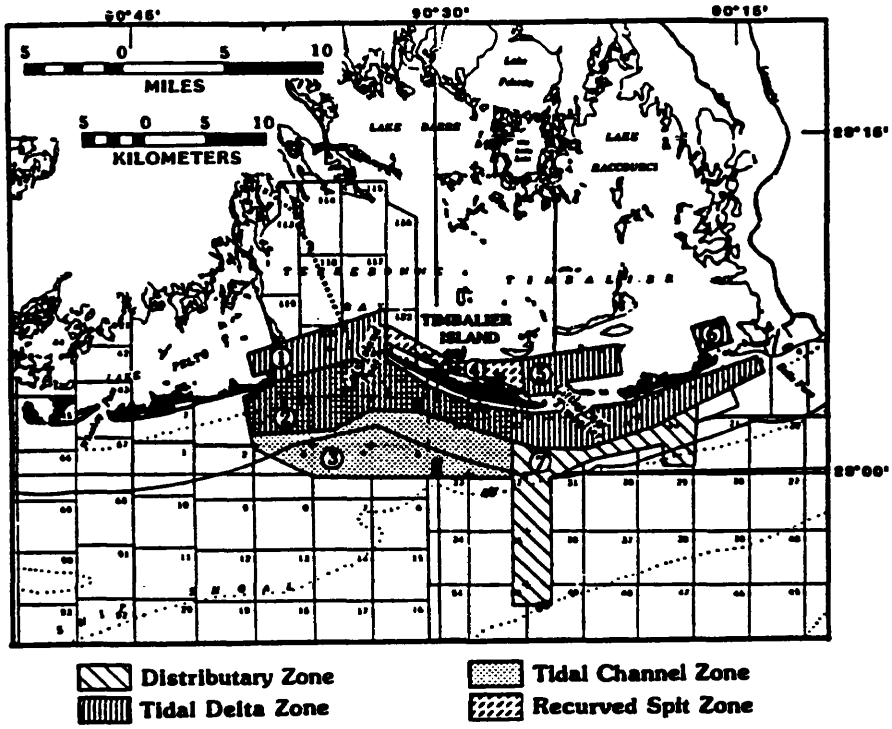

Fig.2. Potential borrow targets in the Timbalier Islands area as interpreted from seismic profiles (from Suter and Penland, 1987).

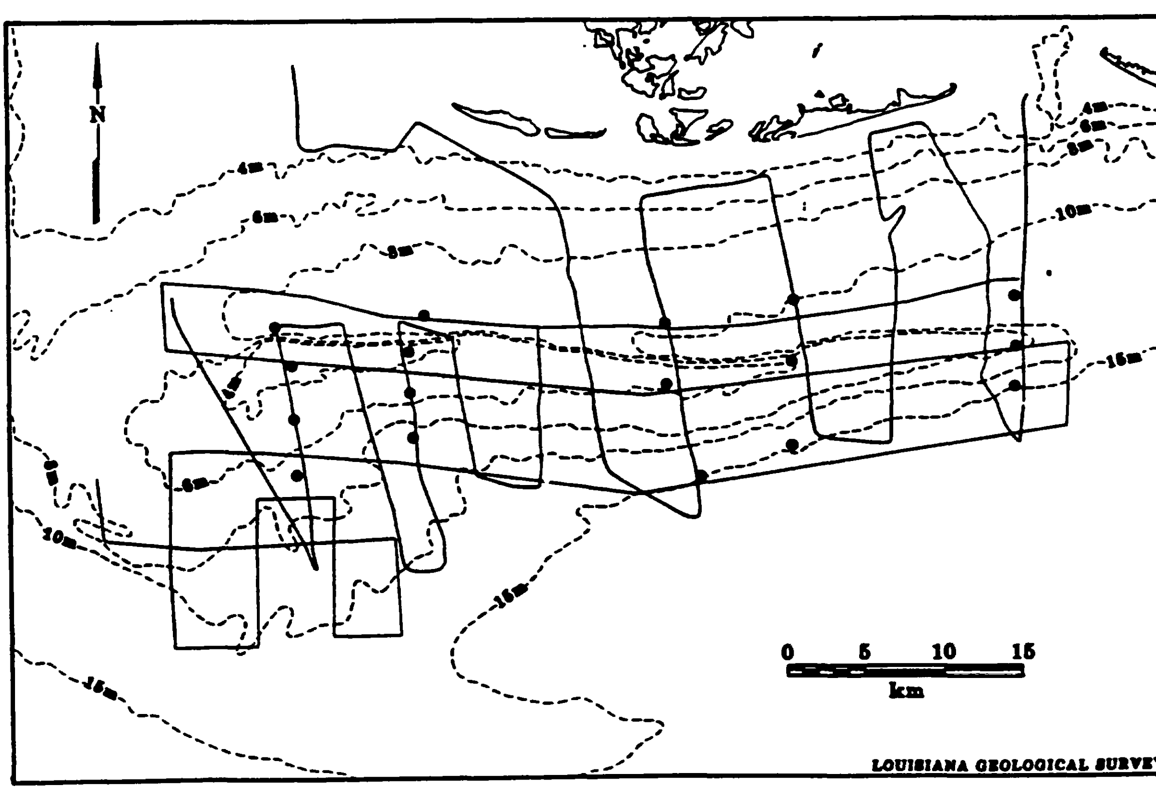

Fig.3. Locations of high-resolution seismic profiles and vibracores near Ship Shoal (after Penland et al., 1986).

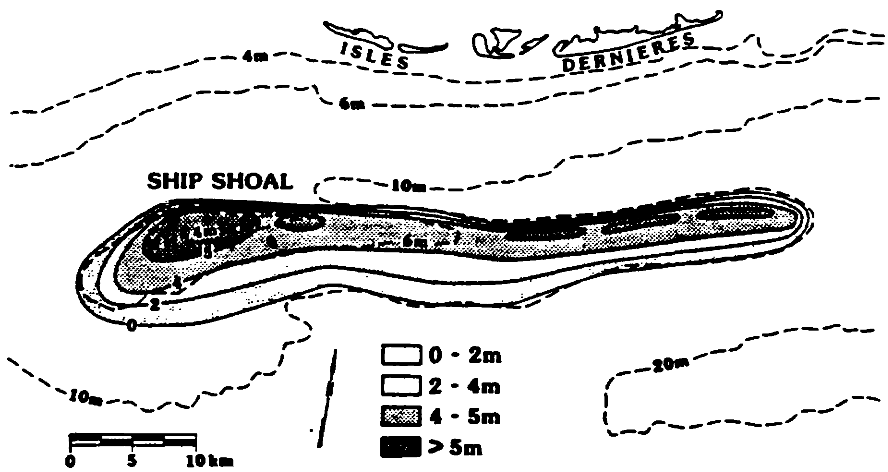

Fig.4. Net-sand isopach map of Ship Shoal compiled from vibracore and seismic data (after Penland et al., 1986).

display of ½ s for the entire record. Filter settings for the ORE Geopulse were variable, depending upon the area surveyed. All data were recorded on magnetic tape on a Hewlett Packard 4300 reel-to-reel recorder for subsequent playback. Navigation was carried out with a Northstar 600 Loran-C receiver corrected with a Morrow XYP-200 real-time Loran plotter. Navigation data were recorded on magnetic tape on a Texas Instruments Silent 700 and processed into trackline maps by the U.S. Geological Survey in Corpus Christi, Texas, and Woods Hole, Massachusetts. Seismic interpretations were plotted onto the trackline charts on mylar overlays at scales of 1:80,000 (Figs.1 and 3).

Vibracoring

The second phase of sand exploration requires that cores be obtained to confirm seismic interpretations and to provide samples for grain-size analysis needed to determine the textural suitability of offshore sands as borrow material. In the preferred method, vibracoring, a vibrating core barrel is driven into the sediment. This technique usually best preserves sedimentary structures, which must be examined for accurate interpretation of the depositional environment and prediction of sand trends. Interpretations of the seismic lines, coupled with analysis of current and historical shoreline geomorphology, provide the target for vibracores.

After vibracore description and textural analysis, seismic interpretations are integrated with the core information to produce maps of potential sand resources. These can be displayed either as simple plan views (Fig.2) or as isopach maps that show the thickness of sand available at a particular site, in a manner analogous to a topographic map (Fig.4).

Wave-refraction analysis

Wave-refraction analysis was conducted near Ship Shoal and the Isles Dernieres by digitizing actual and hypothetical offshore bathymetry. Bathymetric data were acquired in 1934, and the hypothetical situtations were based on the possibility that the shoal sand deposits might eventually be removed for beach nourishment for the nearby Isles Dernieres. Hypothetical situations included removal of only sections of the shoal having more than 75% sand, removal of the entire shoal regardless of sand content, and removal of the eastern half, western half, and central section of Ship Shoal.

The WAVENRG model developed by May

(1974) and modified by P. Lowry (pers. commun., 1985) was chosen because it could be adapted for use on an Intergraph graphics minicomputer with special grid-construction capabilities that produce high-quality illustrations at moderate cost. The model was constructed to handle grid-building and refraction procedures separately, which allows the grid to be modified without affecting the refraction package. Output was generated for waves from the southeast, south, and southwest, with heights of 2 and 4 m and periods of 5 and 7 s. Although these are not typical fair-weather wave conditions, they are fairly common during extratropical and tropical cyclones.

Results of a case study

One of the first projects called for in the Coastal Protection Master Plan is the restoration of the Isles Dernieres barrier-island chain; thus, much work has been performed to assess the sand resources of this area. This research has been funded by the State of Louisiana, the Terrebonne Parish Police Jury and the U.S. Geological Survey. The area has been surveyed in five separate high-resolution seismic cruises and in three different vibracoring cruises. Analysis of this database has revealed that significant quantities of high-quality sand are available in the form of submerged beach ridges, tidal deltas, buried distributary and tidal channels, and the large shore-parallel Ship Shoal located some 10 km offshore of the Isles Dernieres (Penland et al., 1986; Suter and Penland, 1987). Ship Shoal is approximately 50 km long, 5 km wide, and an average of about 5 m thick. Vibracores reveal that this feature is composed almost entirely of fine sand (Fig.4). Simple calculations indicate a volume of some 1.25×10^9 m^3 of sand, enough to perform barrier restoration or beach nourishment of the Isles Dernieres more than 100 times.

Ship Shoal affects wave refraction patterns and tends to attenuate wave energy and modify the amount of longshore sediment transport (Figs.5 and 6). Waves initially break over the shoal and thus have lower velocities and impacts on the shoreline when they redevelop as secondary waves. If the entire shoal were removed, erosion and overwash would increase on the adjacent Isles Dernieres barrier-island shoreline; Fig.6 depicts this scenario with an example incorporating moderate wave energy approaching from the southwest with offshore wave heights of 2 m and wave periods of 5 s.

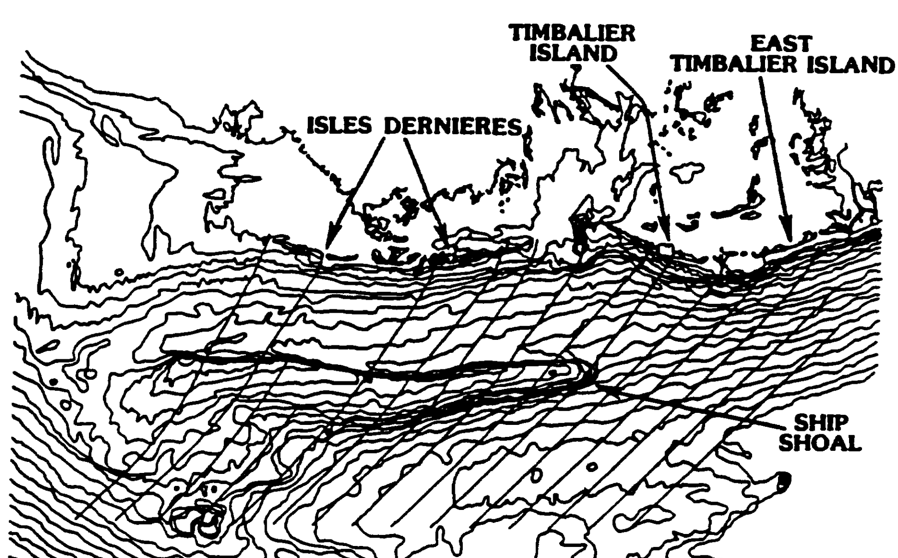

Fig.5. Wave-refraction diagram from the Ship Shoal area. Azimuth = 225°, height = 2 m, period = 5 s (from Mossa, 1986).

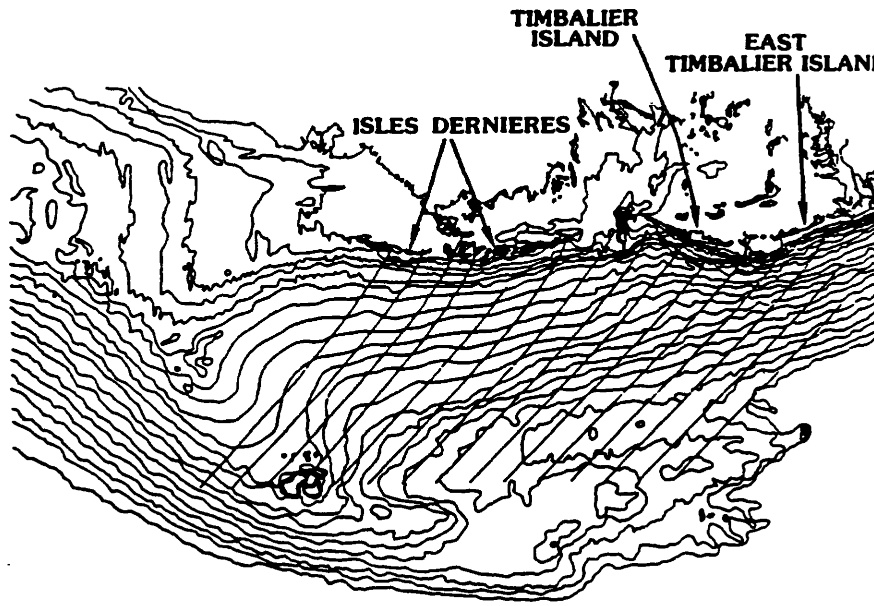

Fig.6. Wave-refraction diagram for the Ship Shoal area if the entire shoal were removed. Azimuth = 225°, height = 2 m, period = 5 s (from Mossa, 1986).

Because large-scale beach nourishment on the Louisiana coastline will eventually require the use of sand and aggregate resources from the inner shelf, assessments of offshore sand resources are an important component of Louisiana's coastal protection plans. Utilizing these deposits as borrow materials for beach nourishment will depend upon the economics of dredging from several kilometers offshore, possible environmental effects of dredging, including alteration of wave-refraction and shoreline-erosion patterns, and the formulation of leasing guidelines to permit use of sand deposits from Federal waters.

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(p 261 follows)

OFFSHORE SAND RESOURCES FOR COASTAL EROSION CONTROL IN LOUISIANA

Shea Penland[1], John R. Suter[1,2], Karen E. Ramsey[1], Randolph A. McBride[1], S. Jeffress Williams[3], and C.G.Groat[1,4]

ABSTRACT

Louisiana has the highest rates of coastal erosion and land loss in the United States. Rates of coastal land loss exceed 50 mi^2/yr. Louisiana's barrier islands are rapidly decreasing in area and eroding at rates up to 65 ft/yr. Between 1880 and 1978, Louisiana's barrier islands decreased in area by 41 percent, shrinking from 37 mi^2 to 22 mi^2. The life expectancy of individual barrier island systems ranges between 30 years for the Isles Dernieres and 225 years for the Chandeleur Islands. Preservation and restoration of our barrier island environments requires a dynamic landscape maintenance program of regularly scheduled beach nourishment, barrier restoration, shoreface nourishment and revegetation projects. Such projects require viable sources of suitable sand for construction. High resolution seismic profiles were collected in the study area during cruises from 1982 through 1986. Approximately 7500 line kilometers of profiles, both 3.5 kHz and ORE Geopulse data, were collected for this paper. Vibracores were obtained in 1983 and in 1986. A total of 152 vibracores were used in conjunction with the seismic reflection profiles to define 55 nearshore sand resource targets in the area between Marsh Island and Sandy Point. The sand resources include distributary channel, inner shelf shoal, recurved spit, tidal delta, tidal channel, submerged beach ridge, and barrier shoreface deposits. The targets range in area from about 2 km^2 to greater than 400 km^2, with estimated volumes of available sand varying from less than 2,000,000 m^3 to greater than 1,600,000,000 m^3.

INTRODUCTION

Louisiana has the highest rates of coastal erosion and wetland loss in the United States and represents the coastal erosion hot spot in the Gulf of Mexico (Figure 1). Louisiana's barrier islands are decreasing in area and eroding at rates up to 65 ft/yr (Penland and Boyd, 1981). Between 1880 and 1978, Louisiana barriers decreased in area by 41 percent, shrinking from 37 mi^2 to 22 mi^2. The life expectancy of individual barrier island systems ranges between 30 years for the Isles Dernieres and 225 years for the Chandeleur Islands. It has become critical for Louisiana to implement projects to impede the high rates of coastal erosion and wetland loss. One such plan of action is to restore the protective barrier islands using offshore sand resources. This paper describes the location of viable sand resources in offshore Louisiana for coastal erosion control.

More than 7,500 km of high-resolution seismic profiles and 150 vibracores were collected cooperatively by the Louisiana Geological Survey (LGS) and the U.S. Geological Survey (USGS). These data sets indicate that major sources of sand occur in a variety of depositional settings. The distribution of these deposits is controlled by the geometry of the fluvial and deltaic channel systems and the effect of the Holocene Transgression on these features. Offshore of the delta plain, seven types of sand sources can be identified: inner shelf shoals, submerged beach ridges, tidal deltas, tidal channels, distributary channels, and barrier shoreface deposits. This paper describes the geology of offshore Louisiana, sand resource methodology, and the distribution of the sand resources.

HOLOCENE GEOLOGIC FRAMEWORK

Relative sea level in the northern Gulf of Mexico during the late Wisconsinan lowstand fell to depths of -130 m below sea level, exposing the continental shelf and producing a set of shelf-margin deltas (Berryhill and Suter, 1986; Kindinger, 1989). Sediments were delivered to the Mississippi Fan through a submarine canyon; the youngest fan lobe was supplied by the Mississippi River between 10,000 and 25,000 yr B.P. (Coleman et al., 1983; Bouma et al., 1986). During the 18,000 yr B.P. lowstand, the Mississippi River incised a trench across the continental shelf and together with tributary streams and subaerial weathering processes, produced an erosional unconformity on the Pleistocene Prairie terrace marked by a widespread oxidation surface (Fisk, 1944). Sediments were largely restricted to infilling the Mississippi Canyon during the period 18,000 to 9,000 yr B.P. Between 9,000 and present the Mississippi River was no longer totally confined to the canyon and proceeded to develop a series of shelf-phase delta plains on the continental shelf during the Holocene transgression (Boyd et al., 1989).

The sediment volume supplied by the Mississippi River to its delta plain appears to have been unable to keep pace with the relative sea level rise that drove the Holocene transgression. The establishment of individual delta plains, built of smaller complexes by the delta switching process, indicates the existence of several periods during which the rate of sea level rise

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[4] American Geological Institute, 4220 King St., Alexandria, Va. 22302

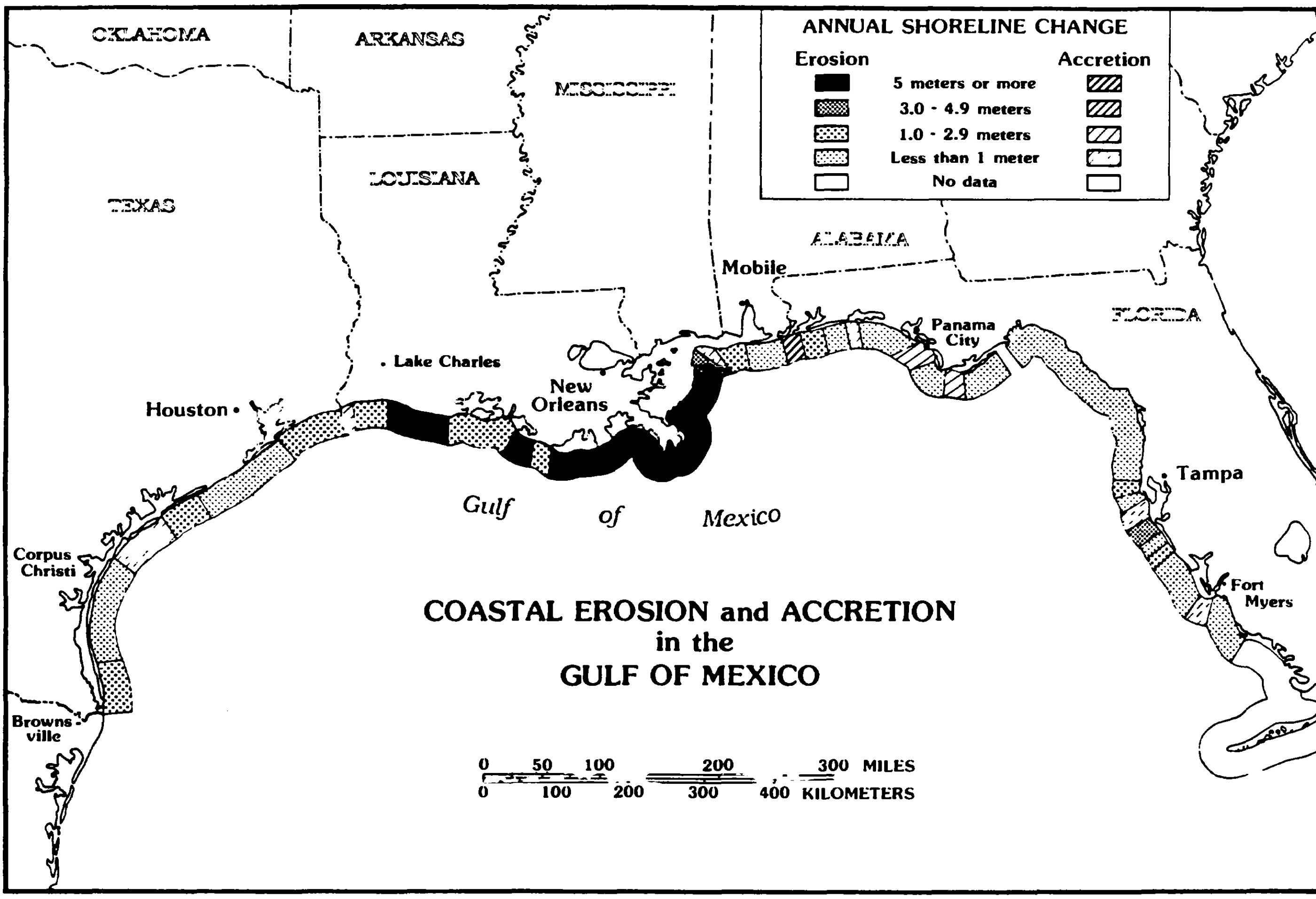

Figure 1. The distribution of coastal erosion in the Gulf of Mexico (U.S. Geological Survey 1988).

slowed of achieved a stillstand during the Holocene transgression. As rates of relative sea level rise again increased, these earlier Holocene shelf-phase delta plains were transgressed and submerged, producing large sand shoals marking the former shoreline position (Penland et al., 1989).

Each shelf-phase delta plain lies on a ravinement surface and consists of a regressive and transgressive component (Penland et al., 1988). The regressive component is built predominantly of distributary sands encased in prodelta muds capped by freshwater marsh deposits. The second component of this shelf-phase delta sequence is transgressive and consists of lagoonal deposits overlain by a barrier shoreline or shelf sandbody. The end of the Holocene transgression is marked by the culmination of the eustatic rise in sea level about 3000 yr B.P. when the Late Holocene delta plain shoreline retreated to the mouth of the Mississippi River alluvial valley. Associated with the current stillstand over the last 3000 years, the subsequent development of the Modern delta plain consisted of a series of prograding delta complexes which advanced the shoreline 150 km southeast of the highstand shoreline (Fisk 1944; Kolb and van Lopik 1958; Frazier 1967; Penland et al., 1987). During this time, the sediment volume supplied by the river exceeded regional subsidence. Deposition of the St. Bernard, Lafourche, Modern and Atchafalaya delta complexes over the last 3000 years has built the Modern delta plain.

SAND RESOURCE METHODOLOGY

Seismic

Geologic framework studies rely on seismic and vibracore tools to determine the character of onshore and offshore sediments. Offshore, this is accomplished through the use of high resolution seismic profiling techniques (Figure 2). Among other factors, the type and intensity of reflections of the sound signal from the subbottom is a function of the lithology of the seabed and submerged strata. Sound sources are towed by a research vessel along pre-plotted tracklines through the area being explored. Trackline grids are designed based upon the amount of ship time available for the cruise, the range and fuel capacity of the research vessel, the location of coastal ports, knowledge of coastal geomorphology and historical shoreline changes, and the degree of detail required for the task at hand. In a comparison of regional seismic reflection data gathered on a relatively coarsely spaced 5.5 km grid with closely spaced lease block data, it was estimated that up to 80 percent of geological features can be observed on the regional grid. This 5 km by 5 km grid is sufficiently detailed for reconnaissance purposes. For actual determination of borrow sites within a specified area, greater detail is necessary and grids were spaced about 1 km by 1 km.

Navigation data is recorded in real time aboard ship and stored on magnetic tape. These data are later processed into a trackline map at a given scale, depending upon the size of the area being surveyed. Interpretations of the seismic profiles are plotted onto mylar overlays of the trackline charts and preliminary maps of geologic targets were made. Because resolution and penetration of seismic signals in the seabed are partly functions of the frequency of the sound signal itself, two types of seismic sources were employed. Using two devices provides the ability to have one high frequency system with better resolution in the upper sediments while a second, lower frequency device can give greater penetration to deeper strata. Additionally, attenuation of the seismic signal due to absorption of the sound by the material of the seabed is related to lithology. Coarser deposits attenuate more of the signal at higher frequencies. Thus, accurate determination of the thickness of a sand section may require a lower frequency device for full penetration. The characteristic of shell beds is the almost total reflection of the sound signal. Fine-grained sediments generally produced the best reflections, except when rich in organic material, which results in high attentuation of the signal.

In this study, a Datasonics 3.5 kHz subbottom profiler was used as the high frequency tool, while an ORE Geopulse was used to provide greater penetration. Vertical resolution of these two tools is about 0.5 m and 1.5 m, respectively. Penetration averaged about 10 m for the 3.5 kHz device, and reached greater than 50 m for the Geopulse. In each case, data quality were usually poorest in shallow water nearshore. The return signals were split traced on an EPC 3200 recorder at sweep rates of 1/8 second for each channel, resulting in an effective display of 1/4 second for the entire record. Filter settings for the ORE Geopulse were variable, depending upon the area surveyed. All data were recorded on magnetic tape on a Hewlett Packard 4300 reel-to-reel recorder for subsequent playback. Navigation was accomplished by using a Northstar 500 Loran-C receiver corrected with a Morrow XYP-200 real time Loran plotter. Navigation data were recorded on magnetic tape on a Texas Instruments Silent 700, and processed into trackline maps by the U.S. Geological Survey. Seismic interpretations

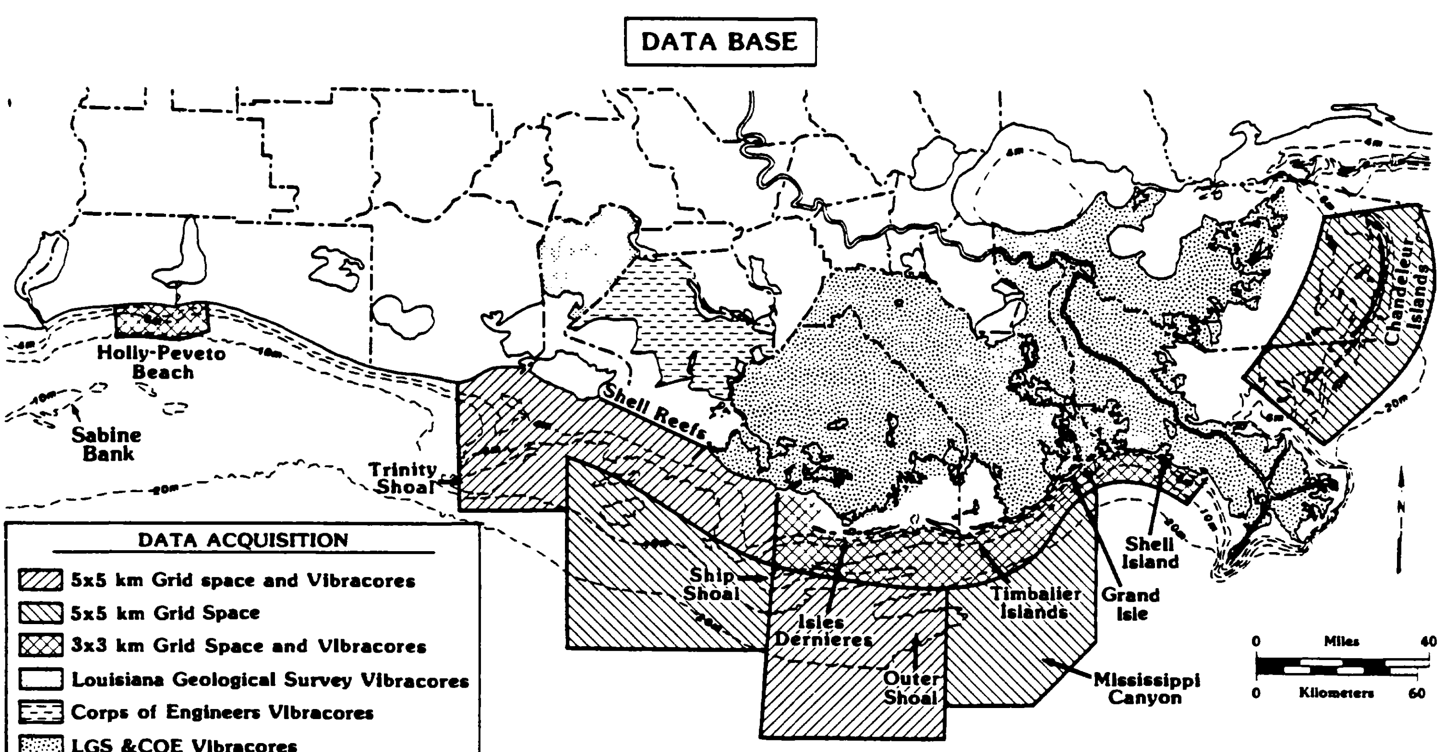

Figure 2. Location of single channel, high resolution seismic and vibracore data in Louisiana.

were plotted onto the trackline charts on mylar overlays at scales of 1:80,000.

Seismic profiles were collected in cooperatively funded cruises between 1982 and 1986. Participating agencies were the U.S. Geological Survey, U.S. Minerals Management Service, the Terrebonne Parish government, and the Louisiana Geological Survey. All cruises were performed aboard the R/V R.J. Russell and R/V Acadiana of the Louisiana Universities' Marine Consortium (LUMCON) in Cocodrie, LA.

Vibracore

Vibracoring is used extensively by the Louisiana Geological Survey to obtain shallow, undisturbed cores from unconsolidated fluvial, deltaic, coastal, and shallow marine sediments. Offshore vibracoring involves the use of a system developed by Alpine Ocean Seismic Survey. This system is capable of obtaining cores 10-15 m length. A 15 m long aluminum tower supported by 1.3 m pads, serves as a guide for a pneumatic vibrator that drives the core pipe into the substrate. Cores are retained in clear plastic liners inserted in a metal core pipe. To obtain maximum depth, two 7.5 m lengths of plastic liner are spliced together to obtain a complete 15 m in one attempt. Hydraulic jetting is used to achieve deeper penetration and longer recovery lengths in sediments that cannot be fully penetrated in one attempt, or to obtain cores of better quality. In this procedure, a new liner is inserted inside the core pipe after the first vibracore attempt is complete. The vibracore rig again is placed on the water bottom very close to the spot where the first run was completed. High pressure water is pumped via a 5 cm diameter hose down through the core pipe, washing away the sediment and allowing the core pipe to penetrate to the depth at which the first ended. Then the water pressure is turned off and the air is turned on to the vibrator, thus driving the core pipe the second 7.5 meters or to refusal.

The core analysis begins by splitting the vibracore in half using a circular saw equipped with a 19 cm carbide-tipped steel blade and an aluminum guide designed so the saw will follow a straight path over the length of the core pipe. A steel wire is then pulled lengthwise through the core pipe along the saw cut dividing the core into equal halves. The first half is cleaned, trimmed with an osmotic knife, described, then wrapped in plastic, and archived for future reference. The other half of the core is processed for grain size samples, radiocarbon dating materials, x-ray radiograph slabs, and epoxy relief peels. Each vibracore is sampled for sediment grain size analysis at an interval averaging 1-2 m except when sand bodies over 1 m thick are encountered. Here, the sampling interval for the sand bodies averages 0.5 m or less. The sediment samples collected from the vibracores are processed for grain size analysis. Analysis of sedimentary structures and facies within the core is accomplished through visual examination of the core itself, the use of epoxy relief peels, and x-ray radiographs of sections. The information from cores is recorded on a standardized description sheet, which accommodates information concerning sedimentary structures, textural characteristics, bedding thickness, particle size, and additional analysis performed on the core.

SAND RESOURCES

Interpretations of the seismic profiles were combined with the vibracore descriptions to produce the set of maps depicting potential sand resource targets in Figures 3, 4, 5, and 6. Additional targets were added based upon pre-existing data (U.S. Army Corps of Engineers, 1962; 1972; 1975; Barrett, 1971; Neese, 1984; Penland and Suter, 1983; 1988b, Suter and Penland, 1987a; Suter et al., 1987), as well as inferences regarding coastal stratigraphy. A total of 55 targets have been mapped between Marsh Island and Sandy Point. Targets shown in Figures 3, 4, 5, and 6 were originally mapped on overlays of the seismic tracklines at a scale of 1:80,00 and then shot down to page size for display purposes. The mapping base used in Figures 3, 4, 5, and 6 consists of a specially prepared combination of the National Ocean Survey 1:80,000 Navigational Charts and the Outer Continental Shelf lease blocks used by the U.S. Minerals Management Service for leasing mineral rights in Federal waters. Estimates of total thickness of sand bodies within targets were made by measurements both from seismic profiles and vibracores (Table 1). Volumetric estimates were made based on the area of the target, and average thickness of sand deposits, modified by correction factors where appropriate.

Coastal Erosion Control

Strategy

Barrier island erosion and land loss is primarily a function of sediment loss, relative sea level rise, and devegetation. Human impacts are secondary, but often serve to drastically increase coastal deterioration. To effectively manage this coastal problem, a consistent strategy must be developed and proper tactics applied. In Louisiana, two management options have been applied. One management option was to build coastal structures to combat natural processes and hold the remaining habitats in place (Figure 7), while the other management option has been to replace the material lost from the barrier island system and to hold it in place by planting dune and backbarrier marsh habitats (Figure 8). Of the two options above, the later using sediment and vegetation have proven to be the most cost-effective techniques capable of preserving and restoring Louisiana barrier shoreline habitats (Penland and Suter, 1988a). As a consequence, the strategy of any comprehensive management plan to preserve Louisiana barrier shorelines must be to pursue sediment and vegetation projects as well as mitigation projects for reversing the human impacts of man. The tactics of this strategy will include barrier island restoration, beach nourishment, shoreface nourishment, and revegetation. In order for this approach to be successful, a regularly scheduled maintenance program must be developed for each barrier-built estuary.

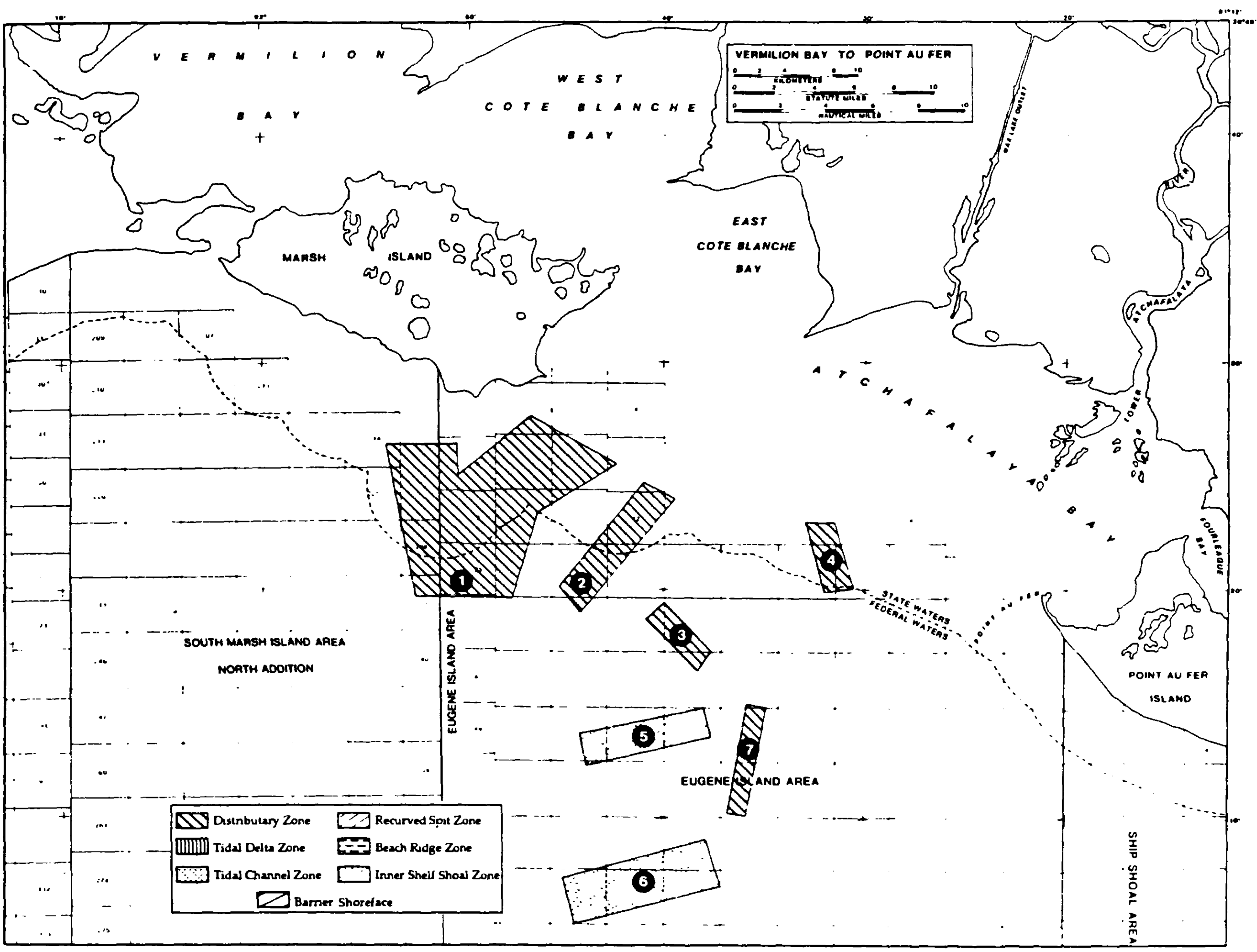

Figure 3. Sand resources offshore of Marsh Island.

Barrier Island Restoration

This is a new technique developed in Louisiana to restore transgressive barrier island habitats and prevent the island from breaching during storms. As described previously, Terrebone Parish built a barrier island restoration pilot project in the eastern Isles Dernieres which restored the island (Jones and Edmonson, 1987). This technique involves placement of fill material directly on the crest and backbarrier areas. The fill requirements are much less than a beach nourishment project per linear foot of shoreline. The restoration cost per linear foot restoration cost was $263. This project restored the dunes, vegetated backbarrier terraces, and salt marsh which prevented the island from breaching during the 1985 hurricane impacts.

Beach Nourishment

Beach nourishment projects require large volumes of high quality sand for construction, as a consequence of the economy of scale results in reduced construction cost per linear foot of beach. The average per linear foot construction cost for the USACOE 1985 Grand Isle project was $233 for 37,100 linear feet of beach; this is less than the cost of the Terrebone Parish barrier island restoration project, which required 10 times less material. In terms of cost per yd^3, the average was $2.94 per yd^3 of fill. Nationwide the typical cost of beach nourishment is $1.40-12.08 per yd^3 of fill (National Research Council, 1987).

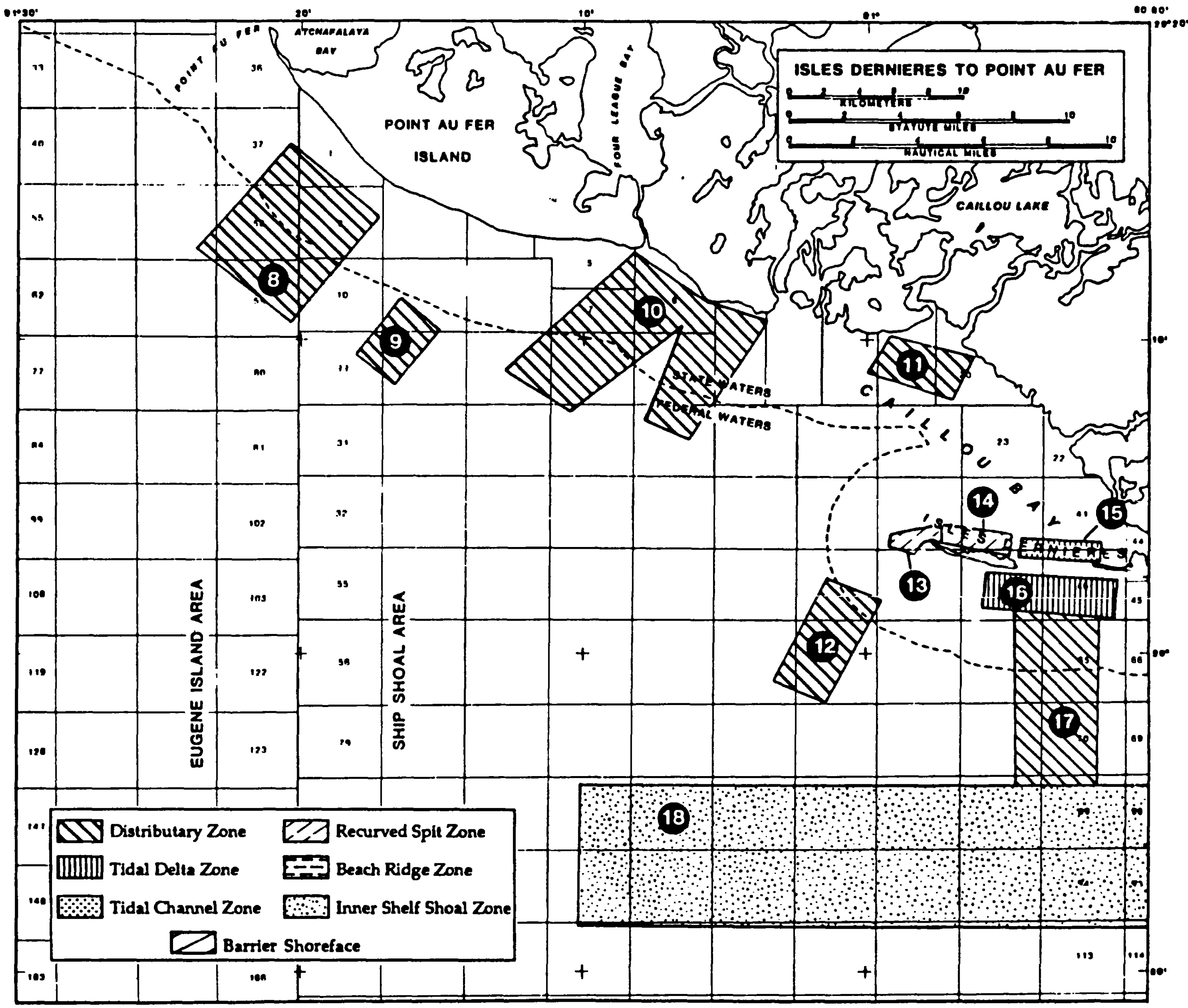

Figure 4. Sand resources offshore of the Isles Dernieres barrier shoreline.

Shoreface Nourishment

Shoreface nourishment is a new technique which has been tested in Australia, Denmark, and at Hilton Head Island, South Carolina (Brunn, 1988a). This technique builds a beach-shoreface profile in equilibrium with its process environment; as a consequence construction and maintenance costs are lower and the rapid beach erosion which immediately follows in the construction of beach nourishment projects does not occur. The advantage of the shoreface nourishment technique is the ease of dumping and the minimal earth moving equipment required. A cost comparison in Queensland, Australia indicated the average beach nourishment cost are \$3.50 yd^3 for beach fill and \$1.50 yd^3 for shoreface fill (Brunn, 1988b).

Revegetation

Building dunes and backbarrier habitats using vegetation on natural island surfaces or on dredged material is the most inexpensive method of protection (Mendelssohn, 1987). Vegetation programs cost significantly less than the various dredged material techniques and hurricane impact research has shown that dune and marsh vegetation are extremely effective at retarding coastal erosion. When vegetation is used in combination with nourishment or restoration projects, new and diverse

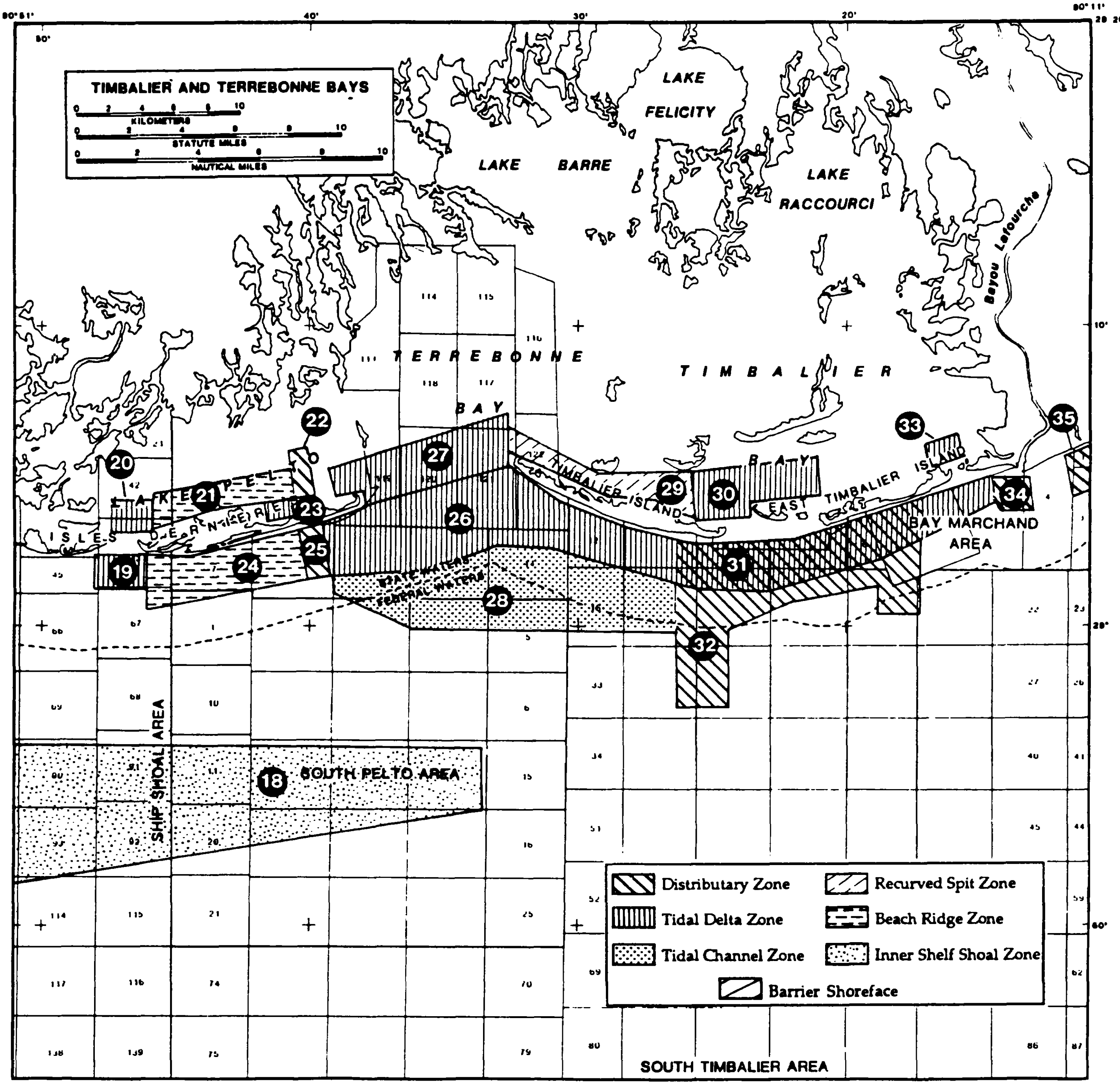

Figure 5. Sand resources offshore of the Bayou Lafourche barrier shoreline.

barrier habitats can be built. The cost for a typical dune building project is $5-10 per linear foot of barrier island.

RESULTS

An analysis of approximately 7500 line kilometers of high resolution seismic reflection profiles and 152 vibracores allowed the identification of 55 nearshore sand resource targets on the Louisiana continental shelf in the area from Marsh Island to Sandy Point. Depositional environments represented include recurved spit shoreface, flood-tidal delta, tidal channel fill, distributary channel fill, inner shelf shoal, and submerged beach ridge deposits. Selection of the most prospective sand resource targets depends upon potential use, as well as location, extent, and nature of the deposit. The primary purpose of this project was to determine the availability and suitability of nearshore sand resources for coastal erosion control. As such,

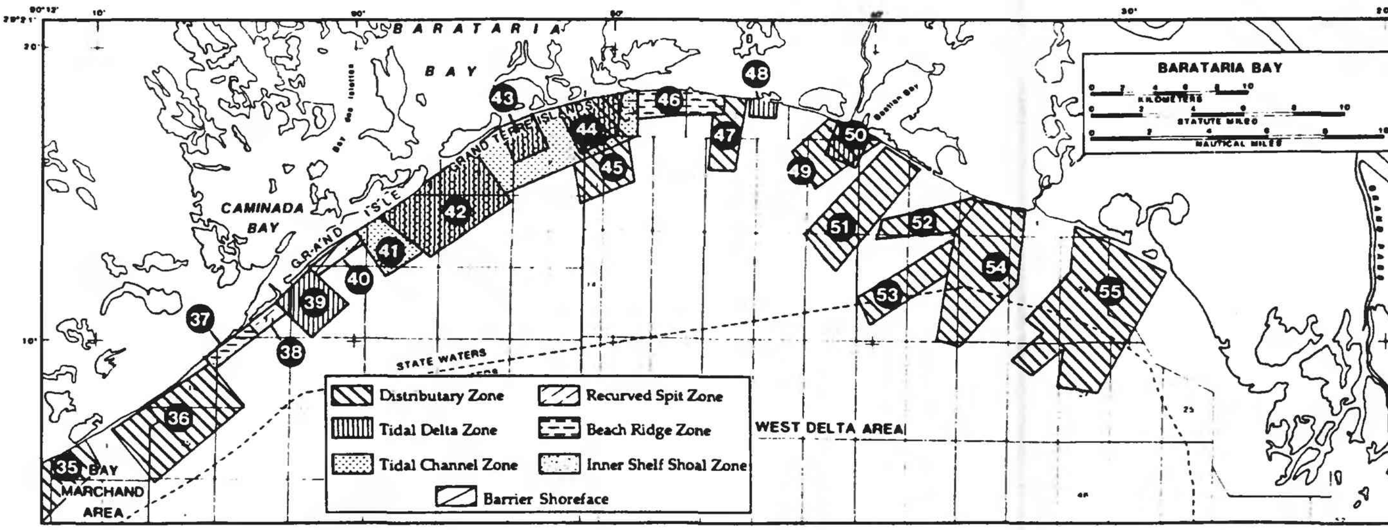

Figure 6. Sand resources offshore of the Plaquemine barrier shoreline.

the emphasis in determination of the recommended borrow sites is determined by extent and textural character of the sand bodies, not by such considerations as economic feasibility, current lack of a consistent leasing policy for non-energy minerals in Federal waters, or environmental effects of utilization of the resource, which will certainly play major roles in determining any future utilization. The most prospective resources found are the huge sand bodies of Ship Shoal and associated distributaries (greater than 1,700,000,000 m^3 of sand) Cat Island Pass tidal channels and associated tidal deltas (about 700,000,000 m^3 of sand), and Barataria Pass/Grande Terre tidal channels and associated tidal deltas (greater than 350,000,000 m^3 of sand). Not only are these deposits the largest found, they match adjacent shoreline textures, and are less variable texturally than some of the smaller targets, such as distributary channels. These smaller sand deposits contain proportionally larger admixtures of fine-grained materials than do the better sorted deposits which are being constantly winnowed by wave energy, such as Ship Shoal and the ebb tidal deltas. Utilization of these or other resources either as borrow material for beach nourishment or for any industrial use will depend upon the economics of dredging at their offshore locations and/or potential environmental effects resulting from altering existing continental shelf bathymetry.

Figure 7. Oblique aerial photograph of the East Timbalier Island seawall.

Figure 8. Oblique aerial photograph of the Eastern Isles Dernieres barrier island restoration project.

SAND RESOURCE TARGET		SAND BODY PARAMETERS				OVERBURDEN	
Number	Name	Area $(Km)^2$	Average Thickness (m)	% Sand	Estimated Volume $(x10^6 m^3)$	Type	Average Thickness (m)
1	Marsh Island Dist.	153	15.0	64	745	S, Sl, Cl, Sh	4
2	Western Shell Reef Dist. Channel	29	9.0	94	75	Cl, Sl	5
3	Central Shell Reef Dist. Channel	11	9.0	cf. #2	29	cf. #2	2-3
4	Central Shell Reef Dist. Channel	13	9.0	cf. #2	33	cf. #2	2-3
5	Marsh Is. Shoal 1	26	1.5	94	39	S, Cl	1
6	Marsh Is. Shoal 2	46	2.0	97	93	—	0
7	Southern Shell Reef Dist. Channel	13	9.0	95	34	S, Sl, Cl	4
8	Western Point Au Fer Dist. Channel	55	8.0	cf. #7	122	Sl, Cl	3-4
9	Central Point Au Fer Dist. Channel	12	0.6	cf. #7	20	Sl, Cl	3-4
10	Eastern Point Au Fer Dist. Channel	73	9.0	cf. #7	193	Sl, Cl	11
11	Grand Caillou Dist. Channel/Ebb Delta	12	8.0	64	27	—	0
12	Raccoon Point Dist. Channel	22	6.0	-75	38	cf. #10	cf. #10
13	Raccoon Point Recurved Spit	3	2.0	>75	6	—	0
14	Relict Raccoon Point Recurved Spit	4	2.0	>75	9	Sl, Cl	1
15	Coupe Colin Flood Tidal Delta	5	1.5	>75	8	—	0
16	Coupe Colin Ebb Tidal Delta	16	2.0	98	32	—	0
17	Ship Shoal Dist. Channel	47	9.0	75	123	Sl, Cl	1.5
18	Ship Shoal	433	4.0	99	1734	—	0
19	Whiskey Pass Ebb Tidal Delta	6	2.0	90	12	—	0
20	Whiskey Pass Flood Tidal Delta	5	1.5	>75	7	—	0
21	Lake Pelto Beach Ridges	15	1.5	>75	11	Cl	1-2
22	Lake Pelto Dist. Channel	3	9.0	cf. #25	9	Sl, Cl	1-2
23	Coupe Carmen Flood Tidal Delta	2	1.5	>75	2	—	0
24	Cheniere Caillou Beach Ridges	29	1.5	95	18	—	0
25	Caillou Dist. Channel	5	6.0	>75	8	S, Cl	1.5
26	Cat Island Pass Ebb Tidal Delta	73	2.0	88	145	—	0
27	Cat Island Pass Flood Tidal Delta	31	1.5	>75	46	—	0
28	Cat Island Pass Tidal Channel	164	4.0	88	492	—	0
29	Timbalier Island Recurved Spit	17	1.5	96	26	Cl	1.5
30	Little Pass Timbalier Flood Tidal Delta	20	1.5	>75	29	—	0

Table 1. Characteristics of Offshore Sand Resources

SAND RESOURCE TARGET			SAND BODY PARAMETERS			OVERBURDEN	
Number	Name	Area (Km)^2	Average Thickness (m)	% Sand	Estimated Volume (x10^6 m^3)	Type	Average Thickness (m)
31	Little Pass Timbalier Ebb Tidal Delta	59	2.0	98	119	—	0
32	Timbalier Island Dist. Channel	88	6.0	cf. #35	155	cf. #35	1-6
33	Raccoon Pass Flood Tidal Delta	3	1.5	cf. #30	4	cf. #30	0
34	Belle Pass Dist. Channel	5	6.0	cf. #35	8	cf. #36	cf. #36
35	Bayou Lafourche Dist. Channel	8	6.0	95	14	cf. #36	0-3
36	Bayou Moreau Dist. Channel	29	6.0	92	33	S, Sl, Cl	2.5
37	Cheniere Caminada Beach Ridges	3	1.5	75	2.5	Cl, Sl, S	0
38	Caminada Pass Spit	2	2.0	>75	4	—	0
39	Caminada Pass Ebb Tidal Delta	9	2.0	99	18	—	0
40	Grand Isle Shoreface	3	1.5	—	4	—	0
41	Barataria Pass/Grand Terre Tidal Channels	70	4.0	82	280	—	0
42	Barataria Pass Ebb Tidal Delta	27	2.0	94	54	Cl	0
43	Pass Abel Ebb Tidal Delta	5	2.0	>90	11	—	0
44	Quatre Bayou Pass Ebb Tidal Delta	10	2.0	>90	20	—	0
45	Cheniere Ronquille Dist.	23	9.0	-90	62	S, Sl, Cl	2.5
46	Cheniere Ronquille Beach Rdiges	10	2.0	-87	10	S, Sh, Cl	1.5
47	Bayou Chaland Dist. Channel	9	9.0	>80	23	S, Cl	5.5
48	Chaland Pass Ebb Tidal Delta	2	2.0	>75	3	—	0
49	Grand Bayou	12	9.0	cf. #45	32	—	cf. #45
50	Grand Bayou Pass Ebb Tidal Delta	5	2.0	>75	9	—	0
51	Shell Island Dist. Channel	21	9.0	cf. #45	56	cf. #45	cf. #45
52	Western Scofield Bay Dist. Channel	8	9.0	cf. #45	22	cf. #45	cf. #45
53	Central Scofield Bay Dist. Channel	11	9.0	cf. #45	28	cf. #45	cf. #45
54	Eastern Scofield Bay Dist. Channel	31	9.0	cf. #45	83	Sl, Cl	3-4
55	Dry Cypress Bayou Dist. Channel	50	9.0	-90	131	Cl, S	cf. #45

Table 1. Characteristics of Offshore Sand Resources. cf.—compare with, Cl—clay, S—sand, Sh—shell, Sl—silt.

ACKNOWLEDGEMENTS

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Chapter Six

Aeolian sand bodies of the south Louisiana coast

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1. INTRODUCTION

Various types of aeolian sand accumulations are found on the deltaic barrier coast of south Louisiana (Fig. 1). They exist as a continuum of landforms that ranges from small ephemeral mounds of sand on the upper beach to fully developed multiple dune ridges. As an integral part of the barrier sand bodies, dunes provide a significant part of the protection that these barrier islands and headlands provide for the Louisiana coastal wetlands. These aeolian accumulations are part of the total sediment store of the barriers and are part of the beach-dune-overwash cycle that is the crux of natural coastline change in this section of the Gulf of Mexico. These barrier dunes are normally lower (1.5 m maximum), and more vulnerable in their early stages than the typical, high-profile established dunes of the Atlantic coast (Godfrey and Godfrey, 1973; Leatherman, 1979). Nevertheless, in their essential relationship to upper beach and washover sedimentation processes, and in the importance of plant survival after sand burial, they are little different from the Atlantic coast barrier dunes which have been described in detail by Zaremba and Leatherman (1984). It is nevertheless suggested that the frequency of geomorphic events may be more rapid and the spatial density of overwash penetrations is greater than in the more northerly barriers.

The geomorphological processes that are involved in the development of these aeolian landforms have been observed and measured for more than 10 years along the Lafourche barrier coastline (Fig. 1), an area that is particularly

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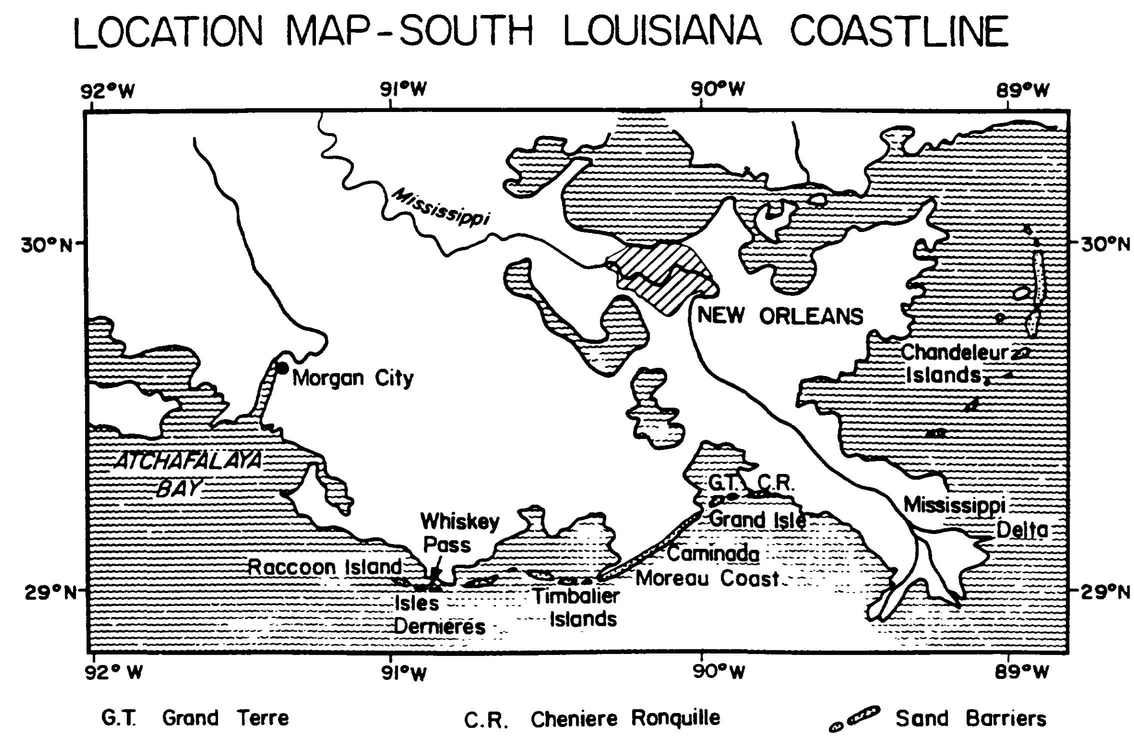


Fig. 1 Location map of deltaic barrier coastline of south Louisiana

suited to such study due to the rapid changes and the variety of coastal landforms in a relatively small area. Since these landforms exist within the rapidly retreating barrier coastline their lifespan is short. Few dunes can exist for more than 10 to 20 years before they are modified or destroyed by hurricane impact. The hurricane or severe tropical storm which has a probable return period, normally of 7 to 12 years, is the event which ends and begins the storm cycle model of barrier development along the Louisiana Gulf coastline. Effectively, the hurricane overwash planes coastal surfaces. Subsequently aeolian action and minor overwash events progressively build-up the barrier dunes (which also become progressively more resistant) until the next hurricane initiates a new cycle (Ritchie and Penland, 1988). In relation to these major and minor changes, elevation and position are the critical local factors; whereas sediment deficiency and sea-level rise due to differential subsidence are the over-riding regional factors.

The general purpose of this study is to evaluate the importance of dune development in the evolution of the barrier coastline of south Louisiana and to compare its development with the general model of barrier development which has been progressively refined from numerous studies on the Atlantic coast of the USA. Studies in Texas (Andrews, 1970; Clary, Stinson and Tanenbaum, 1974; Mathewson, Clary and Stinson, 1975) also provide valuable comparative models as they emphasise the importance of hurricanes and other storms under similar bioclimatic conditions to Louisiana. These Atlantic and Gulf Coast models apply to the south Louisiana coast although sediment deficiency, high subsidence rates and the peculiar geological setting within a major deltaic coastal plain complex (subject to the distinctive regional wave and tidal regimes of the Gulf Coast), suggest that the equivalent model for the Lousiana coast might be a regional sub-type of the standard forms that appear in most modern textbooks of coastal geomorphology. This regional sub-type of the dunes and other landforms of a hypothetical barrier island of south Louisiana is shown in Fig. 2 which provides a conceptual framework for the following detailed description and analysis of coastal aeolian landforms.

2. METHODOLOGY AND SOURCES

During the summer of 1987 the entire coastline (Fig. 1) was examined in detail. For most areas, background field studies and surveys had been completed, at different times, since 1979. Regional airborne video records of the entire coastline are available for 1984, 1985 (3 surveys), 1986, 1987 and 1988. Extensive stocks of aerial photographs dating from 1945 were also studied. Beach profiles for selected sites have been taken systematically since 1979, and for some areas additional ground information is available from reports and literature including dissertations, e.g. Gerdes (1982). However, a significant impediment for detailed morphological study is the absence of large-scale maps; the best scale available is 1 : 24,000. Moreover, the most recent USGS maps date from 1978 and most of the coastline has changed so quickly as to render these base maps of little value for field or office work.

In the field, profiles were surveyed by theodolite and reduced to mean sea level using tide gauges at Cocodrie for the islands to the west of the Caminada-Moreau Headland and at Grand Isle for the islands to the east (Fig. 1). Sediment samples were taken from beach, dune and landward washover deposits along the barrier shoreline and vegetation transects were also made.

3. SAND SUPPLY AND COASTAL PROCESSES

The source of sand for dune growth on the eroding coastline of south Louisiana is from reworking of old deltaic and beach ridge sand bodies. As the barrier islands retreat, distributary sand bodies from abandoned deltaic complexes become available for coastal processes as a result of shoreface erosion. At Caminada-Moreau, the beach ridges of Cheniere Caminada also provide a source of beach material (Fig. 3) with the landward retreating shoreface found at 6 to 9 m below sea level (Penland and Boyd, 1985). The dispersal of this sand along the foreshore depends on eastward longshore transport from a position in the centre of the Caminada-Moreau headland in the vicinity of Bay Champagne while to the west of Bay Champagne drift is westward but interrupted by the Belle Pass jetties. On Timbalier Island and Isles Dernieres

GENERALIZED LOCATION OF AEOLIAN ACCUMULATION FORMS

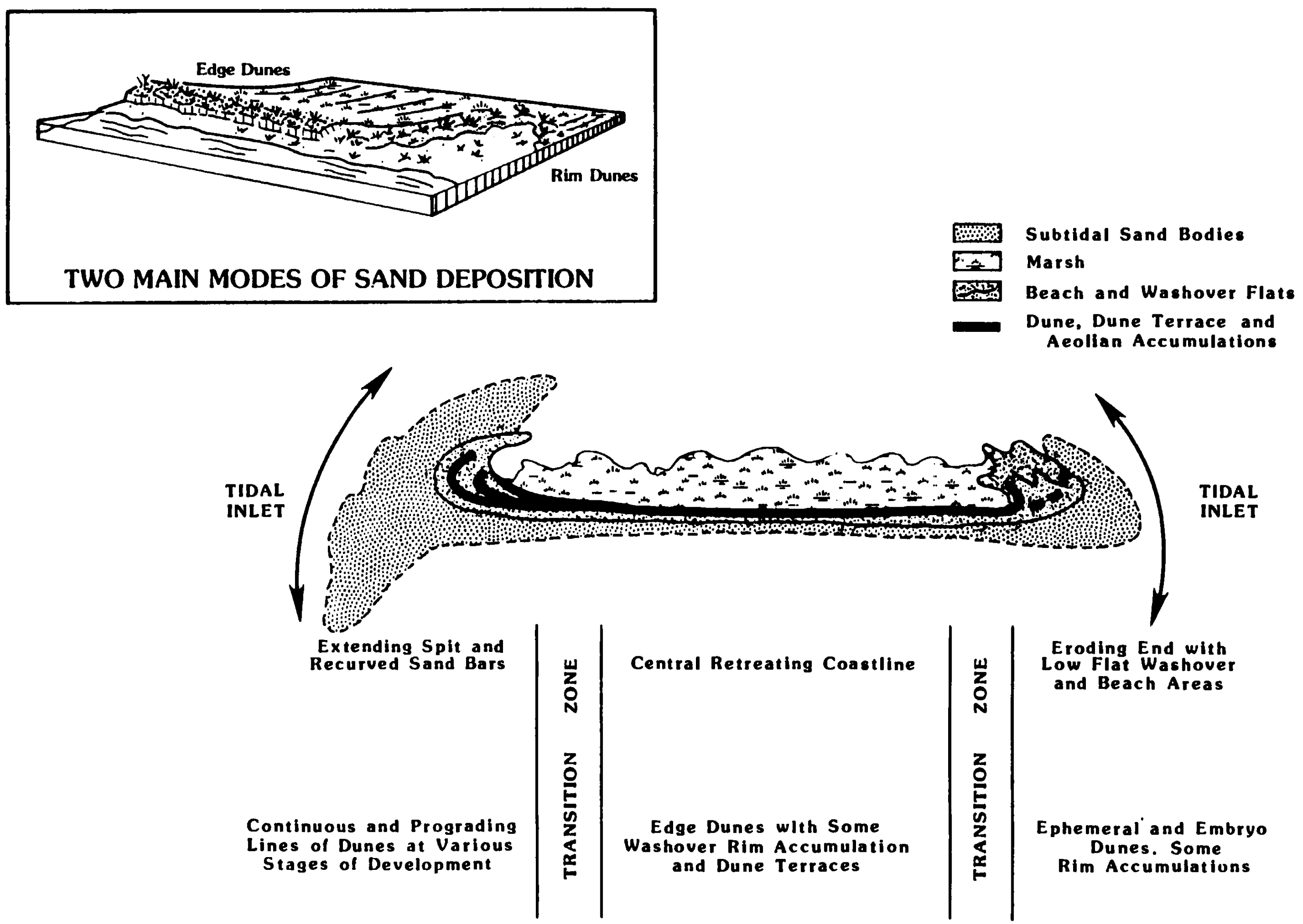


Fig. 2 Types of dunes and their typical locations

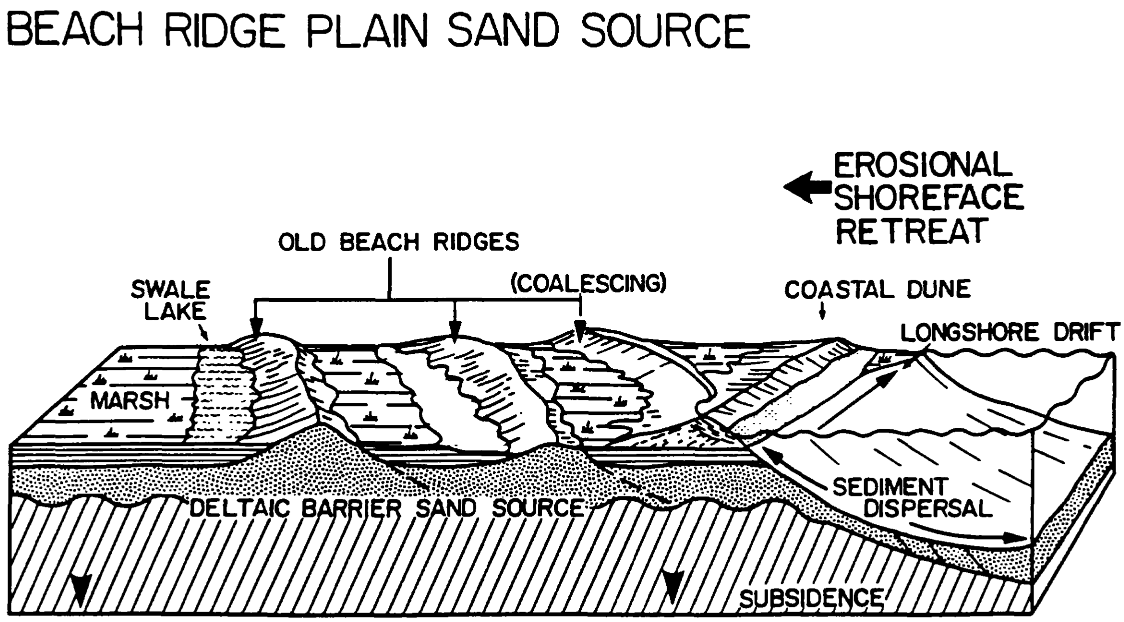


Fig. 3 Sources of sand supply for the coastline

the drift directions are to the west and the islands show elongation and tidal inlet migration in the same direction. Historically, Timbalier Island is migrating westward indicating a net westward sediment movement. The Isles Dernieres are being fragmented as a consequence of subsidence and marine erosion although the residual segments are accreting on either side of the dividing inlets, with sand derived from erosion of the island remnants.

Dune sand is reworked by the well-documented processes associated with overwash and coastal edge retreat. Neither process is unique to the coastline of Louisiana, but the low crest altitudes, variable resistance and local differences in the amount of vegetative cover create subtle changes in the response of the coastline to overwash. Like most dune systems there is a superimposition of old and new dune elements to form a mixture of remnant and active landforms. Residual ridges and new aeolian accumulations combine to provide the typical mosaic of coastal dune landforms. Characteristically, continuous lines of dunes and shore-parallel progradation are confined to downdrift spit formations (Fig. 4). Elsewhere, the coastline consists of alternating short sections of bare washover flats, oblique and shore-parallel ridges, amorphous hummocky dunes and residual areas of marsh and mangrove that have survived sand burial (Fig. 5). In some areas, the remnants of old deltaic landforms, such as levees and inter-distributary lakes emerge at the retreating coastal edge. It is this variety of small-scale coastal landforms, in such a relatively small area, that is the basis of the complexity of the evolution of this barrier coastline.

At the regional scale of south Louisiana, most coastlines are retreating but the rate of erosion varies spatially (e.g. for Caminada-Moreau the average

Fig. 4 The east end of Caminada Spit. This is an area of accretion at the distal end of the barrier headland. Large continuous dune ridges develop from the extensive downdrift beach and spit features

rate was 14 m and the maximum was 60 m over the period 1978 to 1985). This retreat is partly due to a negative sediment budget where normal offshore/onshore and longshore sand movements are not compensated by addition of sand from old beach ridges and levees. There are also variable inputs of shell-derived fragments. Other unknown sediment losses are through leaching, offshore removal to deep water during storms and transport through the tidal inlets into back bays and lagoons. Relative sea level is also rising at a rapid rate (estimated at 6.3 mm a^{-1} for the Caminada-Moreau area). There is also clear historical evidence for the reduction in size of barrier islands indicating a substantial loss of sub-aerial sand. Thus, the positive input of sands both from old beach ridges and the progressive exposure of old deltaic sand bodies does not seem to be adequate compensation for the negative effects of coastal subsidence and for sediment losses offshore and through tidal passes. Accordingly, the sand dune depositional processes of the coast of Louisiana are essentially based on reworking a limited and, probably, reducing quantity of sediment. In the absence of sand-sized sediment input from the active Mississippi, there is little prospect of change, so that beaches, dunes and washovers will continue to develop on the basis of the recirculation and reworking of a comparatively meagre sand volume. Thus, although at any one time coastal dunes are intrinsically depositional landforms, the model of dune-beach-overwash interaction for the coastline of south Louisiana is set essentially within an erosional and cyclic physiographic context.

4. VEGETATION

Typical distributions of the most important coastal plants are shown in Fig. 6 for Timbalier Island and Caminada spit. The most important single species is *Spartina patens*, a creeping, rhizomatous grass which grows up to 1.5 m tall, occurring in dunes, dune terraces and overwash flats. It seems to prefer moist sites and is associated with the typically low aeolian accumulations of the coast of south Louisiana especially to the west of the active delta. Its rate of colonisation and ability to survive sand burial make it the most common and versatile plant of the dune coastlines (Mendelssohn, 1985). In contrast, on Atlantic barrier dunes *Spartina patens* tends to occupy washover deposits inland from the main line of dunes, where the dominant plant is normally grass such as *Ammophila breviligulata* or *Uniola paniculata* (neither plant is common in south Louisiana). It is probable that the ability to recover after overwash burial is the most important reason for the dominance of *Spartina patens*; an ability recognised by Godfrey and Godfrey (1973) who described it as a sub-climax community, maintained by overwash.

On the foredunes, *Panicum amarum* may form dense, tall clumps, especially on foredunes. This plant is also rhizomatous, but unlike *Spartina patens*, does not appear to produce viable seed (Mendelssohn, 1985).

In fresh sand deposits and in brackish zones, primary colonisation is often by *Sporobolus virginicus, Paspalum vaginatum* and *Ipomoea stolonifera*. *Paspalum vaginatum* can withstand saltwater and seems to prefer wet dune areas. On the backshore and in some overwash areas on the Isle Dernieres, the low growing *Sesuvium portulacastrum* is an important pioneer species and may form isolated, rounded dune accumulations. Extensive low wash-out areas in the Isles Dernieres are covered by *Salicornia* spp. indicating salt water inundation. The runners of *Ipomoea stolonifera* cover ground with remarkable speed, especially on the backshore above the reach of storm tides although it is also found on washover terraces and in bare hollows between dune hummocks and low ridges. At Caminada spit, runners were observed to extend up to 12 m in a period of approximately three months on a backshore sand accumulation zone. Other locally dominant plants are the woody, shrub-like *Croton punctatus* and *Iva imbricata*, both of which tend to form hummocky topography especially near the shoreline. As shown on Fig. 6, numerous other plants fill ecological niches on the dune and dune terrace. From a geomorphological point of view the most important characteristic is rapid colonisation and growth. In most low dune and washover terraces overwash occurs regularly and rapid growth rates appear to be the most important characteristic of the typical dune plants of the Louisiana coast.

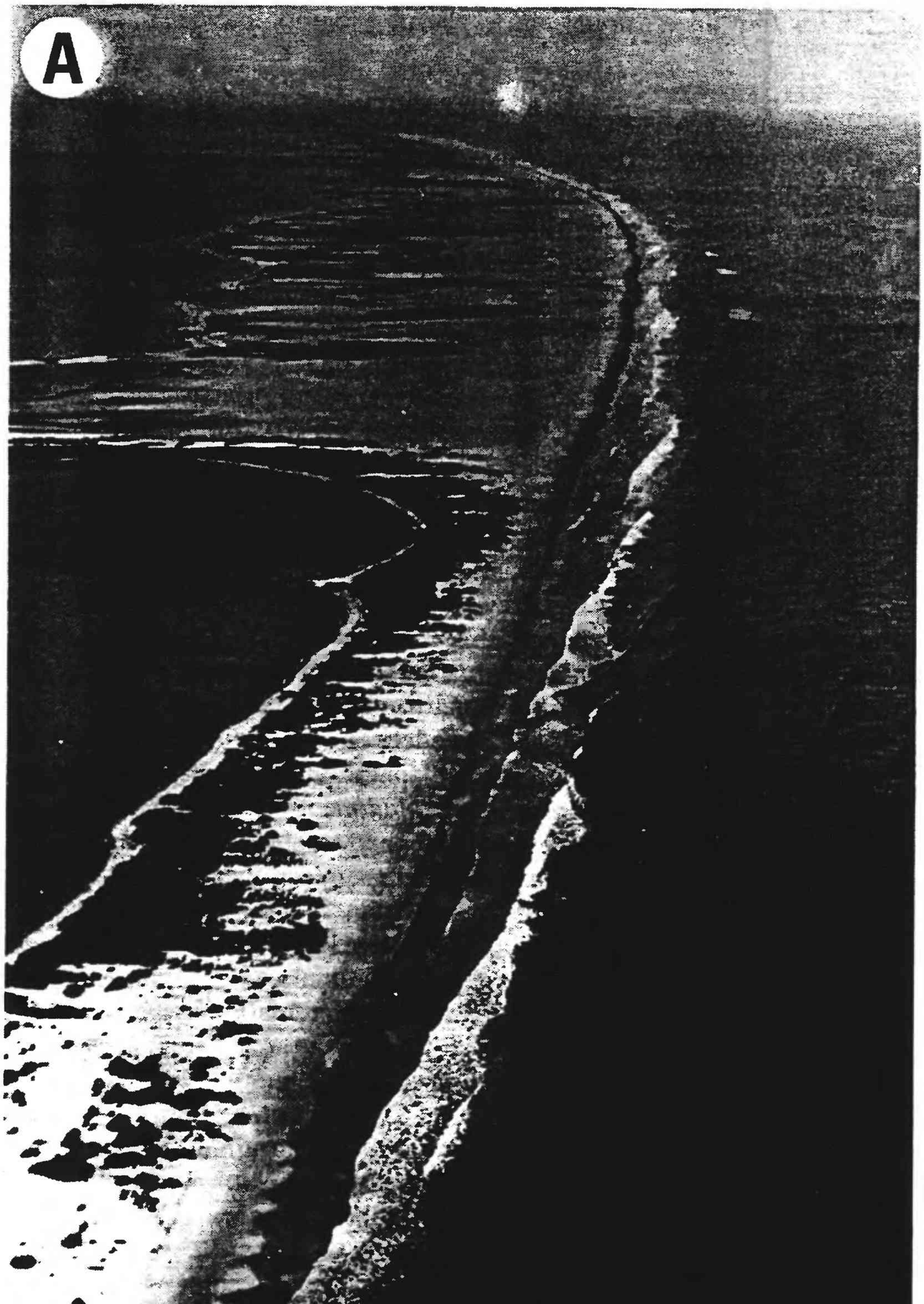


Fig. 5A The north end of the Chandeleurs, showing a narrow part of the barrier with relatively high residual dune ridges. Farther north, the coast consists of wide flat washover deposits with dunes along the margins

Fig. 5B A post-hurricane, vertical aerial photograph of the north part of the Chandeleur barrier island chain. Note the extensive washover channels and associated sand deposits between residual areas of marsh and older dunes

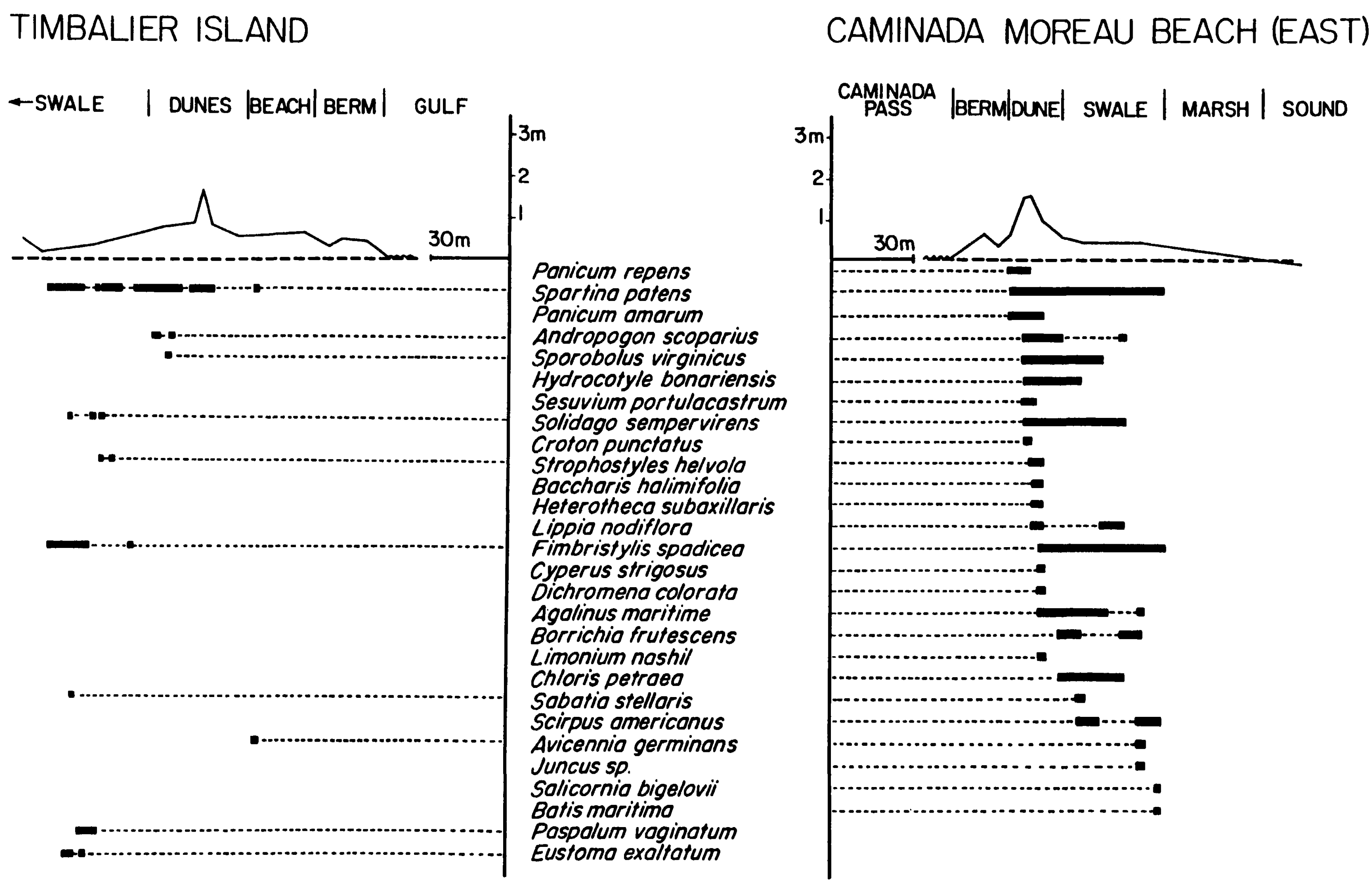


Fig. 6 Dune vegetation profile (from Mendelssohn, 1985) for Caminada Spit and Timbalier Island

5. CLIMATIC CONDITIONS AND SAND MOVEMENTS

Meteorological statistics for the coastline of south Louisiana are generally unavailable but data from New Orleans (80 km north) indicate that precipitation is on average more than 1600 mm a^{-1} with October being the driest month and July the wettest. Maximum daily temperatures range between 14°C in January to over 27°C in July and frost at the coast is unusual.

Unfortunately, reliable wind statistics for the barrier coastline are unavailable and useful calculations of aeolian processes cannot be made.

Sand samples from all the beach and dune areas have been collected and analysed, and median size values fall in the 2.10 to 2.60 ϕ range with more than 80% of all sand lying close to the median value. Thus even moderate winds can transport this fine to medium grade material if other factors such as surface wetness and local vegetation do not prevent entrainment. A very significant local variable is the presence of layers of relatively large shells on the beach and washover surfaces. In the Isles Dernieres, for example on Raccoon Island, these form extensive pavements which prevent sand transport. The most durable layers are formed of oyster shells which are derived from the reworking of reefs and beds exposed offshore by coastline retreat.

Previous research (Conaster, 1971; Murray, 1976; Ritchie and Penland, 1982) suggests that winds from the southeast are the most important in determining sand movements. However, limited data on regional wind velocities contain evidence that strong winds from the north may also be of significance, supported by evidence of sand accumulation on the backslopes of many dunes. Yet until meteorological equipment is installed in suitable locations along the coast, many basic research questions on aeolian transport dynamics will remain unresolved. Similarly, unlike the large areas of dunes such as those found on Atlantic barrier islands, there are no diagnostic morphological patterns of ridge crests, blowouts or sand waves to act as indicators of sand transport directions. The typical level terrace, low ridges and rounded forms of sand accumulation do not permit a systematic topological study of the aeolian relief from which vector information could be deduced.

6. DUNE TYPES

All dune ridges, hummocks and dune terraces grow by accretion in proportion to the availability of sand and the efficiency of vegetation in interrupting the flow of sediment. In Louisiana, there is an abundance of plants available to occupy the relatively narrow range of habitats in the coastal barriers. The warm wet climate, the proximity of the water table and the relative absence of salt spray, produce extremely fast growth rates. There is also an absence of grazing animals to inhibit growth and little evidence of burning and other adverse human impacts. The hot summer sun produces rapid surface drying, and numerous burrowing animals, especially land and beach crabs, loosen the surface.

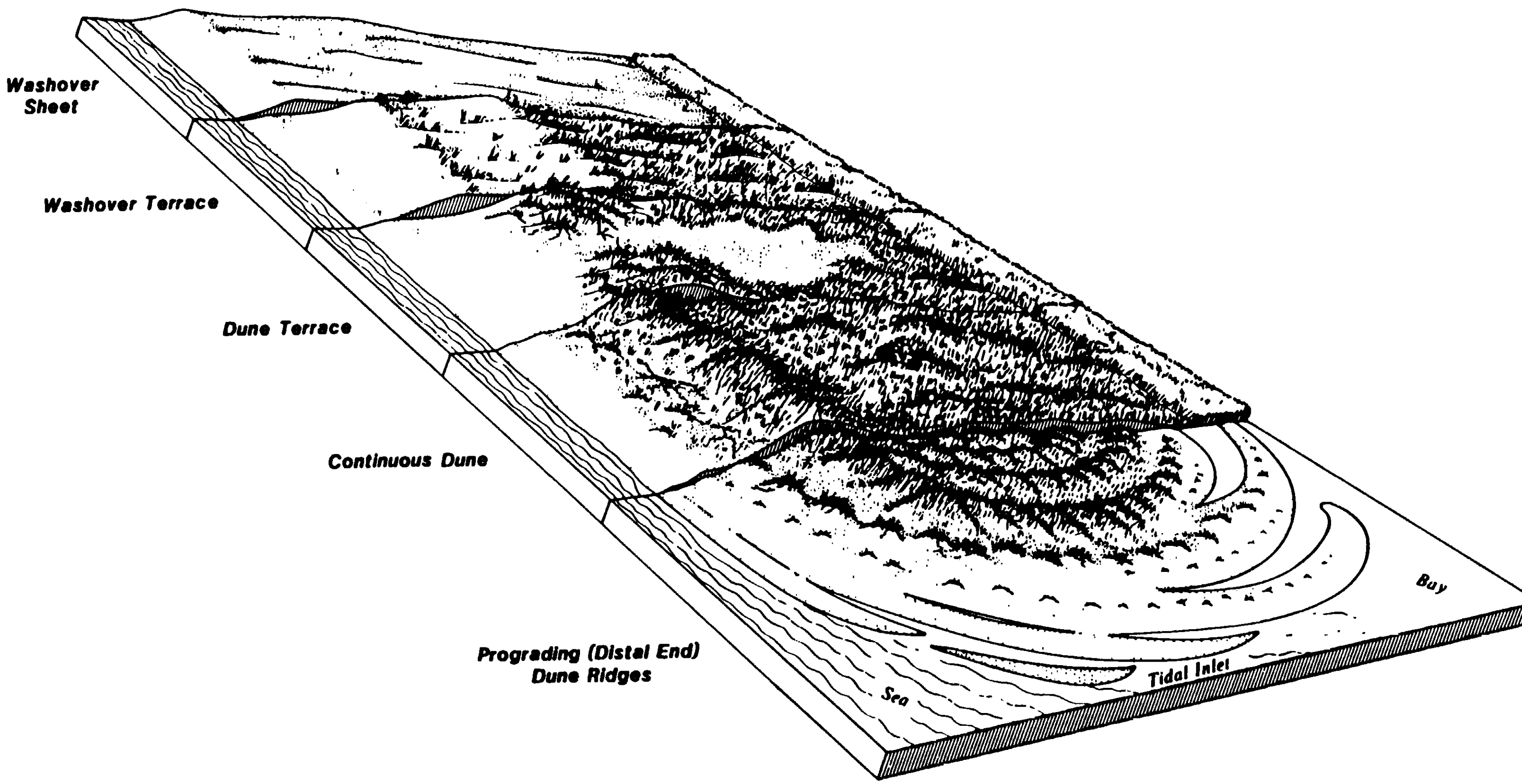


Fig. 7 Dune types of south Louisiana

Three factors control dune growth: (i) the frequency of overwash; (ii) the relative lack of sand in the total beach-dune system; and (iii) the proportion of the bare sand surface that is covered by a veneer of large shells. The dunes of the Louisiana coast are not high, rarely more than 2 m above beach level; they are discontinuous alongshore and rarely extend more than 50 m inland. Typically, dunes extend for short sections and are breached by washovers at various intervals. Mature dunes with shrubs and small trees are uncommon, except in a few areas of exceptional shore-parallel progradation or on old, inland ridges associated with past washover penetrations and stranded beach ridges.

A classification of barrier coastline types is given in Fig. 7 and provides the basic series of washover and dune forms for the south Louisiana coast. The six main types are as follows.

I. Washover sheet: this is a continuous sheet of sand produced by single or multiple washover events. It is low altitude and may be flat or gently undulating. The surface is frequently formed of shells. There are lines and patches of flotsam and dead vegetation (including seaweed). Dune forms are small, isolated or in localised groups. Due to the frequency of washover (often more than ten times per annum), dunes are essentially ephemeral. Nevertheless, being low, the surface is relatively close to the water table and vegetation colonisation can be rapid.

II. Washover terrace: the washover terrace is slightly higher than the washover sheet. The surface is normally covered by vegetation. Usually, the area is undulating or gently ridged. There are no distinctive shore-parallel or transverse dunes; the best description is 'amorphous'. The terrace suffers washover but the frequency is much less than type I, possibly once a year. Washover takes the form of a sheet of sand rather than narrow tongue-shaped penetrations and most of the sand is deposited near the coastal edge. If the washover cover is thin, most of the vegetation survives and continues to grow through the overburden.

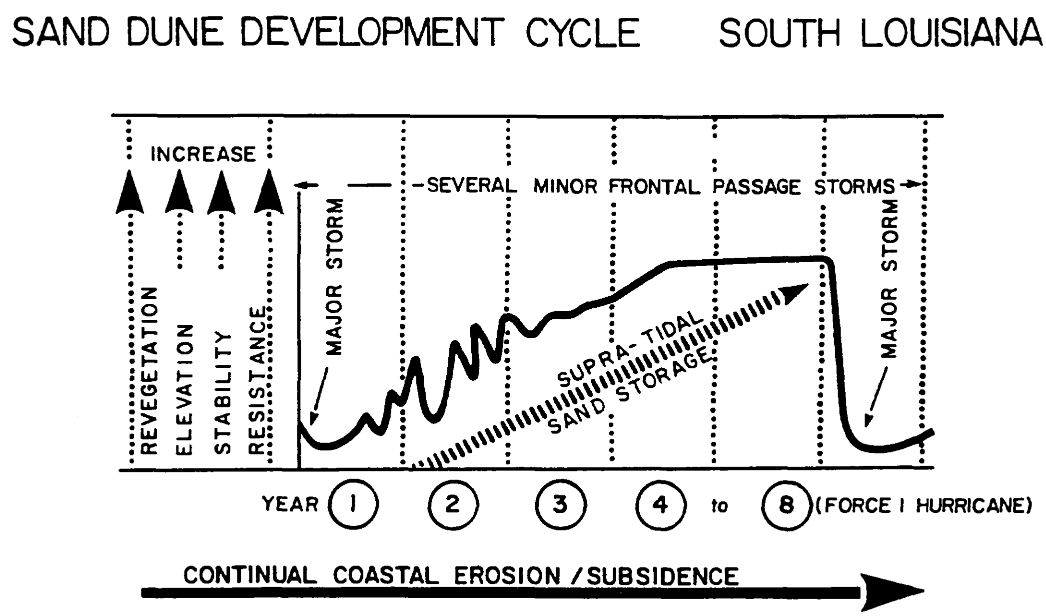
III. Dune terrace: the dune terrace can be distinguished from the washover terrace by its greater height, relief amplitude and relative maturity of vegetation as indicated by density and species mixture. Whereas the washover terrace has amorphous but low aeolian forms, the dune terrace has distinctive ridges and low sand hillocks, usually concentrated near the shoreline. As a consequence of uneven elevations, most washover processes focus on the lower parts of the backshore. Accordingly, overwash is confined and develops higher flow regimes, leading to deep tongue-shaped or linear sand deposits which may extend across the terrace. Since these bare sand areas are often colonised by pioneer vegetation, there is a wide range of species on the dune terrace.

IV. Continuous dune: the essential characteristics of the continuous dune are that it is higher, fully vegetated, more or less unbroken, and only rarely breached, overtopped or overwashed. Sand accumulation is concentrated on the incipient foredune which, as it grows, prevents sand transport farther inland. There may be occasional low points in the foredune crest where high-level overwash penetrates but these tend to be rapidly sealed and revegetated. The foredune is shore parallel and exhibits normal seasonal profile changes in that winter storm surges scarp the dune face; in summer, sand from the upper beach transfers to the dune face and there is accretion and dune progradation. This progradational slope is colonised by pioneer vegetation and in some areas may form the basis of a more 'permanent' encroachment onto the backshore.

V. Prograding lines of dunes: a variation on the continuous dune type may be found in some parts of the south Louisiana coast where longshore sediment transfer produces a rapidly prograding beach platform, often with multiple nearshore bars and upper beach berms. As a consequence of this progradation, dunes develop as a series of shore-parallel ridges. These are normally curved and radiate outwards from a nodal hinge-point at the origin of spit curvature. The dune ridges may continue to curve around the end of the island as shore-parallel features which mirror the extension of the beach. The dunes are at different stages of development and the intervening depressions normally have finer, water-lain sediment and are usually bare of vegetation and occasionally filled with sea water. This progradational type V occurs exclusively at the distal end of islands and headland barrier beaches (Fig. 2).

VI. Artificial dune ridges: on Timbalier Island and Grand Isle there are examples of artificial dunes. These have been raised to provide protection to some low, vulnerable areas of the coastline. At Timbalier Island the dunes were created by sand-trapping fences (Mendelssohn, 1985) and at Grand Isle the ridges were shaped by earth-moving equipment. In both areas, vegetation cover was achieved by a combination of planting and natural processes.

In theory, the five types of natural sand accumulation form a sequence that could proceed from the washover sheet to the continuous dune stage. In practice, complete sequential development seldom takes place either because there is insufficient time to complete the cycle or the barrier headland or island dunes are eroding rapidly and being continuously overwashed. Several detailed examples of these dune types, and the sequence of change from one type to another, are given below. Repeated profile measurements are shown in Figs 9 to 13. These case studies demonstrate both the rates of change and the complexity of real, rather than model, dune and aeolian forms on this rapidly changing coast.



TYPICAL OVERWASH ELEVATIONS ARE:

MINOR COLD FRONT	10-15 PER YEAR	1·42 to 1·73m
FORCE I HURRICANE	I PER 8 YEARS	1·73 to 2·92m
FORCE 5 HURRICANE	I PER 32 YEARS	3·50 to 7·00m

Fig. 8 Cycle of overwash as defined by washover and hurricanes

Any evolutionary sequence of dune growth has to be set within the general model of coastline development which, as shown on Fig. 8, is controlled by the return period of overwash embracing the 10 to 12 year cycle of major hurricane impact. In essence, the capacity for any dune area to grow and to consolidate is controlled by the frequency and intensity of overwash. For low, vulnerable areas such as washover sheets this may occur up to 15 times per year and substantial dune growth is impossible; for high continuous dunes only a major hurricane can interrupt the growth sequence but when such a storm does occur, the dunes are destroyed and the area is reduced to a semi-continuous sand plain.

Since the barrier shorelines of Louisiana are eroding, transgressing landwards and subsiding differentially, there are few areas of accretion, and it is logical to describe the cycle of dune development as being primarily destructive with elements of consolidation and temporary change to higher, more stable landforms. Therefore, the most rapid and dramatic change is from some form of vegetated dune to a bare washover sheet. In this destructive, major storm impact phase, the landforms do not pass progressively through intermediate stages but revert directly to the washover landforms. The major storm destructive phase is not a step-wise sequence, more a reversion to a common starting point—the washover sheet. Within this storm-punctuated model, there are subsidiary changes where minor storms may alter the dunes from one type to another and, in contrast, in the absence of major overwash, the sequence can produce relatively rapid sand accretion with associated vegetation cover, to create higher more continuous coastal landforms.

The modes of sand deposition in these terrace and dune forms are not unique to the Louisiana coastline. Plant survival after overwash burial, superimposition on remnant beach or dune ridges and primary pioneer colonisation on the upper beach or washover flat are common to most dune systems on all coastal barriers dominated by washover cycles. A frequent location for sand accretion is on the perimeter of a washover sheet. This is a variation of the survival type (III/IV) of incipient dune development. Frequently, the limit of overwash penetration is characterised by a slightly higher ridge of sand and beach debris, including root stocks and viable seeds, which are often stranded on this perimeter. Usually the ridge is less than 0.2 m high but this is sufficient to act as a zone of preferred deposition, especially as it marks the limit of vegetation beyond the overwash. Normally this ridge lies on the landward limit of the washover flat but it also occurs on the side (lateral form) and may be skewed according to the precise direction of the overwash surge. Field observations indicate that this 'rim dune' is a favoured area for relatively rapid dune growth because of the presence of vegetation to trap sand blown from the washover flat, the availability of seeds and rhizomes, the stimulation of sand burial and possibly enhanced nutrient availability.

Another favoured area for dune growth is the scarped edge of an old dune ridge or terrace. If run-up fails to surmount the barrier crest, it invariably cuts a low escarpment. When the water level falls, windbown sand is deposited along the scarp. Since only a small amount of sand moves beyond the scarp, there is relatively rapid deposition, although it rarely extends more than a few metres inland, giving rise to the distinctive concave transition between the scarp edge dune and the pre-existing terrace. Normally the vegetation continues across this transition, although the percentage of ground cover is greater on the older terrace surface. An important variant of this type is a ridge of shells, sometimes up to 0.4 m high and 4 m deep which may be left at the top of the wave-cut scarp and formed during storms. Observations at such times reveal that the relatively buoyant shells (and other flotsam) are trapped by the scarp topography especially where remnant vegetation provides an additional barrier. Plants take longer to colonise these shell ridges which are left as distinctive reminders of previous storms. Further inland, overwashed patches of shell are flatter, usually 5 to 20 m in length, and remain as zones of slow vegetation colonisation.

A distinctive feature of aeolian deposition on the Louisiana coast is the relatively short distance of primary and secondary sand transport. Vegetation growth is rapid and bare sand areas tend to seal relatively quickly, especially by rapidly growing creeping plants such as *Ipomoea stolonifera*. Ridges and mounds close to a sand source grow rapidly and only small quantities of sand

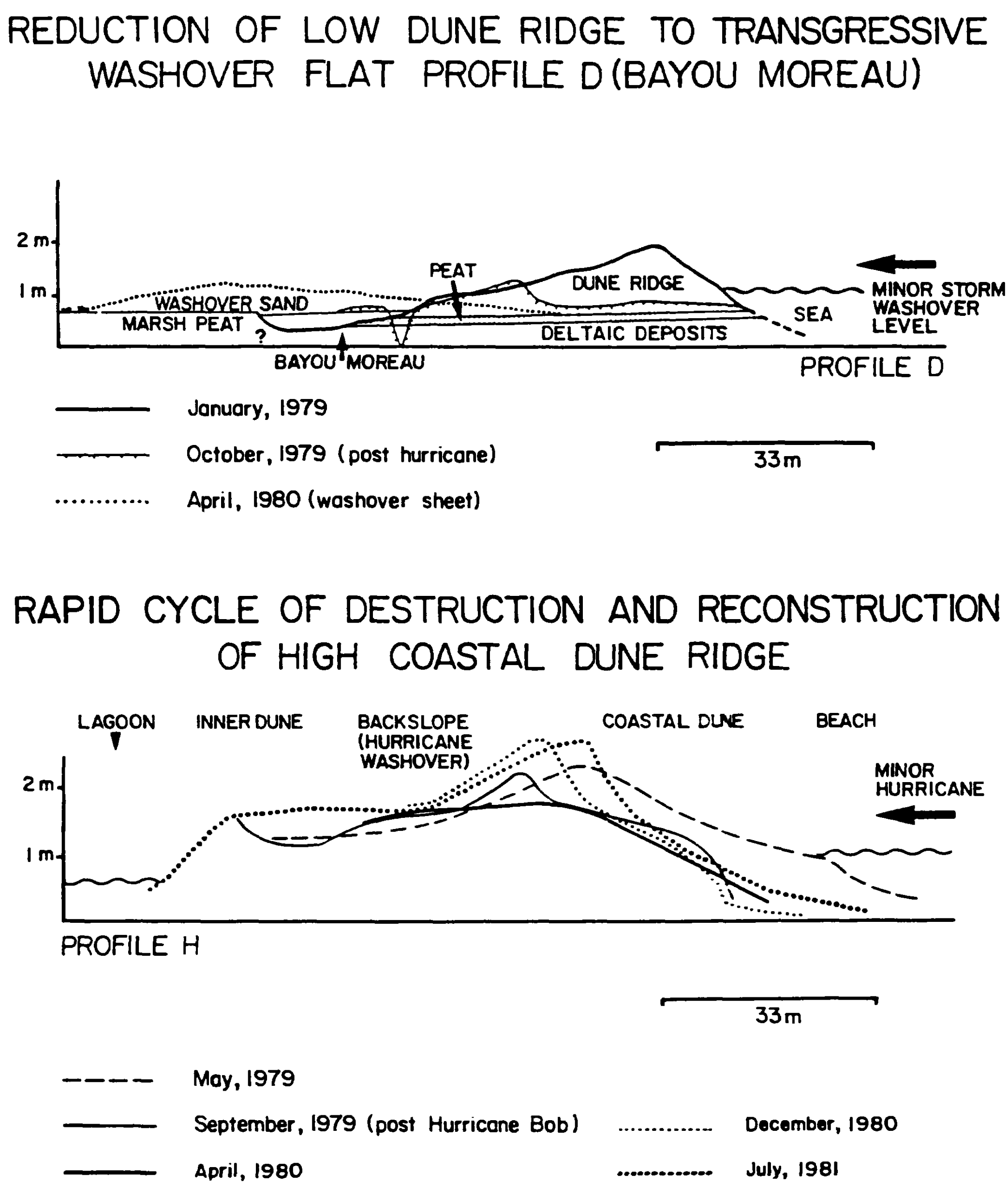


Fig. 9 Profile D and Profile H (Caminada-Moreau)

escape beyond the zone of first contact with vegetation. On days with very strong winds, repeated observations indicate a singular absence of long-distance sand movements. The landward encroachment of sand onto marshes, mangroves, backswamps and lakes is mainly by overwash and only rarely by wind.

7. EXAMPLES OF DUNE TYPES AND SEQUENCES OF CHANGE

The following examples are selected to show the various types of dunes and smaller aeolian accumulations of the barrier coastline of south Louisiana.

They also provide case studies of typical changes from one type of landform to another.

Profile D, Fig. 9, shows the conversion of a dune ridge to a washover sheet as a consequence of coastal erosion proceeding landwards to intersect the shore-parallel meander bend of Bayou Moreau (Caminada Coast). The major change occurred in 1979 to 1980. Since that period the area has remained as a washover terrace and coastal erosion has averaged $17\,\mathrm{m\,a^{-1}}$. The extension of the washover sheet has been greater, averaging $19\,\mathrm{m\,a^{-1}}$. Because of this high rate of change, the area has not been colonised by vegetation due to repeated overwashing, and any incipient dune developments are ephemeral.

Profile H, Fig. 9 (lower) shows an example of simple foredune accretion in an area of the Caminada Coast that is raised above the threshold of most storm surges. The rate of accretion can be gauged by comparing the April and December profiles for 1980. By July 1981 the dune was higher and the form had relocated a short distance to seaward. Nevertheless, the beach zone was relatively narrow and suffered severe damage when the three hurricanes crossed this area in 1985. The sea broke through to the lagoon to form an inlet which closed in 1986.

Profile A (at the west end of the Caminada Coast) (Fig. 10) was surveyed at frequent intervals to record the changes from dune terrace and ridges to hummocky dunes within a small area. The most important profile is July 1979, after Hurricane Bob. The overwash from this event destroyed the main dune ridge and transferred sand landwards as a 0.3 to 0.5 m thick unit. Part of this sand was derived from the upper beach. Within four weeks, dune ridges had reformed from vegetated remnants of the original dune field. The persistence of these clumps of vegetation was vital to rapid sand accumulation and dune rebuilding. In this area, patches of *Panicum amarum* and *Spartina patens* appeared to be stimulated where burial was of the order of 0.1 to 0.15 m. The spread of the surface creeping plant *Ipomoea stolonifera* was particularly important. Since *Panicum amarum* and *Croton punctatus* were vigorous on the frontal dune ridge, it was possible to confirm the view of Mendelssohn (1985) that these plants tend to produce higher, hummocky forms rather than continuous dune ridges. During a full year there was a net increase in supra-littoral sand storage at the expense of the beach zone, producing a net increase in height without extending the sand prism landwards.

Profile J (Fig. 10, lower) is located in an area of continuous dunes at the base of the Caminada spit and is reduced to two time periods to show simple loss and gain positions. After the hurricanes of 1985, the July 1986 profile was surveyed to show the substantial change that had occurred, along with the beginnings of revegetation and geomorphological recovery.

The second group of profiles illustrates local variations from other parts of the barrier coastline and which were surveyed in the Isles Dernieres. Timbalier and Grand Terre Islands.

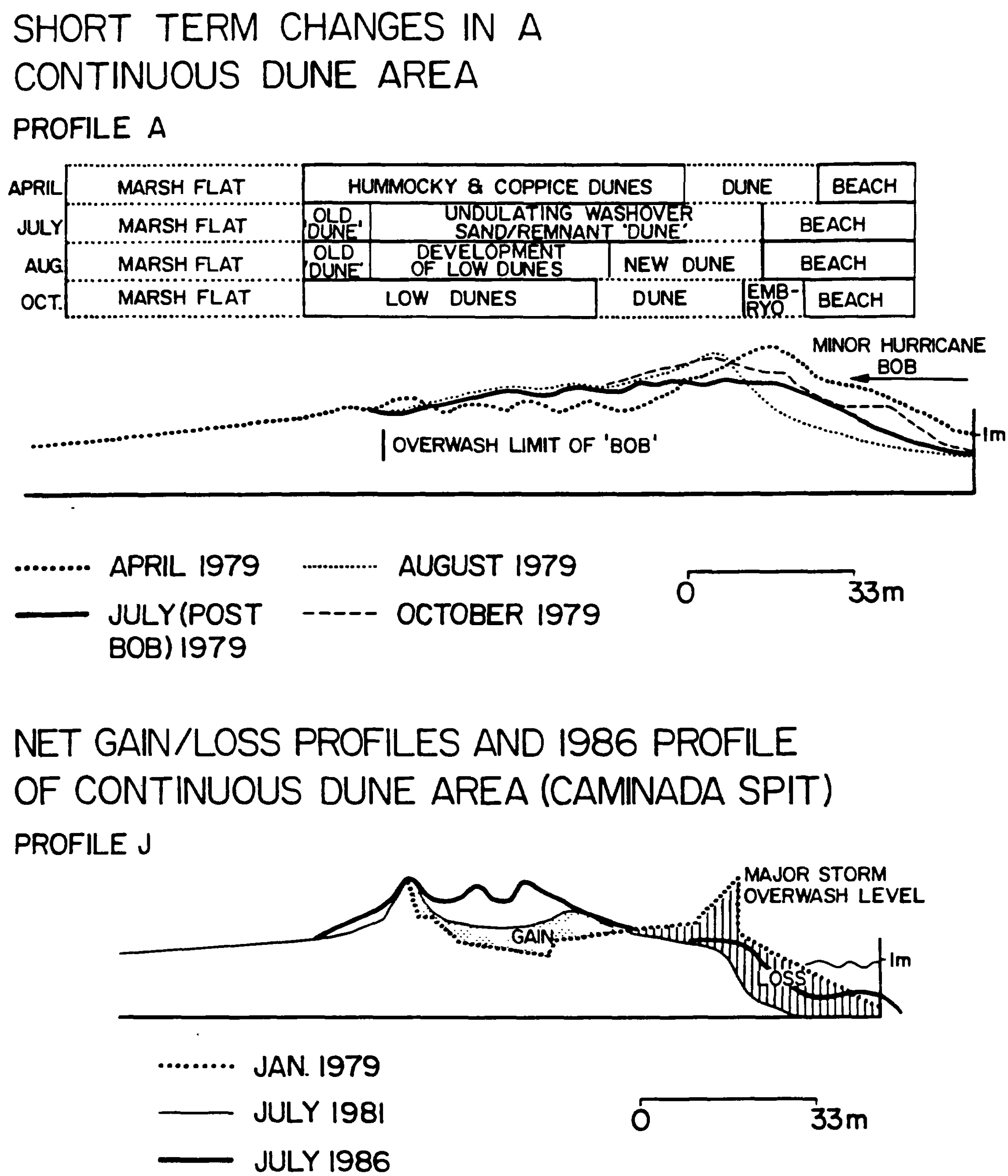


Fig. 10 Profile A and Profile J (Caminada-Moreau)

In the Isles Dernieres, several profiles are available to show typical dune and other aeolian accumulation forms on a rapidly eroding series of low barrier Islands.

Profile 3 is located near the west end of the island to the east of Whiskey Pass (Isles Dernieres) and is an example of simple accumulation at the edge of a fully vegetated terrace. The vegetation is dominated by *Spartina patens* and the edge is only 0.4 m above the level of the upper beach so that in terms of height and width it is a typical frontal dune. It is also representative

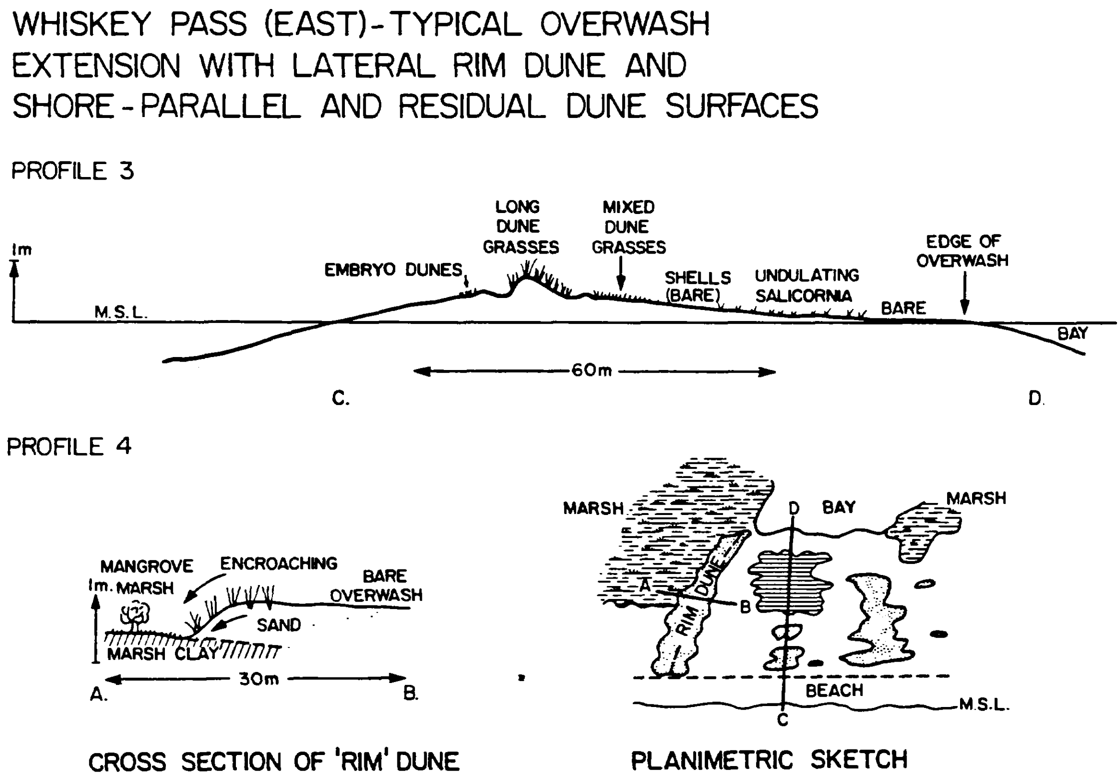


Fig. 11 Profiles 3 and 4 (Whiskey Pass, Isles Dernieres) and sketch of features near Profile 3

of a rapidly changing area in that only 20% of the ground is vegetated, and coastal erosion will ensure that full revegetation will not occur.

Further east on the same island, Profile 4 (Fig. 11) represents typical first-stage colonisation of an extensive, partly shell-covered washover flat with rim dune accumulation on the west margin (Profile 4). The sketch on Fig. 11 shows the spatial relationships of these small-scale features. The vegetated hillocks tend to be forming normal to the beach, but there are many individual clumps of vegetation with rounded pioneer sand accumulations, rarely more than 0.4 m high.

With the rapidity of change along the coastline of south Louisiana, the most common dune type is some form of accumulation at the scarped edge of a dune terrace. Since the coastline is retreating at rates that are never less than a few metres per year, the frontal dune or dune terrace is being aperiodically undercut, depending on its elevation and position on the barrier shoreline. The profile from Timbalier Island (Fig. 12) is an actual example of the steep, narrow, sinuous and continuously evolving edge dune shown in idealised form in Fig. 2.

At the ends of most islands, longshore drift causes sand to accumulate and the amount of erosion is less. Within the barrier island model this location is typically stable or accreting until a hurricane reduces the area to a washover

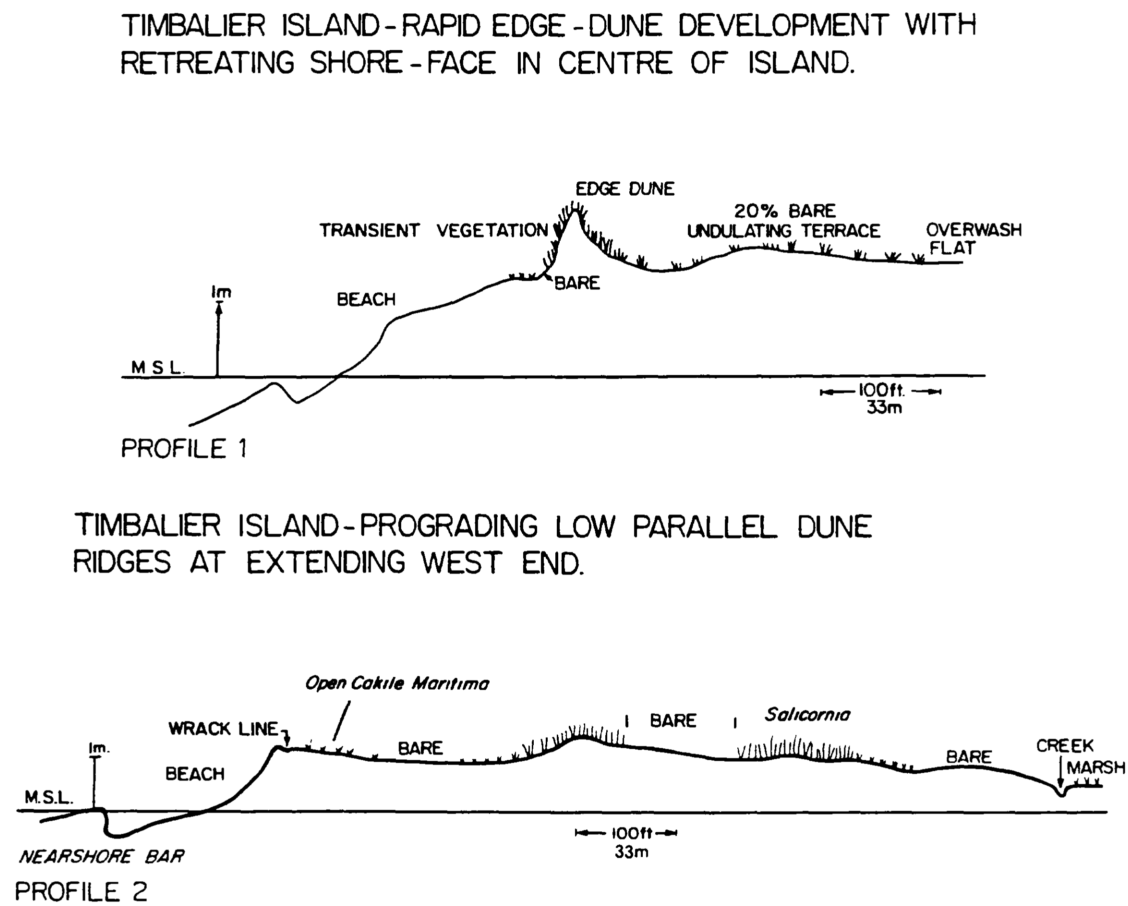


Fig. 12 Profiles 1 and 2 Timbalier Island (including progradational downdrift location)

surface, with sand coming from longshore transport and tidal inlets (Fig. 2). Swash bars and recurved beach ridges form around inlet margins and dunes develop on these higher sub-parallel ridges. Some islands, like Timbalier, are migrating rapidly westward as a series of elongating beach ridges that provide the foundation for prograding sand dunes (Fig. 12). In contrast, the west end of Grand Terre is relatively stable due to the influence of the important, navigational tidal inlet at Barataria Pass and the dunes here do not display the characteristic series of low, young, immature ridges of the more dynamic islands. This profile (Fig. 13) has a thick wedge of sand with distinct hummocky forms leading to a well-developed sand ridge. The vegetation is different, being dominated by shrubs (i.e. *Croton punctatus*) on the uneven frontal dune terrace succeeding to a mature dune ridge with relatively large shrubs and small trees. In contrast, the central part of Grand Terre has simple edge accumulation dunes, with beach sand and reworked dune terrace sand encroaching onto the relatively high, mature dune terrace that is characteristic of most of this flanking barrier island (Fig. 13). This pattern is typical of the subsiding barrier islands east of Grand Isle.

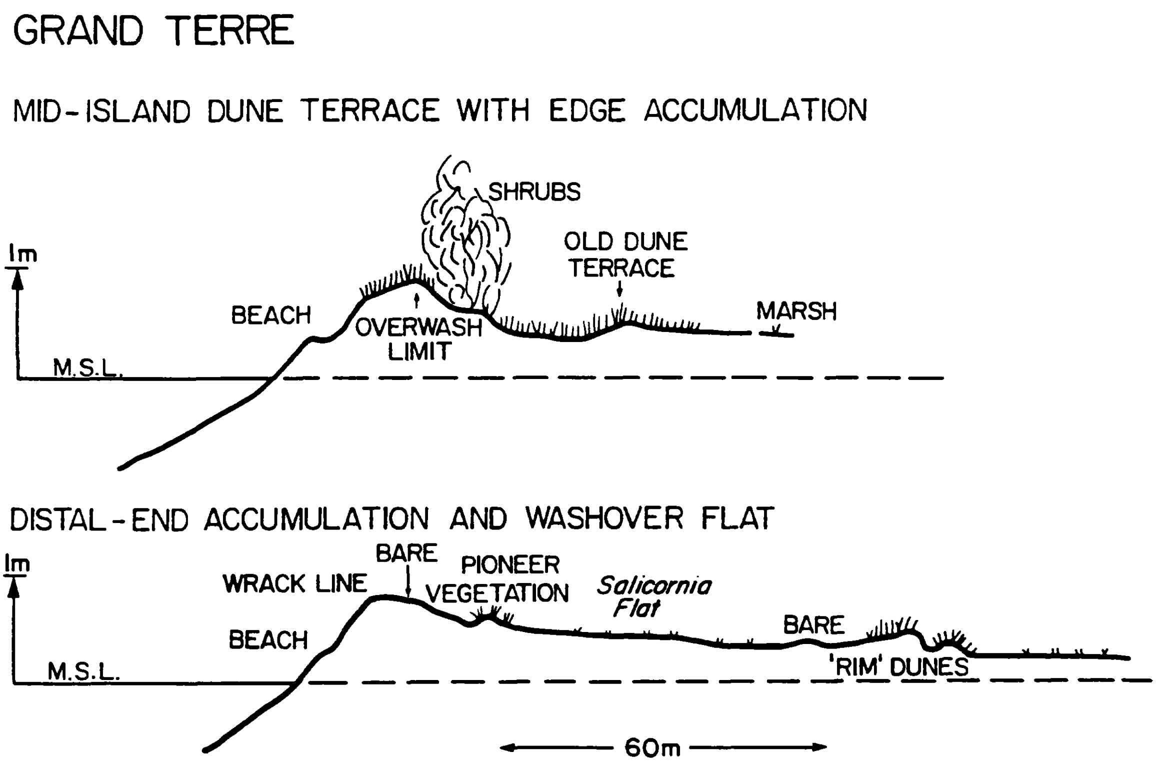


Fig. 13 West end and central part of Grand Terre

8. CONCLUSION

The aeolian coastal forms of the barrier coastline of south Louisiana are low, small, dynamic, short-lived, and characterised by rapid vegetational consolidation by a great number of indigenous species. They are little disturbed by man or animals. The sand is fine grained and easily transported. Aeolian processes are almost entirely constructive with deflation and blowout development almost unknown. Topographically, they are simple, in that there is an absence of older parallel or oblique or redepositional dune ridges. Complexity is introduced by sand accumulating on older non-aeolian landforms such as beach ridges or levees. Dune ridge or aeolian sand sheet migration is almost unknown. The life cycle of any dunescape is rapid with most dunes existing for 1 to 15 years before being overtaken by coast erosion or modified by overwash. Nevertheless, to describe these aeolian forms as being short-lived and easily destroyed is slightly misleading, in the sense that it would be better to describe them as being subjected to rapid changes. The south Louisiana dunes are the protection of the barrier coast. They are in a state of dynamic evolution both in terms of form and position, within the context of the exceptionally rapid sequences of erosion and migration that characterise all shorelines of this region of the Gulf of Mexico. These rapidly changing aeolian accumulations raise interesting conceptual issues especially when viewed across a range of geomorphological and geological scales. In one sense, they are fragile, easily destroyed and short-lived coastal landforms. In another sense, they are adaptive, persistent and effective coastal barriers. They exhibit an intrinsic strength common to most low, soft and unconsolidated coastlines with their adaptability and mobility epitomising a particular meaning of the term 'dynamic equilibrium'. Thus the dunes possess the freedom to move and reform continuously so that the landforms attain a net position of least disturbance in relation to the geomorphological environment.

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FACIES ARCHITECTURE OF THE BAYOU GRAND CAILLOU AREA: AN ABANDONED SHALLOW WATER DELTA OF THE MISSISSIPPI RIVER DELTA PLAIN

Randolph A. McBride, Shea Penland, and John T. Mestayer[1]

ABSTRACT

Interpretations of vibracores from the Bayou Grand Caillou area form the database for delineating the facies architecture of an abandoned shallow water delta lobe within the Lafourche delta complex of the Mississippi River delta plain. The modern landscape of this shallow water delta is dominated by a network of distributary channels, which bifurcate and isolate smaller portions of the delta plain into small-scale interdistributary basins characterized by extensive swamps that occur at the apex of these basins and grade seaward into fresh, intermediate, and saline marshes.

The Bayou Grand Caillou distributary network, which consists of Bayou Grand Caillou, Bayou Chauvin, Four Point Bayou, and Bayou Sale, was the third delta lobe of the Lafourche complex to build. This distributary network prograded seaward between Bayou du Large to the west and Bayou Petit Caillou to the east less than 2000 years B.P. With delta abandonment, shoreface erosion reworked the Bayou Grand Caillou distributaries, generating the Isles Dernieres barrier island arc over approximately the last 600 years. This protective transgressive barrier shoreline forms the seaward geologic framework of the Bayou Grand Caillou deltaic estuarine system.

The average thickness of the shallow water delta is <10 meters. The regressive component of the delta generally averages 7-8 meters thick, increasing to as much as 15 m thick in areas of distributary channelling. The regressive component coarsens upward and consists of prodelta mud at the base overlain by outer and inner fringe silty sand deposits. Typically, this sequence is capped by fine-grained organic-rich (>35%) marsh deposits. The distributary channel deposits are characterized by a sharp erosional contact at the base overlain by a clean fine-grained sand that is normally characterized by a subtle fining-upward sequence.

These shallow water delta deposits, which are bound by *transgressive surfaces of erosion*, form a parasequence. The base of the parasequence is characterized by an erosional unconformity interpreted as a *ravinement surface* produced by shoreface erosion. The top of the parasequence is characterized by a *marine flooding surface* produced by transgressive submergence as a function of deltaic abandonment, eustatic sea level rise (0.23 mm/yr), and regional subsidence (≈1 cm/yr). A parasequence is the building block of a systems tract. Overall, the Bayou Grand Caillou is part of the highstand systems tract of the modern Mississippi River delta plain.

INTRODUCTION

The Bayou Grand Caillou distributary network is located in Terrebonne Parish, Louisiana approximately 100 km southwest of New Orleans and about 120 km west of the mouth of the Mississippi River. The associated delta lobe lies between the town of Thibodaux to the north and the Isles Dernieres barrier island arc to the south (Figure 1). In contrast to the modern Mississippi bird-foot delta, which is fluvially-dominated, >150 m thick, and extends into deep water (Fisk, 1944, 1961; Coleman and Prior, 1980), the remainder of the Mississippi River delta plain consists of shallow water deltas typically < 20 m thick such as the Bayou Grand Caillou area. The abandoned Bayou Grand Caillou shallow water delta is lobate in shape, with numerous bifurcating distributaries, and exits within the Lafourche delta complex of the Mississippi River delta plain. Although numerous studies have been conducted on the Mississippi River delta plain (Trowbridge, 1930; Russell, 1936; Fisk et al., 1954; Fisk and McFarlan, 1955; Welder, 1959; Scruton, 1960; Coleman and Gagliano, 1964, 1965; Coleman, Gagliano, and Webb, 1964; Kolb and Van Lopik, 1966; Frazier, 1967, 1974), more recent studies have refined our understanding of the processes, geometry, and facies of deltaic sedimentation in shallow water settings (Van Heerden and Roberts, 1980; Tye and Kosters, 1986; Penland et al., 1987, 1988a, 1988b; Kosters, 1989; Tye and Coleman, 1989; Boyd et al., 1989). The objective of this paper is to describe the composite sedimentary environments, facies relationships, and bounding surfaces of the Bayou Grand Caillou shallow water delta.

METHODS AND TERMINOLOGY

Subsurface data were acquired using a vibracore system that employs a Dreyer concrete vibrator powered by a 5 HP Briggs and Stratton gasoline engine. The unit induces high-frequency vibrations of 20 to 40 cycles/sec transmitted through a 4.3 m-long cable to an aluminum vibrating head. The head is attached to a 10 cm-diameter, 9 m-long aluminum core pipe

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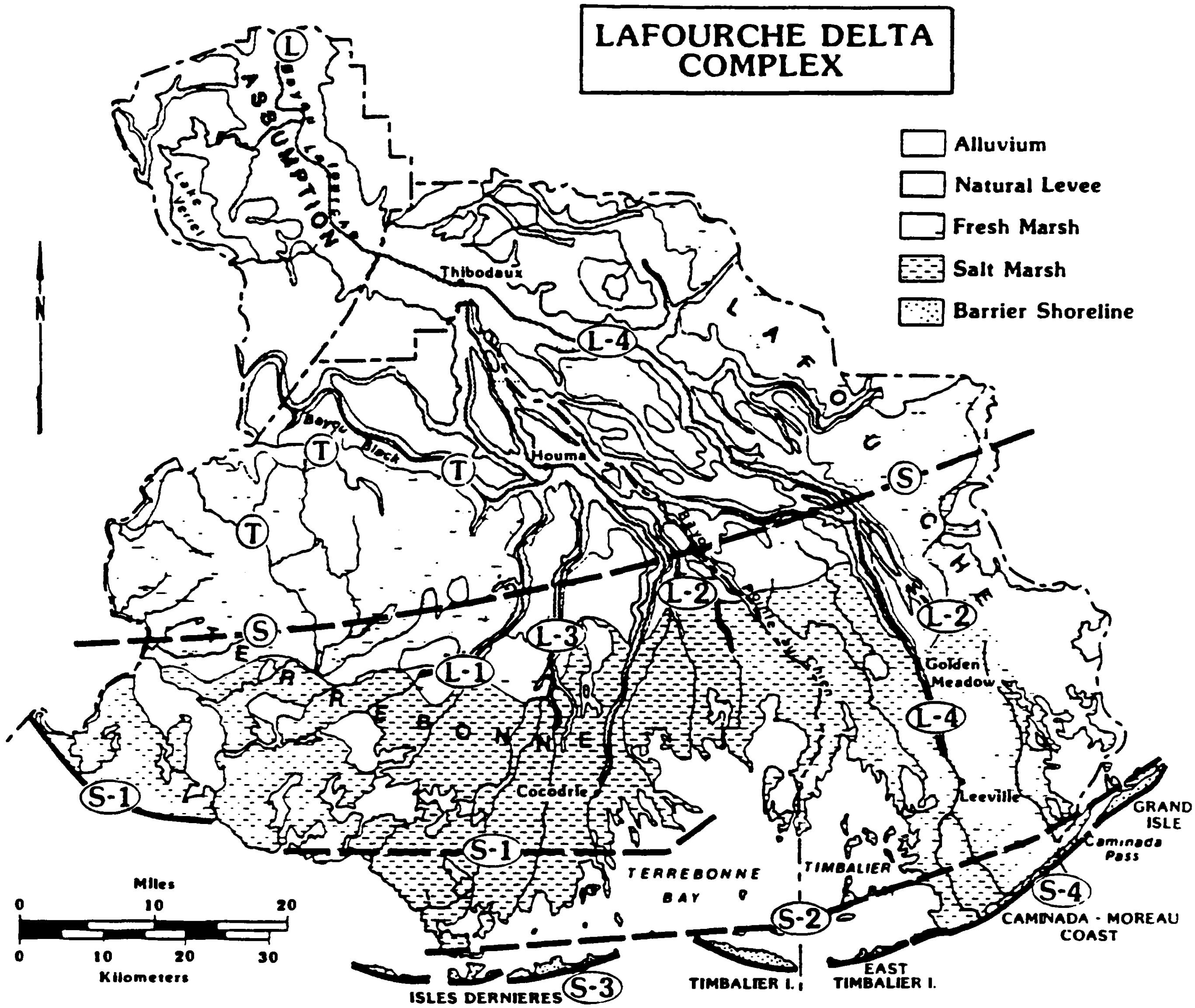


GEOMORPHIC FEATURES

(T) Teche Deltas	(S) Teche Shoreline
(L-1) Bayou du Large	(S-1) Caillou Bay Shoreline
(L-2) Bayou Terrebonne	(S-2) Terrebonne Shoreline
(L-3) Bayou Grand Caillou	(S-3) Isles Dernieres
(L-4) Bayou Lafourche	(S-4) Lafourche Shoreline

Figure 1. Surficial geology of the Terrebonne Parish region showing the Bayou Grand Caillou area of the Lafourche delta complex (Penland et al. 1987).

(irrigation pipe), which is vertically erected at the coring site. Sediment penetration is accomplished through liquefaction of a thin layer of sediment as the core pipe is driven downward to a desired depth or until refusal occurs (see Lanesky et al., 1979; Smith 1984). A description of lithology, grain size, physical and biogenic structures, and sedimentary facies was logged on a standardized core description sheet.

Interpretations of the shallow water delta cycle can be divided into regressive and transgressive facies and are based on terminology from Coleman and Gagliano (1965); Coleman et al., (1964), and LeBlanc (1973, figure 17; 1977). The regressive sedimentary facies include prodelta, outer fringe, inner fringe, distributary, levee/overbank, freshwater marsh, and swamp. The prodelta facies is the depositional platform of a delta complex representing the initial phase of mud accumulation on the inner shelf. Fringe (outer and inner) deposits are coarser than the underlying prodelta deposits. Outer fringe deposits show the first signs of silt and sand laminations due to the increasing influence of the approaching distributary mouth (Figure 2). The outer fringe deposits coarsen upward and the basal contact is gradational with the underlying prodelta facies. Inner fringe deposits represent progradation in close proximity to the distributary channels. The inner fringe sediments are dispersed by marine energy to form a fringe of sand in front of the delta plain. Overall, the fringe facies coarsens upward and is controlled by two main factors: (1) the amount and type of sand introduced to this environment by the distributary channels, and (2) the amount of energy in the marine environment (i.e., wave, tidal, current) (LeBlanc, 1977). The distributary facies represents the environments of deposition associated with distributary channels including coarse and fine-grained channel fill and distributary mouth bar environments. The base of distributary sequences is erosional due to channel cutting within the delta plain. However, at the distal ends of distributaries, the contact is gradational between the distributary mouth bar and fringe deposits. As the distributory migrates laterally or becomes abandoned, finer-grained levee/overbank deposits will overlie the distribution deposits. Fresh marshes represent the establishment of herbaceous vegetation on emergent distributary and fringe surfaces. *Sagittaria spp.*, *Eleocharis spp.*, and *Bacopa monniri* are the dominant vegetation found in fresh marsh areas (Kosters, 1989). Fresh marshes are characterized by thick organic soils of rooted marsh with a matrix of silty clay lenses and detrital organic layers. The organic content of fresh marsh deposits typically is 35-75%. A true peat is >75% organic content and is normally associated with cypress swamps. LeBlanc's (1972, 1977) terminology is of particular importance because it is based on shallow water deltas and applicable to the Bayou Grand Caillou area. Specifically, LeBlanc's term fringe (outer and inner) is preferred over delta front to more accurately describe the sedimentary environments around thin, prograding, bifurcating distributaries associated with shallow water deltas (Figure 2).

The transgressive sedimentary facies include salt marsh and surficial sand sheet. The sand sheet facies represents thin sand deposits on the lower shoreface and inner shelf seaward of a retreating shoreline and is normally associated with storm processes and deposition. The sand sheet is often massive in appearance with abundant shell hash, but can contain graded bedding and flasers. The salt marsh facies is used to describe the deposits which accumulate in the *Spartina alterniflora* dominated salt marshes surrounding backbarrier bays and sounds. Other common plants are *Juncus roemerianus*, *Distichlis spicata*, and *Spartina patens*. Salt marsh deposits are characterized by rooted silty clay deposits containing detrital organic layers, burrows, and low-angular to horizontal laminations. The organic content is normally 5-35% (Kosters, 1989).

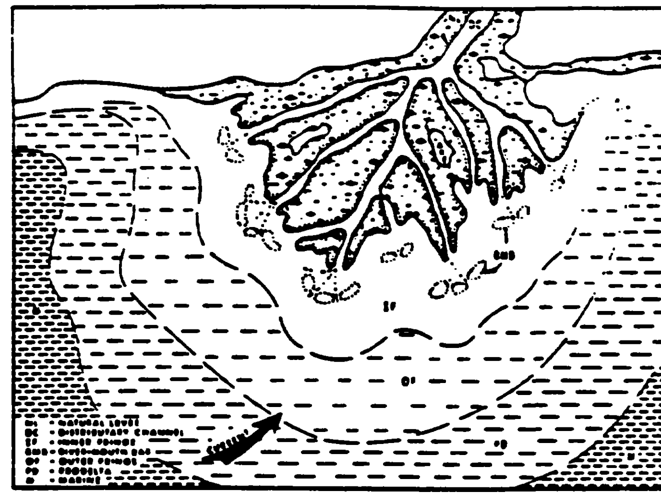


Figure 2. Sedimentary environments of a shallow water delta (after LeBlanc, 1977).

Finally, the Bayou Grand Caillou delta facies architecture is described within a sequence stratigraphic framework. Sequence stratigraphy is the study of rock/sediment relationships within a chronostratigraphic framework of repetitive, genetically related strata bound by surfaces of erosion or nondeposition, or their correlative conformities (Van Wagoner et al., 1988). The fundamental unit of sequence stratigraphy is the sequence, which is subdivided into system tracts (i.e., lowstand, transgressive, and highstand system tracts). The individual system tracts consist of stacked parasequence sets or parasequences, which are bound by *transgressive surfaces of erosion* (Figure 3). In the Bayou Grand Caillou area, two types of *transgressive surfaces of erosion* are identified: 1) *a marine-flooding surface* and 2) *a ravinement surface*. The former results from landward intrusion of marine waters. The latter is produced by waves eroding the active shoreface during shoreline retreat (Swift, 1975). Both surfaces are produced in response to relative sea level rise, and they are identified as surfaces that separate younger deposits from older deposits, marking an increase in water depth (Van Wagoner et al., 1988).

STRATIGRAPHY

Individual shallow water deltas commonly form an upward-coarsening sequence (2-5 m) of prodelta, fringe (outer and inner), and distributary deposits capped by a fining-upward sequence (2-4 m) of overbank, fresh marsh, and salt marsh deposits (Figures 4, 5, and 6). Salt marsh at the top of cores represent the present marine flooding surface. Prodelta deposits represent the base of the deltaic sequence and are underlain by a transgressive surface of erosion, probably produced by shoreface retreat (ravinement surface). A thin surficial sand sheet (<8 cm) normally exists between the erosional unconformity and overlying prodelta mud. This ravinement surface lies on pre-existing lagoon or salt marsh deposits,

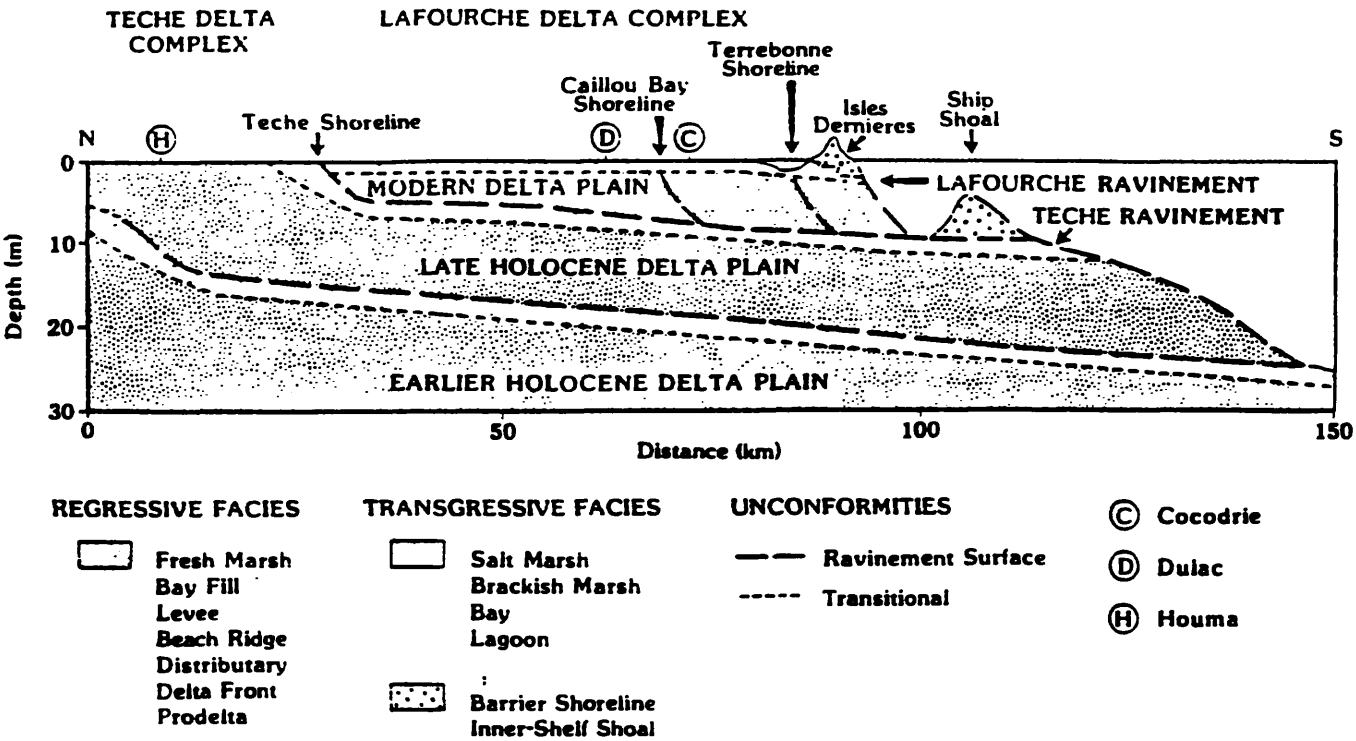


Figure 3. Schematic dip section (B-B') illustrating the stratigraphic relationships between the parasequences and the parasequence sets separated by transgressive surfaces of erosion (ravinements). Location of cross-section B-B' is found on Figure 4.

which represent the top of the underlying shallow water delta (Teche delta complex). This surface is typically an erosional unconformity characterized by a sharp contact between underlying lagoon deposits and the overlying surficial sand sheet (Figures 5 and 6). The surficial sand sheet normally consists of fine-grained sand with broken shell material (Figures 7 and 8). The ravinement surface and overlying sand sheet represent a local marine transgression.

The stratigraphy of the Bayou Grand Caillou delta area illustrates at least two stacked shallow water deltas separated by a transgressive surface of erosion. Initially, the Bayou Grand Caillou began prograding seaward covering the surficial sand sheet with prodelta deposits. Prodelta deposits are normally dark grey clays that can contain subtle bands of red and yellow. These colors suggest diagenetic processes that produce secondary deposits such as siderite (iron carbonate); occasionally, siderite nodules are identified. Prodelta deposits can also contain subtle bioturbation and flecks of detrital organic matter.

At the top of prodelta deposits, the presence of thin silt and sand layers indicates a gradual change intooverlying fringe deposits. The outer fringe is dominated by interlaminated silt and clay, wavy bedding, and some lenticular bedding. As the delta continues to prograde seaward, the inner fringe is deposited above the outer fringe. The inner fringe has a coarser mean grain size and is dominated by interlaminated silt and clay and thicker sand layer (2-10 cm). Overall, inner fringe deposits contain more sand, can form a fairly continuous sand sheet, and occur immediately adjacent to the active distributary mouth. Most distributary sand deposits identified average 1-3 m thick (Figures 3 and 4). Because these are relatively thin deposits, they could represent the upper portion of inner fringe deposition.

Upper inner fringe/distributary deposits for Bayou Grand Caillou are characterized by a sharp erosional contact at the base, overlain by a clean, fine-grained sand that is normally characterized by a subtle, fining-upward sequence. Primary sedimentary structures include parallel laminations, small scale trough cross-laminations (ripple drift), and small scale planar cross-laminations. Shells, glauconite, and rooting are rare to non-existent. As the prograding distributary network migrates laterally or becomes abandoned, finer-grained levee/overbank sediment is deposited. Grey, interlaminated clay, silt, and sand with wavy bedding and in-situ rooting dominate these deposits. Zones of oxidized sediment (reddish color) can occur, indicating a fluctuating water table and exposure to air. In the Bayou Grand Caillou area, levee/overbank deposits display the best examples of yellow siderite banding and siderite nodules.

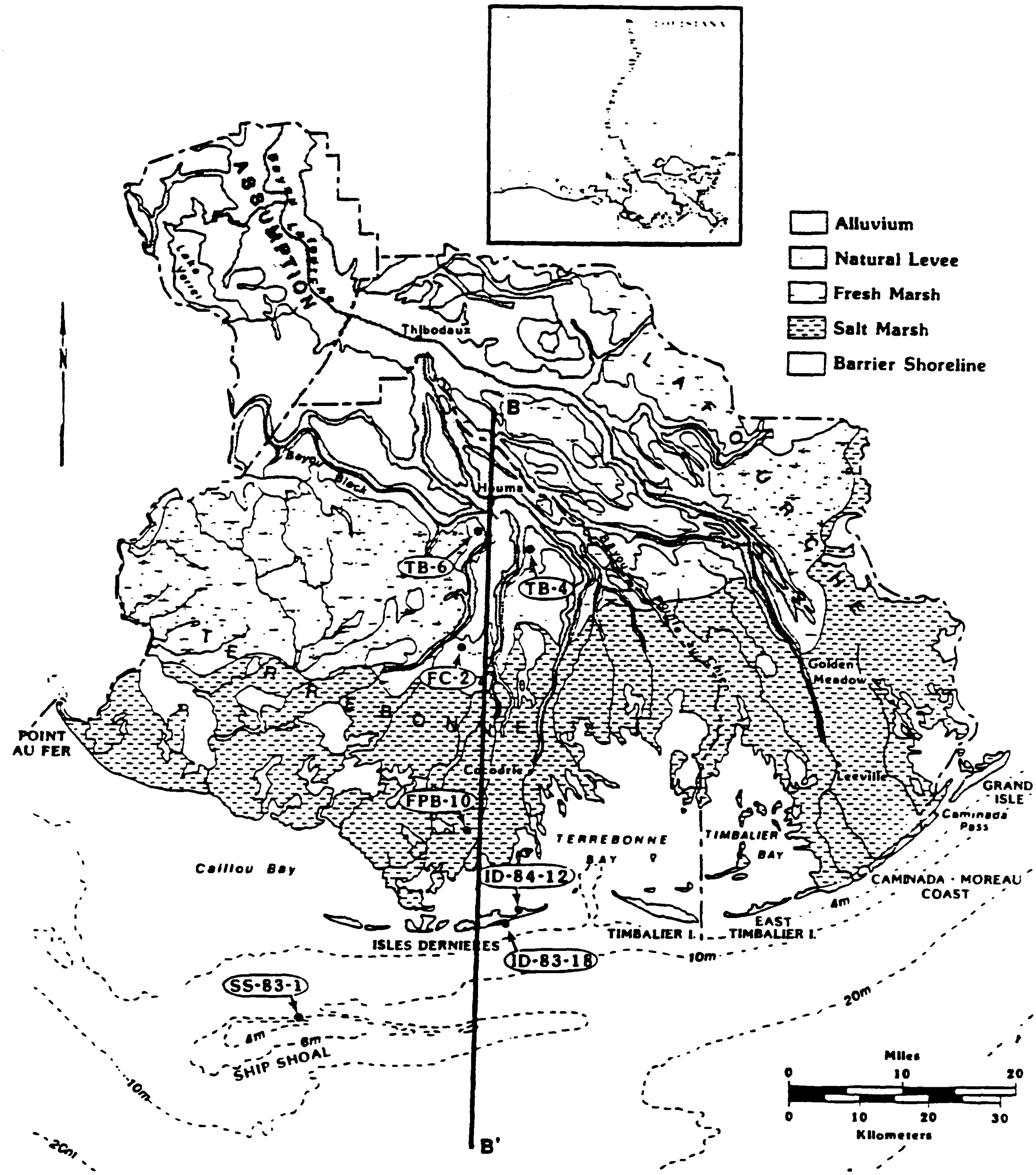


Figure 4. Vibracore sites and the B-B' cross-section location (see Figure 3) for the Bayou Grand Caillou area (Penland et al., 1987).

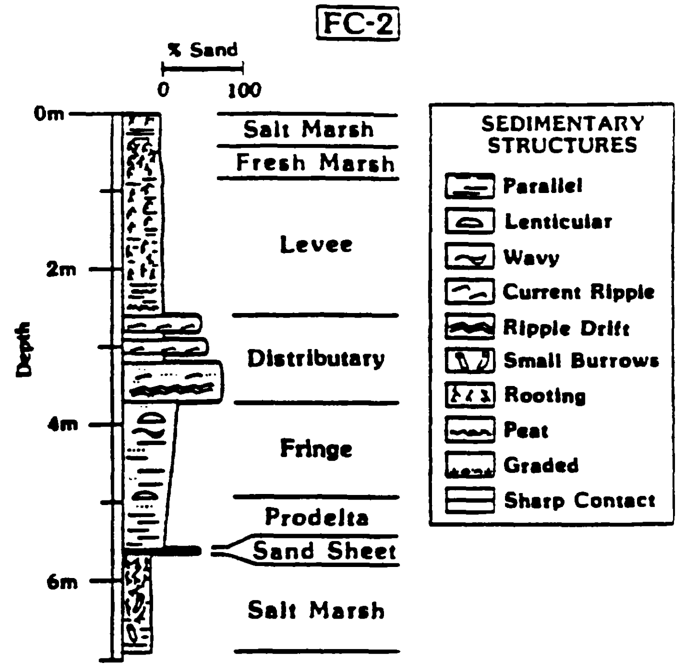
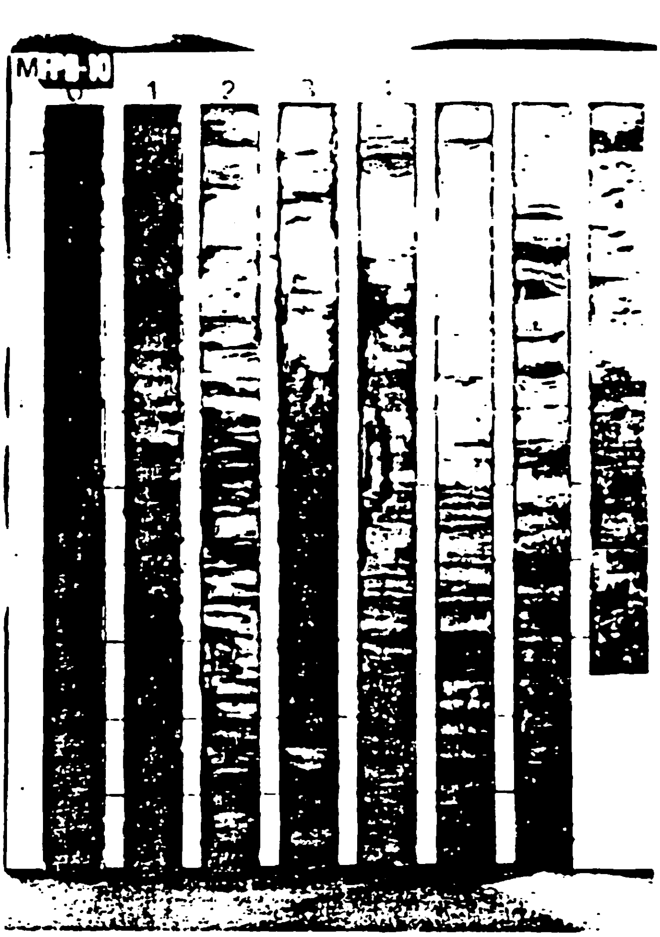


Figure 5. Vibracore from the Bayou Grand Caillou delta (see Figure 4 for location). A. Photograph of vibracore FC-2. B. Interpretation of the sedimentary environments of FC-2.

As the amount of transported clastic material declines with delta abandonment. wetland colonization encroaches upon subsiding levees as fresh marsh. Freshwater marsh deposits are dominated by in-situ rooting. complete faunal bioturbation. and dark grey clay. As the shallow water delta becomes completely abandoned. the delta subsides and becomes transgressed. producing a marine flooding surface. The transgression leads to salt water intrusion. and the fresh marsh is replaced or buried by salt marsh.

The Bayou Grand Caillou shallow water delta is bound by two transgressive surfaces of erosion and therefore. is considered a parasequence. The marine flooding surface at the top of each core will either become buried and preserved by a new pulse of sedimentation in the form of another delta lobe or removed by shoreface erosion. thus forming a ravinement surface. The latter scenario is more likely because the predicted life expectancy of the Isles Dernieres is only 27 years (McBride et at., 1989). Therefore. once the Isles Dernieres barrier island arc undergoes transgressive submergence (Penland et al., 1988a). the eroding shoreface would translate rapidly landward into the fragile interior wetlands. removing the present marine flooding surface. This repetitive process of delta progradation and transgression produces stacked shallow water deltas or parasequence sets separated by transgressive surfaces of erosion (Figure 3). Both ravinement and marine flooding surfaces can be preserved between these stacked shallow water deltas. However. the preservation of marine flooding surfaces depend upon the landward extent and depth of the ravinement process. Overall the Bayou Grand Caillou is part of the highstand systems tract of the modern Mississippi River delta plain. The underlying Teche delta represents another parasequence. which is part of the transgressive system tract associated with the Late Holocene delta plain (Penland. 1990).



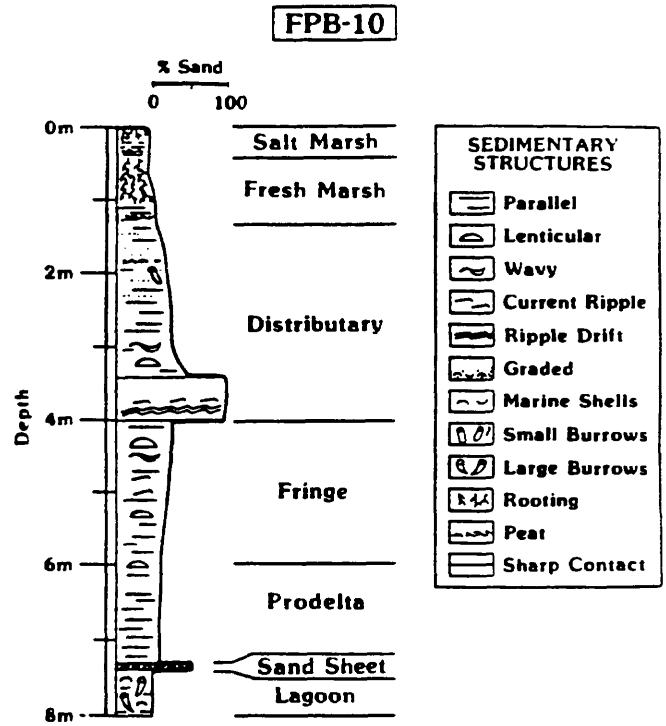


Figure 6. Vibracore from the Bayou Grand Caillou delta (see Figure 4 for location). A. Photograph of vibracore FPB-10. B. Interpretation of the sedimentary environments of FPB-10.

SUMMARY

The Bayou Grand Caillou area is an abandoned shallow water delta of the Mississippi River. This shallow water delta is less than 10 m thick and consists of prodelta deposits at the base overlain by outer and inner fringe, distributary, and levee deposits. The deltaic sequence is capped by marsh deposits. Two *transgressive surfaces of erosion* bound these genetically-related sedimentary environments—*a ravinement surface* at the base and a *marine flooding surface* at the top. This relatively conformable succession of genetically related beds, bound by transgressive surfaces of erosion, defines a parasequence, which is the primary building block of systems tracts. The Bayou Grand Caillou delta lobe represents a parasequence within the highstand systems tract of the modern Mississippi River delta plain.

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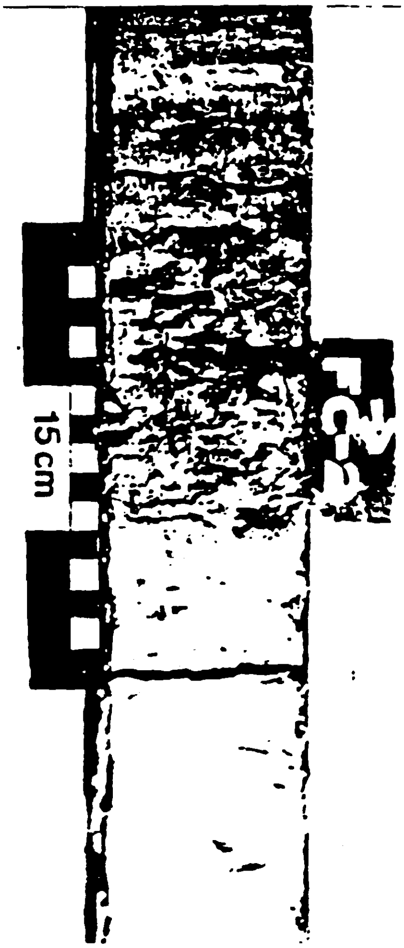

Figure 7. Close-up photograph of ravinement surface in FC-2. The arrow points down hole. Lagoonal mud overlain by ravinement surface (erosional unconformity), surficial sand sheet (shell hash), and capped by prodelta mud.

Figure 8. Close-up photograph of ravinement surface in FPB-10, showing fine-grained marsh/lagoon deposits overlain by an erosional unconformity (ravinement surface) characterized by shells.

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RESULTS OF GEOLOGIC PROCESSES STUDIES OF BARRIER ISLAND EROSION AND WETLANDS LOSS IN COASTAL LOUISIANA

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Asbury H. Sallenger, Jr.[3]

Abstract

The U.S. Geological Survey (USGS), as part of its Coastal Geology Research Program, is conducting geologic research throughout the delta plain of south central Louisiana. The objective is to provide basic information necessary to improve our understanding of the geological processes responsible for coastal erosion and wetlands deterioration. The Louisiana Geological Survey (LGS), Louisiana State University (LSU), U.S. Fish and Wildlife Service (FWS), and the Argonne National Laboratory (ANL) are cooperating partners in two studies which the USGS has undertaken.

The first study examines the function of coastal barrier islands in the protection of bays, estuaries, and wetlands from ocean waves, storm surge flooding, and saltwater intrusion. The USGS and LGS are mapping and interpreting the physical changes that have occurred over the past several thousand years on the inner continental shelf, along the barrier coastline, and in the wetlands landward of the barriers, paying particular attention to geomorphic evolution during the past century. A series of atlases and reports presenting the results are available. Additionally, a data base of 15,000 line-km of offshore geophysical profiles, 400 continuous vibracore samples, 565 grab samples, and digital hydrographic and shoreline data from maps and surveys of the deltaic plain over the past 136 years (1853-1989) have been incorporated into a computer Geographic Information System (GIS).

The second study is a comparative investigation of critical physical processes in the wetlands of representative sediment-deficient and sediment-rich basins in Louisiana. The Terrebonne basin, sediment-deficient with badly deteriorated wetlands, and the Atchafalaya basin, sediment-rich with an emergent and recently vegetated delta and healthy wetlands, typify the two

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extremes and were selected as study sites. Joint field studies by USGS, LSU, and LGS were recently completed on both regional and local levels in Terrebonne basin, with the focus on:

- Storm effects,
- Freshwater and saltwater dispersal,
- Fine-grained sediment dispersal,
- Marsh deterioration,
- Soils development, and
- Subsidence and sea-level rise.

Similar field investigations in the Atchafalaya basin are underway in 1991. Included in this effort is a compilation of baseline data into a GIS network for use by coastal resource and management agencies.

Field investigations are also underway to evaluate the potential effectiveness of small-scale freshwater diversions from the Mississippi River as a means to mitigate wetlands deterioration. This study is being conducted at White's Ditch, just downriver from New Orleans. Measurements of dispersion and retention of freshwater and sediments in the wetlands of Plaquemines Parish were initiated in February 1990 by Coastal Environments, Incorporated.

Introduction

Coastal erosion and wetlands deterioration are serious and widespread problems affecting all regions of the Nation. All 30 of the coastal States are experiencing erosion, and the long term social, environmental, and economic consequences are major concerns to the coastal zone population as well as to resource managers. As shown on the plate (Figure 1) depicting coastal erosion and accretion in the U.S. Geological Survey's *National Atlas of the United States of America* (1988), Louisiana has the distinction of experiencing the highest coastal erosion rates in the United States (Morgan and Larimore, 1957; Penland and Boyd, 1981; Morgan and Morgan, 1983; McBride and others, 1989). Coastal erosion rates average - 4.2 m/yr with a standard deviation of 3.3; the rates of shoreline change range between + 3.4 m/yr and - 15.3 m/yr. The majority of erosion is concentrated on the barrier islands that front the Mississippi River delta plain.

Louisiana's average coastal erosion rate of 4.2 m/yr represents long-term conditions and is not representative of individual storm events. Coastal erosion is not a uniform process; especially rapid erosion rates occur with the passage of major cold fronts, tropical storms, and hurricanes (Penland and

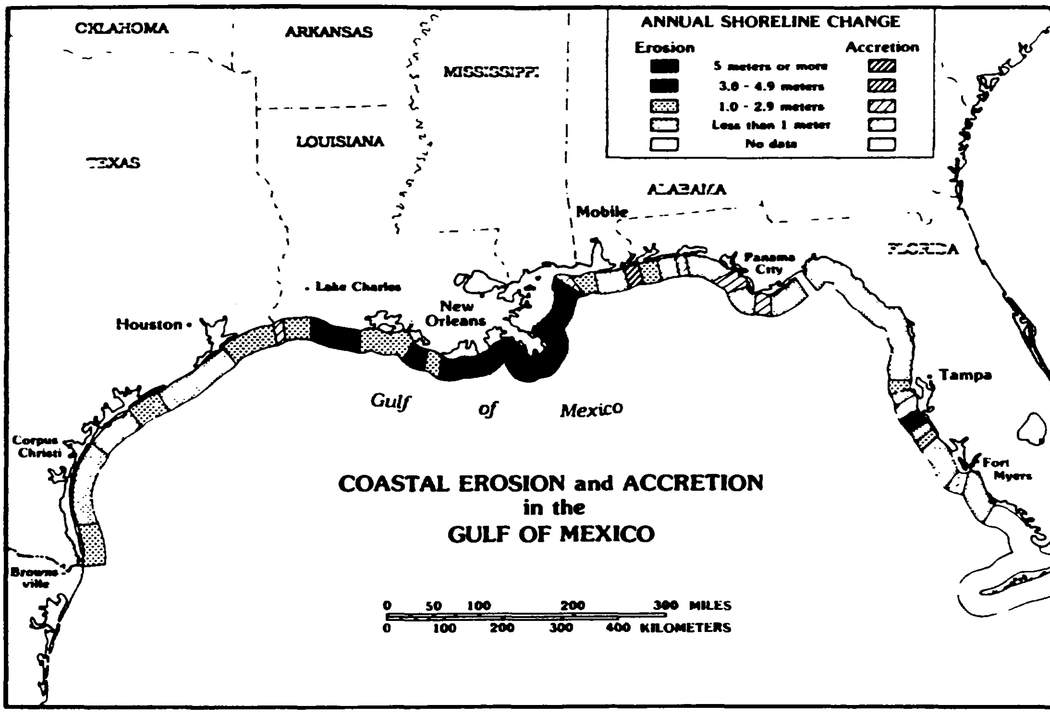

Figure 1. - ***Map showing the extent and magnitude of coastal erosion around the five-state region of the Gulf of Mexico. (Based on U.S. Geological Survey Atlas, 1988.)***

Ritchie, 1979; Boyd and Penland, 1981; Ritchie and Penland, 1988; Dingler and Reiss, 1990). Field measurements have documented 20 - 30 m of coastal erosion during a single storm event lasting 3 - 4 days. In addition to erosion at the shoreline, the total area of Louisiana's barrier islands is decreasing rapidly. According to Penland and Boyd (1982), the coastal barriers lost nearly 50 percent of their surface area between 1880 and 1980.

The natural processes of wetlands degradation and wetlands destruction and alteration by public agencies and private landowners have resulted in the loss of more than 50 percent of the wetlands that existed in the contiguous United States at the start of European settlement over 200 years ago. These wetlands losses are continuing, and nowhere is the problem greater than in the Mississippi River delta plain of Louisiana, an area which accounts for an estimated 25 percent of the vegetated wetlands and 40 percent of the tidal wetlands in the 48 conterminous States. Louisiana is undergoing the greatest amount of wetlands loss and deterioration of any State in the Nation; an estimated 80 percent of the Nation's tidal wetlands loss has occurred in Louisiana, and by current estimates, approximately 100 km^2 are lost each year (Figure 2). These losses are the result of a combination of physical erosion by waves and currents as well as conversion of vegetated marsh to open water estuaries due to disintegration of the marshlands, sea-level rise, and regional subsidence (Williams and Sallenger, 1990).

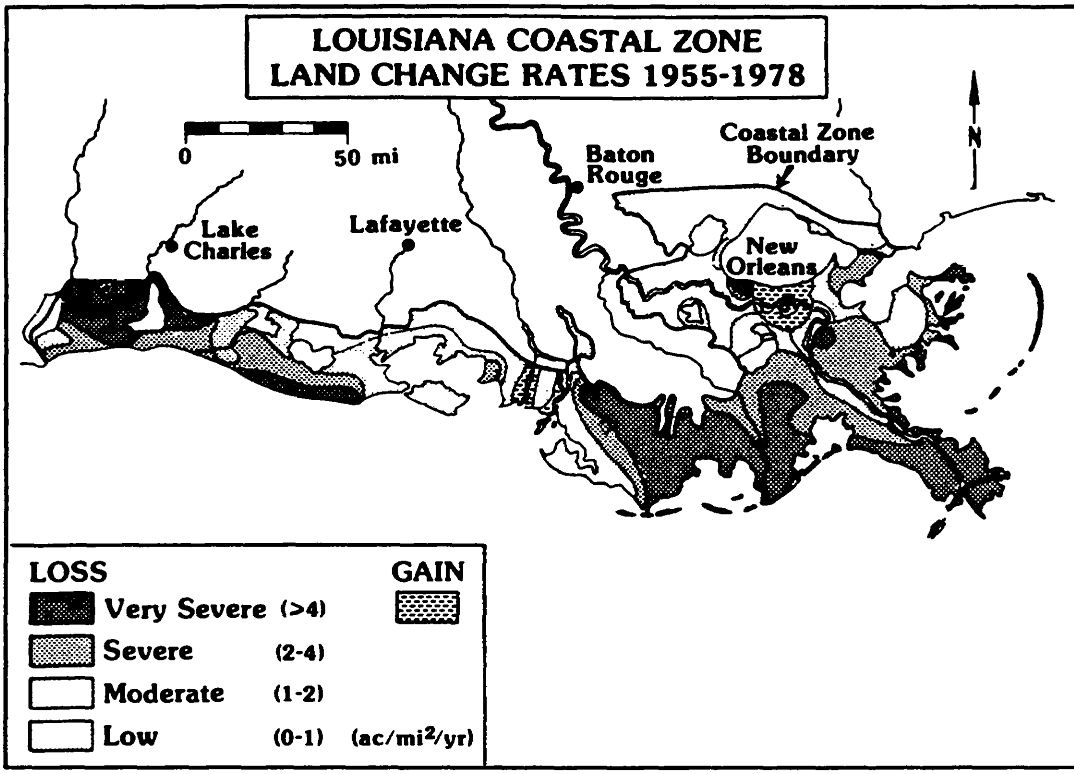

Figure 2. - ***Map of the distribution and extent of coastal wetlands loss in Louisiana. (Based on van Beek and Meyer-Arendt, 1982.)***

Louisiana Delta Plain

The Mississippi River has been the dominant force controlling delta plain development and evolution along the north central coastline of the Gulf of Mexico. Interpretations of the geologic record from the coast and continental shelf of Louisiana show that over the past 6,000 to 8,000 years, large shifts in the course of the Mississippi River have occurred at roughly 1,000-year intervals (Figure 3). Such changes in the river's channel have been responsible for repeated cycles in the evolutionary development of the delta plain. Each cycle consists of coastal progradation during the delta building process followed by rapid sediment compaction, subsidence, and widespread coastal erosion and wetlands deterioration after the channel shift has occurred (Penland and others, 1990).

As part of these cyclic changes in the delta, sandy barrier islands form at the seaward margins of the delta plain. These barriers, in many cases, provide a buffer to the wetlands and estuaries from ocean waves and currents. With continued subsidence and a lack of adequate coastal sediment, however, the barriers undergo rapid erosion, at rates up to 20 m/yr, and eventually are broken into smaller, less protective segments exhibiting very low profiles and separated by wide tidal inlets. Ultimately, the coastal barriers are unable to maintain their subaerial geomorphology and become submerged sand bodies.

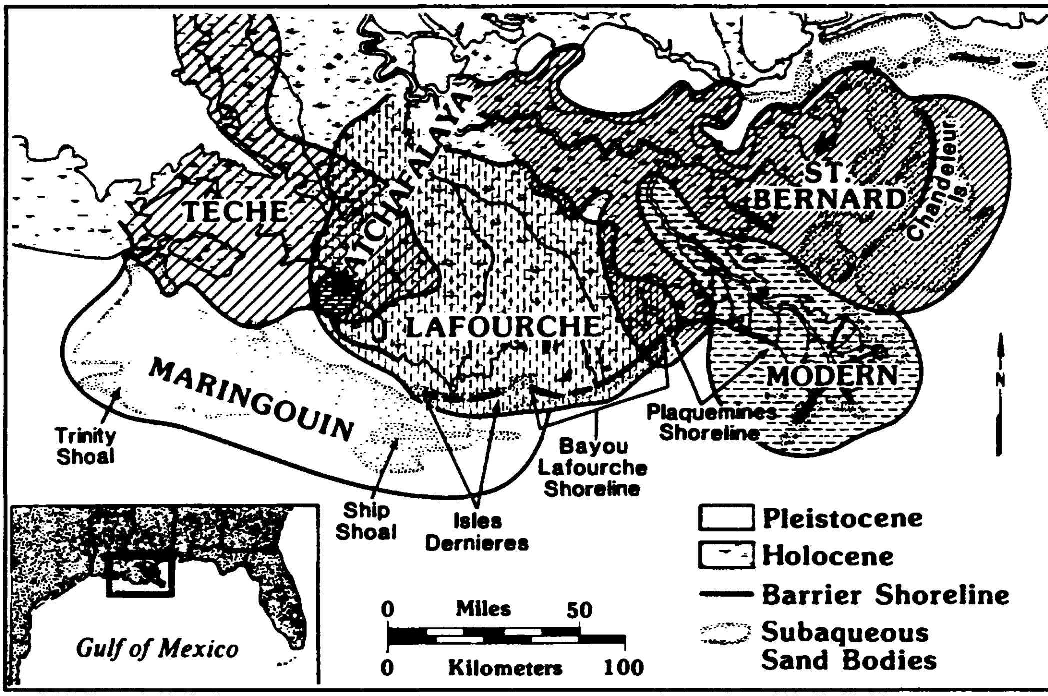

Figure 3. - ***The Louisiana delta plain is the product of a series of deltaic lobes which resulted from shifts in position of the Mississippi River over the past 7,000 years. (From Frazier, 1967)***

A discussion of how the delta plain coast has rapidly changed and evolved since the mid-1800's is contained in McBride and others (1989). Examples of ancestral barrier coastlines can be seen on offshore seismic-reflection profiles and in core samples as buried sand bodies on the Louisiana continental shelf.

Effects of Human Activities

In addition to the natural geologic processes that cause coastal erosion and wetlands loss, human activities during the past century and, especially, in the past 50 years have had dramatic effects (Figure 4). For example, dam building on the Mississippi River and its tributaries since the 1930's has reduced the volume of sediment being transported by the river and, therefore, available to the wetlands (Meade and Parker, 1985). The massive levees that channel the flow of the Mississippi River for more than 1500 km are intended to enhance navigation and reduce flood potential, but they also have significant detrimental effects on the downstream delta plain and adjacent wetlands. Widespread and seasonal flooding that once provided sediments to build and maintain the wetlands no longer occurs. The sediment that is carried by the Mississippi River is now discharged far out on the continental shelf, rather than being widely distributed throughout the delta plain as it was before the levees and other engineering control structures were built.

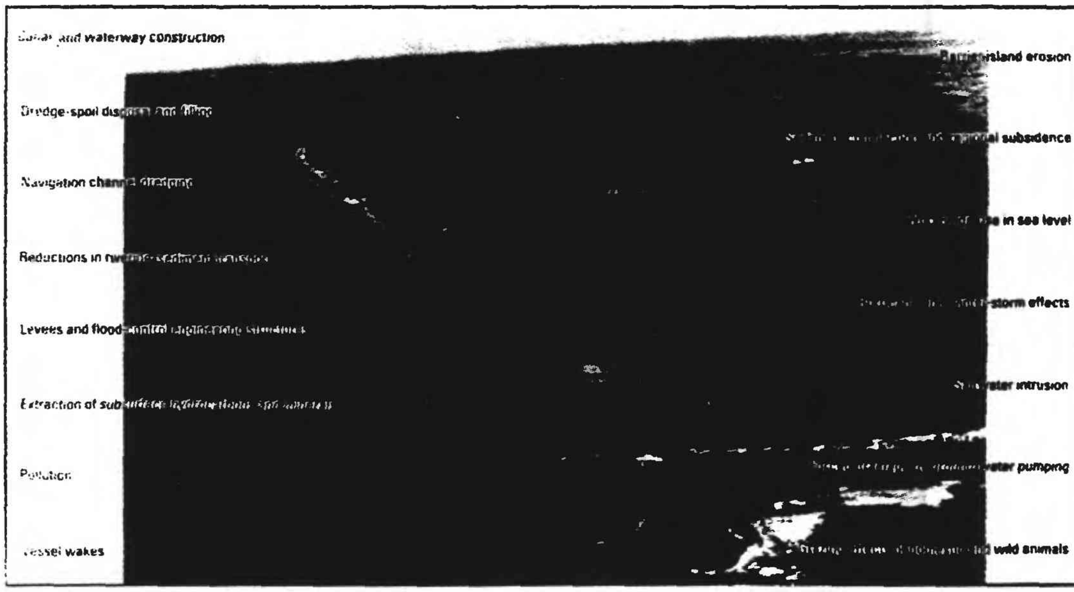

Figure 4. - ***Coastal land loss and the widespread deterioration of Louisiana's wetlands is due to a complex combination of natural processes and the effects of human activities over the past century. (From Williams and Sallenger, 1990)***

An additional human activity that contributes to wetlands loss in Louisiana is an extensive system of dredged canals and waterways. These serve as pipeline paths, access routes for hydrocarbon exploration and production, and waterways for boat traffic (Figure 4). Not only does dredging and maintaining these canals impact the wetlands, but many of them that open to the Gulf of Mexico enable saltwater to intrude brackish and freshwater wetlands, accelerating their deterioration. Other causes that are suspected to be important, but not well documented as yet, involve subsidence that is associated with the extraction of hard minerals and fluids in the shallow subsurface. For example, sulfur mining over salt domes has resulted in localized subsidence of several meters in just the past few decades (Hunt, 1990). Forced drainage, where marsh areas are diked and pumps are used to draw down the ground water, is a widespread agricultural and developmental practice which seems to contribute greatly to wetlands loss by increasing soil compaction and subsidence.

Information Needs - Research Results

The physical processes that cause coastal erosion and wetlands deterioration are extremely complex, highly varied, and still not particularly well defined or understood. The rates and magnitudes of future land loss, therefore, are not predictable with any high degree of confidence. Also, much debate still exists in the technical and scientific community about which of the natural and human-induced causes are most responsible for coastal erosion and wetlands loss.

Various measures and recommendations have been proposed to mitigate natural and man-made causes. However, considerable controversy also exists over some of the mitigation measures such as marsh management, river diversions, barrier island nourishment, and wetlands restoration. Much of the debate has to do with uncertainties in predicting the long-term success of these measures, all of which require varying expenditures of time and money to design, construct, and maintain.

Since 1986, the U.S. Geological Survey, working cooperatively with the LGS, coastal researchers at LSU, ANL, and the FWS, has been conducting research on erosion and wetlands loss in Louisiana. As shown in Figure 5, the region included in the study extends from the Chandeleur Islands west to the Atchafalaya River, a distance of approximately 300 km. The objective of these efforts is to improve our knowledge and scientific understanding of the geologic processes responsible for the erosion and land loss. Such information is critical for predicting future conditions and for developing a strategy to conserve and in some cases restore coastal Louisiana. To meet these information needs, field investigations are focused on:

- Mapping and interpreting the recent geologic framework and evolutionary history of the delta plain, onshore, along the coast, and throughout the inner continental shelf. Obtained as part of this effort are a data base of 15,000 line-km of high resolution seismic profiles, 400 vibracore samples, 565 sediment grab samples, precision bathymetric data from 1880 to 1989, digital shoreline positions from 1853 to 1989, and tide-gauge records for measuring historic changes in relative sea level. Analyses of the shoreline data show that the barriers are eroding very rapidly by a process of in-place narrowing and inlet enlargement. Extrapolation of the historic record suggests that the Isles Dernieres barriers will convert to a submerged shoal by the early 21st century;
- Measuring a wide array of meteorological and oceanographic parameters which influence sediment transport at the coast and in the nearshore zone. A long term monitoring station on the Isles Dernieres barriers provided high quality information, vital to deciphering the sediment budget for the Louisiana coast, during both fair weather and storm conditions (Sallenger and Williams, 1989a);
- Comparing the geologic character and processes of the sediment-deficient Terrebonne basin in the Louisiana delta plain with the sediment-rich Atchafalaya basin. These comparative investigations are focusing on sediment compaction, sea-level rise, and land subsidence (Penland and Ramsey, 1990; Bailey and Roberts, 1990); effects of meteorological events such as hurricanes; dispersal of fine-grained sediments; movement of fresh and saline water; processes of physical erosion; and conditions required for soils to develop in wetlands. Field investigations on all these topics are complete for the Terrebonne basin, and analyses and evaluations are underway. Experiments to measure sediment flux in salt and brackish marshes in Terrebonne basin were carrier out at the same sites during winter cold front conditions and summer fair weather

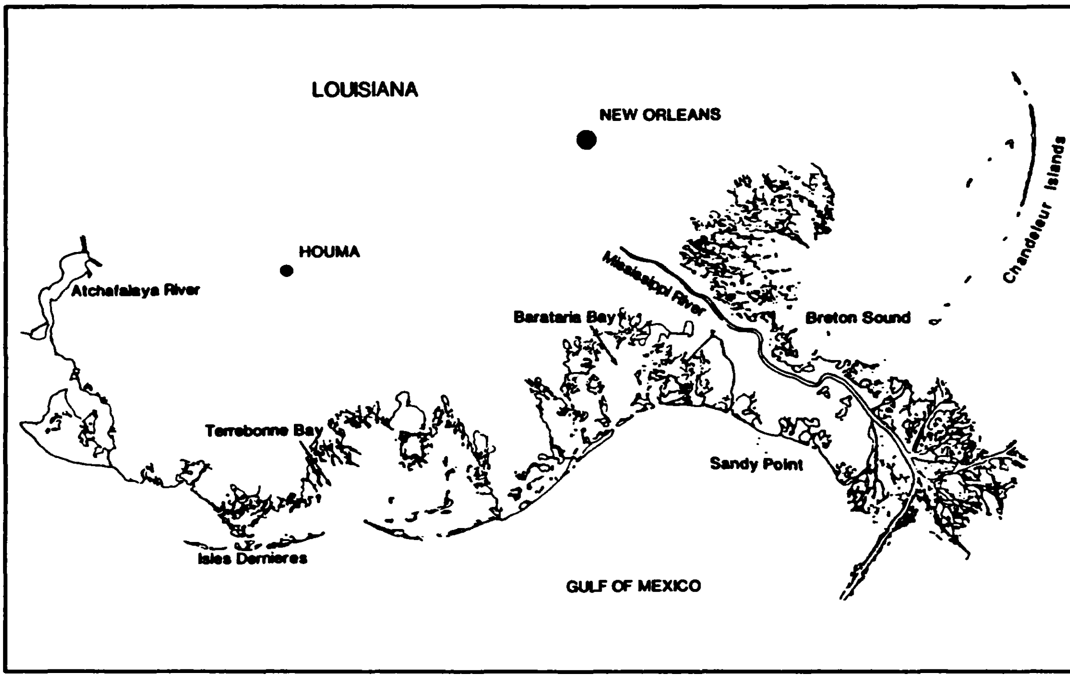

Figure 5. - ***Location map of the southern Louisiana delta plain encompassing areas included in the USGS coastal erosion and wetlands studies.***

conditions. To decipher rates and variability of regional subsidence in the basin, five strike and five slip sections are being developed by a combination of deep borings and cores and instrumented subsidence monitoring stations. Similar field investigations are underway in the Atchafalaya basin.

- Developing a comprehensive coastal data base and using these data in a network of computer-based geographic information systems (GIS) available in Federal, State, and local agencies and private companies. All available baseline data are being incorporated. A listing of data sets judged by the Federal and State agencies and the research community to be important in addressing Louisiana's land loss problems is included in Table 1. Incorporating many of these data sets into a Louisiana GIS network is underway.

- Field investigations by scientists at Coastal Environments, Incorporated, were carried out over a one-year cycle on the Mississippi River at White's Ditch in Plaquemines Parish. The purpose was to assess and evaluate the potential effectiveness of small scale freshwater diversions on mitigating wetlands deterioration. Systematic measurements and observations were made on the dispersion and distribution of river water and suspended sediment; the results will aid in the design and operation of diversions under construction or planned (van Beek and others, 1990).

A listing of interim reports is contained in Sallenger and Williams (1989b).

Table 1. Ranking of most important data sets in coastal Louisiana.

1. 7.5 minute USGS quadrangle maps for the coastal zone
2. Spatial index of available photos and remote sensing data
3. U.S. Fish and Wildlife Service habitat change maps
4. Hydrography and hydrology
5. Geology and engineering framework
6. Mineral extraction information: textual and spatial
7. Land use maps
8. Biological surveys
9. Land elevation data, less than 5-foot contour intervals
10. Detailed soils maps
11. Point source discharge sites and records
12. Land loss maps
13. Weather records
14. Canal and pipeline data
15. Federal and State regulatory information specifically related to the physical environment
16. Shoreline history and geomorphology
17. Land cover information along with thematic mapper data
18. Land ownership records
19. Ecologically sensitive areas
20. Soil Conservation Service national resource
21. Census data from the TIGER files
22. Potable water sources
23. Recreational uses of the coastal zone
24. Economic zones and industrial sites

Summary

Coastal erosion and the deterioration and loss of valuable wetlands are widespread problems of national concern. The delta plain region of Louisiana, however, leads all other regions in land loss due to a combination of natural processes and a long history of human intervention and development. To provide the high quality scientific information necessary to understand and quantify the processes responsible, the USGS, working jointly with LGS, LSU, FWS and ANL, is undertaking studies of the barrier islands and inner shelf region and the coastal wetlands west of the Mississippi River delta. The 5-year study of the barriers is complete, and a variety of reports and atlas products are available. Field investigations in the wetlands of the sediment-starved Terrebonne and Barataria basins are complete, and results are being compared with similar field studies in the sediment-rich Atchafalaya basin. As interim and final results are obtained, they are published and made available to the coastal resource community.

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EFFECTS OF SEA LEVEL RISE ON THE MISSISSIPPI RIVER DELTA PLAIN

Shea Penland[1], Randolph A. McBride[1], S. Jeffress Williams[2], Ron Boyd[3], and John R. Suter[4]

ABSTRACT: Geologic studies of the Mississippi River delta plain and continental shelf reveal the occurrence of several relative sea level stillstands during the last stages of the Holocene transgression. Three shelf-phase delta plains have been identified to date, each separated by a regional transgressive surface of erosion produced by a rise in relative sea level. Sequence stratigraphic relationships suggest that whenever relative sea level rise rates exceed 2 cm/yr for several centuries, the delta cycle process of the Mississippi River stops, and wetlands, estuarine bays, and barrier islands disappear. In contrast, it appears that whenever relative sea level rise rates drop below 2 cm/yr, the delta cycle process builds new wetlands, estuarine bays, and barrier islands. The implication of this pattern of coastal landscape evolution, in light of future sea level rise scenarios, is if the rate of eustatic sea level rise approaches 1-3 cm/yr over the next century, as predicted, and this eustatic rate is compounded with the current subsidence rate of about 0.5-1 cm/yr, an acceleration in the drastic landscape changes currently taking place in coastal Louisiana is expected to occur.

INTRODUCTION

The relationship between sediment supply, sea level change, and process environment controls the development and stability of river deltas throughout the world (Curray 1964, Coleman and Wright 1975). During periods of rapid relative sea level rise, delta plains experience coastal submergence and land loss as their lower alluvial valleys fill with transgressive sediments. During relative sea level stillstands, this trend of transgression and submergence is reversed as the river begins to fill its lower alluvial valley with lacustrine delta complexes behind the high-stand shoreline. Eventually, bayhead deltas build out into shallow coastal bays and evolve into shelf-phase delta plains on the continental shelf. In the Gulf of Mexico, one can observe river deltas in all stages of evolution, since sea level reached the current highstand about 3,000 years ago (Curray 1960). The lacustrine and bayhead delta complex stage can be observed in the Atchafalaya basin in Louisiana (Van Heerden and Roberts 1988, Tye and Coleman 1989). Other examples of bayhead deltas can be found at the Trinity River in Texas, the Pascagoula River in Mississippi, the Mobile River in Alabama, and the Escambia River in Florida. The timing of delta formation is tied to sea level highstand when the rate of rise dropped below a critical threshold valve that allowed river delta development. These bayhead deltas have not yet filled their alluvial valleys

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because of their small drainage basins and low fluvial input to the Gulf of Mexico. In contrast, the Mississippi River, North America's largest river, has filled its alluvial valley and built a large shelf-phase delta plain composed of a series of delta complexes (Fisk 1944, Kolb and van Lopik 1958, Frazier 1967). All of these deltas have one thing in common, a low-relief landscape sensitive to sea level changes. Low-relief landscapes experience the greatest amount of landward coastal zone displacement in contrast to high-relief coastal zones under conditions of relative sea level rise. Global climatc change driven by natural and human-induced processes are forecast to create a worldwide coastal crisis in the next century (Barth and Titus 1984, Williams et al. 1990). Sea level rise rates are predicted to increase due to global warming, and population movement to the coast is predicted to continue, both will adversely impact the quality of our coastal zone. River deltas of the world are predicted to be one of the most sensitive coastal environments at the greatest risk (Delft Hydraulics 1989).

Louisiana is experiencing the worst coastal land loss conditions in North America, with coastal erosion and wetland loss currently exceeding 80 km^2/yr (Britsch and Kemp 1990, Dunbar et al. 1990). These extreme coastal land loss conditions are a function of natural and human-induced causes. The delta switching process, relative sea level rise rates exceeding 1 cm/yr, repeated storm impacts, and man's attempts to control and exploit the Mississippi River delta plain are important factors contributing to land loss and shoreline erosion (Coleman and Roberts 1989; Penland et al. 1990; McBride et al., this volume). The extreme coastal land loss conditions in Louisiana has been used as an analogy for the future coastal conditions predicted to occur over the next century. The Environmental Protection Agency (EPA) predicts 30 - 80% of this nation's coastal wetlands will disappear due to global relative sea level rise over the next century (Titus 1987). Scientists today are faced with trying to predict future coastal conditions for management purposes, however, the reliability of those predictions are uncertain and the thresholds at which certain landscape changes take place in response to specific relative sea level rise scenarios are unknown.

The objective of the paper is to examine the Holocene history of the Mississippi River delta plain and continental shelf in light of trying to understand the relationship between sea level change and coastal landscape stability. In order to accurately predict future coastal conditions, the threshold rates of sea level rise and landscape response must be understood. The continental shelf and delta plain of the Mississippi River contains a 18,000 year record of sea level changes and coastal evolution. By examining high resolution seismic profiles, deep cores, and shallow vibracores combined with new radiocarbon dating results, it is our intent to develop a better understanding of the sea level rise thresholds required to drive regional landscape changes in the Mississippi River delta plain.

HOLOCENE GEOLOGIC FRAMEWORK

Mississippi River sediment accumulates in deltaic depositional sequences consisting of a regressive, or constructional phase followed by a transgressive or destructive phase (Russell 1936, Bernard and LeBlanc 1965, Coleman 1988). Scruton (1960) used the term *delta cycle* to refer to those alternating phases of deltaic evolution. The delta-building process consists of prodelta platform formation, followed by distributary progradation and bifurcation, which results in delta plain establishment during the regressive phase of the delta cycle. This process continues until the distributary course is no longer hydraulically efficient. Abandonment occurs in favor of a more efficient course, initiating the transgressive phase of the delta cycle. The abandoned delta complex subsides, and coastal processes rework the seaward margin, generating a sandy barrier shoreline backed by bays and lagoons. Each transgressive depositional system is derived from a single abandoned delta or delta complex (Penland et al. 1988). The term *delta plain* delineates a *systems tract* comprised of a set of delta complex *parasequences* deposited during a period of relatively stable sea level (Boyd et al., 1989) and bound by transgressive surfaces of erosion (McBride et al. 1990). The term *delta complex* delineates a *parasequence* comprised of smaller delta lobes that are tied to a common distributary and are built by the delta-switching process.

Fisk (1944) produced the first depositional model of the Mississippi River delta plain. This model depicts a single Holocene delta plain 4250 years old consisting of five delta complexes (Figure 1). From oldest to youngest, these are Maringouin, Teche, Lafourche, St. Bernard, and Modern Mississippi. Within these delta complexes, Fisk (1944) identified 20 individual stages. Kolb and Van Lopik (1958) presented a simplified depositional model for the Mississippi River delta plain, 5400 years old, consisting of seven delta complexes: the Sale-Cypremort, Cocodrie, Teche, St.Bernard, Lafourche, Plaquemines, and Balize, in order of decreasing age (Figure 2). The most recent depositional model of the Mississippi River delta plain was developed by Frazier (1967, 1974), which depicts a single Holocene delta plain, 7250 years old, consisting of sixteen separate delta lobes organized into five delta complexes (Figure 3). From oldest to the youngest, these are the Maringouin, Teche, St. Bernard, Lafourche, and Plaquemines-Modern delta complexes. The major theme expressed by all three depositional models is the single Holocene delta plain concept. Each model suggests that during the Holocene transgression, which began about 18,000 years ago, relative sea level rise rates were sufficient enough to overwhelm Mississippi River sedimentation, transgress the lower alluvial valley, and prevent the development of a shelf-phase delta plain. The shoreline moved over 100 km landward under the effects of relative sea level rise during the Holocene transgression. It was not until the later phases of the Holocene transgression that relative sea level rise dropped below a threshold rate that allowed the Mississippi River *delta cycle* process to operate and build a delta plain sometime after 6,000 yBP. These models also suggested that the rise of sea level during the Holocene transgression was somewhat constant, producing a smooth sea level curve at rates above the threshold for regional transgression and submergence. There classic studies were based primarily on deep boring, radiocarbon, archeological, and geomorphic data primarily from the mainland.

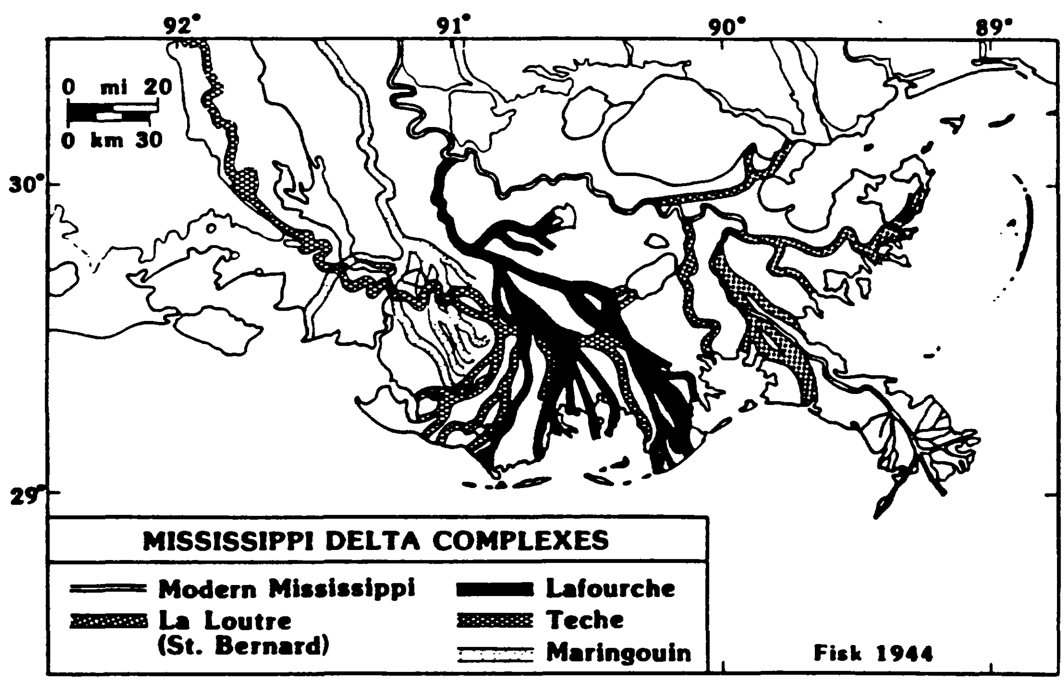

Figure 1. Fisk's (1944) depositional model of a single Holocene Mississippi River delta plain 4,250 years old.

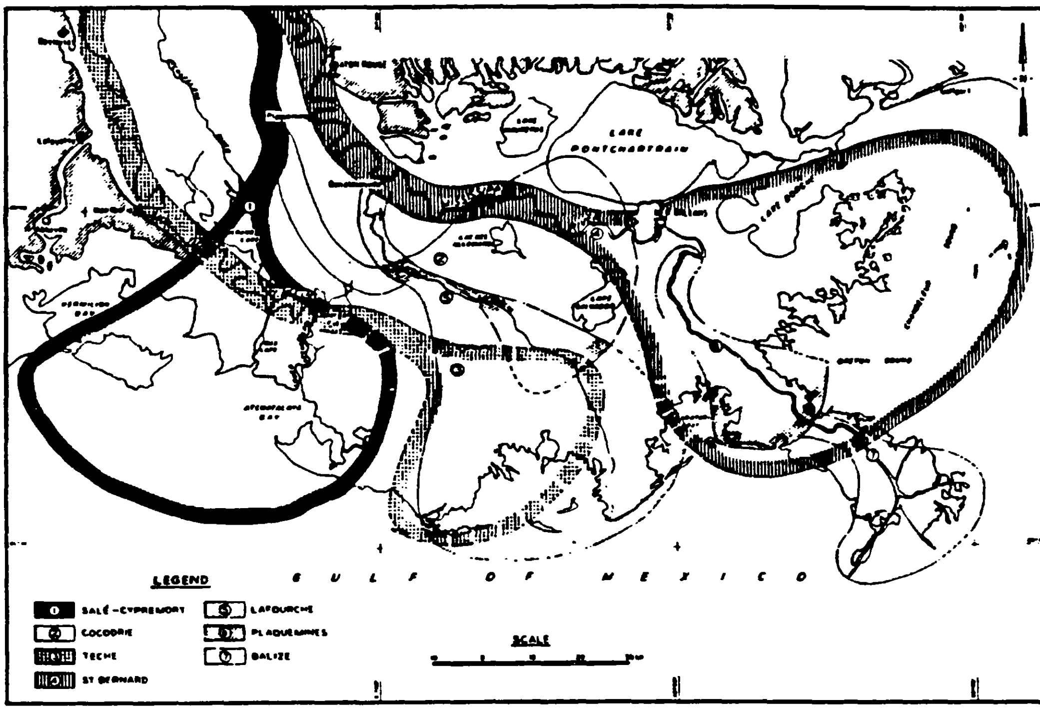

Figure 2. Kolb and Van Lopik's (1958) depositional model of a single Holocene Mississippi River delta plain 5,400 years old.

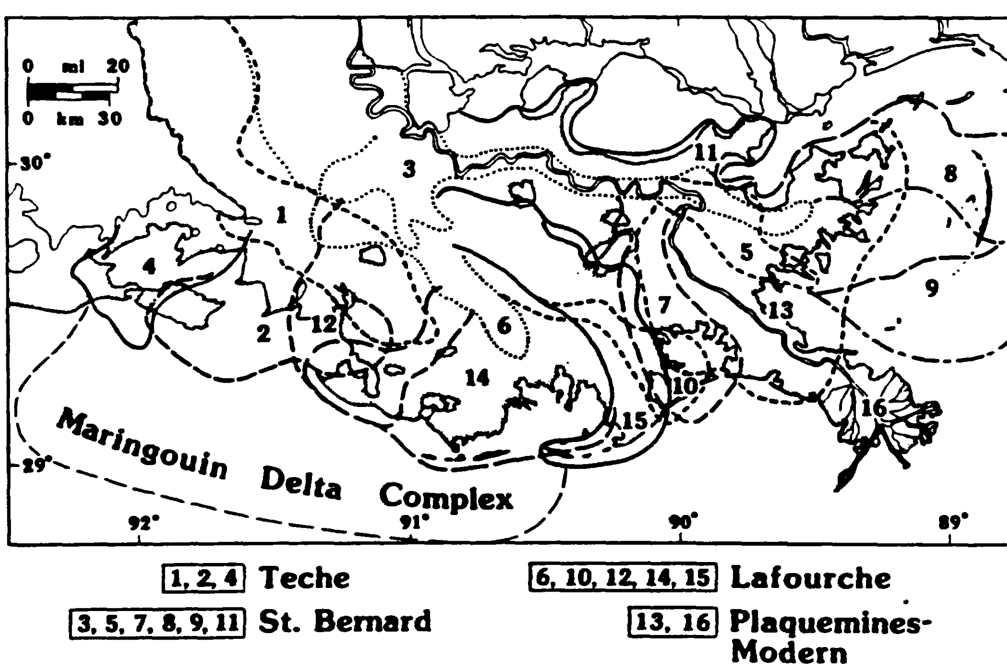

Figure 3. Frazier's (1967) depositional model of a single Mississippi River delta plain 7,250 years old.

Over the last decade, the Louisiana Geological Survey in cooperation with the U.S. Geological Survey has conducted regional geologic framework studies on the Louisiana continental shelf surrounding the Mississippi River delta plain (Figure 4). Through the analysis of this new data set we began to recognize submerged shoreline positions on the continental shelf and relict shorelines within the delta plain (Suter et al. 1987, Penland et al. 1989, McBride et al. 1990). The best defined submerged shoreline is the Ship Shoal/Trinity Shoal trend at about the -10 m isobath, this ancient shoreline can be traced west to Sabine Bank offshore of eastern Texas (Nelson and Bray 1970, Thomas and Anderson 1989). Another distinct submerged shoreline is the Outer Shoal trend at about the -20 m isobath, this ancient shoreline may extend east around the delta plain to the St. Bernard shoal trend offshore of the Chandeleur Islands (Penland et al. 1989). The existence of these ancient shorelines indicates that relative sea level stillstands probably occurred during the Holocene transgression (Curray 1960, Nelson and Bray 1970). The identification of relict shorelines such as the Teche, Caillou Bay and Terrebonne as well as the modern Isles Dernieres and Lafourche shorelines also indicate periods of regression and transgression, particularly in the Terrebonne coastal region (Figure 5). Evidence of a former sea level stillstand was found at about 5-6 m below present in the Terrebonne coastal region of the Lafourche delta complex when a major seismic reflector was discovered and correlated to vibracores in order to map its continuity. This transgressive surface of erosion could be mapped from high resolution seismic profile and vibracore from Trinity Shoal east to the St. Bernard delta complex and offshore to Ship Shoal. It became evident that this seismic reflector represented a regional transgression dominated by an eustatic event because it truncated multiple delta complexes, and it could be correlated with other relict shorelines outside of the delta plain. In figure 6, vibracores in the Terrebonne basin, between Houma and Ship Shoal, illustrate this regional transgressive surface of erosion which we term, the Teche, and its relationship with a relict shoreline with which this surface merges updip. Offshore, Ship Shoal and Trinity Shoal are part of the Teche transgression and represent the former, most seaward shoreline of this submerged shelf-phase delta plain.

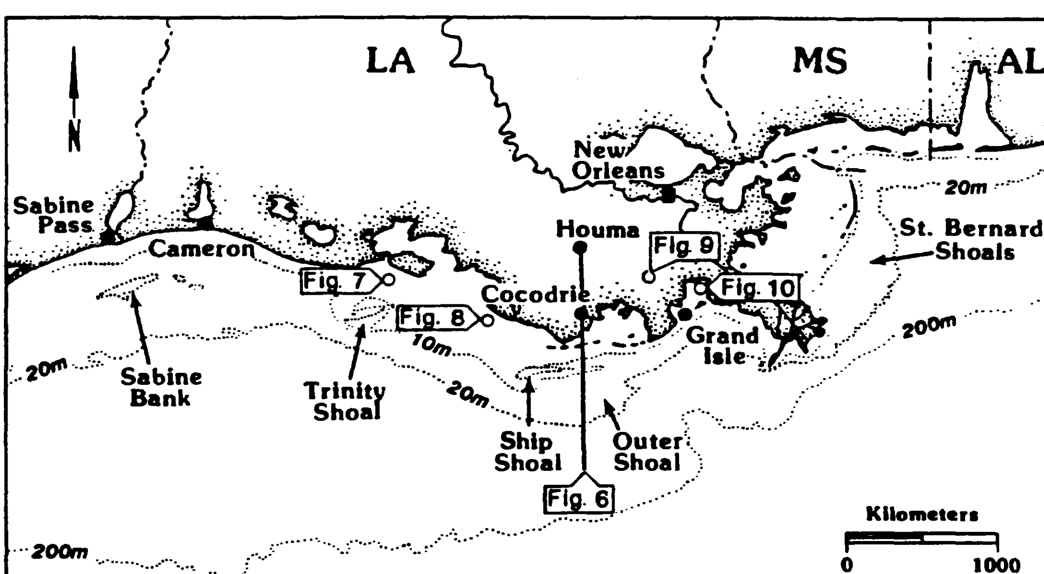

Figure 4. Study area showing the major geologic features, place names, data, and figures used in the text.

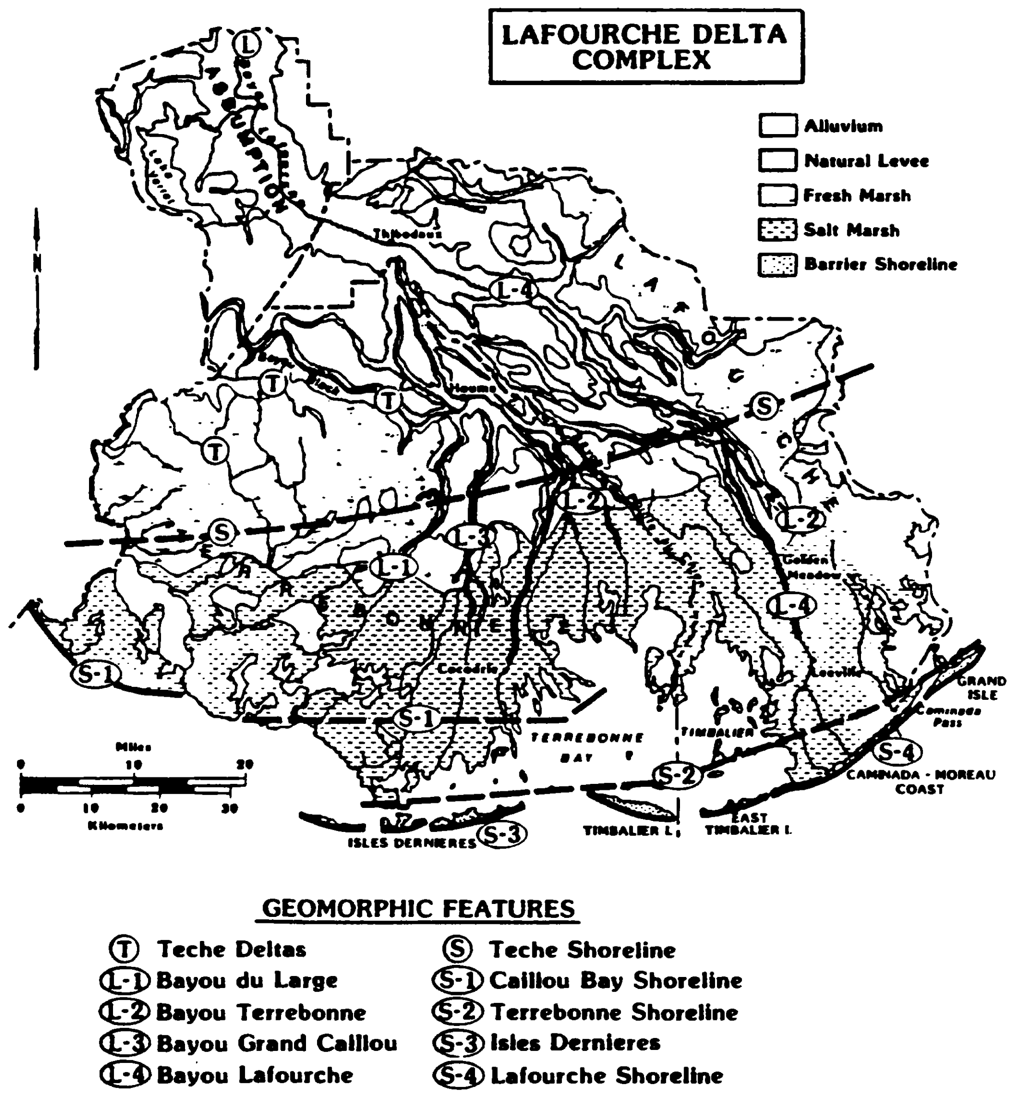

Figure 5. The major geologic features found in the Terrebonne coastal region of the Lafourche delta complex (Penland et al, 1987).

New evidence of the existence and regional extent of the Teche transgressive surface of erosion can be found in the Trinity Shoal area where Frazier (1967) originally mapped the Teche delta complex overlying the Maringouin delta complex of a single delta plain. The vibracore and seismic data in figure 7, illustrate that only a single delta complex occurs in the Trinity Shoal area and that the Teche and Maringouin delta complexes are one in the same delta complex associated with a single delta plain lying below the Teche transgressive surface. The Teche transgressive surface can be traced eastward from Trinity Shoal to beneath the Lafourche delta complex offshore of Point Au fer Island, west of the Terrebonne coastal region. The vibracore in figure 8 illustrates the stratigraphy and age relationships between the Modern delta plain and the Late Holocene delta plain. Shell hash from the Teche transgressive surface date 4180 yBP and the underlying marsh deposits date 4780 yBP and 5440 yBP with increasing depth. The Late Holocene delta plain sequence is prodelta mud capped by transgressive marsh and lagoonal sediments.

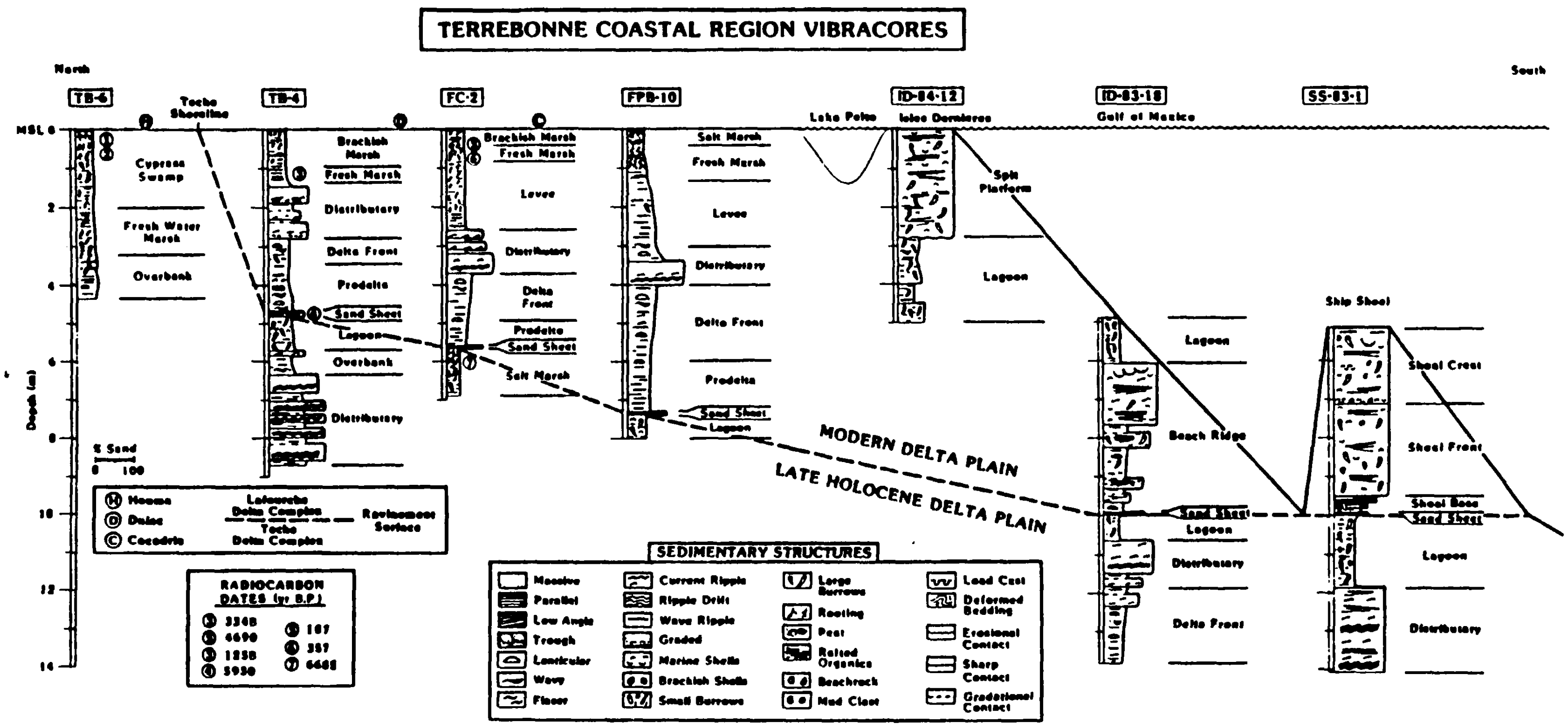

Figure 6. Geologic cross-section (dip) illustrates the stratigraphic and age relationship in the Terrebonne coastal region of the Lafourche delta complex (Penland et al, 1987).

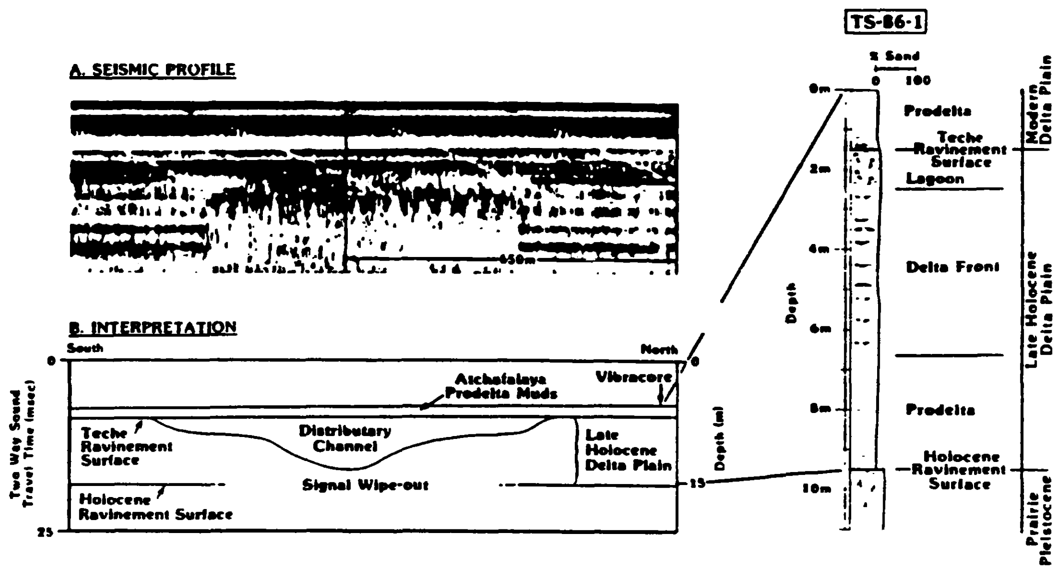

Figure 7. Seismic and vibracore data from the Trinity Shoal area, offshore of Marsh Island, illustrating the stratigraphic relationships between the Modern and Late Holocene delta plains.

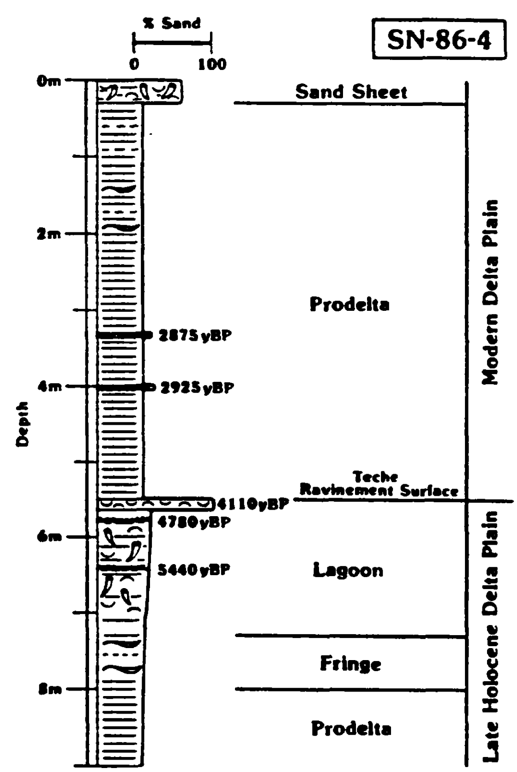

Figure 8. Vibracore log from the Lafourche delta complex, offshore of Point Au Fer Island, illustrating the stratigraphic and age relationships between the Modern and Late Holocene delta plains.

Radiocarbon dates found shell hash within the prodelta Lafourche delta complex are 2875 yBP and 2925 yBP with depth. The Teche transgressive surface is persistent and not easily recognized in seismic and vibracore data but also delineated in engineering studies by the U.S. Army Corps of Engineers (USACE 1962a,b). In the eastern Terrebonne basin and western Barataria basins, the USACE conducted three studies to identify the best location for the Bayou Lafourche and Lafourche-Jump waterway. Figure 9 is located on the east side of the Bayou Lafourche channel in the Barataria basin between Belle Pass and Golden Meadow. This diagram illustrates the continuity of the Teche transgressive surface. In lower Barataria Bay, the seismic profile in figure 10 shows the eastern continuation of the Teche transgressive surface which continues to be a predominant reflector on high resolution seismic profiles. Kosters (1989) mapped the occurrence of a transgressive surface beneath the Barataria basin using an extensive network of vibracores combined with radiocarbon dated material. Eastward out of the Barataria Basin, Frazier et al.

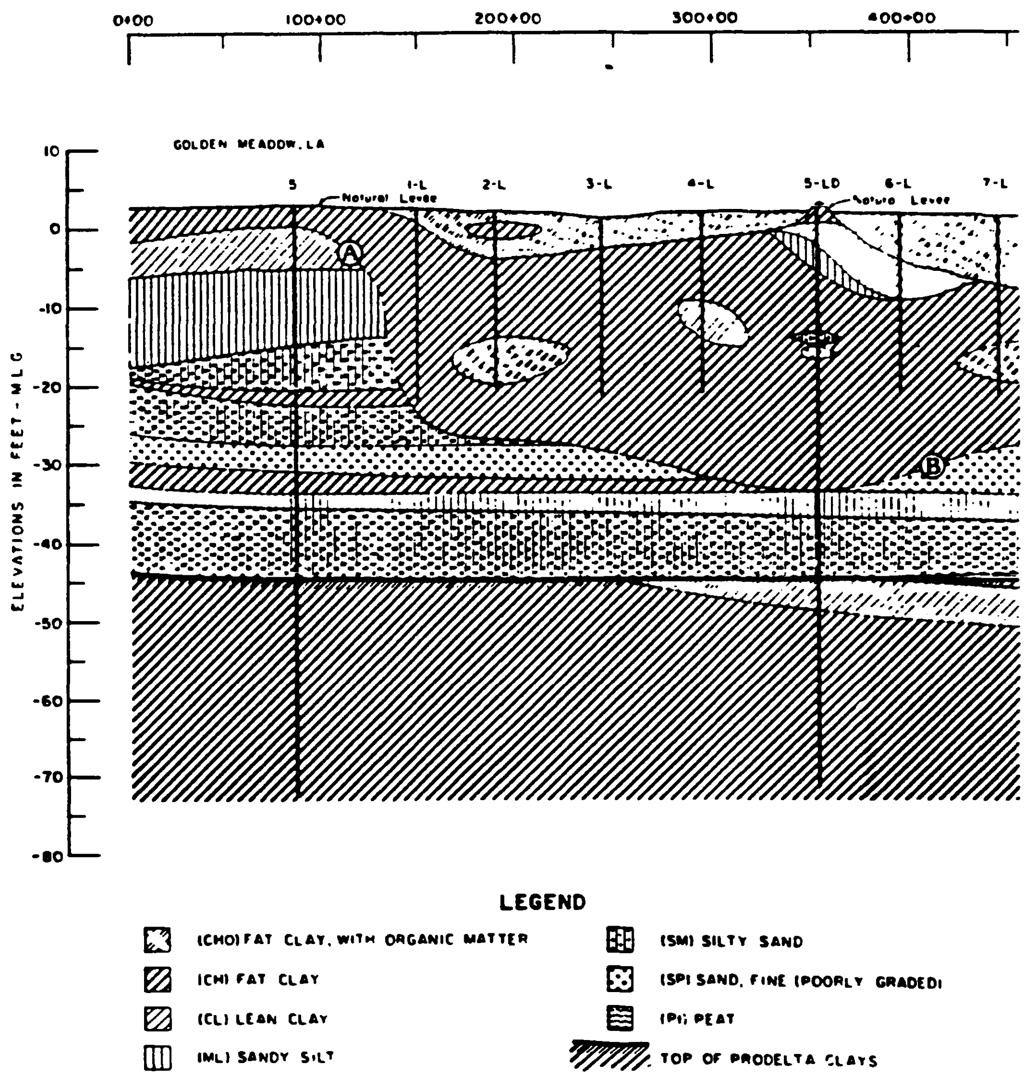

Figure 9. An USACE (1962b) engineering cross-section illustrating the Teche shoreline (A) and ravinement surface (B).

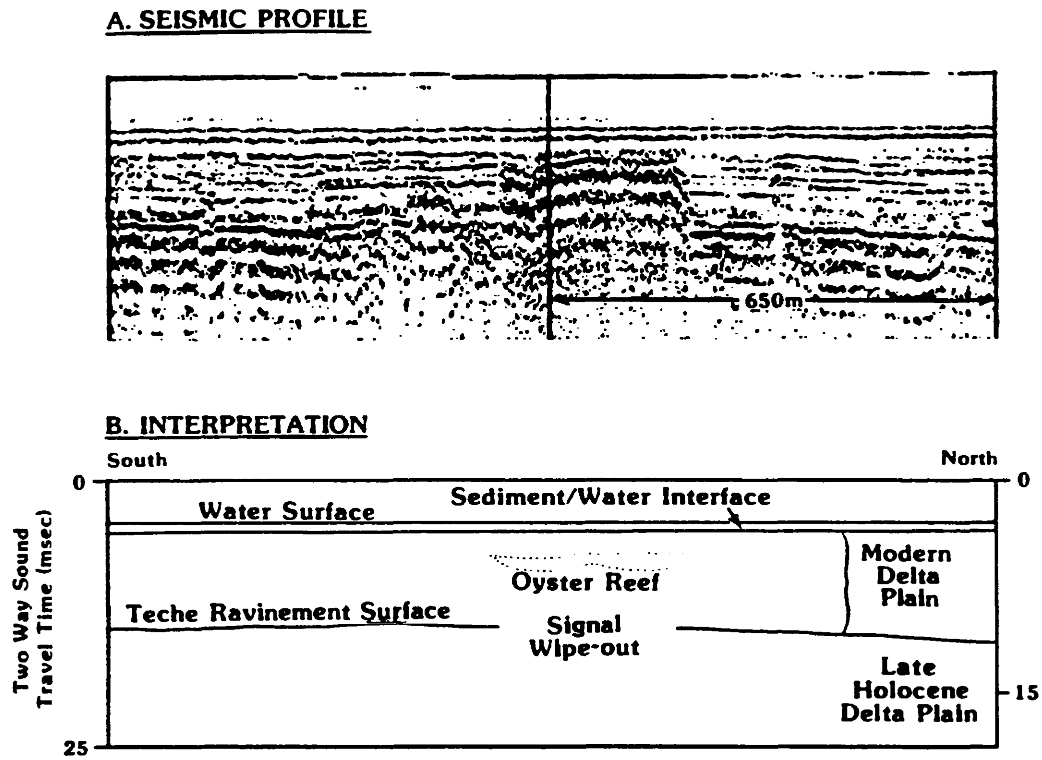

Figure 10. High resolution seismic profile in lower Barataria Bay illustrating the Teche ravinement surface separating the Modern and Late Holocene delta plains.

(1978) mapped the location of a transgressive shoreline buried by the St. Bernard delta complex, however, it is difficult to locate the exact position of the Teche shoreline into the St. Bernard delta complex. Within a small interdistributary basin in the St. Bernard delta complex, Yi (1987) mapped the location of the Teche transgressive surface truncating a sequence of lagoon deposits.

The best indicator of the position of the Teche shoreline can be delineated by the lagoonal relationship between thick old marshes and thin young marshes. Landward of the Teche shoreline, the typical marsh sequence is 3-4 m thick and contains basal radiometric dates of 4,000-7,000 yBP. Seaward of the Teche shoreline, the marsh sequence is thin, 1-2 m thick, and is typically 500-2,000 years in age. The old, thick marshes, landward of the Teche shoreline, are the product of sustained marsh aggradation landward of a retreating shoreline undergoing submergence. The facies architecture and age relationship suggest relative sea level rose 5-6 m in about 500-1,000 years (Penland et al. 1989, McBride et al. 1990). The young thin marshes reflect development since sea level stabilization and delta plain formation about 3,000 years ago.

The recognition of these features allowed the subdivision of the single Holocene delta plain model into Modern and Late Holocene delta plains. A comparison of the cross sections in figures 11A and 11B illustrate the concept of a single delta plain (Fisk, 1944) and multiple delta plains (Penland et al. 1987). The cross section from Fisk (1944) depicts a single Holocene delta plain in

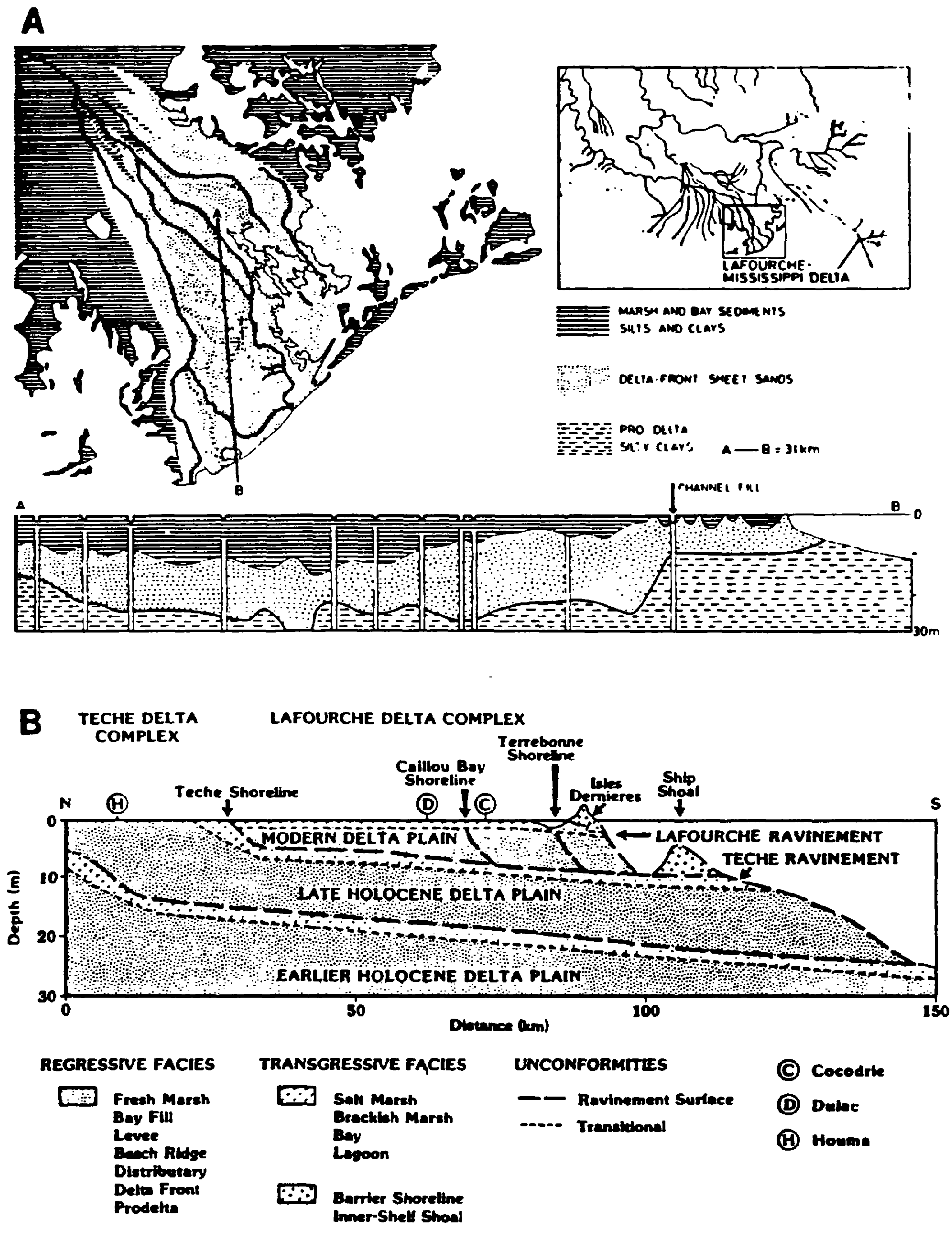

Figure 11. A) Fisk's (1944) cross-section through the Terrebonne coastal region showing a single, thick Holocene delta plain.
B) Penland et al.'s (1987) cross-section through the Terrebonne coastal region showing multiple, thin Holocene delta plains.

the Terrebonne coastal region (Figure 11A). The second cross section in Figure 11B is arefinement of the first cross section by subdividing this 30 m section into two delta plains termed the Modern and Late Holocene based on new seismic, vibracore, and radiometric data. A plot of the radiocarbon data from throughout the Modern and Late Holocene delta plains illustrates the chronostratigraphic relationship between samples landward/below the Teche transgressive surface, and seaward/above the Teche transgressive surface. Two distinct populations become apparent from this graph, the Modern delta plain, and the Late Holocene (Figure 12). The distribution of the radiocarbon populations indicate two periods of different sea level stillstands separated by a major transgression about 3,000 - 4,000 yBP.

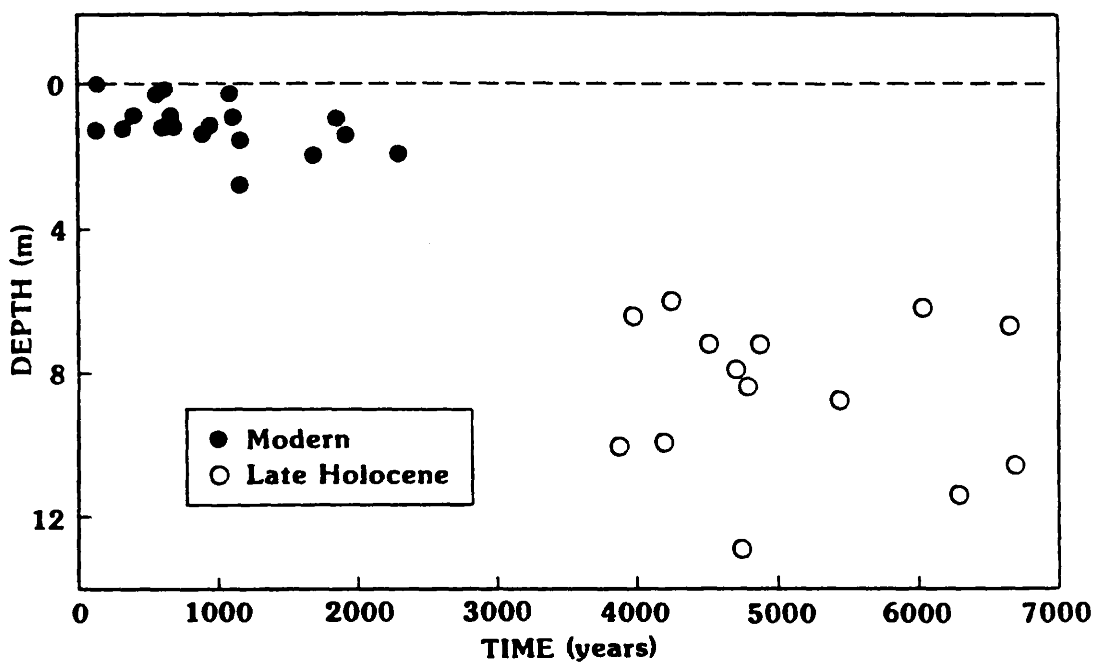

Figure 12. Graph of radiocarbon dates from basal marsh deposits in the Modern and Late Holocene delta plains. Two distinct radiocarbon populations can be observed separated by time and depth.

HOLOCENE COASTAL EVOLUTION

Relative sea level in the northern Gulf of Mexico during the late Wisconsinan lowstand fell to depths of -130 m below present sea level exposing the continental shelf and producing a set of shelf margin deltas supplied by the Mississippi River prior to 15,000 yBP (Coleman et al. 1983, Berryhill and Suter 1986, Kindinger 1989). These shelf-margin deltas represent lowstand system tracts. During the lowstand, the Mississippi River incised an alluvial valley across the continental shelf and together with tributary streams and subaerial weathering processes, produced an erosional unconformity on the Pleistocene Prairie terrace marked by a widespread oxidation surface (Fisk, 1944). Sediments were largely restricted to infilling the Mississippi River alluvial valley and submarine Canyon prior to 18,000 yBP. Between 18,000 yBP and present, the Mississippi River was no longer totally confined to the canyon and proceeded to develop a series of shelf-phase delta plains on the outer- to mid-continental shelf during the Holocene transgression. Individual shelf-phase delta plains were coupled with these stillstands, and backstepped landward in the form of transgressive system tracts, filling the lower alluvial valley of the Mississippi River. Each transgressive systems tract is built of a set of regressive lacustrine, bayhead, and shelf-phase delta complexes organized into a delta plain truncated by a transgression surface of erosion and overlain by a major marine sand body.

This pattern of sea level change during the Holocene transgression corresponds very closely to the sea level curves for the Gulf of Mexico by Curray (1960), Coleman and Smith (1964), Nelson and Bray (1970), and Frazier (1974). All the Holocene sea level curves in figure 13 show a sea level highstand about 3,000 years ago. Maximum withdrawal estimates range between 90 m and 130 m respectively (Curray 1960; Frazier 1974). The earliest sea level curve by Curray (1960) indicates sea level stillstands at -60 m about 10 - 12,000 yBP and at -20 m about 8 - 10,000 yBP. The Nelson and Bray (1970) curve closely match Curray's (1960) sea level stillstands at -20 m about 7-9,000 yBP and -5 m about 3 - 6,000 yBP. Frazier's (1974) curve identified a similar pattern of Holocene sea level stillstands at slightly different levels and ages. Frazier (1974) recognized sea level stillstands at -20 m about 7 - 9,000 yBP and -5 m about 4 - 6,000 yBP. The pattern of Holocene sea level changes recognized by our investigation represents a hybrid curve of Curray (1960), Coleman and Smith (1964), Nelson and Bray (1970), and Frazier (1974). This Holocene curve recognizes three relative sea level stillstands in the last 10,000 years and each is identified by a major transgressive sandbody. The outer shoal is associated with the Early Holocene stillstand. Ship Shoal and Trinity Shoal are associated with the Late Holocene stillstand, and the transgressive barrier islands associated with the modern stillstand. The Early Holocene stillstand occurred 7 - 9,000 yBP, the Late Holocene stillstand occurred 4 - 6,000 yBP, and the Modern stillstand occurred 0 - 3,000 yBP (Figure 14).

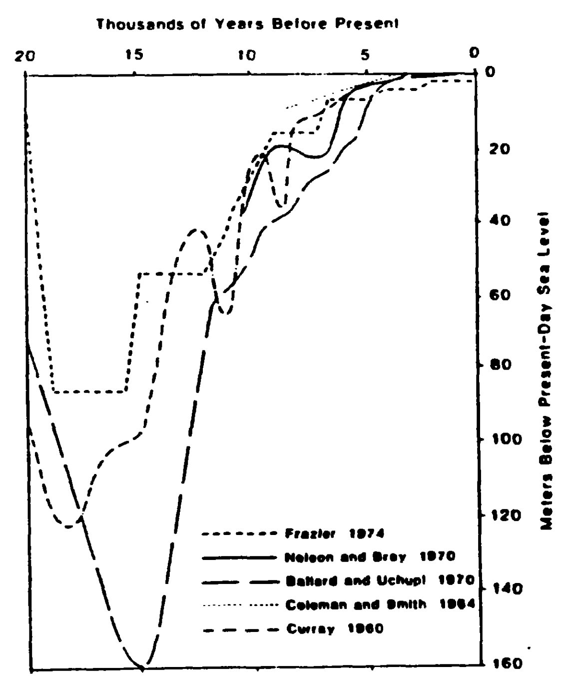

Figure 13. Holocene sea level curves for the Gulf of Mexico.

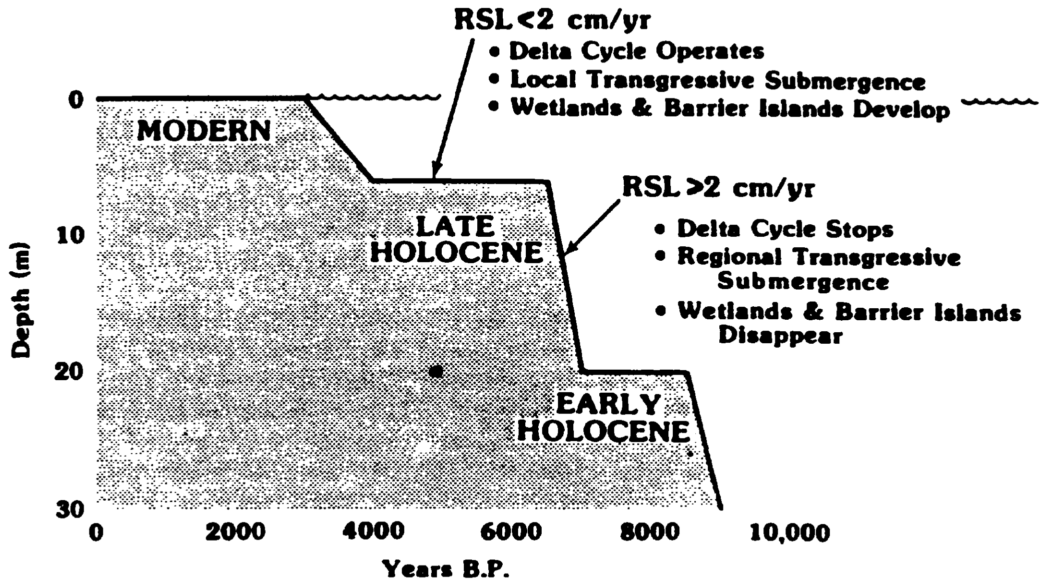

Figure 14. Relationship between sea level history and coastal stability. This curve represents a hybrid of Curray (1960), Nelson and Bray (1970), and Frazier (1974) combined with new seismic, vibracore, and radiometric data from the U.S Geological Survey and Louisiana Geological Survey.

DISCUSSION

Assuming relative sea level rise during the Holocene transgression was constant produces an average rise rate of 0.7 cm/yr using 130 m as the lowstand withdrawal depth. According to this scenario, highstand was achieved about 5,000-7,000 years ago at which time the Mississippi River began building its single modern delta plain. However, the existence of earlier Holocene delta plains seaward on the continental shelf terminated by large sand shoals indicates the rise of relative sea level during the Holocene transgression was not constant and that eustatic dominated stillstands took place. The occurrence of these shoals indicates that a threshold value for relative sea level rise exists, at which a particular rate of rise produces either coastal retreat or progradation. Within the Modern delta plain, subsidence ranges from >0.50 cm/yr for young sediments to <0.10 cm/yr for older sediments based on data from the Terrebonne coastal region (Penland et al., 1987). Under these conditions, the Mississippi River has built a delta plain of four smaller delta complexes over the last ≈3,000 years. The timing of these stillstands is based on previous work by Curray (1960), Nelson and Bray (1970), and Frazier (1974). Coleman and Smith (1964), McFarlan (1961), and Gould and McFarlan (1959) all suggest the current stillstand started ≈3,000 yBP. The recognition of regional transgressive surfaces separating the individual delta plains and the stratigraphic relationships between overlying shoals and underlying delta plains indicate several hiatuses in delta plain development occurred during the Holocene transgression. New radiocarbon dates lying below the Late Holocene transgressive surface indicate a stillstand in the period 4,000-6,000 yBP.

Because three major stillstands took place between 3,000 and 10,000 yBP, less time was available for sea level to rise 20 m; therefore the rate of rise must be higher than the average rate indicated for the Holocene transgression (Figure 12). During the period 3,000-10,000 yBP, a 20 m rise in sea level occurred incorporating two periods of rapid relative sea level rise. Assuming the Early (7,000-9,000 yBP) and Late (4,000-6,000 yBP) Holocene stillstands each lasted 2,000 years, this allows only 2,000 years available to accomplish a 20 m rise in sea level, at a rate of 1 >cm/yr or greater. If these transgressive events are only 500 years in duration, as some radiometric data suggest, the sea level rise rates would increase to >2 cm/yr. Thomas and Anderson (1988) suggest marine ice sheet decoupling as a potential mechanism for rapid, episodic rises in relative sea level during the Holocene transgression. These relative sea level rise rates suggest that the threshold value for regional coastal erosion, wetland loss, and submergence to occur in the Mississippi River delta plain is probably at rates greater than 2 cm/yr.

CONCLUSION

Geologic studies of the Holocene evolution of the Mississippi River delta plain led to the identification of a relative sea level rise threshold rate for coastal transgression and submergence. The Holocene transgression filled the lower Mississippi River valley with a series of backstepping, transgressive system tracts deposited during periods of relative sea level stability. Each transgressive system tract represents a shelf-phase delta-plain separated by a transgressive surface of erosion. The sequence stratigraphic relationships of the transgressive system tracts, filling the lower alluvial valley, indicate the threshold rate for the regional transgression and submergence of a single shelf-phase delta plain to take place is about 2 cm/yr for a sustained period of centuries. It also appears that whenever the rates of seal level rise drop below 2 cm/yr and achieve relative stability for a sustained period of centuries, the lower alluvial valley fills with lacustrine delta complexes behind a highstand shoreline. Once the lower alluvial valley is filled, bayhead delta complexes develop and evolve into shelf-phase delta plains. The Mississippi River delta is currently experiencing catastrophic coastal erosion and wetland loss within a subsiding basin experiencing subsidence rates of 0.5 - 1.0 cm/yr. Compounding the current relative sea level rise rate with the forecasted eustatic rate of 1.0 - 2.0 cm/yr will dramatically accelerate the coastal land loss crisis in Louisiana.

ACKNOWLEDGEMENTS

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GEOLOGIC CONTROLS ON THE FORMATION AND EVOLUTION OF QUATERNARY COASTAL DEPOSITS OF THE NORTHERN GULF OF MEXICO

S.J. Williams[1], S. Penland[2], A.H. Sallenger, Jr.[3],
R.A. McBride[2], and J.L. Kindinger[3]

Abstract

Shoreline erosion and the loss of tidal wetlands have become major problems for many coastal regions of the Nation due to a combination of complex natural (e.g. sea-level rise, storms, land subsidence, sediment deficiency) and man-made causes (e.g. dams, canals, engineering structures). The coastline of the northern Gulf of Mexico comprises almost 20 percent of the U.S. coastline. Composed mostly of low-relief, mainland-type sandy beaches and barrier islands separated by shifting tidal inlets and backed by shallow estuaries and tidal wetlands, this coastline is undergoing erosion at widely varying rates along 95 percent of its length.

In the deltaic plain of Louisiana, erosion and wetlands loss rates are the highest, not only in the Gulf region, but in the United States. To document these rapid changes and to learn more about the processes responsible and the geologic framework within which they operate, the U.S. Geological Survey (USGS), the Louisiana Geological Survey (LGS), and Louisiana State University (LSU) have just completed a 5-year study of the barrier islands and are in the third year of a 6-year wetlands study. The barrier islands investigations consisted of the systematic collection and analysis of precision nearshore hydrographic data, 15,000 line-km of high-resolution seismic profiles, 565 surface sediment samples, 500 continuous vibracores (12 m length), digital shoreline plots from 1853 to 1989, a 4-year record of storm overwash events, and analysis of tide gauge records over the past 50 years to quantify the rise in relative sea level. The study area includes the coast and inner shelf of central Louisiana, west of the Mississippi River delta to the Isles Dernieres barrier system and east to the Chandeleur Islands.

The 300 km-wide Mississippi River delta plain is a complex of six distinct ancestral delta lobes which resulted from periodic channel switching of the river over the past 7,000 years. Following the river's switch to a new system of distributary channels, the abandoned deltas undergo rapid deterioration due to subsidence and sediment starvation. As part of the evolutionary process, the barrier island arcs marking the distal ends of the delta complexes experience progressive erosion and sand loss by overwash, inlet breaching, and longshore transport. For example, the

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Isles Dernieres barrier system, associated with the Lafourche delta, has lost 78 percent of its land area from 1890-1989, and erosion rates average 10-20 m/yr, but are as great as 30 m/yr when hurricanes impact the islands. Ultimately, these island arc systems transform into submerged, inner-shelf sand bodies, such as Ship Shoal. The shoals, in turn, are substantially reworked by nearshore processes, eventually losing the morphology and sedimentary structures of a barrier and increasingly taking on the characteristics of a marine sand body.

Results from these studies demonstrate that deltaic progradation, river channel switching, and subsequent rapid erosion accompanying the marine transgression are regular and predictable events along the Mississippi River delta plain and will likely continue in the future. Mitigation measures, such as shoreline nourishment and barrier restoration, that mimic the natural processes may slow the land loss.

Introduction

Coastal erosion and wetlands loss and deterioration are serious and widespread problems affecting all regions of the Nation. All 30 of the coastal States are experiencing erosion, and the long term social, environmental, and economic consequences are major concerns to the coastal zone population as well as to resource managers. As shown in Figure 1, depicting coastal erosion and accretion, Louisiana has the distinction of experiencing the highest coastal erosion rates in the United States (Morgan and Larimore, 1957; Penland and Boyd, 1981; Morgan and Morgan, 1983; McBride and others, 1989). Erosion rates along the Louisiana coast average - 4.2 m/yr with a standard deviation of 3.3; the rates of shoreline change range between + 3.4 m/yr and - 15.3 m/yr (Penland and others, 1990). The highest rates of erosion are concentrated on the barrier islands and deltaic headlands that front the Mississippi River delta plain.

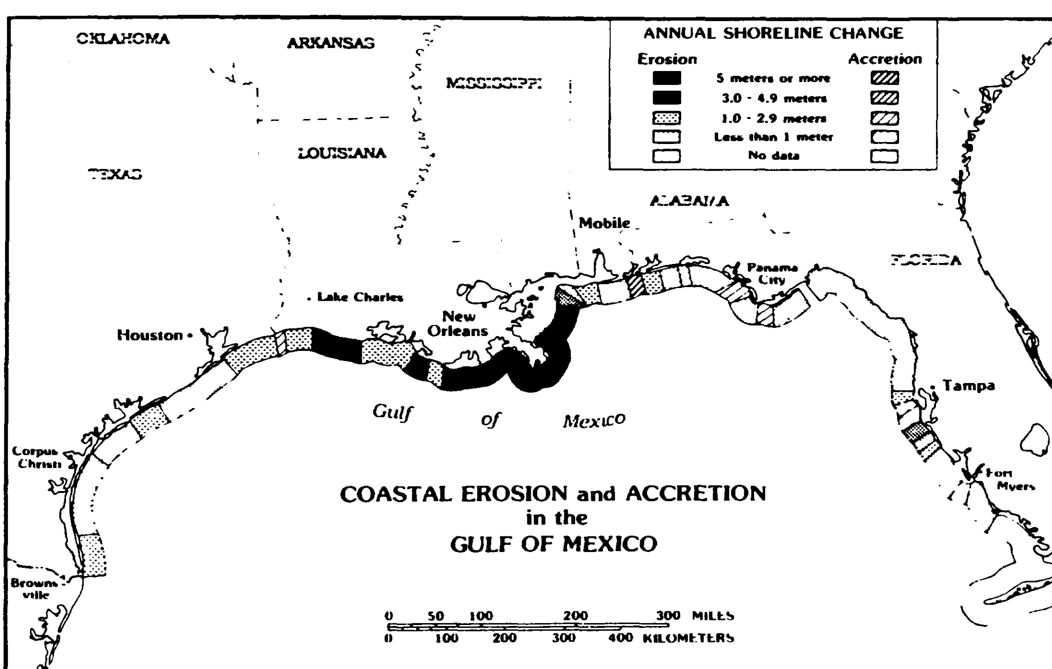

Figure 1. - *Map depicting the extent and magnitude of coastal erosion around the northern Gulf of Mexico. (Based on USGS National Atlas of the USA, 1988.)*

Louisiana's average erosion rate of 4.2 m/yr represents long-term conditions and is not representative of individual storm events. Coastal erosion is not a uniform process; especially rapid erosion rates are often associated with the passage of major cold fronts, tropical storms, and hurricanes (Penland and Ritchie, 1979; Boyd and Penland, 1981; Ritchie and Penland, 1988; Dingler and Reiss, 1990). Field measurements have documented 20-30 m of coastal erosion during single storm events lasting only a few days. In addition to erosion at the Gulf shoreline, the total area of Louisiana's barrier islands is also decreasing rapidly. According to Penland and Boyd (1982), the coastal barriers lost nearly 50 percent of their subaerial surface area between 1880 and 1980. Map comparisons by McBride and others (1989) indicate that the area loss has continued to the present.

The natural processes of wetlands degradation combined with wetlands destruction and alteration by public agencies and private landowners have resulted in the loss of more than 50 percent of the wetlands that existed in the contiguous United States at the start of European settlement over 200 years ago. These wetlands losses are continuing at rapid rates, and nowhere in the Nation is the problem greater than in the Mississippi River delta plain of Louisiana, an area which accounts for an estimated 25 percent of the vegetated wetlands and 40 percent of the tidal wetlands in the 48 conterminous States. An estimated 80 percent of the Nation's tidal wetlands loss has occurred in Louisiana, and by current estimates, as much as 100 km^2 are lost each year (Figure 2). These losses are the result of a combination of physical erosion by waves and currents and conversion of vegetated salt and intermediate marsh to open water estuaries due to disintegration of the marshlands by salt-water intrusion, sea-level rise, reduction of fine-grained sediment supply, and regional compactional subsidence (Williams and Sallenger, 1990).

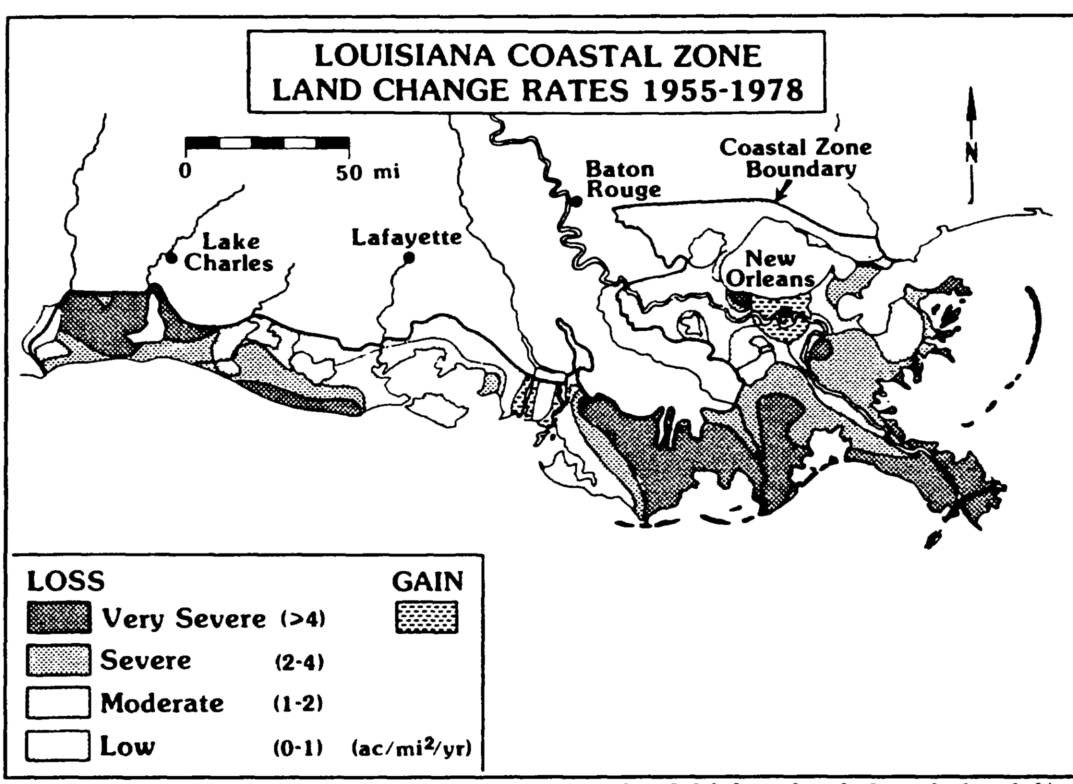

Figure 2. - *Map showing the extent and magnitude of tidal wetlands loss in Louisiana from 1955 to 1978. (Based on van Beek and Meyer-Arendt, 1982.)*

To address the erosion and wetlands loss problems in Louisiana, the USGS has been working in cooperation with the LGS and the Coastal Studies Institute at LSU. The objective of the studies, begun in 1986, is to quantify the spacial and temporal extent of erosion and provide better understanding of the geologic controls, conditions, and sedimentary processes responsible for rapid changes affecting the coastal environments of Louisiana (Table 1). The study area encompasses a 300 km stretch of the coast and adjacent inner shelf region, west of the Mississippi delta from Sandy Point to the Isles Dernieres and the Chandeleur Islands east of the delta. Figure 3 shows the extent of the study area and the locations of major seismic and vibracore data used. A list of the major sets resulting from the barrier erosion study is included in Table 2.

This paper presents some of the final results from the barrier island study and is intended to complement other papers presented in this volume by USGS/LGS/LSU investigators.

Table 1. Primary Natural Geologic Factors Affecting Coastal Environments in Louisiana

- River discharge/channel switching cycles
- Sea-level change
- Subsidence/sediment compaction
- Storm impacts
- Normal coastal processes (waves, longshore transport, winds)
- Human activities (dredging, fluid withdrawal, coastal structures)

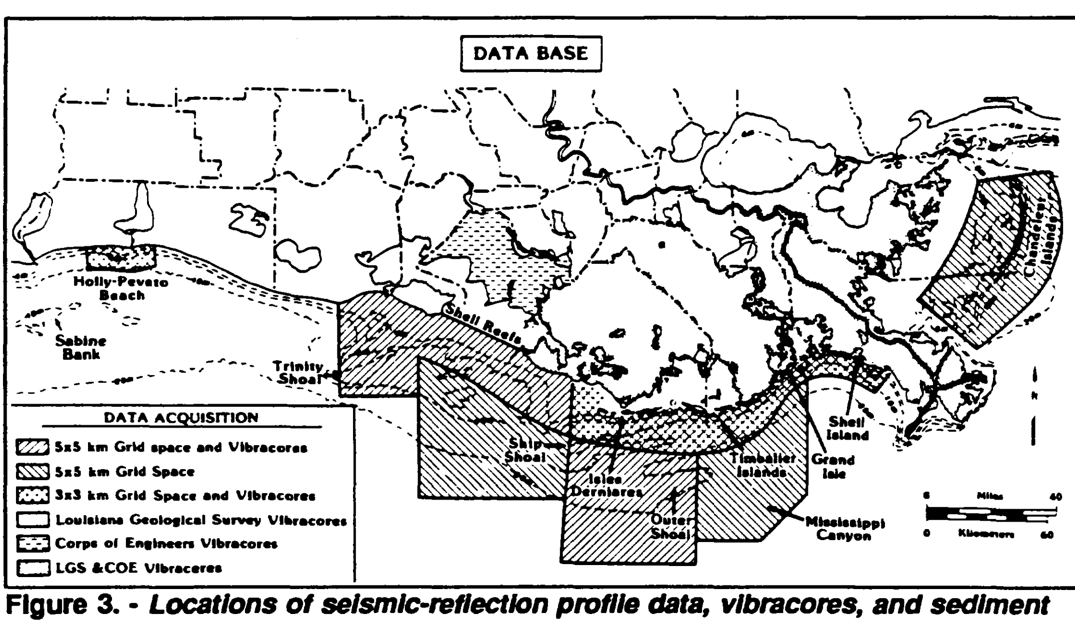

Figure 3. - ***Locations of seismic-reflection profile data, vibracores, and sediment grab samples used to decipher the geologic framework.***

Table 2. Primary Information Sets Resulting From the USGS/LGS/LSU Louisiana Barrier Island Study

- Precision digital shoreline data (1853 - 1989)
- High-resolution seismic-reflection profiles (15,000 line-km)
- Continuous vibracores, 12 m in length (500 cores)
- Surficial sediment grab samples (565 samples)
- Precision digital nearshore/shelf hydrographic survey data (1890 - 1989)
- Four-year record of meteorological and storm overwash events
- Analysis of 50-year tide-gauge records

Louisiana Deltaic Plain

The 300 km wide deltaic plain is the product of continuous accumulation of sediments deposited by the Mississippi River and its distributaries over the past 7,000 to 8,000 years as sea level rose to within ±10 m of its present position. Assembled as overlapping, stacked sequences of unconsolidated sands and muddy sediments, the deltaic plain is composed of six major delta complexes consisting of at least 18 smaller deltaic lobes. Using geophysical data, results from deep sediment borings, and careful mapping of surficial landforms, Van Andel (1960), Van Andel and Poole (1960), Frazier (1967), and Coleman (1988) discuss the evolutionary history of the delta plain. The spacial relationships of the four ancestral and two active deltas are shown in Figure 4.

The processes controlling deltaic plain development consist of establishment of a prodelta platform in shallow water followed by progradation of the delta and bifurcation of the distributary channel. The delta construction phase continues until the channel becomes so distended that it is no longer hydraulically efficient. Channel shifting and then abandonment of the old channel occurs in favor of the shorter and more efficient course to the coast. Cut off from its sediment source, the abandoned delta subsides by consolidation and compaction at a rate which is a function of sediment thickness. Marine coastal processes erode, winnow, and rework the seaward margin of the abandoned delta. Sandy headlands and barrier beaches result from the reworking process and continue to undergo transgression, resulting in segmented barriers separated by tidal inlets and backed by shallow bays and lagoons.

Along with periodic shifts in the course of the Mississippi River, sea-level rise also has been a dominant influence on the development of the deltaic plain region. From a maximum low stand at depths of -130 m at the end of the Pleistocene Epoch, sea level rose rapidly (>2 cm/yr) in early Holocene to around -10 m by 7,500 yr BP (Coleman, 1988; Penland and others, 1988). Since the middle Holocene, relative sea level has continued to rise, primarily due to compactional subsidence of thick (>100 m) Holocene sediments. With analysis of an array of tide gauge records, Penland and Ramsey (1990) demonstrate that relative sea-level rise across the entire delta plain exceeds 1 cm/yr (Figure 5). Comparison with a world-wide eustatic rise of about 0.15 cm/yr suggests that, on average, the subsidence component accounts for

approximately 80 percent of the relative sea-level rise. As a result, south central Louisiana is experiencing rates of relative sea-level rise seven times greater than the world average.

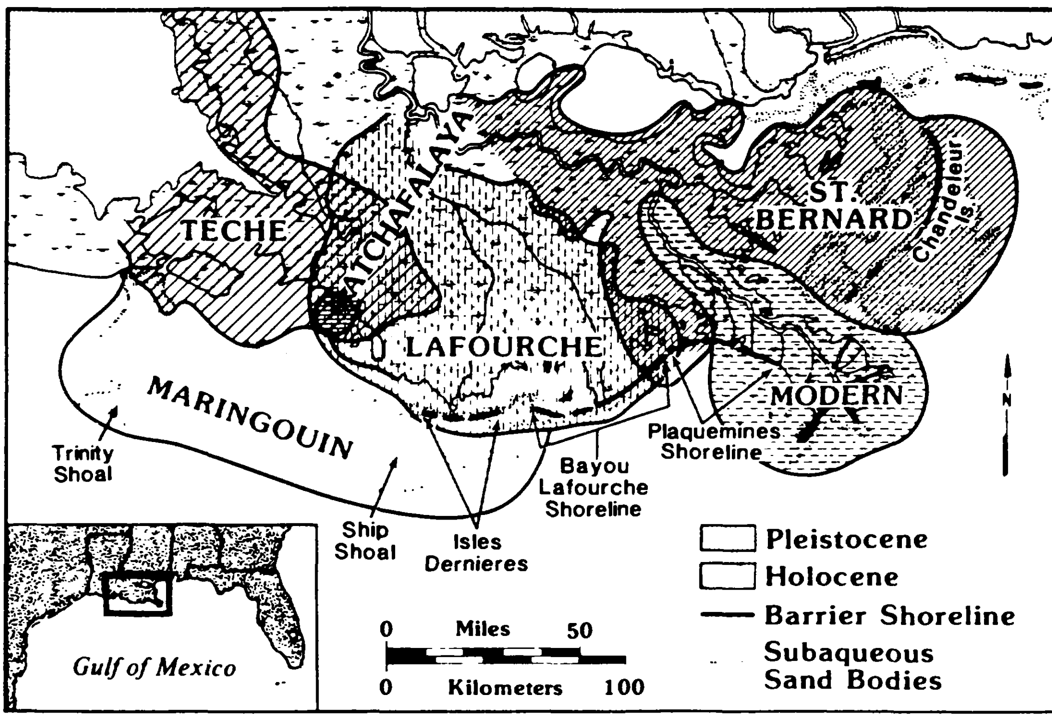

Figure 4. - *The product of an overlapping series of deltaic lobes created by shifts in the Mississippi River over the past 7,000 years, the Louisiana deltaic plain comprises five ancestral and two active lobes. (From Frazier, 1967.)*

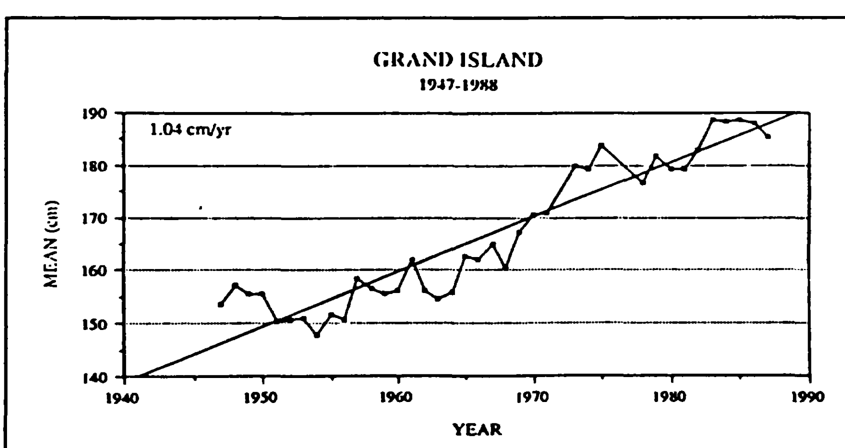

Figure 5. - *Analysis of tide-gauge records (1947-1988) from Grand Isle, Louisiana, show an average rise in relative sea level exceeding 1 cm/yr. (From Penland and Ramsey, 1990.)*

The Isles Dernieres barrier arc system (part of the Bayou Lafourche delta complex), the Chandeleur Islands (part of the St. Bernard delta), and Ship Shoal are prototypical examples of the deltaic evolutionary process. The Isles Dernieres system

and Ship Shoal will be described in this paper; the Chandeleur barrier system is discussed by Kindinger and others in a paper in this volume.

Isles Dernieres Barrier Arc

Five islands presently comprise the 35 km-long barrier system that has, since the 1850's, undergone dramatic land loss, rapid transgression, and island fragmentation as described in detail by McBride and others (1989, this volume). The earliest maps show the Isles Dernieres as a continuous island attached to the Lafourche headland, but since the mid-19th century, the island arc has eroded more than 2 km and lost 78 percent of its area due to a combination of in-place narrowing by erosion and submergence on both the Gulf and back bay shorelines. Wine Island, the easternmost island segment, has nearly eroded completely and is primarily a shoal platform.

The normal processes, dominated by tropical storms and passage of cold fronts, are responsible for frequent overwash (±10 events/yr) that have reduced the island relief by planing off much of the berm and dunes, leaving mostly low sand flats, terraces, and small (<1 m relief) incipient dunes. On the foreshore, broken and whole shells (primarily *Crassostrea virginica, Mulinia lateralis, Rangia,* and *Mercenaria*) are abundant and act to armor the beach surface. The beaches are greater than 99 percent quartzose sand, with mean grain size ranging from 2.35 to 3.05 phi (fine sand) and sorting from 0.28 to 0.95 (moderately to very well sorted). Williams and others (1989) have demonstrated that the sands are derived from a single source, the actively eroding deltaic margin, and represent well-winnowed lag deposits.

The four stratigraphic strike and dip sections in Figure 6 show that the subsurface of the Isles Dernieres consists of flat-lying, interfingering, distributary deltaic and beach facies overlain by a transgressive sequence of lagoonal muddy facies and sandy barrier shoreline facies. Sand thickness of the islands varies from about 1 m in the central body of the barrier arc to as much as 5 m toward the ends.

Inner Shelf Surficial Sediments

The Isles Dernieres shoreface and inner shelf from Raccoon Point to Cat Island Pass have an even, gently seaward sloping surface to the 10-m isobath at the base of Ship Shoal (Figure 6). Seaward of Ship Shoal, the regional slope continues to depths of 18 m in the southeast corner of the study area, about 25 km from the Isles Dernieres coast. Williams and others (1989) show that fine quartz sand is a major component of the surficial sand sheet, but percentages are found to vary widely. The minimum sand content is 0.5 percent where lagoonal facies crop out on the shelf, while nearshore areas, Cat and Wine Island Passes and most of Ship Shoal, are 90 to 99 percent quartz sand.

Ship Shoal Sand Body

Ship Shoal, aligned parallel to the shoreline, is approximately 50 km long, ranges in width from 5-12 km, with a relief of 7 m in the west to 5 m at the eastern end (Figures 4 and 6). Water depths vary from 3 m in the west to 8 m in the east. The strongly landward asymmetry of the shoal, as shown in Figure 6, suggests it is migrating landward. This is supported by comparisons of historic bathymetric profiles; over the past century, Ship Shoal has migrated more than 1 km landward, driven by wave activity.

The dip sections in Figure 6 reveal that Ship Shoal is composed exclusively of sand, which averages 5-6 m thick along the entire 50 km length. Lagoonal muddy facies 1-1.5 m thick underlie the shoal and these are underlain by a 10-m thick sequence of the Maringouin deltaic complex (Penland and others, 1988). Vibracores detail that Ship Shoal and the underlying lagoonal-deltaic deposits represent a continuous regressive-transgressive stratigraphic sequence. No evidence of primary barrier shoreline sands are found in the cores, yet the lagoonal facies are in situ beneath Ship Shoal and underlie the inner shelf, often exposed in the flat between Ship Shoal and the Isles Dernieres shoreface (Williams and others, 1989). The sedimentary character and stratigraphic sequences indicate that Ship Shoal is a marine sand body transgressing landward on the lagoonal ravinement surface. Evidence suggests its origin is a former barrier shoreline that underwent transformation and submergence during the very late Holocene transgression. With continued sea-level rise, the shoal is migrating landward at a rate similar to that of the Isles Dernieres barrier arc.

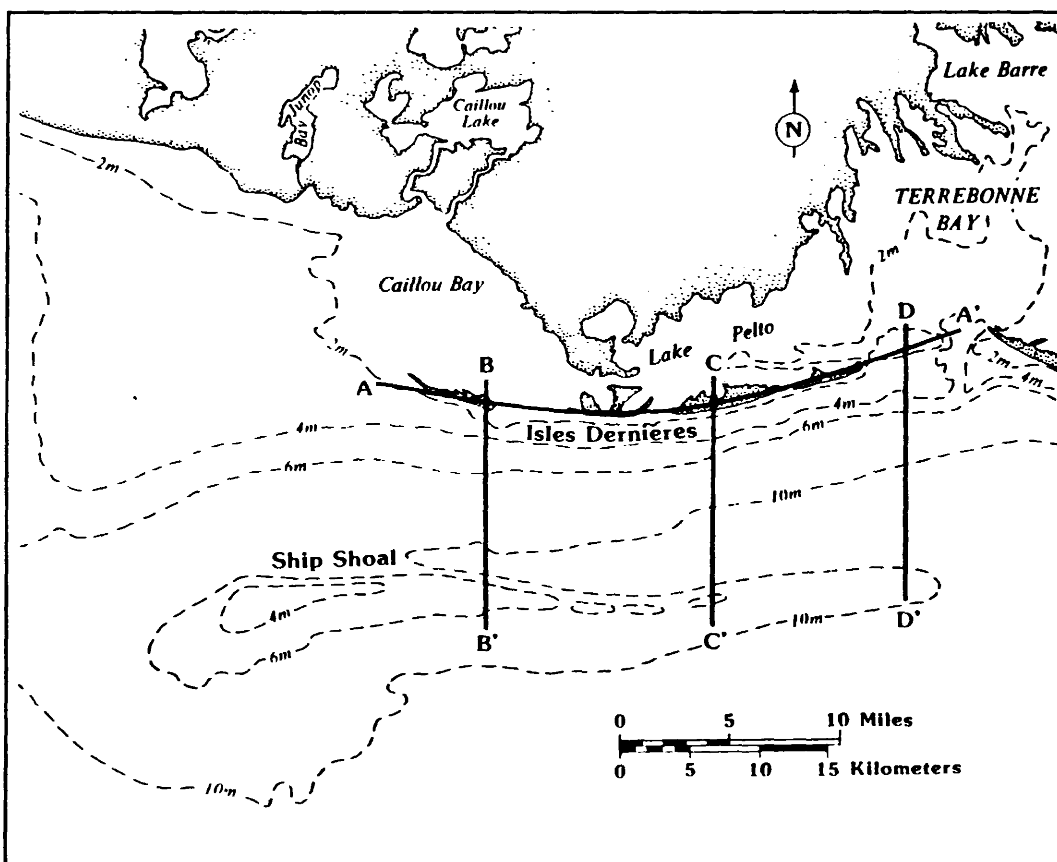

Figure 6. - (A) *Location map of the Isles Dernieres barrier arc and Ship Shoal depicting the locations of geologic strike and dip sections as constructed from vibracores and seismic-reflection profiles.* (B) *Strike section of the Isles Dernieres showing stratigraphic squence of deltaic units and overlying transgressive barrier facies.* (C) *Dip section from Raccoon Island to Ship Shoal. (D) Dip section from Trinity Island to Ship Shoal.* (E) *Dip section from Wine Island Shoal to Ship Shoal.*

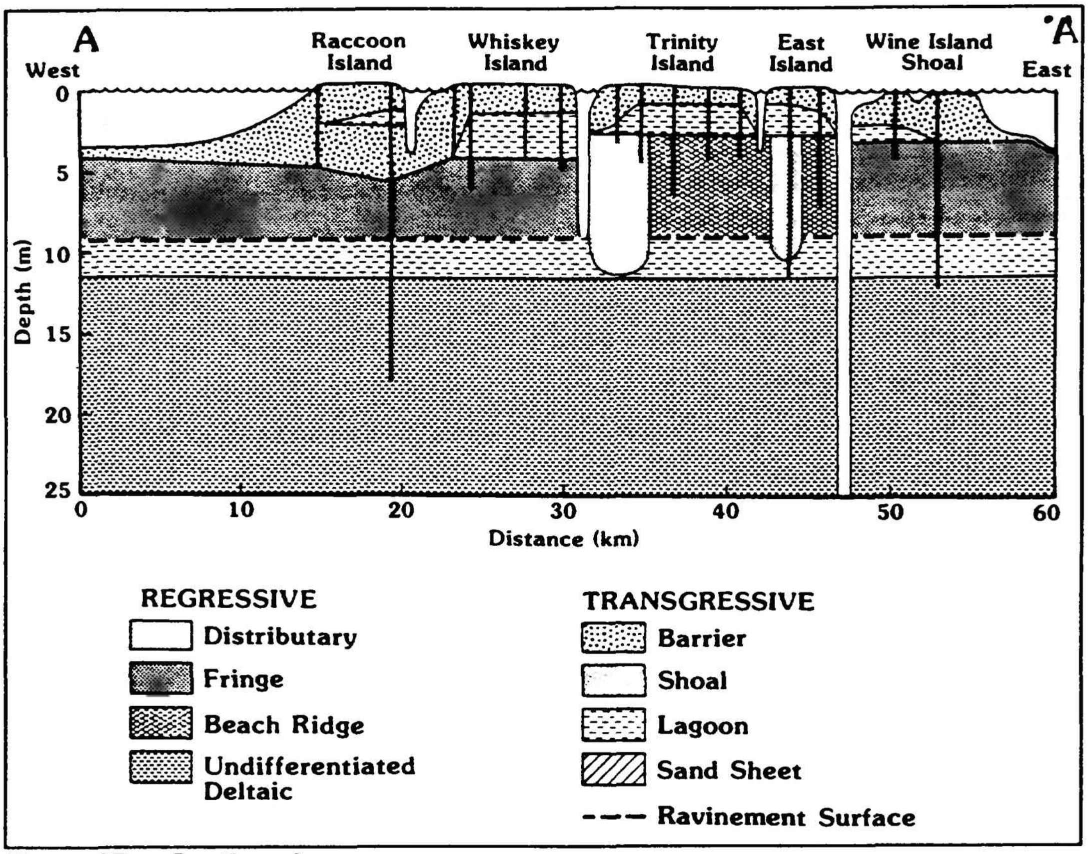

Figure 6B. - *Continued*

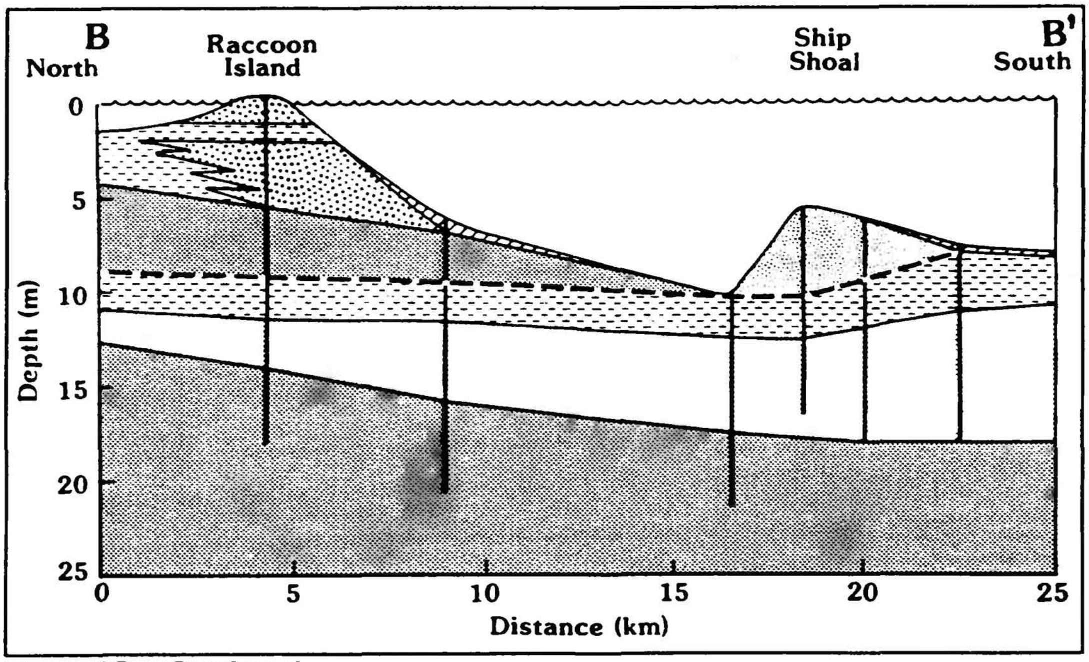

Figure 6C. - *Continued*

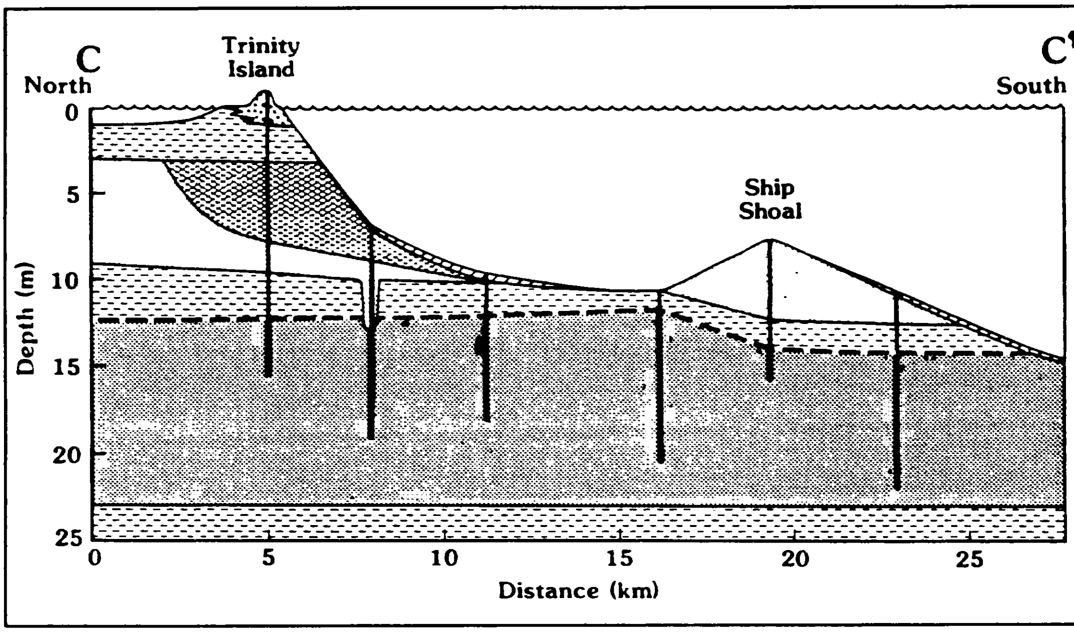

Figure 6D. - *Continued*

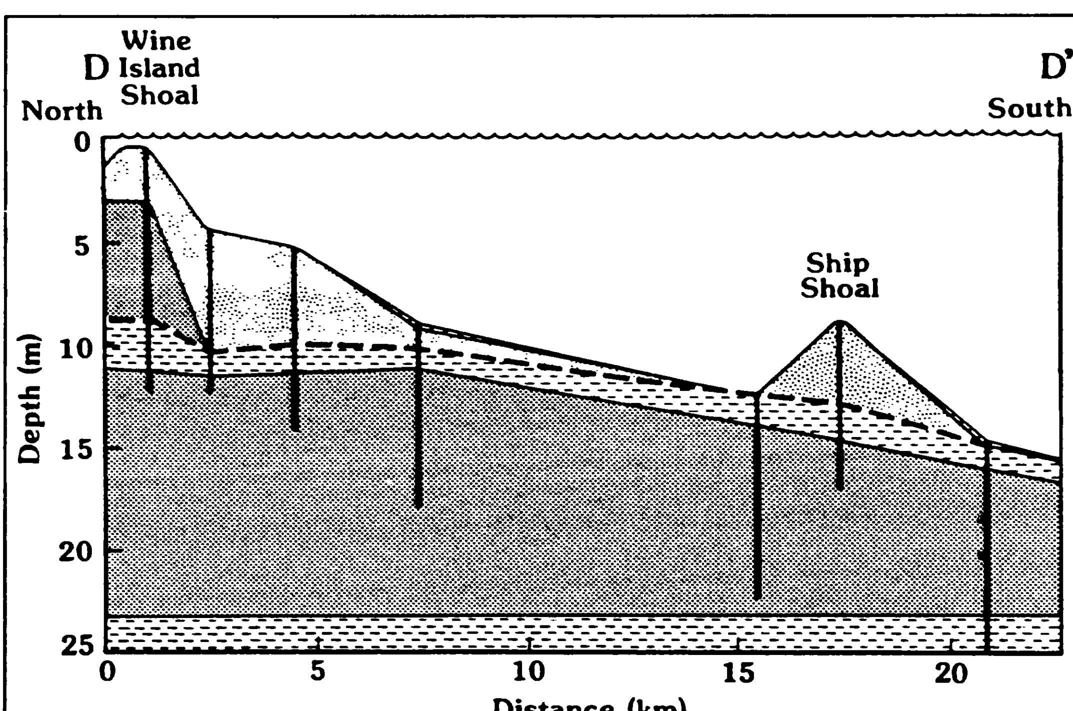

Figure 6E. - *Continued*

Model of Delta Plain Evolution

Throughout the Quaternary, the Mississippi River and its distributaries have been a dominant force controlling the location and thickness of sediments along the north central coastline of the Gulf of Mexico. The geologic record from the coast and inner shelf show that over the past 7,000 to 8,000 years, wide shifts in the river channel have occurred at approximately 1,000-year intervals (Coleman, 1988). Such repeated changes in channel position, location of the resultant delta, and the effects of the Holocene transgression have resulted in an evolutionary sequence as shown in Figure 7. Described in Penland and others (1988), each sequence is characterized by distinctive geomorphic and subsurface stratigraphic features that are a reflection of its position in the evolutionary cycle.

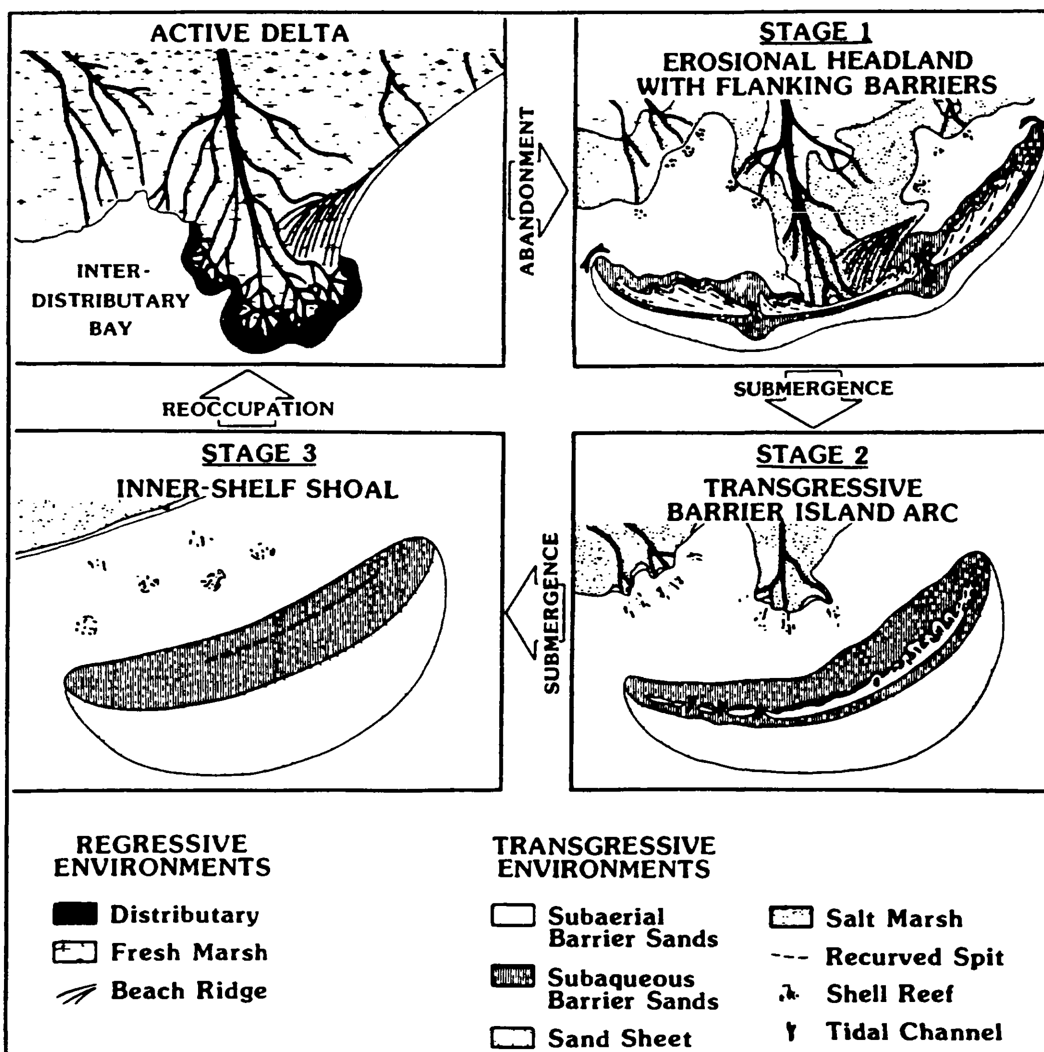

Figure 7. - *Summary three-stage model of the origin and evolutionary development of the Mississippi River delta plain. (From Penland and others, 1988.)*

The cycle begins when the channel shifts and the abandoned delta is no longer the primary depocenter. In stage 1, open marine processes erode the deltaic headland, and sand winnowed from erosion of the shoreface is transported east and west, creating recurved sand spits and flanking barrier islands. Continued erosion, compactional subsidence, and sea-level rise lead to separation of the barrier arc from the headland in stage 2. As exemplified by the Isles Dernieres, stage 2 barriers undergo rapid loss of area, fragmentation into segmented barriers separated by tidal inlets, rapid landward migration, and increasingly frequent storm overwash. Finally, stage 3 is reached during which rise in relative sea level and overwash processes overwhelm the barrier arc and it is unable to maintain subaerial integrity. The resultant shoal is thoroughly reworked by shelf processes, eventually obliterating the sedimentary character of the former barrier. As is happening with Ship Shoal, landward migration of the shoal occurs through erosion of the seaward slope and crest and deposition on the landward slope. The shoal eventually reaches an equilibrium position on the inner shelf and maintains its position and sand volume through either submergence below wave base or eventual burial by renewed deltaic deposition.

Summary and Conclusions

Coastal erosion and the widespread loss and deterioration of wetlands habitats are problems of concern in all regions of the Nation. Louisiana, however, and the Mississippi deltaic plain in particular, lead the country in loss of valuable coastal resources. To gain a better understanding of the causes of erosion and the geologic processes responsible, the USGS, working jointly with LGS and LSU, conducted field studies of the barrier-inner shelf region and, more recently, the tidal wetlands. The 5-year study focusing on barrier erosion is now complete, and the wide array of information resulting from it are available in a variety of reports, maps, large-format atlases, and papers. Much of the data is in digital form and is being incorporated into a Geographic Information System network. Results from this study demonstrate that the present Louisiana coast is the product of complex natural processes involving cycles of delta building by the Mississippi River followed by channel relocation, creation of headland-barrier shorelines, and marine transgression accompanied by rapid erosion. In addition to the natural factors controlling erosion, a century or more of human intervention and development has also contributed to the land loss process. Information from these studies is being used by Federal, State, and local decision makers to deal most effectively with erosion problems confronting Louisiana.

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LATE QUATERNARY GEOLOGIC FRAMEWORK, NORTH-CENTRAL GULF OF MEXICO

Jack L. Kindinger[1], Shea Penland[2], S. Jeffress Williams[3], Gregg R. Brooks[4], John R. Suter[5], and Randolph A. McBride[6]

ABSTRACT

The geologic framework of the north-central Gulf of Mexico shelf is composed of multiple, stacked, delta systems. Shelf and nearshore sedimentary facies were deposited by deltaic progradation, followed by shoreface erosion and submergence. A variety of sedimentary facies has been identified, including prodelta, delta fringe, distributary, lagoonal, barrier island, and shelf sand sheet. This study is based on the interpretation and the synthesis of >6,700 km of high-resolution seismic profiles, 75 grab samples, and 77 vibracores.

The nearshore morphology, shallow stratigraphy, and sediment distribution of the eastern Louisiana shelf are the products of transgressive sedimentary processes reworking the abandoned St. Bernard delta complex. Relatively recent Mississippi delta lobe consists

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primarily of fine sand, silt, and clay. In the southern portion of the St. Bernard delta complex, asymmetrical sand ridges (>5 m relief) have formed as the result of marine reworking of distributary mouth-bar sands. Silty sediments from the modern Mississippi Birdsfoot delta onlap the St. Bernard delta complex along the southern edge. The distal margin of the St. Bernard complex is distinct and has a sharp contact on the north near the Mississippi Sound barrier island coastline and a late Wisconsinan delta to the south..

The Chandeleur Islands and the barrier islands of Mississippi Sound have been formed by a combination of Holocene and Pleistocene fluvial processes, shoreface erosion, and ravinement of the exposed shelf. Sediments underlying the relatively thin Holocene sediment cover are relict fluvial sands, deposited during the late Wisconsinan lowstand. Subsequent relative sea-level rise allowed marine processes to rework and redistribute sediments that formed the nearshore fine-grained facies and the shelf sand sheet.

INTRODUCTION

The morphology of the north-central Gulf of Mexico has been strongly influenced by glacio-eustatic fluctuations in sea level: Beard et al. (1982), Curray (1960), Fisk (1944, 1956), Frazier (1974), Lehner (1969). Extension of the Gulf Coast shelf has resulted primarily from a series of events: coastal-plain facies deposited during a lowstand, transgression, Shelf phase delta deposited during sea withdrawal across the continental shelf, and the deposition of deltas at the shelf edge (Suter and Berryhill, 1985; Suter et al. (1987), Kindinger, 1989b).

The bathymetry and subsurface characteristics of the Mississippi-Alabama shelf and upper slope are the result of deltaic deposition and intervening periods of erosion during lowstands. Typically the progradational sediments overlie sediments deposited during a transgression. Little evidence of structural deformation, such as faulting, diapirism, and deformation by shallow gas, is present on the shelf. In contrast, the shelf break and upper slope are marked by several diapirs with associated faults.

According to Frazier (1974), late Quaternary surficial sediments across the shelf and upper slope may relate to several different depositional episodes. The surficial and shallow subsurface sediments of the shelf area are generally sandy, as evidenced by grab samples and the presence of buried stream channels and bedforms inferred from profiles.

Previous studies in this area used shallow borings to characterize the local geology. Coleman and Gagliano (1964), Coleman (1976), and Frazier (1974) discussed the cyclic sedimentation of the Mississippi River delta complex and included the St. Bernard delta complex that extends on to the Mississippi-Alabama shelf. Several investigators have identified shelf-margin deltaic deposits and fluvial systems on the Louisiana shelf. Roemer and Bryant (1977) discussed episodes of fluvial and deltaic deposition. More recently, Suter and Berryhill (1985), Berryhill (1986), and Coleman and Roberts (1988) described upper Quaternary delta deposits on the Texas-Louisiana shelf margin,using high-resolution seismic profiles. Kindinger (1988), Kindinger (1989a), and Kindinger (1989b) utilized high-resolution single-channel seismic profiles to describe the geologic history of the Mississippi-Alabama shelf.

The Chandeleur Islands is the oldest trangressive barrier island arc found in the Mississippi delta plain. Penland et al. (1988) discussed the transgressive history of the Chandeleur Islands and developed a transgressive Mississippi Delta barrier model using vibracores and high-resolution single-channel seismic profiles. The model represents a comprehensive approach to the transgressive phase of Mississippi River delta-plain depositional systems.

This paper examines the stratigraphic record of the upper Pleistocene to Holocene deposits of the Mississippi-Alabama nearshore and continental shelf. The objective is to describe the late Quaternary evolution of the Mississippi-Alabama shelf and coast. Mississippi-Alabama shelf stratigraphy represents a good example of cyclic sedimentation caused by changes in sea level and the reworking of upper Quaternary sediments.

DATA BASE

This study is based on >6,700 km (Fig. 1) of high-resolution single-channel seismic-reflection profiles (Kindinger et al., 1982; Kindinger, 1989a). Several seismic systems were utilized: (1) 400-Joule minisparker; (2) 3.5-kHz transducer; (3) 40- and 5-in.^{3} air guns; (4)

12-kHz transducer; and (5) Geopulse boomer system*. Other sample materials included equally spaced grab samples (75) collected on the shelf and slope for correlation with the seismic data (Fig. 1) and 77 12-m-long vibracores were collected. Navigation was accomplished using a combination of systems: (1) an integrated system of Loran C, satellite, and gyrocompass, and (2) Northstar Loran C (Kindinger et al., 1982).

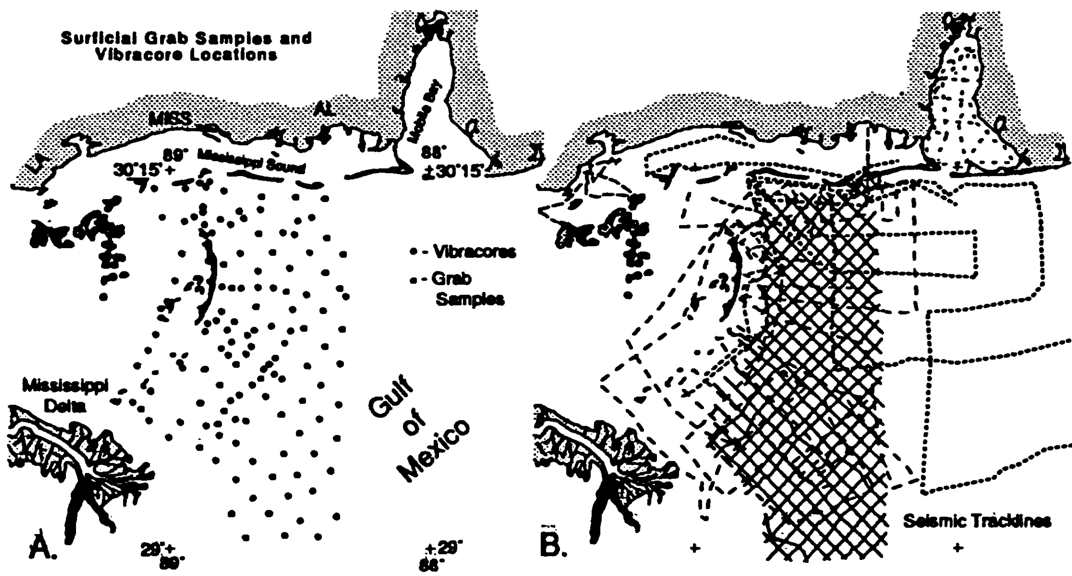

Figure 1. Mississippi-Alabama shelf study area in the Gulf of Mexico: (A) locations of the 77 vibracores and 75 grab samples used in this paper, and (B) trackline map of >6,700 km of high-resolution single-channel seismic profiles collected on 6 major cruises since 1981.

SEQUENTIAL SHELF EVOLUTION

A schematic five-stage model was proposed by Kindinger (1988) for the evolution of the Mississippi-Alabama shelf. The earliest stage (stage 1) represents shelf erosion during the early Wisconsinan lowstand including associated sediments deposited outside the area. The following transgression, stage 2, shifted the zone of active deposition to the inner shelf and deposited a sediment layer <10 m thick. Third-stage shelf development began during the late Wisconsinan regression and occurred as a succession of delta lobes and interdeltaic facies from mid-shelf to the shelf break. During stage 3, the exposed shelf was eroded, and marine sediments were deposited contemporaneously on the upper slope as a

*Use of brand names in this report is for identification only and does not imply endorsement by the U.S. Geological Survey.

lowstand wedge on the slope. Stage 3 is considered the transition from Pleistocene to Holocene. The continuing transgression shifted the zone of active deposition to the inner shelf (stage 4). The most recent stage of shelf development occurred as sea level rose to its present level, during which time the Mississippi River prograded the St. Bernard delta complex and extended prodelta deposits to the mid-shelf region. Because the depocenter of the Mississippi River is now outside the area, little deposition is presently occurring on the Mississippi-Alabama shelf.

SURFICIAL SEDIMENTS

Large areas of the Mississippi-Alabama shelf are covered by sandy sediments (Fig. 2). The average sand-silt-clay percentages from the 75 grab samples 56, 26, and 18 (Kindinger et al., 1982). The sands on the southeast and northeast corners of the shelf are the oldest sediments in the area. These orthoquartzite sands were derived from the Cretaceous and younger sedimentary mantle of the Appalachians (van Andel and Poole, 1960; Mazzullo and Bates, 1985) and were emplaced as fluvial, shoal, and/or beach deposits on the subaerial shelf during the last major lowstand (Ludwick, 1964; Frazier, 1974; Penland and Suter, 1983).

The analyses of high-resolution seismic profiles, grab samples and cores show the occurrence of broad sandy shoals (sand ridges) in several areas (Penland et al., 1989). The inner shelf of this region has been reworked by marine processes such as longshore transport and shoaling, which have winnowed out much of the fine-grained sediments to form the shoals.

The latest depositional event in the area was the progradation of the St. Bernard delta complex. The sand ridges seaward and southeast of the Chandeleur Islands were developed by the reworking of distributary mouth-bar sands of ths delta complex. Sand from the St. Bernard delta complex coalesced to form the Chandeleur Islands chain (Ludwick, 1964). The silty sand and sandy silt located north, shoreward, and south of the Chandeleur Islands sand salient (Fig. 2) represent reworking of the St. Bernard delta complex. The tongue of silty sand extending into the Chandeleur Islands sand salient represents either settling of reworked finer grained sediment into a topographic low or possibly a reworked lagoonal/tidal flat deposit behind an earlier barrier chain. The shelf sand sheet is the result of late Wisconsinan deltaic deposits being reworked during transgression.

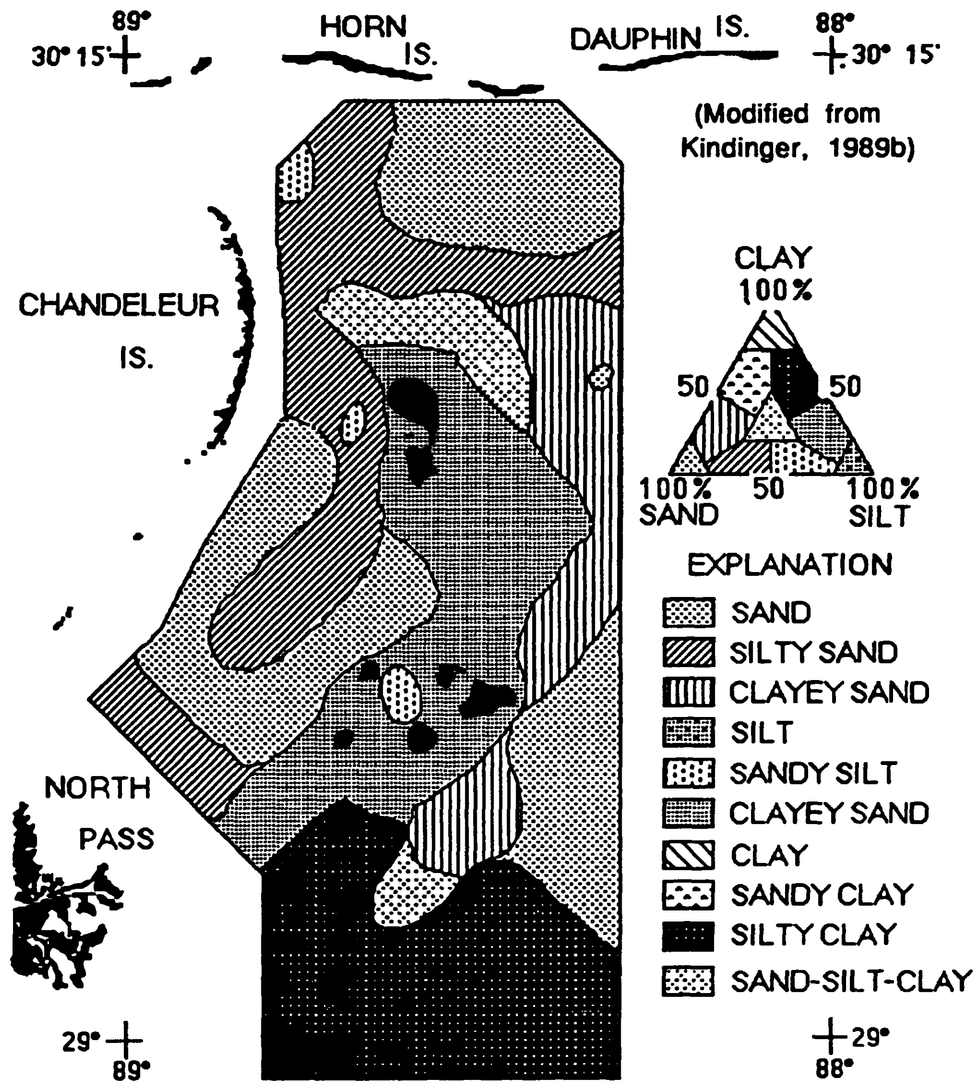

Figure 2. Surficial sediment distribution map of the western Mississippi-Alabama shelf (modified from Kindinger et al., 1989b).

DEPOSITIONAL ENVIRONMENTS

The most recent sea withdrawal left the inner shelf subaerially exposed, allowing streams to entrench the area. Seismic profile A-A' shows stream incisions with channel deposits, which typify numerous channel-fills on the inner shelf (Fig. 3). In general, the channel deposits consist of one or more of the following: coarse-grained sand, medium-grained sand, or poorly sorted medium- to silty-fine sand (Allen, 1965). The channel deposits are occasionally overlain by an abandoned channel fill of clay.

Basically, the broad mid-shelf region is constructed of sediments deposited by two delta complexes: (1) delta-front sediments of a late Wisconsinan shelf-margin delta, overlain by (2) prodelta sediments of the St. Bernard delta complex (Fig. 4). The surficial sediments down to the first reflector are prodelta clays of the St. Bernard delta complex. Underneath the clays are the sandier deposits of prograding clinoforms of the late Wisconsinan Lagniappe Delta (Kindinger, 1989a).

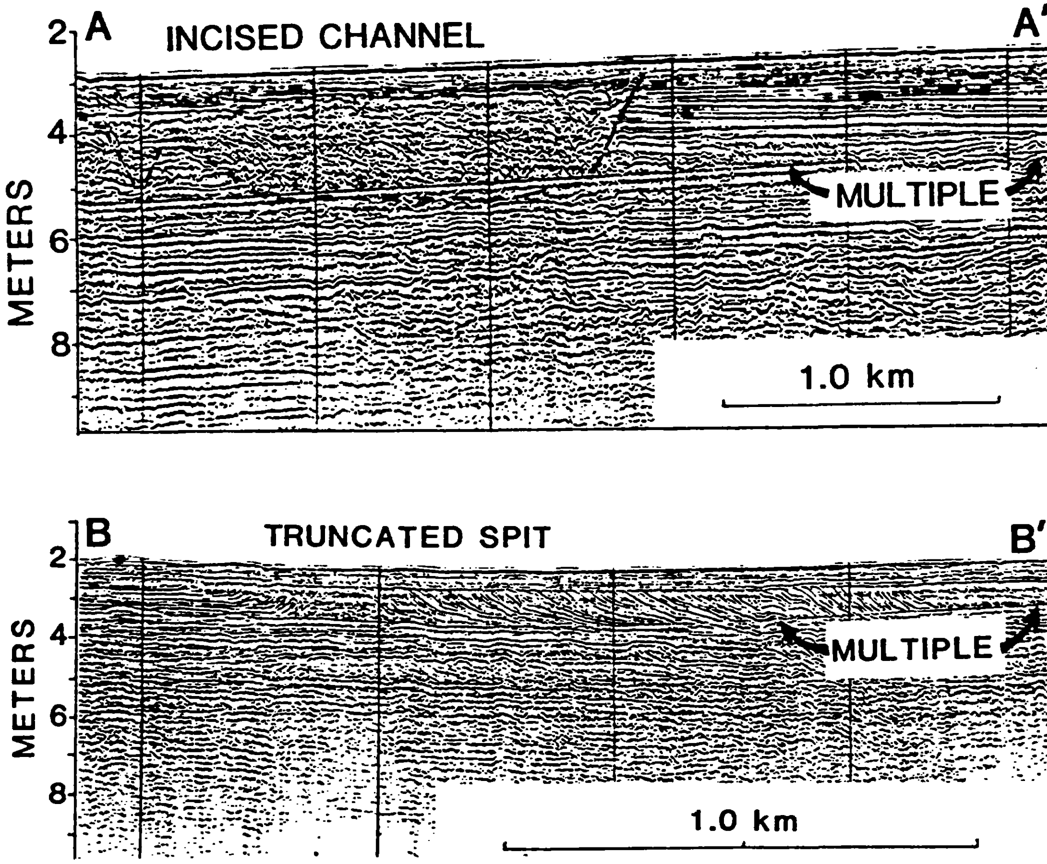

Figure 3. Seismic profile A-A' is an example showing a buried incised channel or valley. Profile B-B' shows a truncated sand ridge or spit, located off Petit Bois Island and is the most eastern remnant of Petit Bois Island. Locations of profiles are shown in Figure 5.

Lagniappe Delta

Deposits of the late Wisconsinan shelf-margin delta (Lagniappe delta) prograded basinward from mid-shelf to the shelf break. The deposits at the shelf break form the thickest portion (>90 m) of the delta and are seen in seismic profile as foreset and bottomset bedding. The extent of the delta complex is shown in Figure 5. The distributaries incised from the north and east, which would indicate the deposits at the shelf break form the thickest portion (>90 m) of the delta and are seen in seismic profile as foreset and bottomset bedding. The extent of the delta complex is shown in Figure 5. The distributaries incised from the north and east, which would indicate the paleo-Pearl and/or paleo-Mobile rivers as fluvial sources. The average thickness of the delta is 30 m; its areal distribution and thickness are affected by diapirs. As the delta prograded basinward, sediment ponded in an area between uplifted diapirs and spread outward laterally until it bypassed the obstructions. The basic geometry of this particular delta was modified during deposition by the presence of the diapirs.

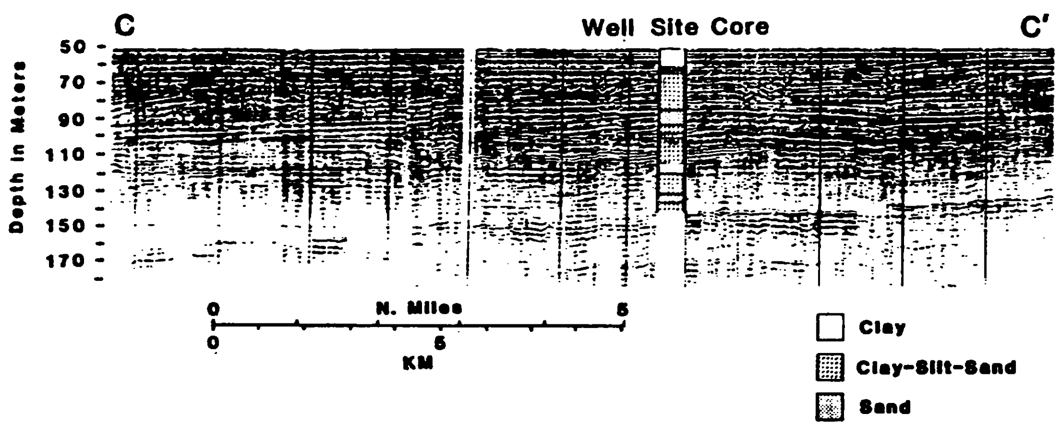

Figure 4. Seismic profile C-C' with superimposed core illustrating the bedding of the St. Bernard and Lagniappe deltas. Location of profile is shown in Figure 5.

The St. Bernard Delta Complex

As the most recent sea-level transgression flooded the shelf, very little deposition occurred in the area until progradation of the St. Bernard delta complex. Deposition began in the northwest corner of the region, where it results in the accumulation of an average thickness of 4 m. The St. Bernard delta complex systematically thins from the northwest to the southeast. Due to poor penetration of the seismic signal, very little internal structure can be seen except for low-angle clinoforms near the pinchout on the shelf. The St. Bernard delta ceased its progradational phase approximately 1.2 ka (Frazier, 1967), and is in the destructional phase of deltaic sedimentation cycle. Penland et al. (1988) and Suter et al. (1988) proposed depositional models for the development of transgressive barrier arcs including inner shelf shoals. On eof the primary examples used wa the St. Bernard delta complex. Typically, once the active delta lobe is abandoned, the unconsolidated mass of sediment becomes increasingly subjected to marine reworking, which is caused by a combination of the termination of sediment supply and subsidence. The net result of such reworking and winnowing is the formation of sandy shoals (discussed earlier) and the formation of the transgressive barrier island arc. The seaward margin of the delta is composed of thin beds in which most of the progradational foresets have been reworked and destroyed.

The inner shelf area was systematically sampled with vibracores to gather data in the area where the poor signal-to-noise ratio provided poor high-resolution

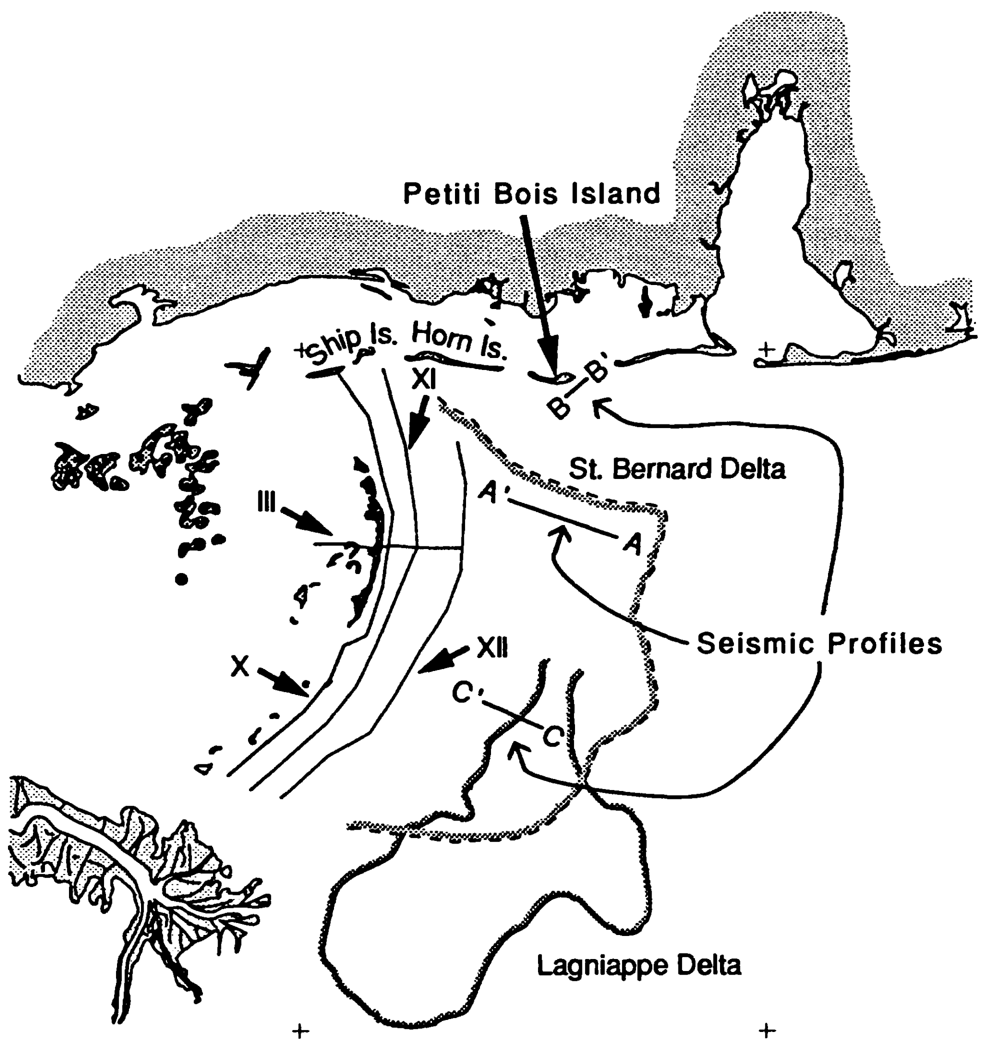

Figure 5. Extent of delta facies for the St. Bernard and Lagniappe Deltas. Shown are the locations of the seismic profiles in Figures 3 and 4, also cross sections in Figure 6 a-d.

single-channel seismic data. These cores were analyzed to provide a series of cross sections (Fig. 6 a-d). Figure 6a is a west-to-east cross section, from Chandeleur Sound across the Chandeleur Islands. In Figure 6a, the typical set of delta facies is seen, from prodelta to delta-fringe to distributary to lagoonal facies. The sand forming the Chandeleur Islands was deposited seaward of the distributary as a sandy mouth bar. The sands were winnowed and have transgressed shoreward back over the lagoonal deposits that were originally behind the mouth-bar sands (Penland et al. 1988, Fig. 16).

Three successive cross sections shown in Figure 6 b-d are displayed south to north and demonstrate sedimentary facies changes with increased distance seaward from the Chandeleur Islands. The cross sections also give dip view of facies extending seaward from the Mississippi Sound barrier-island chain. In the south and middle of Figure 6b are examples of distributaries. The southernmost distributary is overlain with lagoonal to shoal facies and are an example of an early transgressional stage similar to that in the development of the Chandeleur Islands in Figure 6a. Figure 6c primarily shows the prodelta and delta-fringe facies of the St. Bernard delta complex. An excellent cross section of the St. Bernard shoals is seen in the mid-section of Figure 6d. Prodelta facies is overlain by a delta-fringe facies that has been incised by a distributary. The distributary channel supplied sandy material for the formation of the St. Bernard shoals. A shelf sand sheet covers the area and was deposited during present sea level.

Coastal Mississippi-Alabama

The Mississippi-Alabama inner shelf has been affected by several processes. Shoreline migration and coastal processes, such as longshore transport and shoaling, have reworked the sands and winnowed out much of the finer sediments. Profile B-B' (Fig. 3) shows a sand ridge truncated by a ravinement surface and similarly truncated shingled reflectors that may be associated with the sand ridge. The sand ridge is located on the east end of Petit Bois Island and can be traced onto the beach. The buried channels shown on the profile may have been stream or tidal channels.

Cross sections X, XI, and XII, Figure 6 b-d, show the variability of facies found along the Mississippi Sound barrier islands. Cross section X terminates near Ship Island and is interpretated as barrier facies over prodelta deposits (Fig.6b). The lagoonal facies normally found in this sequence is absent from this core section and is possibly absent as an artifact of sample collection or

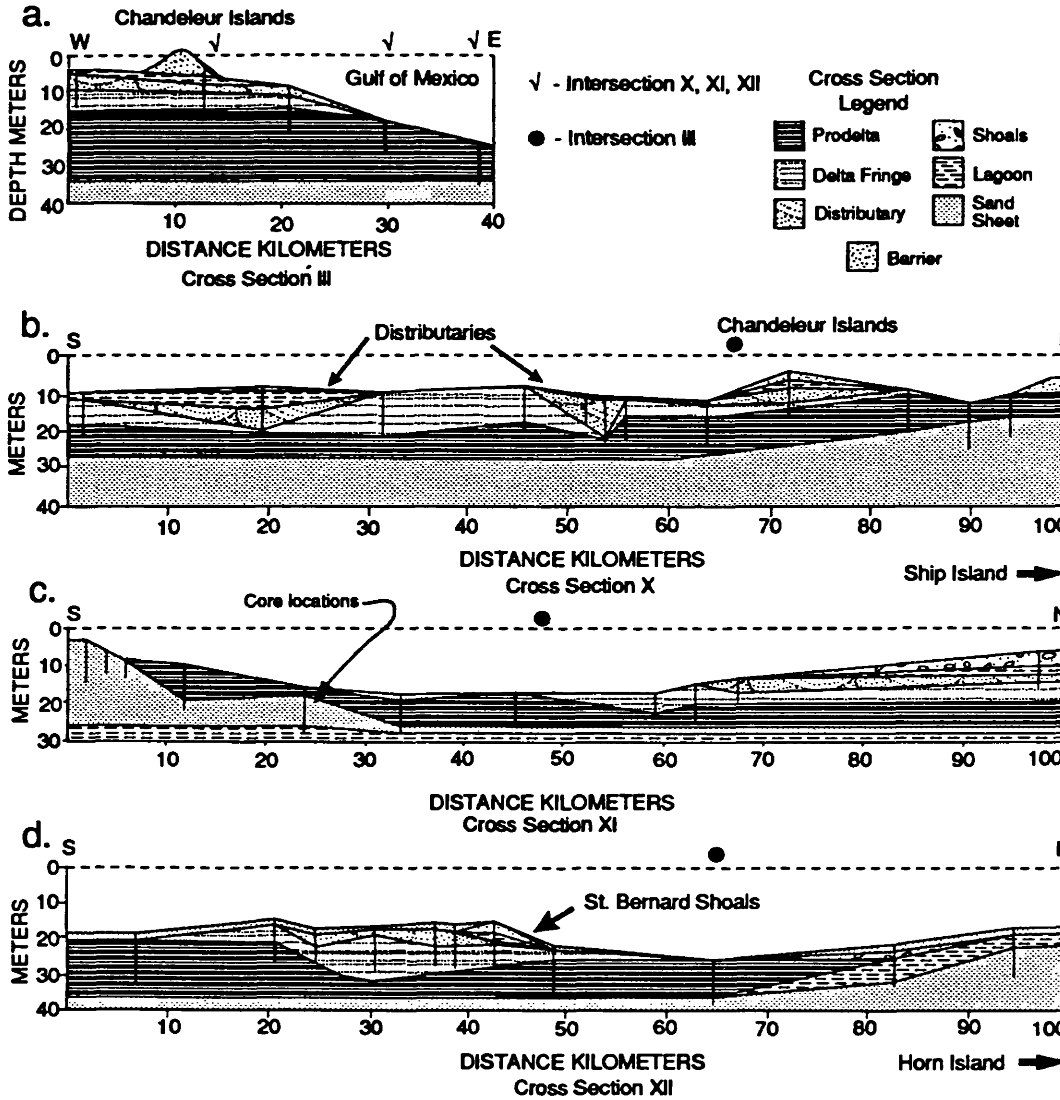

Figure 6. Cross sections constructed from vibracores taken on the Mississippi-Alabama shelf; locations of cross sections are shown on Figure 5.

location. To the east, cross section XI shows a relatively thick shoal over lagoonal, distributary, delta fringe and prodelta facies (Fig.6c). Cross section XII terminates near Horn Island with a sand sheet overlying lagoonal deposits (Fig.6d). The cross sections indicate the extent of the St. Bernard prodelta deposits and the transitional interfingering of the St. Bernard delta facies with the coastal Mississippi Sound barrier-island facies.

CONCLUSIONS

1. Bathymetry of the Mississippi-Alabama region depicts a gently sloping shelf (<0.1°) and a relatively steeper slope (1.0°-2.5°).

2. Effects of local tectonics on the shelf are minimal with surface and subsurface faults exhibiting a relatively random pattern.

3. There are basically two depositional environments: coastal and continental shelf. Each of these environments has been affected by marine processes associated with shoreline regressions and transgressions.

4. Surficial sediments of the Mississippi-Alabama shelf are sandy, whereas the upper-slope surficial sediments have a relatively low-sand content. Sands on the shelf were emplaced during the late Wisconsinan lowstand as deposits of a shelf-margin delta and by the more recent deposition of the St. Bernard delta complex. The shelf sediments have been reworked by coastal processes to form a patchy distribution of modern surficial sands.

5. Stream entrenchment has been extensive on the shelf. The earliest set of streams incised the subaerially exposed late Wisconsinan middle and outer shelves. Sediment deposited by the late Wisconsinan streams prograded from mid-shelf to the shelf break, forming a shelf-margin delta complex. Coastal and inner-shelf facies have been incised and sediment deposited by distributaries associated with delta deposition.

6. The Pleistocene-Holocene transgression deposited a thin layer of sediment over parts of the shelf, and the last depositional episode was the Holocene progradation of the St. Bernard delta.

7. Transitional interfingering from St. Bernard delta facies with Mississippi Sound barrier-island facies is very evident, including preserved structures such as tidal passes and truncated spits.

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MAPPING BARRIER ISLAND CHANGES IN LOUISIANA: TECHNIQUES, ACCURACY, AND RESULTS

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ABSTRACT

Changes in shoreline position along Louisiana's rapidly changing barrier coastline were compiled using cartographic data sources and aerial photography from 1855 to 1989. An interactive computer mapping system was employed to compile and to quantify shoreline data at about 880 shore-normal transects, which are presented in terms of magnitude, direction, and rate of change. Based on this comprehensive data set, two types of barrier island evolution are identified 1) **landward rollover, and 2) in-place breakup.**

INTRODUCTION

Studies on barrier island migration began in the late-1930s and focused on post-storm qualitative observations and slowly progressed to process-oriented, morphodynamic investigations by the early 1980s (Leatherman, 1987). By the late-1980s, quantitative evaluation of shoreline movement and wetland loss along coastal areas of the United States became a national concern because of increasing coastal development and associated environmental degradation (National Research Council, 1987; Titus, 1988). In response to the highest rates of coastal erosion and wetland loss in the country, the United States Geological Survey (USGS) and the Louisiana Geological Survey (LGS) developed a 5-year cooperative research project focused on barrier island erosion in Louisiana (Sallenger et al., 1987). One of the major goals of this project was to compile and quantify changes in shoreline position along Louisiana's barrier coastline from the mid-1850s to 1989. This goal has been accomplished, and as an end product, a full-color atlas is currently being published by the USGS. Mapping techniques and major research findings of this atlas (McBride et al., 1991) are highlighted in this paper.

Louisiana's gulf coastline is approximately 625 km long; 240 km is characterized by barrier islands that only occur along the Mississippi River delta plain. They formed in response to reworking of abandoned Mississippi River deltas and they play an integral role in the evolution of Louisiana's complex deltaic-estuarine system (Penland et al., 1988). The four barrier shoreline systems in Louisiana are the Isles Dernieres, Bayou Lafourche, Plaquemines, and Chandeleur Islands (Figure 1). These systems can respond instantly to the impact of extratropical and tropical storms (Kahn and Roberts, 1982; Roberts et al., 1987; Ritchie and Penland, 1988; Debusschere et

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al., this volume) or gradually, over periods of time (e.g., 100 years), in response to normal incident processes, cumulative storm impacts, and relative sea level fluctuations (Morgan and Larimore, 1957; Penland and Boyd, 1981; Morgan and Morgan, 1983; Shabica et al., 1984; McBride et al., 1989).

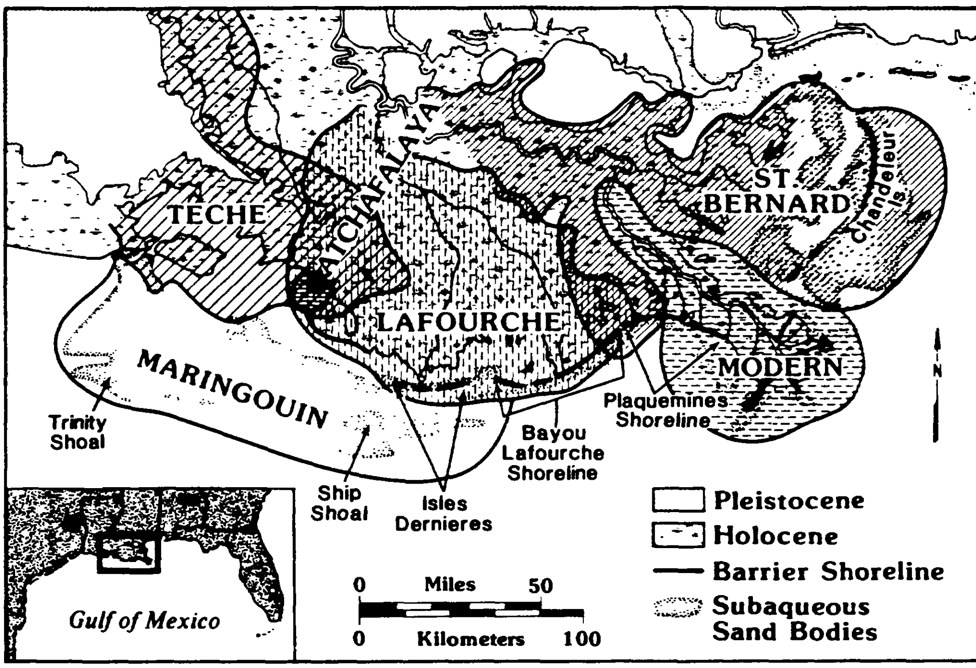

Figure 1. Study area showing the four barrier systems of Louisiana (after Frazier, 1967).

This paper presents historical shoreline change data for Louisiana's barrier shoreline within a framework of a metric computer mapping strategy developed by the LGS. Specifically, this paper (1) discusses techniques and potential errors associated with mapping shoreline change, (2) presents shoreline change data showing magnitude, direction, and rate of change along the gulfside and bayside shorelines, and (3) identifies two types of barrier island evolution in Louisiana.

METHODS

During the 1970s, numerous manual and partially-automated techniques were used to document changes in shoreline position (Stafford, 1971; Morton, 1977; Dolan and Hayden, 1978). With time, more coastal researchers depended on digitizers and computer processing to compile shoreline change data (Leatherman, 1983; Clow and Leatherman, 1984; Anders and Reed. 1989; Byrnes et al., 1989; Demirpolat et al., 1989). More recently, advances in computer mapping have revolutionized traditional shoreline mapping techniques by integrating interactive computer-aided-design and drafting (CADD), computer cartography, and geographic information system (GIS) software packages designed for personal computers and Unix-based workstations (McBride, 1989; Byrnes et al., this volume). Advances in computer technology, especially those in computer cartography, have reduced the amount of potential error in compiling and quantifying changes in shoreline position. However, computer hardware and mapping software are only as good as the utilized data sources; they cannot increase the accuracy of original data. As the precision of computer hardware and software increases (e.g., double precision digitizers and cursors), potential measurement errors will decrease.

Shoreline Change Mapping Strategy

A shoreline change mapping strategy was developed at LGS to compile changes in shoreline position derived from cartographic data sources and near-vertical aerial photography (Figure 2). Mylar- or bromide-based topographic sheets (T-sheets) available from the National Ocean Survey (NOS) were used for all shorelines compiled before 1950. In Louisiana, most NOS T-sheets were published at a 1:20,000 scale. Cartographic shorelines between 1950 and 1979 were recorded from NOS T-sheets and USGS 7.5-minute quadrangles. No NOS T-sheets are available for Louisiana's shoreline after 1956. Black and white aerial photography, dated January 1988 and taken at a scale of 1:15,000, was used to construct a 1988 shoreline west of the mouth of the Mississippi River. To the east of the mouth, the 1978 and 1989 Chandeleur Islands shorelines were interpreted using National Aeronautic and Space Administration (NASA) high-altitude color-infrared photography enlarged to scales of 1:33,000 and 1:24,000, respectively. All NOS T-sheets were checked for multiple graticles, updated datum coordinates (e.g., NAD 27), folds and tears, appropriate scale (usually 1:20,000 or larger), and at least four primary control points to be used for digitizer setup. Aerial photography, in particular the land-water interface, was checked for good contrast and amount of distortion.

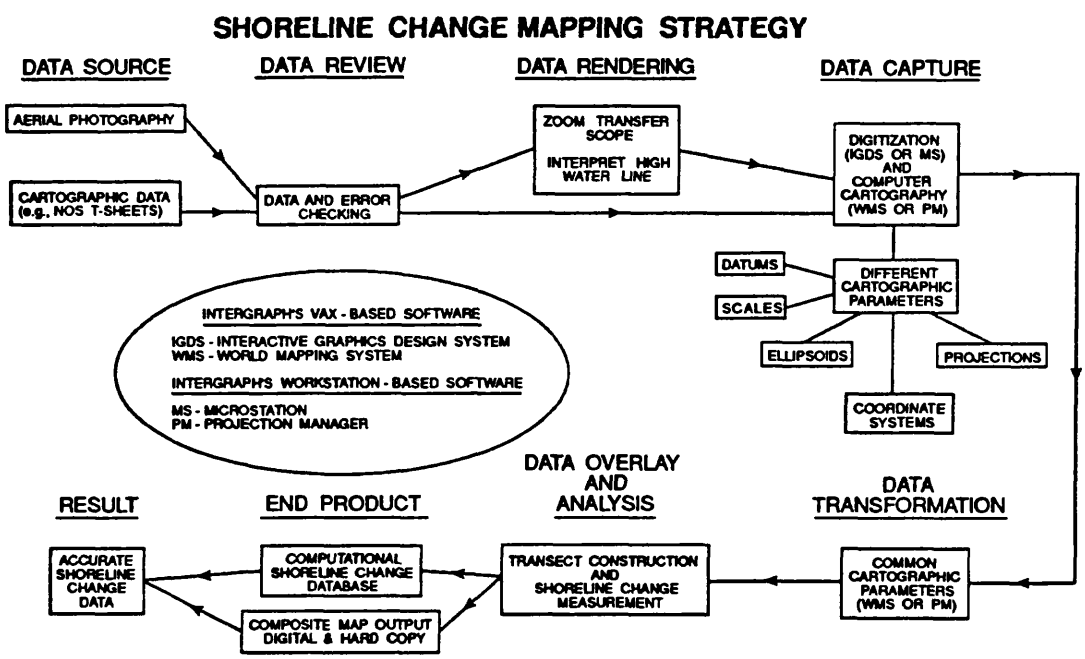

Figure 2. Shoreline change mapping strategy developed by the Louisiana Geological Survey (reprinted from McBride et al., 1991).

For accurate mapping of shoreline position, aerial photography data sources require rectification and interpretation. Delineating the land-water interface is the most important step in compiling shoreline position from photography, and requires a detailed understanding of local coastal processes, geomorphology, and human impacts operating past and present along the coastline (Stafford, 1971; Morton, 1977, 1979). For this study, aerial photography was registered to USGS 7.5-minute quadrangle maps using a Bausch and Lomb Zoom Transfer Scope. The high-water shoreline (HWL) was interpreted according to the location of the wet- and dry-beach contact or the high-water debris line visible on aerial photographs. This same position is used as the official shoreline on cartographic data (Shalowitz, 1964; Anders and Byrnes, 1991). The high-water line is the most appropriate reference for measuring change in shoreline position because its position on the upper foreshore represents the landward limit of influence by average waves and water level (Langfelder et al., 1968). Therefore, in this study, the same shoreline reference position derived from different data sources was compiled and compared.

Shoreline data were digitized at a 1:1 scale according to original projection, ellipsoid, and datum using Intergraph's computer mapping hardware and software including a large format, high-precision digitizer and cursor (McBride, 1989; Wright, 1989) (Figure 2). Once in digital form, shoreline data for each year were converted to a common projection (Polyconic), coordinate system (latitude-longitude), horizontal datum (NAD 27), and ellipsoid (Clarke 1866), using Intergraph's World Mapping System and Projection Manager software. About 880 shore-normal transects were established at approximately 15-second intervals of latitude or longitude (depending on shoreline orientation) along the gulfside and bayside shorelines. A computational data base consisting of linear and area values was compiled. Linear and area measurements were obtained in Polyconic projection because the majority of source maps were in Polyconic, and the properties of this projection preserve shape, area, distance, and azimuth in their true relation to the earth's surface (Shalowitz, 1964; Synder, 1987). Average rates of shoreline movement and area change were calculated by dividing absolute measurements by elapsed time (year, month, and day--where available). Shoreline data were then converted to Universal Transverse Mercator projection (UTM zones 15 and 16) for map output.

Sources of Error

All source materials and compilation techniques associated with shoreline change mapping contain potential errors (Anders and Byrnes, 1991). Several procedures are used to minimize these errors, thus increasing confidence in shoreline change measurements (Morton, 1978; Leatherman, 1983; Clow and Leatherman, 1984; Byrnes et al., 1989; McBride et al., 1991). This section will highlight some of the primary sources of error encountered during this project and discusses total potential error.

Probably the single largest potential source of error stems from delineating the high-water line from aerial photography. Original field surveys had the advantage of direct measurement rather than remote interpretation of the HWL position. However, in both cases, interpretation involved a certain level of error. Shalowitz (1964) suggests a potential 3- to 4-m measurement error associated with field surveys, while Morton (1979) states a much larger deviation relative to interpretation from aerial photography (about 10 m). These problems are especially noticeable along low relief barrier islands and headlands in Louisiana ($\leq$2.5 m above mean sea level). A majority of the barrier shoreline is <1 m in relief with extremely gentle slopes. Generally, berms are poorly developed. Consequently, elevation differences are subtle and sometimes present problems associated with delineating the high-water line. Due to the low beach slopes, normal wind shifts, which slightly elevate or depress the sea surface, move the land-water interface tens of meters horizontally. Rapidly changing water levels can create an indistinct boundary that is better described as gradational between wet and dry zones. As a result, interpretation of the high-water line position becomes subjective at best unless detailed ground truthing and familiarity with the coastal setting is maintained by the photo interpreter. Fortunately, the LGS maintains an active field program including annual and post-hurricane aerial videotape surveys of the coast (Debusschere et al., 1991). This low-oblique color video footage is taken from a helicopter at an altitude of 70 m and is viewed during air photo interpretation to aid in the delineation of the high-water shoreline and the recognition of coastal environments (e.g., intertidal vs. subaerial).

Interpretation of shoreline position along the bay side of an island poses another problem. Because emergent vegetation can mask the boundary between barrier islands and back-barrier environments, these areas may be mapped as land regardless of actual water depth. Delineating a shoreline when a mixture of vegetation, sand, and water exist, or when the water line is hidden by lush vegetation, becomes subjective without extensive ground truthing. Therefore, a minimum density and size of individual stands of vegetation must be established and mapped consistently. Once again, aerial videotape surveys play a important role in this process.

Lack of control points is a serious problem. Certain areas along the Louisiana barrier shoreline are both undeveloped and rapidly migrating landward (e.g., Grand Gosier, Curlew, and southern Chandeleur Islands). In these areas, the few traditional control points used to register photography (e.g., well heads, stable natural features, etc.) are often too infrequent or eroded away. As a result, new control points must be established or the shoreline photographically bridged between existing control points.

Pen-line width is another source of error when delineating the HWL. A typical pen width of 0.25 mm results in a potential error of 2.5 m at 1:10,000 scale, 6.0 m at 1:24,000, or 16.3 m at 1:65,000 scale. However, a pen line 0.18 mm wide was used during all air photo interpretation which translates to 3.6 m at 1:20,000 scale, 4.3 m at 1:24,000 scale, and 5.9 m at 1:33,000 scale. As a result, using the thinnest pen line possible can reduce the potential source of pen-line width error by 25% or more. Moreover, digitizing operator error will be reduced when tracing a thinner line. Furthermore, all computer hardware and software utilized for digitizing is limited by precision. Intergraph's large format digitizer and cursor are precise to within 0.1 mm, which translates to a potential error of 2.0 m at 1:20,000 scale and 2.4 m at 1:24,000 scale.

Because total potential error is a function of time-independent variables (e.g., data source, measurement technique, HWL interpretation, line widths) and the magnitude of shoreline change is time-dependent (e.g., 1887 vs. 1988), long-term rates of shoreline movement will have the lowest rate of potential error, whereas short-term rates will have the highest (McBride et al., 1991). For this project, maximum potential error is about ±26 m for any one shoreline (Root mean square of this value is ±13 m [Merchant, 1987]). This maximum value includes error associated with shoreline placement (±10 m), line width (±3.0 m), digitizer setup (±4.4 m), operator inconsistency (±6.0 m), and digitizing equipment (±2.5 m). Therefore, when superimposing two shorelines, the maximum rate of potential error for long-term rates of change (>100 years) is ±0.4 to 0.5 m/yr, while short-term rates of change (10-15 years) are accurate to within about ±3.4 to 5.1 m/yr.

RESULTS

When the long-term record of shoreline change is examined along Louisiana's barrier shoreline, it clearly illustrates a coastline characterized by rapid landward movement and massive landloss (e.g., Figure 3). Both long- and short-term change data are presented, but due to lower total potential error, the long-term record of shoreline change is emphasized in the following sections. The average long-term record for the four barrier systems is about 110 years.

Isles Dernieres Barrier System

Since 1887, the Isles Dernieres, once a continuous deltaic headland, has fragmented into five islands: Raccoon, Whiskey, Trinity, East, and Wine Islands (Figure 3). The entire gulf side was surveyed in 1887, and the remaining bayside shoreline was finished in 1906. The gulfside rate of shoreline change averaged -11.1 m/yr between 1887 and 1988 and ranged from +3.4 to -23.2 m/yr (Table 1). Meanwhile, the bayside rate of change between 1906 and 1988 ranged from +23.5 to -4.9 m/yr, producing an average rate of -0.6 m/yr. Overall, the two shorelines are converging, causing a decrease in average width from 1171 to 375 m. This narrowing trend leads to the process of in-place break up due to the greater potential for tidal inlet development associated with storm events and subsequent inlet widening (McBride et al., 1989). Moreover, the Isles Dernieres have suffered a 78% reduction in area from 3,532 to 771 ha.

Bayou Lafourche Barrier System

At 65 km long, the Bayou Lafourche shoreline is almost twice the length of the Isles Dernieres. Consequently, the barrier shoreline is divided into two sections (1) the Timbalier Islands (Figure 4), and (2) the Caminada-Moreau Headland and Grand Isle (Figure 5). Because differences in

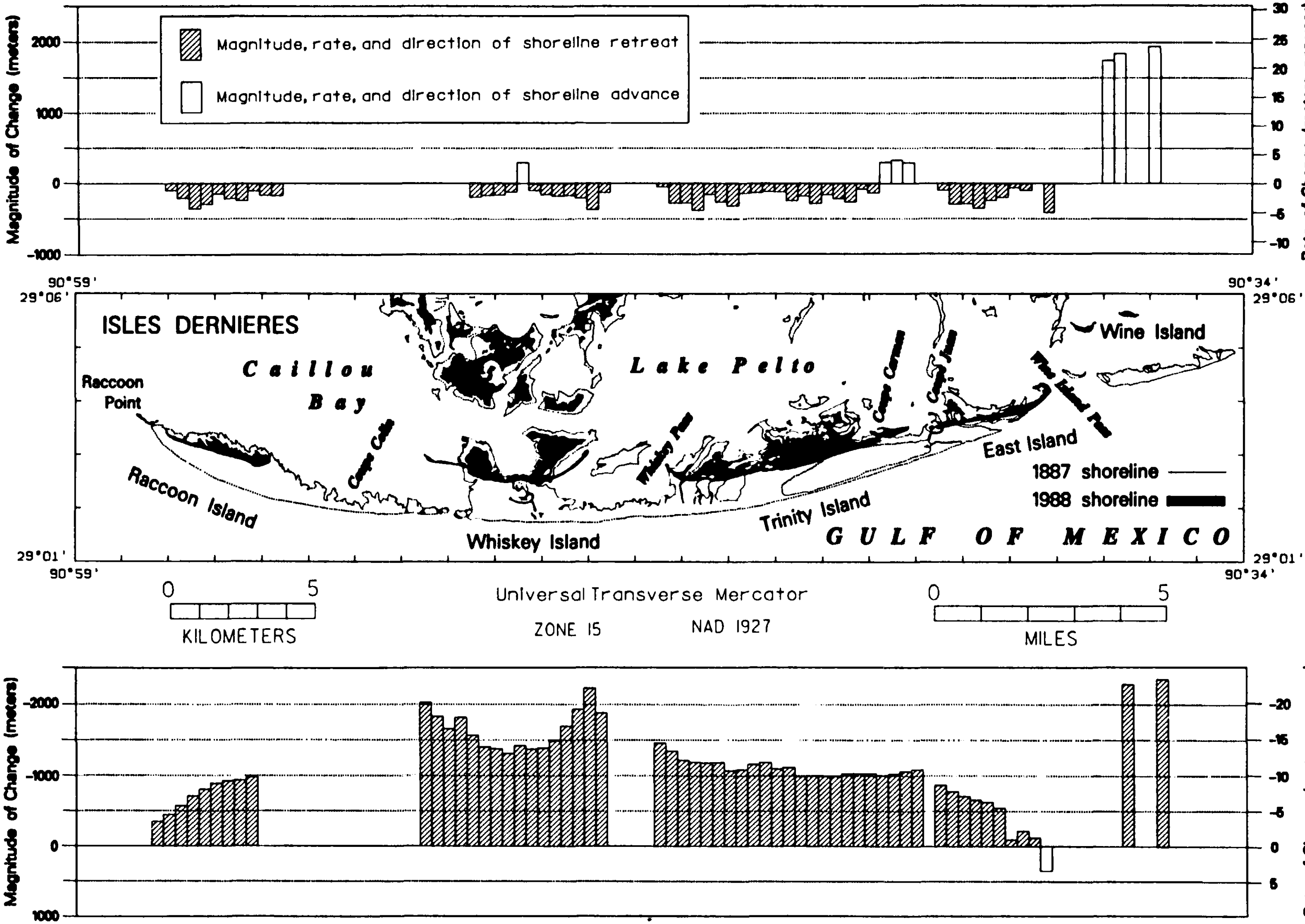

Figure 3. **Shoreline changes of the Isles Dernieres barrier system (adapted from McBride et al., 1991).**

Table 1. Summary of Louisiana's barrier shoreline change statistics (reprinted from McBride et al., 1991). Note: for the gulf side, a plus sign (+) indicates shoreline movement in a seaward direction, while a minus sign (-) indicates shoreline movement in a landward direction (toward the mainland). For the bay side, a plus sign indicates landward movement, while a minus sign indicates seaward movement. Abbreviations used include: Avg. = average; STD = standard deviation.

		GULFSIDE SHORELINE CHANGE RATES (m/yr)						BAYSIDE SHORELINE CHANGE RATES (m/yr)						ISLAND AREA CHANGE RATES (ha/yr)		PROJECTED DATE OF DISAPPEARANCE (yr)	
		Long Term *			Short Term **			Long Term *			Short Term **			Long Term *	Short Term **	Long Term *	Short Term **
BARRIER SYSTEM	ISLAND/BEACH	Avg.	STD	Total Range	Avg.	STD	Total Range	Avg.	STD	Total Range	Avg.	STD	Total Range				
1. Isles Dernieres		-11.1	5.2	3.4 / -23.2	-19.2	12.7	6.0 / -64.3	-0.6	5.8	23.5 / -4.9	-5.2	12.8	43.4 / -24.3	-28.2	-47.2	2015	2004
	Raccoon	-7.2	2.1	-3.4 / -9.7	-17.7	7.3	-8.2 / -34.0	-2.4	0.9	-1.2 / -4.3	2.0	18.1	31.4 / -21.9	-7.7	-6.8	1998	2000
	Whiskey	-18.3	2.8	-12.9 / -22.0	-30.1	18.3	-11.8 / -64.3	-1.7	1.8	3.5 / -4.5	-3.3	17.7	43.4 / -19.0	-3.7	-12.7	2042	2007
	Trinity	-11.0	1.2	-9.8 / -14.4	-17.6	4.5	-9.9 / -25.3	-1.8	2.3	4.0 / -4.6	-8.4	12.5	38.4 / -24.3	---	-18.9	---	2007
	East	-4.8	3.9	3.4 / -10.7	-8.7	9.5	8.0 / -21.0	-2.7	1.4	-0.7 / -4.9	-8.8	7.0	0.1 / -24.2	---	-9.0	---	1998
	Wine	-22.9	0.4	-22.5 / -23.2	---	---	--- ---	22.4	0.9	23.5 / 21.3	---	---	--- ---	-1.5	---	1995	---
2. Bayou Lafourche Timbalier Islands		-15.2	11.6	8.0 / -33.3	-14.0	23.7	27.6 / -64.6	11.7	15.0	32.7 / -14.6	-7.8	24.8	52.2 / -122.7	-8.9	-71.5	2076	1999
	Timbalier	-2.4	5.9	8.0 / -13.0	-7.0	16.5	27.6 / -54.0	-5.0	3.1	-1.0 / -15.0	-14.1	26.7	52.2 / -122.7	-9.3	-45.7	2046	2000
	East Timbalier	-23.1	4.4	-16.3 / -33.3	-21.2	28.7	4.6 / -84.6	24.0	4.3	33.0 / 18.0	-1.2	21.4	41.1 / -61.3	0.4	-25.7	---	1997
Caminada-Moreau Headland and Grand Isle		-7.9	8.4	8.2 / -20.0	-6.5	11.5	16.7 / -42.0	-0.1	2.4	7.0 / -2.8	-3.0	4.3	5.5 / -13.0	---	---	---	---
	Caminada-Moreau Headland	-13.3	5.6	-2.9 / -20.0	-13.6	7.8	-2.8 / -42.0	4.1	1.9	7.0 / 1.9	-1.8	1.4	0.4 / -3.7	---	---	---	---
	Grand Isle	0.9	3.1	6.2 / -3.4	5.2	5.7	18.7 / -2.5	-1.0	1.3	2.8 / -2.8	-3.2	4.6	5.5 / -13.0	-1.0	1.1	2948	---
3. Plaquemines		-5.5	4.5	1.9 / -15.6	-9.9	11.1	14.9 / -70.1	0.4	4.5	12.5 / -4.7	3.7	17.8	66.1 / -19.8	---	---	---	---
	Grand Terre	-3.9	3.5	1.9 / -9.2	-7.9	6.5	5.9 / -15.6	-2.2	1.9	1.5 / -4.7	-1.2	6.8	17.2 / -7.5	-11.4	-10.8	2033	2036
	Shell	-10.1	2.8	-2.5 / -12.5	-24.2	17.6	-3.6 / -70.1	7.9	12.0	12.5 / 2.4	20.6	12.4	66.1 / -1.1	-0.6	-5.0	2103	2002
4. Chandeleur Islands South Chandeleur Islands		-11.6	6.5	5.9 / -21.1	-19.7	15.9	6.9 / -41.3	10.7	6.9	22.6 / -7.7	19.8	20.8	60.1 / -8.9	-2.9	13.3	2199	---
	Breton	-5.7	4.7	5.9 / -9.2	-4.1	10.2	3.8 / -23.7	3.9	5.8	10.0 / -7.7	-1.2	3.1	5.6 / -3.7	-1.4	2.2	2106	---
	Grand Gosier/Curlew	-18.2	3.3	-6.1 / -21.1	-23.9	14.5	6.9 / -41.3	15.0	2.9	22.6 / 11.1	26.8	19.4	60.1 / -8.9	-1.5	11.1	2174	---
North Chandeleur Islands	Chandeleur	-8.5	4.1	-0.2 / -17.6	-12.2	6.6	-3.7 / -27.5	2.9	3.3	15.0 / -2.0	5.3	11.9	46.1 / -5.0	-7.6	-4.5	2218	2360
	North	---	---	--- ---	---	---	--- ---	---	---	--- ---	---	---	--- ---	-3.8	-0.1	2019	3079
	New Harbor	---	---	--- ---	---	---	--- ---	---	---	--- ---	---	---	--- ---	0.0	1.2	---	---
	Freemason	---	---	--- ---	---	---	--- ---	---	---	--- ---	---	---	--- ---	-1.5	-0.9	1997	2002

* Long Term = Shoreline record covering more than 100 years. (except long-term island area rate for Whiskey Island - 54 years)

** Short Term = Shoreline record for the last 10 - 15 years.

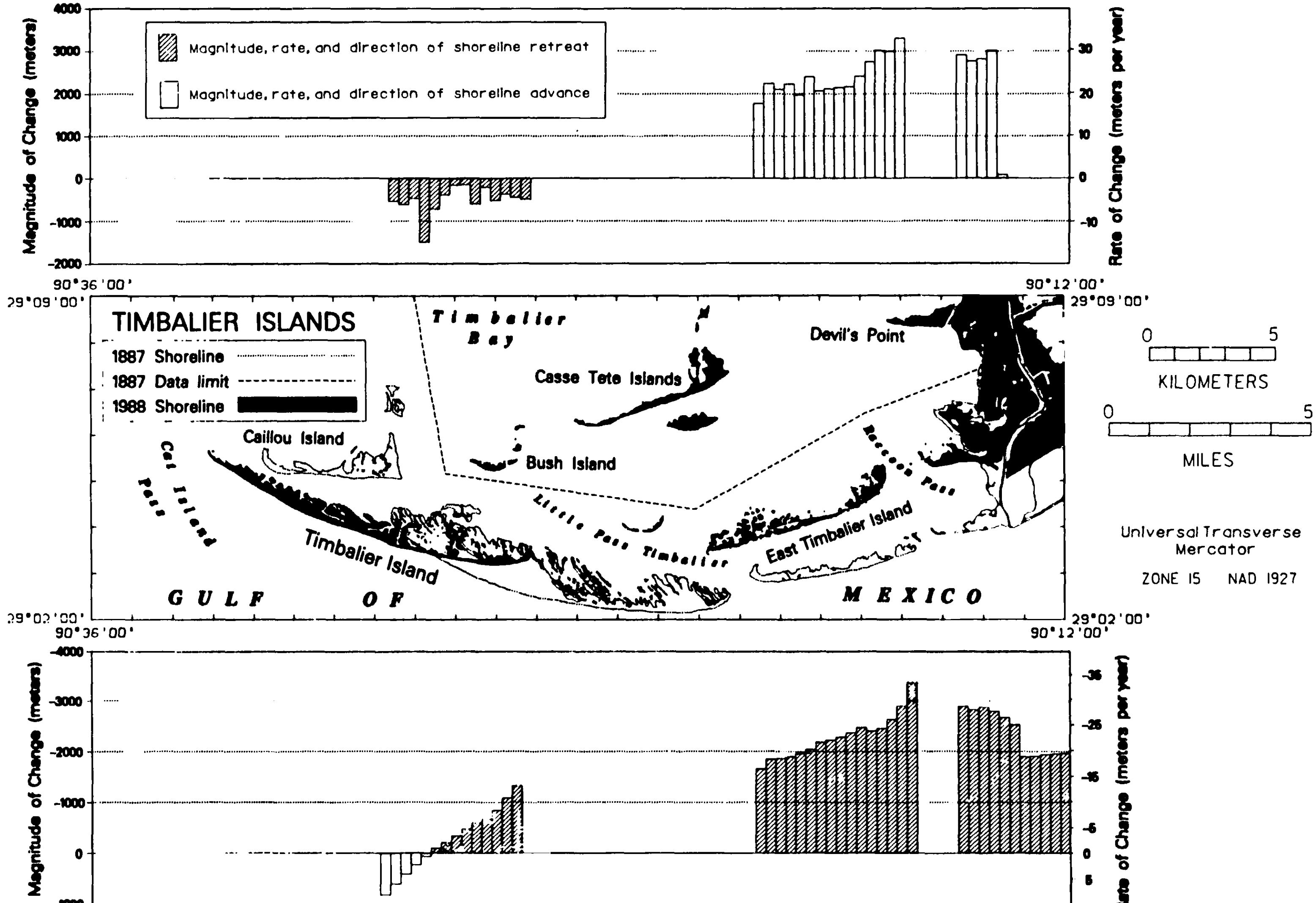

Figure 4. Shoreline changes of the Timbalier Islands along the western portion of the Bayou Lafourche barrier system (adapted from McBride et al., 1991).

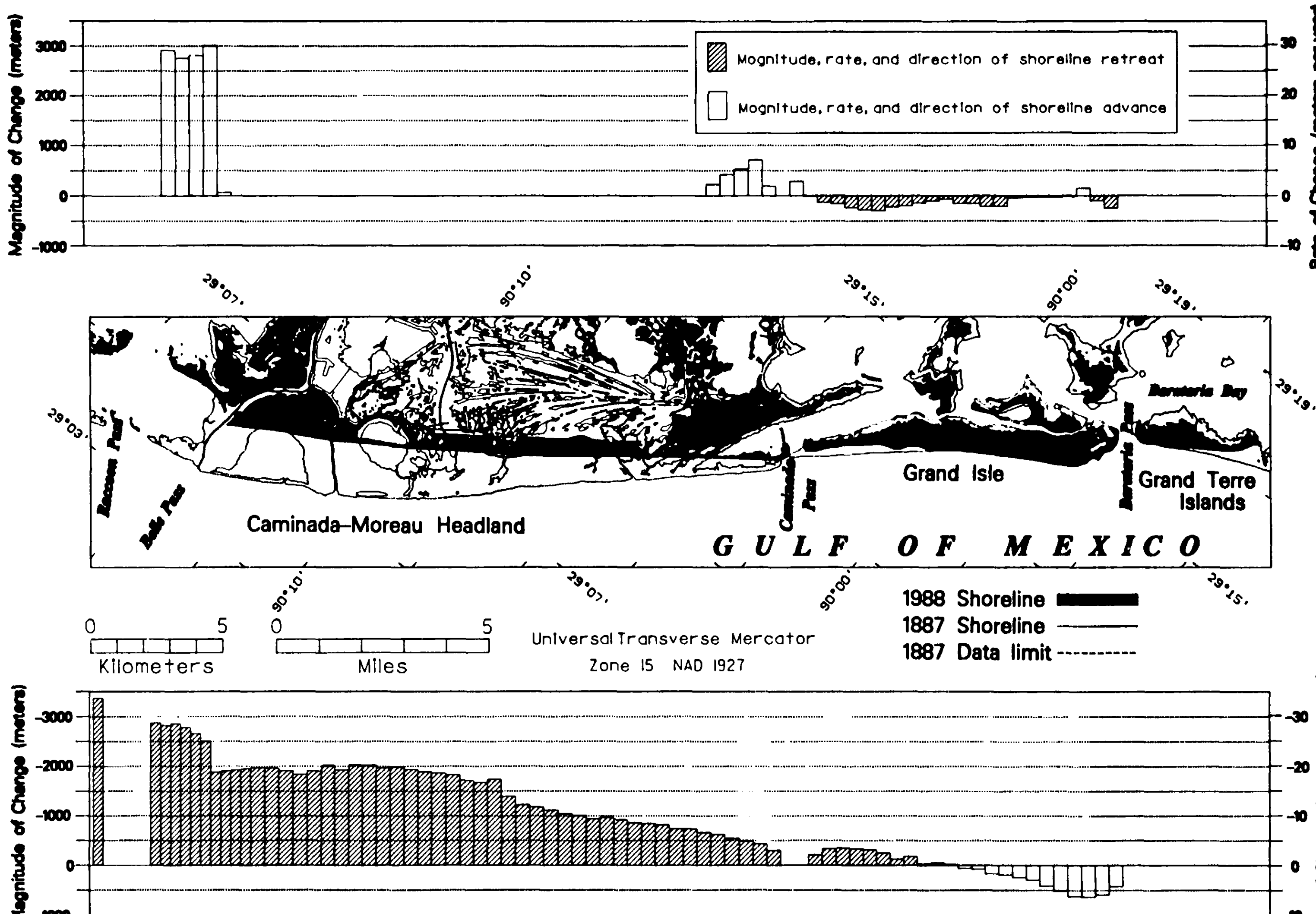

Figure 5. Shoreline changes of the Caminada-Moreau Headland/Grand Isle area along the eastern portion of the Bayou Lafourche barrier system (adapted from McBride et al., 1991).

dominant direction of sediment transport occur, Timbalier and East Timbalier Islands were examined separately. Between 1887 and 1988, the average gulfside rate of change along Timbalier Island was -2.4 m/yr, whereas the bayside shoreline was retreating twice as fast in a seaward direction at -5.0 m/yr. This island is rapidly migrating laterally to the west, indicating the dominant influence of longshore transport. The area of Timbalier Island decreased 64% from 1485 to 542 ha. Meanwhile, the landward migration of East Timbalier Island was extremely rapid. The average gulfside rate was -23.1 m/yr, while the bay shoreline raced landward even faster at +24.0 m/yr. Interestingly, East Timbalier Island experienced extreme fluctuations in area, increasing slightly between 1887 and 1988 from 193 to 238 ha. Major increases in area, which offset recent decreases, occurred prior to extensive human interference in the mid-1950s (Mossa et al., 1985); the island is now surrounded by a rock-rubble revetment.

The Caminada-Moreau Headland and Grand Isle shorelines also are investigated separately because of prominent differences in sediment transport patterns. The Caminada-Moreau area is an eroding abandoned deltaic headland, whereas Grand Isle is a downdrift flanking barrier island. The gulfside rate of change for the Caminada-Moreau Headland was -13.3 m/yr between 1887 and 1988; no bayside shoreline exists. Conversely, between 1887 and 1988, the average gulfside rate of change along Grand Isle indicated relative stability to slight seaward advance at +0.9 m/yr. Meanwhile, the average bayside rate was -1.0 m/yr. Area calculations for Grand Isle decreased about 9% from 1,059 to 960 ha. Average width of Grand Isle also was relatively stable ranging between 882 to 821 m. Over the years however, beach nourishment projects have contributed to the stability of Grand Isle (e.g., Combe and Soileau, 1987).

Plaquemines Barrier System

The Plaquemines shoreline is the youngest barrier system and extends 48 km from Grand Terre Islands to Sandy Point along the eastern flank of the Barataria Bight (Figure 6). Between 1884 and 1988, the average gulfside rate of change was -5.5 m/yr, while the bayside change rate was essentially stable at +0.4 m/yr. Only three locations along the Plaquemines gulf shoreline experienced shoreline advance, the western ends of Grand Terre and Shell Islands and the area east of Fontanelle Pass. The area east of Fontanelle Pass is on the updrift side of the Empire jetties, which capture sediment in the longshore transport system. In contrast, Shell Island, which lies to the west of the jetties, experienced some of the highest shoreline retreat rates (-10.1 m/yr), culminating with the impact of Hurricane Bob in 1979, which breached the island. In 1884, Grand Terre Island was a large continuous barrier island. Through time, the island experienced landward movement along the gulf side and seaward movement along the bay side, with contemporaneous inlet development breaking the island into three remnants by 1988.

Chandeleur Islands Barrier System

The Chandeleur Islands are the largest barrier system in Louisiana extending 72 km from Breton Island north to Hewes Point. Due to its size, the Chandeleur Islands system is divided into two sections: (1) south Chandeleur Islands (Figure 7), and (2) north Chandeleur Islands (Figure 8). The south Chandeleur Islands are comprised of Breton, Grand Gosier, and Curlew Islands, while to the north, the islands include Chandeleur, Freemason, New Harbor, and North. In the north however, only Chandeleur Island was examined in terms of changes in shoreline position.

The southern Chandeleur Islands are fragmented into three groups of small ephemeral islands and shallow shoals separated by wide tidal inlets. The average rate of gulfside change was -11.6 m/yr between 1869 and 1989, while the bayside rate was +10.7 m/yr, causing island width to narrow as the barriers retreated. Average barrier width decreased from 384 to 232 m and area was reduced 44% from 784 to 441 ha.

The north Chandeleur Islands are dominated by a large, arcuate-shaped barrier island system, which protects three groups of smaller, irregular-shaped islands that lie to the west. Between 1855 and 1989, average shoreline movement along the gulf and bay shorelines of Chandeleur Island was -6.5 m/yr and +2.9 m/yr, respectively. The gulf shoreline is migrating landward twice as fast,

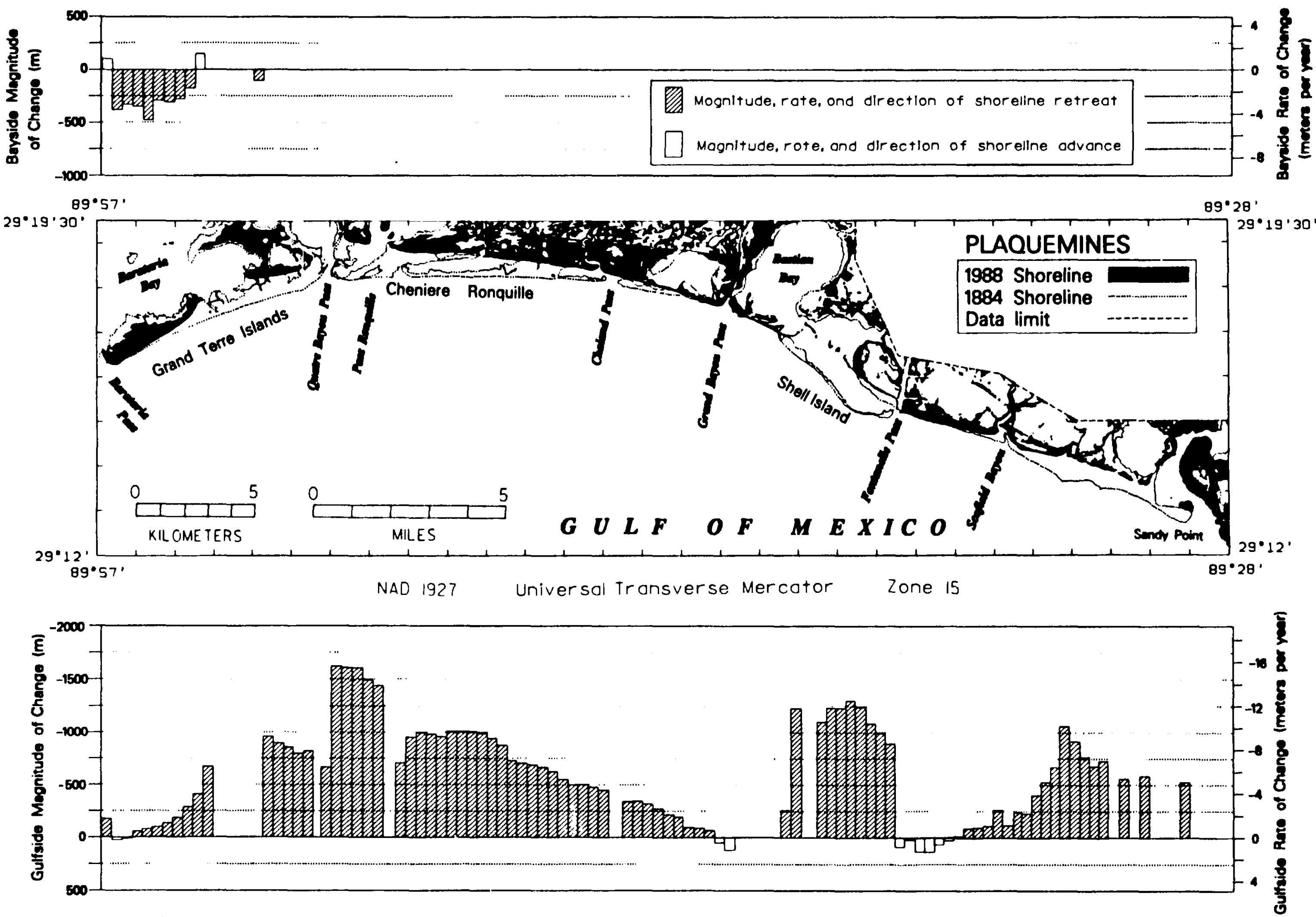

Figure 6. Shoreline changes of the Plaquemines barrier system (adapted from McBride et al., 1991).

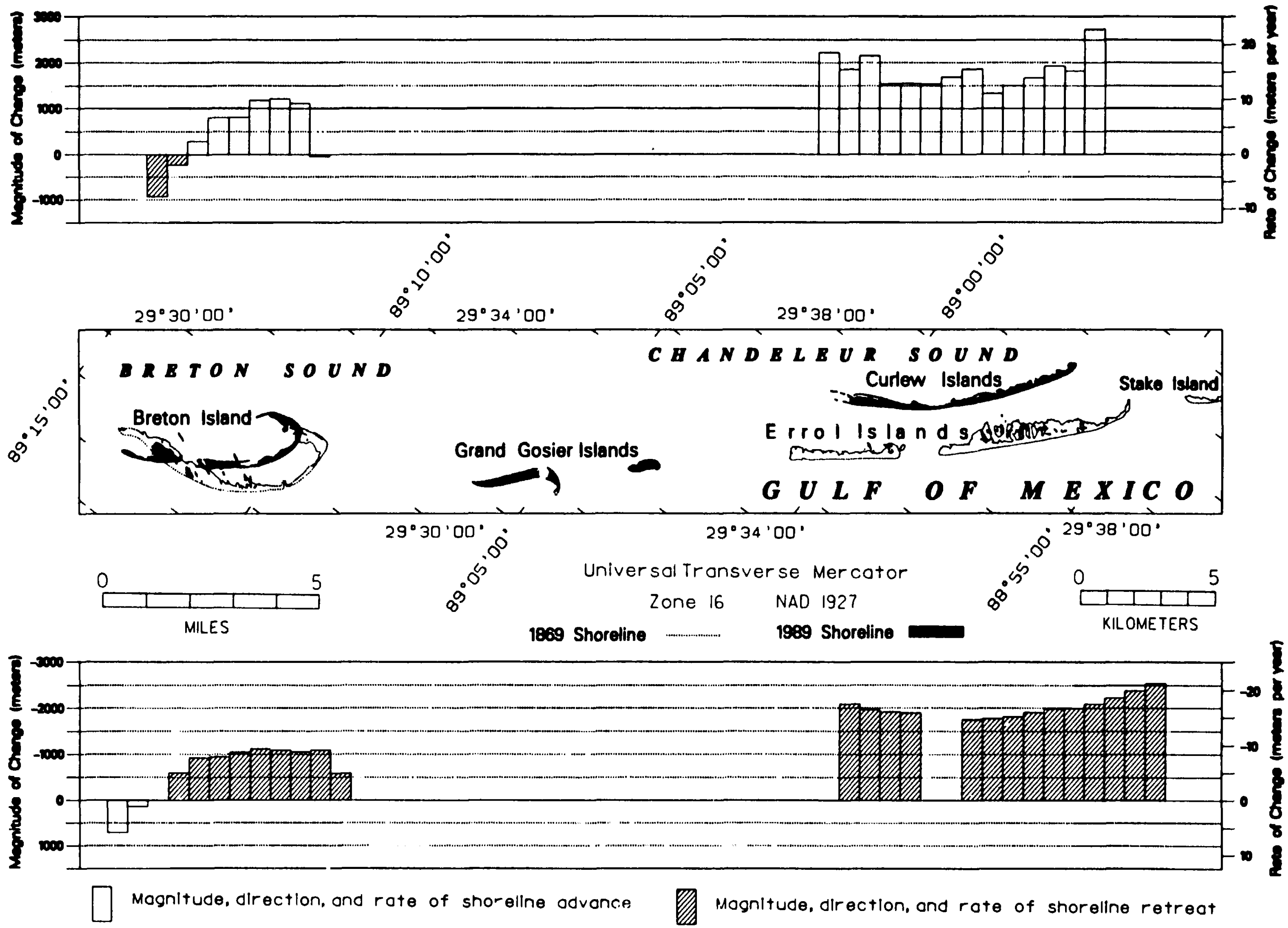

Figure 7. Shoreline changes of the south Chandeleur Islands (adapted from McBride et al., 1991).

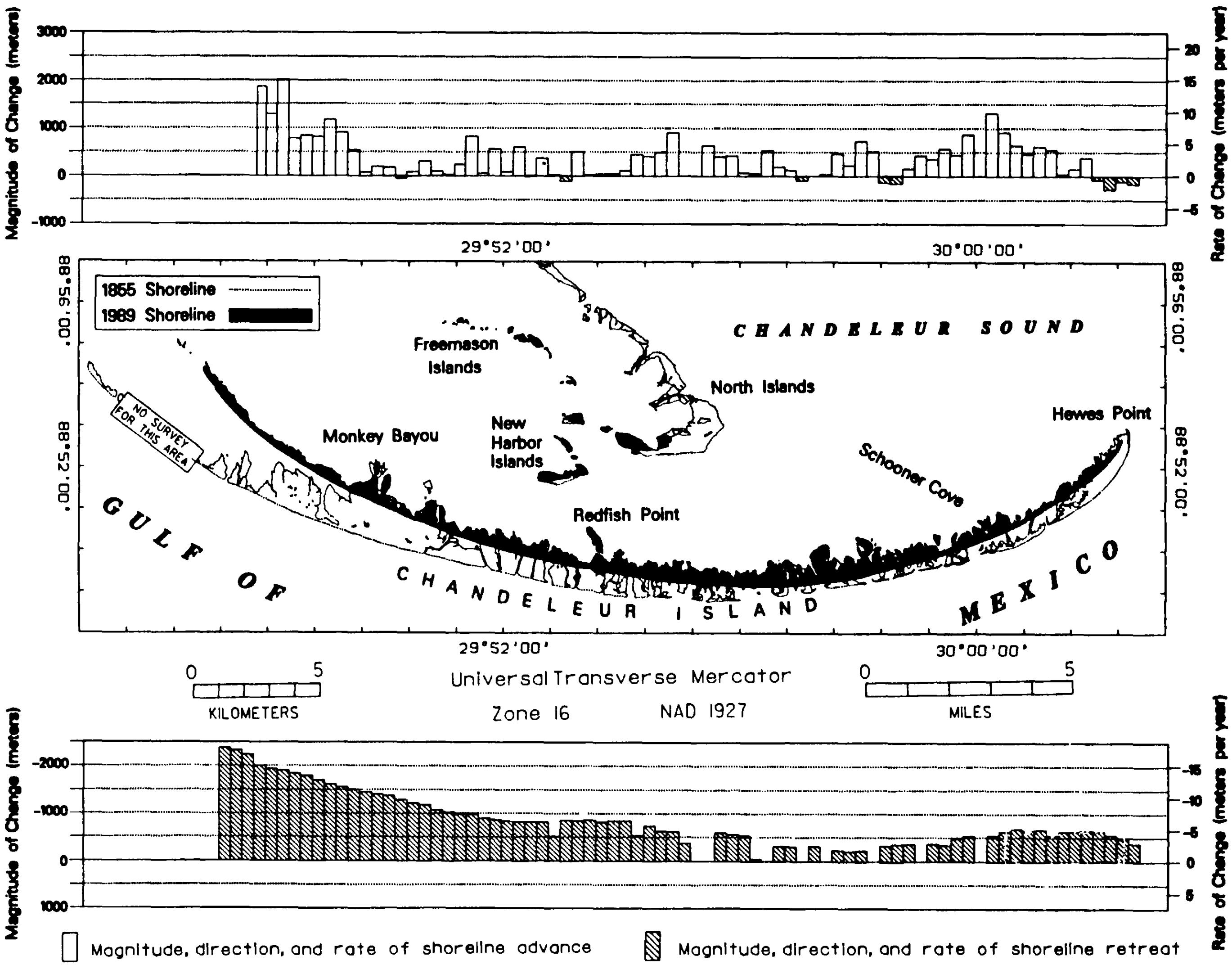

Figure 8. Shoreline changes of the north Chandeleur Islands (adapted from McBride et al., 1991).

causing average island width to narrow by 50% from 941 to 473 m for the same period. Island area decreased 37% from 2,763 to 1,749 ha.

CONCLUSIONS

The barrier systems of Louisiana have undergone landward migration, area loss, and island narrowing as a result of a complex interaction among subsidence, sea level rise, wave processes, tropical and extratropical storms, inadequate sediment supply, and intense human disturbance (levees, oil and gas activities, seawalls, jetties). As a consequence, the structural continuity of Louisiana's barrier shoreline continues to weaken as the barrier islands continue to narrow, fragment, and finally disappear (Table 1). This deteriorating trend will continue if no action is employed to artificially restore and strengthen the fragile barrier coastline.

In Louisiana, the highest average rates of landward migration (gulfside shoreline) occurred along the Bayou Lafourche barrier system at East Timbalier Island and the Caminada-Moreau Headland. In general, gulf barrier shorelines in Louisiana show rapid rates of shoreline retreat. Only the gulfside shoreline of Grand Isle, which has received beach nourishment through the years, shows a net seaward advance. In terms of bayside barrier shoreline movement, East Timbalier Island also had the highest average rate of landward movement. Overall, bayside shorelines tend to show either rapid landward movement or relatively stable to slow seaward movement. Therefore, most of the Louisiana barrier islands can be classified into two types of barrier island evolution: Type 1-- **landward rollover** which involves the landward movement of both the gulfside and bayside shorelines (e.g., East Timbalier Island, north and south Chandeleur Islands), and Type 2-- **in-place breakup** which involves the landward movement of the gulfside shoreline and stability or seaward movement of the bayside shoreline (e.g., Isles Dernieres, Timbalier Island, and Grand Terre Islands). In both cases the barrier island narrows because in Type 1 the gulfside shoreline migrates faster than the bayside shoreline, whereas in Type 2, the two shorelines are converging. Typically, landward rollover barriers are dominated by washover processes, which transport sediment across the island and deposit it along the bayside shoreline. In Louisiana, this type of landward retreat can only occur if an adequate supply of sediment exists for the barrier to respond to the high rates of relative sea level rise. In contrast, barriers that break up in-place, are characterized by an insufficient sediment supply and/or the island is too wide to be completely overwashed. Seaward movement along the bayside shoreline occurs in response to wave activity (erosion) and subsidence. Contemporaneously, storm impacts cause inlets to breach and fragment the barrier island. As a result, barrier islands that break up in-place deteriorate rapidly through time (about 150-200 years) and have short life expectancies (e.g., Isles Dernieres, Timbalier Island). Consequently, they are the most critical areas of coastal land loss in Louisiana and thus necessitate immediate but prudent coastal restoration.

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Accuracy of Shoreline Change Rates as Determined from Maps and Aerial Photographs

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INTRODUCTION

QUANTITATIVE KNOWLEDGE OF SHORELINE position change is essential for most planning and design aspects of projects in the coastal zone. Scientists, engineers, and planners have long recognized the usefulness of mapping shoreline positions to make estimates of erosion and accretion. These data are also important in developing sediment budgets, monitoring engineering modifications to a beach, examining geomorphic variations in the coastal zone, studying the role of natural processes in altering shoreline position, establishing set-back lines, and predicting future shoreline change through mathematical modeling. Recently, the Federal Emergency Management Agency's Federal Insurance Administration asked the National Research Council to provide advice on appropriate erosion management strategies to be administered through the National Flood Insurance Program[22]. A primary recommendation of the study was to use historical shoreline data to immediately begin mapping erosion hazard zones. Shoreline change information is most commonly obtained from repetitive field surveys or historical maps and near-vertical aerial photographs (hereafter referred to as air photos). Maps dating back to the middle-to-late 1800's and air photos beginning in the 1920's are available for most U.S. shorelines. These provide a length of record which is not typically available from field surveys alone. In addition, use of maps and air photos does not require extensive field time or expensive equipment to collect data and, therefore, is often the most economical means of measuring shoreline position.

The scientific literature contains many reports documenting shoreline change, however, only a relatively few authors discuss potential errors associated with their specific procedures[24,27,10,14,29,12,15,21,8,18,11,6,5]. Resource agencies using this information are sometimes unaware of the potential misrepresentation that could be present in reported rates of change. To date, a comprehensive analysis of errors associated with particular data sources and measurement techniques is lacking. The purpose of this paper, therefore, is to provide coastal managers, planners, engineers, and scientists with a comprehensive survey of potential errors associated with measuring shoreline position from maps and air photos with respect to calculated rates of change. These potential errors are introduced in Table 1. It is recommended that this information be used to gage the significance of shoreline change rates, based on historical maps and air photos, in future studies.

ERRORS ASSOCIATED WITH SHORELINE MAPPING

Technically, the shoreline is the line of intersection defined by land, sea, and air. Shoreline position at any point in time and space is a function of the interaction among five primary factors: 1) wave and current processes, 2) sea level change, 3) sediment supply, 4) coastal geology and morphology, and 5) human intervention. In general, developing an accurate map is a complex surveying and cartographic task; however, these five factors make shoreline mapping additionally difficult because of constantly changing conditions. Historically, shoreline field surveys were quite time consuming, resulting in long periods between successive maps. Infrequent data collection can make trends in historical shoreline change difficult to interpret. More recently, air photos have been used to update historical maps. Major benefits include a relatively synoptic view and potentially frequent collection and analysis.

Although difficulties in preparing a shoreline map are numerous, comparing shoreline positions on successive maps and air photos is even more challenging. Shoreline maps should be corrected to reflect a common datum and brought to a common scale, projection, and coordinate system before data from successive maps can be compared[26,19]. Electronic digitizers and computers with a variety of software have

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Table 1. Potential Errors Associated with Shoreline Mapping

ACCURACY		PRECISION
Maps and Charts	Air Photos	
scale	interpretation of HWL	annotation of HWL
datum changes	location of control points	digitizing equipment
shrink/stretch	quality of control points	temporal data consistency
surveying standards	aircraft tilt and pitch	media consistency
publication standards	altitude changes (scale)	
photogrammetric standards	topographic relief	
projection	negatives vs contact prints	

greatly facilitated the use of maps for comparing shoreline position. However, inherent map errors must still be estimated to assess the significance of calculated changes. In addition, if air photos are to be treated as maps, images must be rectified to eliminate or minimize the effect of distortions present in the photographic process. Several techniques have been developed to correct distortions in air photos. To date, the best possible photographic rectification can be achieved through stereoscopic plotting.

Potential errors in shoreline change rates are introduced in two ways. Accuracy refers to the degree to which a recorded value conforms to a known standard. In the case of mapping, this relates to how well a position on a map is represented relative to actual ground location. Precision, on the other hand, refers to how well a measurement taken from this map can be reproduced. Both types of error should be evaluated relative to original data sources and measurement techniques.

Map and Chart Accuracy.

Shoreline measurements obtained from historical maps can only be as reliable as the original maps themselves. Accuracy depends on the standards to which each original map was made and on changes which may have occurred to a map since its initial publication. Since 1941, strict standards of accuracy have been defined for published maps. For examining shoreline position, the two most commonly available maps are United States Geological Survey (USGS) Quadrangles and National Ocean Service (NOS) Topographic Charts. Both of these map types meet or exceed national map accuracy standards. United States National Map Accuracy Standards[10] state:

> "For maps on publication scales larger than 1:20,000, not more than 10 percent of the points tested shall be in error by more than 1/30 in [0.846 mm] measured on the publication scale; for maps on publication scales of 1:20,000 or smaller, 1/50 in [0.508 mm]. These limits of accuracy shall apply in all cases to positions of well-defined points only. Well-defined points are those that are easily visible or recoverable on the ground, such as the following: monuments or markers, such as bench marks, property boundary monuments; intersections of roads, railroads, etc.; corners of large buildings or structures (or center points of small buildings); etc."

USGS topographic maps at a scale of 1:24,000 are the most commonly used maps for coastal studies. Applying the accuracy standard to these maps, maximum allowable error for 90% of the stable points is 12.2 m. However, the accuracy with which any shoreline point is located could be less. For example, at a 1:24,000 scale, several closely spaced linear features often cannot be plotted in their correct positions. Although both roads and railroads are normally considered stable points, a railroad may be plotted in its true location and a parallel road displaced the minimum amount necessary to make each symbol legible[30]. Thus, selecting control points along the road could result in greater measurement error associated with shoreline change rates.

The NOS produces nautical charts at a variety of scales. For determining shoreline change, the most commonly used chart is the Topographic Sheet, the basic chart from which nautical and aeronautical charts are constructed. Topographic (T) sheets are most often produced at a scales of 1:10,000 and 1:20,000, although 1:5,000 and 1:40,000 charts are available for selected locations. At the 1:10,000 scale, national standards allow up to 8.5 m of error for a stable point (up to 10.2 m of error at 1:20,000), but the location of these points can be more accurate[24,5]. Non-stable points are located with less accuracy; however, features critical to safe marine navigation are mapped to accuracy stricter than national standards[10]. The shoreline is mapped to within 0.5 mm (at map scale) of true position, which at 1:10,000 scale is 5.0 m on the ground. Fixed aids to navigation and objects to be charted as landmarks must be located to within 3.0 m at this scale. As a test of these standards, Everts, Battley, and Gibson[11] measured 36 random features such as road intersections and shoreline features, including points of marsh, using NOS charts compiled from air photos. These features were located by field traverse and were compared with the map geodetic coordinate values. The check revealed a maximum error of ±3.0 m.

For detailed and most reliable shoreline change measurements, NOS T sheets are the preferred data source. However, in cases where T sheets are not available, and a less accurate estimate of shoreline change is sufficient, USGS topographic maps can be used. Other maps depicting the shoreline may also be available from U.S. Army Corps of Engineers offices and state and local government offices. Usefulness of these maps for quantifying shoreline change depends on their accuracy standards and scale.

The question of accuracy becomes even more important when dealing with maps made prior to the 1941 National Map Accuracy Standards. Older maps are useful for describing the long-term history of shoreline change, but their reliability must be carefully evaluated. Earliest NOS T sheets (U.S. Coast and Geodetic Survey) date back to the 1830's, and USGS topographic maps date back to formation of the USGS in 1879. Accuracy of maps developed before the 1830's T sheets is highly suspect. Local large-scale maps may be reliable enough for quantitative documentation of shoreline change, but older regional maps can, at best, be used only for qualitative assessment of shoreline movement.

Originally, T sheets were made from actual topographic field surveys. Shalowitz[24] notes that during these surveys, mapping the high-water shoreline was the most important consideration. However, accuracy of early surveys can still be questioned since the only standards were those maintained by the chief surveyor of the field party. In 1840, the Superintendent of the U.S. Coast and Geodetic Survey, Ferdinand Hassler, issued the first instructions for carefully surveying the high-water shoreline[11]. While surveying the high-water line (HWL), the low-water line was to be mapped by taking offsets, unless the two lines were far apart, which would require separate surveys.

More specific instructions on topographic mapping of the shoreline were written in 1889 by Wainwright[31]. Shalowitz[24] interprets instructions to field parties as follows:

> "The mean high-water line along a coast is the intersection of the plane of mean high water with the shore. This line, particularly along gently sloping beaches, can only be determined with precision by running spirit levels along the coast. Obviously, for charting purposes, such precise methods would not be justified, hence, *the line is determined more from the physical appearance of the beach*. What the topographer actually delineated are the markings left on the beach by the last preceding high water, barring the drift cast up by storm tides."

> "In addition to the above, the topographer, who is an expert in his field, familiarizes himself with the tide in the area, and notes the characteristics of the beach ... and the tufts of grass or other vegetation likely along the high-water line."

In summary, Shalowitz[24] notes it was the intention of the surveyors to determine the HWL for delineation on maps. Therefore, despite a lack of standards, this task was not treated lightly by individual survey parties.

Just how accurately the HWL was located on these early maps was also addressed by Shalowitz[24]. He notes:

> "The accuracy of the surveyed line here considered is that resulting from the methods used in locating the line at the time of survey. It is difficult to make any absolute estimates as to the accuracy of the early topographic surveys of the Bureau. In general, the officers who executed these surveys used extreme care in their work. The accuracy was of course limited by the amount of control that was available in the area."

> "With the methods used, and assuming the normal control, it was possible to measure distances with an accuracy of 1 meter (Annual Report, U.S. Coast and Geodetic Survey 192, 1880) while the position of the plane table could be determined within 2 or 3 meters of its true position. To this must be added the error due to the identification of the actual mean high water line on the ground, which may approximate 3 to 4 meters. It may, therefore, be assumed that the accuracy of location of the high-water line on the early surveys is within a maximum error of 10 meters and may possibly be much more accurate than this. This is the accuracy of the actual rodded points along the shore and does not include errors resulting from sketching between points. The latter may, in some cases, amount to as much as 10 meters, particularly where small indentations are not visible to the topographer at the plane table."

Measurement accuracy of the high-water shoreline on early surveys is thus dependent on a variety of factors, not the least of which was the ratio of actual rodded points to sketched data used by an individual surveyor. The more sketching used, the lower the overall accuracy. However, by triangulation control, a continuous check was applied to overall exactness of the work so that survey errors were not allowed to accumulate.

Based on this knowledge of past and present topographic and cartographic procedures, combined use of old and modern T sheets and quadrangles for quantifying shoreline change seems reasonable provided potential errors are taken into consideration. It must be recognized that rates of shoreline change derived from analysis of maps cannot be considered absolute. The accuracy of maps is generally insufficient to give more than a good estimate of trends in shoreline movement. Dependability of original data sources often is just not sufficient to discriminate between shorelines measured at short time intervals or between slowly changing shoreline positions (e.g. bay shorelines).

To illustrate this point, consider a shoreline that has receded an average of 8 m over the past 8 years. To determine the rate of shoreline retreat, two maps are required and deficiencies present in each map should be evaluated. Accuracy standards for modern 1:10,000 NOS T sheets allow an error of up to 5.0 m in locating the shoreline. Summing the errors for each map gives a maximum range of ±10.0 m; further sources of inaccuracy would be additive. The 8 m of "measured" retreat falls within this error band, and thus observed map differences cannot be considered significant. Conversely, if the same rate of change is assumed for two maps 100 years apart, 100 m of shoreline change is significant in comparison to ±10.0 m of error. In another instance, if the rate of shoreline change were only 0.1 m/yr (as is the case with many bay shorelines), over 50 years a total of only 5 m of change would be recorded, which again falls within the limits of map error. Therefore, to quantify historical shoreline change rates with some degree of confidence, the absolute magnitude of movement must be greater than the combined potential map error.

Map accuracy is also influenced by changes in the horizontal reference datum since map production. The first official nation-wide triangulation network was established in 1901 as the United States Standard Datum. However, it was not until the period 1927 – 1932 when all available primary data for North America were adjusted into the North American 1927 Datum[26]. Maps completed before this time require adjustments to the coordinate system to conform with the new datum. In 1983, the horizontal datum (North American Datum - NAD) was recalculated using a newly defined ellipsoid (Geodetic Reference System 80) referenced to the earth's center of mass[26]. Adjustment resulted in a change in State Plane and Universal Transverse Mercator (UTM) coordinate systems with respect to geographic coordinates (latitude and longitude) and each other. Differences range from 0 to 110 m in the 48 lower states and up to 200 m in Alaska and 400 m in Hawaii[9]. As of this writing, nautical charts are being published with the new horizontal datum, but USGS maps have not been regularly published with the new datum. Eventually all published charts and maps will reference the 1983 NAD.

An additional factor to consider when measuring shoreline position from maps is which shoreline has been mapped. The high-water and low-water shorelines are the two most commonly mapped features. Typically, these are registered on maps as the mean high water (MHW) and mean low water (MLW) lines. In practice, shoreline position is based on visual identification of these "datums" in the field or on air photos. On gently sloping beaches with a moderate tidal range, horizontal differences between these two shorelines are often significant[21]. Correction to a common vertical datum must be made when using maps with different shorelines. USGS topographic maps usually plot the high-water shoreline position as MHW, and recent maps may also have the low-water shoreline plotted as MLW. NOS T sheets often have the high-water line marked as bold and a dashed line representing the low-water shoreline.

Also important are changes in the horizontal position of features resulting from shrinking or stretching of the medium on which the map is printed. Shrink and stretch is a problem which can occur over very short periods with paper maps. Typical map paper can expand over 1 percent with a 60 percent increase in humidity, and expansion varies in different directions on the same sheet[26]. Knowles and Gorman[16] estimate potential changes between 0.03 and 0.25 mm, which at 1:10,000 scale is ±0.3 to 2.5 m of ground distance. Furthermore, discussions with USGS personnel indicate that at present no quality standards exist for map paper which specifically address minimization of scale variability. This problem can be avoided by using maps printed on a stable base material such as drafting film.

Finally, a variety of projections have been used to represent earth surface features on maps. Ellis[10] notes that all maps contain distortions in their particular projections. The problem for shoreline mapping occurs when data from different projections are compared. The NOS typically uses a Mercator projection for charts and Polyconic projections for T sheets, while the USGS uses Lambert Conformal Conic, Polyconic, and Transverse Mercator projections for their large scale maps[10,26]. If comparisons are being made from a quadrangle near the edge of a projection zone, the differences between measurements of diagonals on two maps of the same quadrangle, one using Lambert Conformal Conic projection and the other using Transverse Mercator projection, can be as much as 0.05 mm[26]. These differences are within National Map Accuracy Standards and typically are exceeded by expansion and contraction of paper maps.

Generally speaking, only very long-term trends can be determined from NOS T sheets and USGS topographic maps since they are produced at infrequent intervals. This may prevent a detailed understanding of the effects of short-term physical processes and morphologic responses. Many natural and cultural features on the beach are not represented on these maps, which can make location of control points for shoreline analysis difficult.

Air Photo Accuracy.

Air photos are not as limited by the same temporal constraints as maps and thus, are often more useful in understanding shoreline changes along complex stretches of coast such as those adjacent to inlets. For example, FitzGerald[13] noted cyclical changes in shoreline configuration at Price Inlet, South Carolina, caused by periodic landward migration and welding of the ebb-tidal delta to the adjacent beach. Maps separated by intervals greater than the cycle of ebb shoal migration would not be able to represent this process or be used to estimate the short-term variability and magnitude of shoreline change in this region.

Interpretation of air photos as a technique for measuring shoreline change began in the late 1960's[20,17,28]. Prior to this, air photos had been used qualitatively to assess changes in coastal landforms. Vertical black and white air photos date back to the 1920's, but reasonably good quality stereo air photos were not available until the late 1930's. Subsequent shoreline positions have been mapped using individual stereoscopic images or air photo mosaics that have been corrected for distortions. In recent decades, air photos have been routinely obtained by numerous Federal, state, and local government agencies, and private organizations. Consequently, air photo sets are available at a reasonable cost for most U.S. shorelines.

For locating specific coastal features while performing field work, good quality air photos can be used directly without concern for absolute accuracy. However, they cannot be directly treated as maps for quantifying shoreline change. Most features on a photograph occupy positions other than their true relative map positions. A variety of distortions intrinsic to air photos must be eliminated or minimized to reduce measurement errors to an acceptable level. These include: 1) radial distortion due to topographic relief as represented on a two-dimensional photograph, 2) tilt and pitch of the aircraft at the time of exposure, and 3) scale variations caused by changes in altitude along a flight line[1,32]. Photographic distortions are a problem with older air photos, but are not a major consideration after the mid-1940's because of improved camera optics. However, the use of contact prints instead of negatives to annotate shoreline position could affect mapping accuracy due to shrink and stretch of old paper prints and distortion during printing. Currently, use of stable material for making standard prints, as well as improved photographic processing, reduces the impact of this problem.

Relief or elevation distortions occur when features further from the lens at the moment of exposure, such as swales between large dunes, appear on the air photo at a scale smaller than that of features closer to the lens, such as dune crests. Displacement of points on an air photo, as a result of relief-produced scale variation, changes radially from the nadir point (the point vertically below the camera). For truly vertical aerial photographs, the nadir point and principal point (center of the photo) coincide. Displacement of an image due to radial distortion resulting from elevation changes (D_e) can be calculated as,

$$D_e = rh/H \qquad (1)$$

where r is the distance on the photograph from the center of the image to the top of the object, h is the ground elevation of the object, and H is the flight altitude of the camera relative to the same datum as h [33]. Most coastal features have low relief so radial distortion due to elevation differences is not a serious problem. However, measurement of shorelines backed by bluffs or cliffs with a relief of several meters could result in misrepresentation of shoreline position. The location of stable points on top of bluffs, relative to shorelines at the base, could be significantly distorted. For example, assume a control point located on top of a bluff 10 m above mean sea level (MSL) is 7 cm from the center of the air photo. If the altitude of the airplane were 3,048 m (10,000 ft) above MSL and a 152.4 mm (6 in) focal length lens was being used (this would correspond to a 1:20,000 scale air photo), geographic position of the control point would be displaced 0.23 mm on the air photo. This corresponds to 4.6 m of displacement on the ground.

Tilt distortion can result if an airplane (and camera) is not exactly parallel to the mean plane of the earth's surface at the instant of exposure. About half of near-vertical air photos taken for domestic mapping purposes are tilted less than 2 degrees, and few are tilted more than 3 degrees[33]. For this reason, many coastal scientists have ignored the problem of point displacement due to tilt in imagery. However, up to 7 degrees of tilt can occur in air photos taken for non-mapping or reconnaissance purposes. Some correction for tilt distortion should be made on almost every air photo before mapping. The relationship between a tilted and exactly vertical air photo is illustrated in Figure 1. On the upper side of the air photo, images appear displaced radially toward the isocenter, and radially away from the isocenter on the lower side of the image.

Displacement of a point on an air photo due to tilt (D_t) from its actual ground position can be calculated using the following relationship[32],

$$D_t = \frac{[r^2(\sin t)(\cos^2 P)]}{[f - (r \sin t)(\cos P)]} \qquad (2)$$

where r is the distance from the point to the isocenter, f is the focal length of the lens, t is the angle of tilt of the photograph, and P is the angle measured clockwise from the principal line to the radial line between the isocenter and the point (within the plane of the photograph). As is apparent from this equation, the amount of displacement increases with distance from the isocenter and with increasing tilt. For example, with a tilt angle of only 1 degree, a control point 10.0 cm from the isocenter and 40 degrees from the principal line on a 1:20,000 air photo would be in error by 13.6 m relative to its true ground location. Under similar conditions, a point on an air photo with 3 degrees of tilt would yield an error of 41 m in its ground location. Using air photos with minimal tilt and working only at the center portion of the air photo minimize point displacement.

Another possible source of measurement error with air photos is changing scale due to shifts in altitude along the photographic flight line. Especially with light aircraft, altitude of the airplane may change slightly as it follows the flight path. The result is that scale may vary slightly from one air photo to the next. Exact scale for each air photo should be determined so appropriate factors are used when digitizing or scaling data from an air photo. Photographic scale (S) can be calculated by,

$$S = (H/f)^{-1} \qquad (3)$$

where f is the focal length of the camera lens and H is the height of the camera above the mean elevation of the terrain (in similar units)[33]. The result is a representative fraction corresponding to map scale. Scale may also be determined if the distance between two points or the size of an object is known in the field or on an accompanying map.

To illustrate the effect of scale variation, the following example is presented. At the start of an air photo mission, the elevation of the plane is 3,048 m (10,000 ft) and a 152.4 mm (6 in) focal length lens is used, for a scale of 1:20,000. During the mission, if the elevation of the aircraft decreases by 10 m (15 m is not uncommon in small light planes), at the moment of exposure, the scale of that air photo will be 1:19,934. If this air photo were used to measure distance between a stable point and a shoreline position (eg. 10 cm), ground distance would be calculated at 2,000 m, assuming a 1:20,000 scale. However, if the scale were actually 1:19,934, the distance between the points is 1,993.4 m. This would produce about 6.6 m difference in location of the shoreline point. In an unpublished report, Pope[23] examined shoreline changes along the Rhode Island coast using air photos from 1951 and 1963. Published scale of these photos was 1:20,000. However, examination of the scale for each individual photo revealed that actual scales ranged from 1:19,205 to 1:20,918.

Measurement and Interpretation Errors.

In addition to deficiencies inherent in maps and air photos, measurement errors associated with interpretation of high-water shoreline position and digitization of the shoreline and control points are introduced. On maps, the shoreline is delineated; however, on air photos the shoreline must first be annotated by an experienced interpreter. The HWL on a beach, generally recognized by a change from dark to light tones, is typically mapped as the shoreline[28]. Correct interpretation of this line and careful annotation are required to avoid large miscalculations. Even width of the annotated line may introduce an error of several meters at ground scale. For example, the thinnest drafting pen point commonly available (000000) makes a line 0.13 mm thick. At a 1:20,000 scale, this would correspond to a ground distance of 2.6 m. A "00" pen point makes a line 6 m wide at this map scale. Therefore, it is best to use the largest scale air photos possible in order to minimize error associated with shoreline annotation.

Most techniques for rectifying air photos require location of stable control points on both base maps and air photos. Road intersections and buildings are logical control points, but scale of the air photo or the undeveloped character of a coastline often eliminate these features from the range of coverage. In these cases, less reliable control points can be used at the expense of accuracy (e.g., a meander bend in a tidal creek which appears to have remained stable over the time span of the shoreline change study). Alternatively, control can be bridged from adjacent air photos. This method enables overlapping air photos to use accurate control established on an adjacent image for rectifying distortions. Unless high-precision stereoscopic plotters are used for bridging, both techniques reduce credibility of shoreline measurements.

Several mapping software packages are currently available for recording shoreline position and adjusting to a common coordinate system, datum, and scale[18,19]. In all cases, an electronic digitizer is used to accurately measure points of interest. Although modern digitizers are very precise (0.025 mm for a Calcomp 9100 model), some small amount of error is present due to accuracy. For example, a standard Calcomp 9100 model digitizing table can reproduce measurements to ±0.25 mm (0.01 in), which at a scale of 1:10,000 is a potential ground error of ±2.5 m. However, the precision with which an operator can visualize and move the cursor along a line can lead to much greater errors[29]. Fortunately, improper tracking associated with shoreline digitizing generally is random and may be dampened when averaged over finite distances of shoreline. To evaluate the magnitude of operator error associated with digitizing shoreline position, at least three repetitive measurements should be compared[3]. If electronic digitizing equipment is not available, manual techniques exist for recording shoreline position relative to control points (e.g., Stafford[27]). Depending on the manual technique used, additional errors may be introduced due to physical measurements on maps and air photos.

When considering all the potential errors discussed above, it should be recognized that these apply to each individual map or air photo. When making comparisons of shoreline position, error is cumulative because separate maps and air photos are being used. In addition, seasonal and water level differences between successive maps and air photos must be

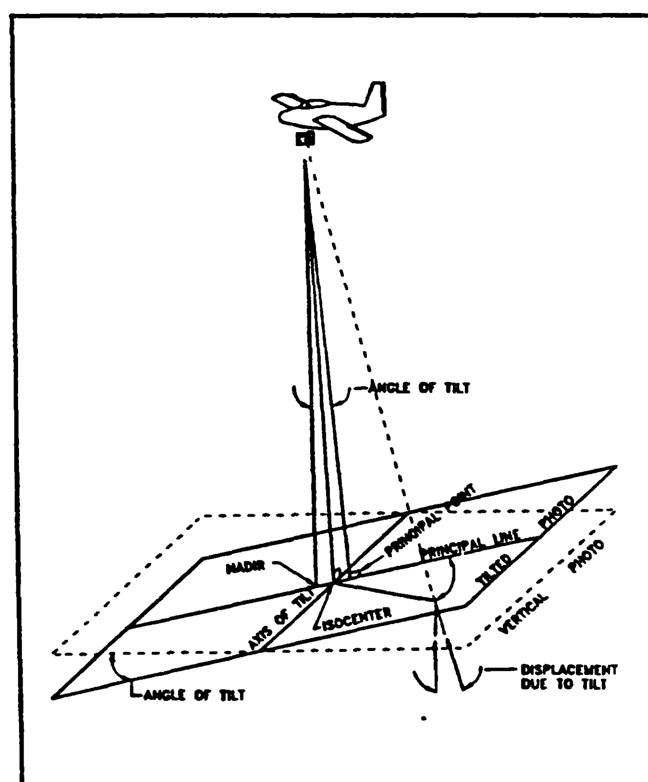

Figure 1. Diagram showing the relationship between a normal and tilted air photo.

considered. The position of the shoreline can vary significantly from summer to winter and from normal to storm conditions. Smith and Zarillo[25] estimate potential errors of up to ±40 m in shoreline position when comparing air photo sets taken during different seasons. Meaningful shoreline change rates demand that original data sources be consistent in conditions affecting the beach. Normal and storm conditions should never be compared if the objective is to examine long-term trends in shoreline change. Even differences in water level from high to low tide on gently sloping beaches with moderate tide range can significantly displace the shoreline. Extreme care should be taken to insure that all data sets used in a shoreline analysis are approximately consistent with respect to season, water level, and short-term history of incident processes. If this is not possible, then some estimate of resulting variability should accompany the reported rates of change.

TECHNIQUES FOR QUANTIFYING SHORELINE CHANGE

The use of maps and air photos to determine rates of shoreline change generally requires two separate tasks: 1) compilation of a series of digitized shoreline positions and 2) a comparative analysis of these shorelines to determine specific rates of change. A variety of methods have been presented for creating composite shoreline change maps[12,7,4,19]. These techniques require measurement from a composite map to generate data for determining rates of change. More recently, automated systems have become available which allow compilation of composite shoreline data and rapid calculation of shoreline change rates from maps and air photos[3,2].

Quantifying shoreline change using only historical maps and charts is a straightforward process; however, datum changes must be taken into account. In a less accurate sense, this involves enlarging or reducing all maps and charts to a common scale and using common control points for reference. Once completed, a composite map can be drawn and changes in shoreline position can be measured. Enlargement or reduction and overlaying can be accomplished in a variety of ways. Numerous instruments, such as a Map-O-Graph, Zoom Transfer Scope, several types of projecting light tables, and electronic digitizers can make this an easy task. As a more accurate alternative, map data can be digitized, and without plotting a composite map, a variety of software packages can be used to adjust measurements to a common scale. These data can then be used for calculating temporal and spatial rates of shoreline change and generating a composite map, if desired.

The use of air photos for determining rates of shoreline change is significantly more involved than using only maps. Stafford[27] and Stafford and Langfelder[28] present the point measurement technique for determining shoreline change rates from air photos. This method uses only the center portion of air photos, which reduces tilt distortion (radial distortion due to topographic relief generally is not a problem for most seaside areas unless cliffs border the coastline). Scale variations must always be taken into account. Stable control points are selected along the coast and used to make shoreline position measurements for each air photo and map. After these data are adjusted relative to a common scale, rates of shoreline change can be calculated adjacent to each control point. This technique does not produce a composite shoreline change map and is limited in density of measurements to the number of control points available.

Any technique which uses air photos to accurately evaluate the magnitude of shoreline change must include rectifying the air photo or data derived from the air photo. In recent years, a variety of manual techniques have been used. Most photogrammetric companies and government agencies can produce rectified air photos (orthophotos) by removing tilt and scale variations on large stereoscopic plotters. This equipment places the air photo back into its tilted position and then projects the image downward at the proper scale. The projected image has all tilt and scale variations removed, producing a rectified vertical aerial photograph that can be treated as a regular map. Smaller instruments, such as the Vertical Sketchmaster, work on the same basic principle to remove tilt, but are not as accurate. Projecting instruments, such as light tables and the Map-O-Graph, can remove scale variations between air photos but cannot correct for tilt distortion. Similarly, the Zoom Transfer Scope can correct for scale variations, and also partially compensates for tilt by shrinking or stretching an image in one direction. However, since tilt causes differential scale distortion across the photograph, shrinking or stretching in one direction is not sufficient to remove all tilt effects. Aligning carefully selected control points and working in small areas of the air photo produce the most satisfactory results[1].

Over the past decade, a variety of automated techniques have been developed to produce composite shoreline maps from air photos. Several computer software packages are now available that allow a small mapping laboratory to generate composite shoreline maps from original map and air photo data sources[18,19]. For air photos, most of these techniques use various algorithms, including a least squares adjustment to rectify the data to a scaled, non-tilted condition. This procedure involves digitizing control point information on an air photo and comparing the location of each point to its known location in a geographic coordinate system. The least squares procedure uses a calculated correction factor to adjust a group of control points to their "proper" position. Therefore, the correction is not specific to tilt or scale variations, but simply corrects for all inherent errors simultaneously. The resulting correction is a "best fit" position for all control points on an air photo. Using more control points usually improves the fit. After a correction factor is calculated, it is applied to all shoreline data points digitized from the air photo.

Once shoreline position has been recorded accurately, temporal comparisons can be determined manually from composite maps or calculated directly from digitized data. The manual process involves establishing transects perpendicular to the composite shoreline trend at the desired along-the-coast interval and measuring distances between shorelines along each transect. The measured distance is divided by the time interval between shorelines to determine rate of change. For projects covering large areas that require a high density of calculated shoreline position changes, automated techniques can save significant amounts of time. The basic procedure is similar to the manual technique. Transects are established perpendicular to an arbitrary baseline that is parallel to the average trend of all digitized shorelines, and the intersection of these transects with each shoreline represents a data point. Baseline length depends on general shoreline orientation and natural breaks in shoreline continuity. Anders, Reed, and Meisburger[2] used a cartesian coordinate system for each baseline with the x-axis directed alongshore and the y-axis directed offshore. Digitized data were used to generate shoreline changes at approximately 50 m intervals along-the-coast. Byrnes et al.[3] used a similar technique; however, high-water shoreline position was digitized as latitude-longitude pairs. Digital data were converted to state plane coordinates and referenced to a baseline parallel to the shoreline trend. Cubic spline interpolation was used to compare temporal data at exact alongshore positions.

An improvement to these techniques, which addresses potential problems at inlets, is currently being developed. Based on changes in shoreline orientation, a best-fit line is created through a series of digitized shoreline points for all time periods. Depending on orientation, each segment could be described by 2 to N points, where N is the total number of coordinate pairs. Straight line segments are averaged for each shoreline to create a mean shoreline orientation. Transects are created perpendicular to the mean shoreline at an along-the-coast interval specified by the user. Temporal comparisons of digitized data are made for each transect, producing rates of shoreline change.

In the techniques discussed above, problems routinely occur which require special treatment. These include areas that show pronounced shoreline reorientation and extremely rapid changes in the alongshore direction, as might occur near inlets, capes, and spit tips, and along estuarine shorelines. The validity of using a transect method to measure changes in these areas may be tenuous since it is often difficult to create a transect that is perpendicular to all digitized shorelines. An area measurement technique could be used to quantify areal changes at these locations[11]. Manual measurements by an experienced interpreter can also provide useful information for quantifying changes in these dynamic regions[2].

SUMMARY

Several important factors should be considered when quantifying change in shoreline position. First, original data sources and techniques used to extract information must be of high quality so determination of shoreline position can be as accurate as possible. Map and air photo techniques developed for field use or rudimentary measurements are not suitable for quantitative shoreline mapping projects. Second, large scale maps and air photos have the greatest potential for providing reliable shoreline change measurements. A 1:10,000 scale map has considerably less inherent error than a 1:24,000 scale map (e.g. USGS 7.5 minute topographic maps). Therefore, 1:10,000 NOS T sheets are the preferred data source for measuring shoreline position. Third, the time period spanned by two sets of shoreline position information must be significant relative to potential errors in mapping procedures so that the magnitude of measured change is larger than inherent errors. As discussed, large temporal spacing between data sets (e.g. 100+ years) improves the credibility of recorded shoreline movements.

Regardless of the method used to measure shoreline position, it should be accompanied by a statement concerning its reliability, including the cumulative effect of potential errors. The ultimate test of map accuracy (original data sources or secondary composites) is to compare the location of points on the map with their actual field location. For example[30], the procedure followed by the USGS to evaluate their maps involves selection of several stable, well defined points, such as road intersections. The location of these points in the field is determined by precise surveying or special photogrammetric techniques. The mapped positions are then checked against the positions determined in the field. If the map is accurate within the tolerances allowed by U.S. National Map Accuracy Standards, it is certified and published with the statement that it complies with those standards.

A variety of methods have been developed to extract shoreline change information from maps and air photos. These procedures include simple direct measurements which are appropriate for small areas and modest levels of accuracy. Mechanical and computerized procedures are available to develop composite shoreline maps (with varying levels of dependability) from combinations of historical maps and air photos. Regardless of which technique is used to make a composite shoreline change map and calculate shoreline movement rates, various sources of error must be evaluated to determine credibility of the final product. It is recommended that the factors listed in Table 1 be considered when evaluating the significance of measured shoreline change relative to individual project requirements. Large potential errors with base maps (e.g. USGS 1:24,000 paper maps) and uncorrected air photos suggest that meaningful shoreline change data can only be developed for areas undergoing rapid change or where a long history of shoreline position data is available.

Proper application of shoreline position information requires a clear understanding of inherent data source errors and limitations associated with analysis techniques. Planning and design of all projects dependent on this kind of data should be qualified within the context of these errors and limitations. Project examples include establishing erosion hazard zones, developing benefit/cost analysis for to beach nourishment, determining impacts of coastal structures, and mathematical modeling of shoreline change. Ultimately, success of coastal planning using shoreline information will increase with greater awareness of basic limitations.

ACKNOWLEDGEMENTS

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ADDENDUM

Addendum to Beach Response to the Presence of a Seawall: A Comparison of Field Observations by James F. Tait and Gary B. Griggs; *Shore & Beach*, Vol. 58, No. 2, April 1990:

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CORRECTION

SHORE & BEACH OBSERVATIONS

Ripple Structure and Rill Structure, Mudga Beach, West Coast, India

(74° 13' – 74° 15' E., 14° 44' – 14° 45' N., 11 December 1989). *Shore & Beach*, Vol. 58, No. 3, July 1990, page 30.

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LARGE-SCALE COASTAL EVOLUTION OF LOUISIANA'S BARRIER ISLANDS

Jeffrey H. List[1], Bruce E. Jaffe[2], and Asbury H. Sallenger, Jr.[3]

ABSTRACT: The prediction of large-scale coastal change is an extremely important, but distant goal. Here we describe some of our initial efforts in this direction, using historical bathymetric information along a 150 km reach of the rapidly evolving barrier island coast of Louisiana. Preliminary results suggest that the relative sea level rise rate, though extremely high in the area, has played a secondary role in coastal erosion over the last 100 years, with longshore transport of sand-sized sediment being the primary cause. Prediction of future conditions is hampered by a general lack of erosion processes understanding; however, an examination of the changing volumes of sand stored in a large ebb-tidal delta system suggests a continued high rate of shoreline retreat driven by the longshore re-distribution of sand.

INTRODUCTION

Since 1986, the U.S. Geological Survey and the Louisiana Geological Survey have conducted a cooperative study focused on the geologic framework and processes responsible for the rapid erosion of the Louisiana barrier islands. The range of investigations carried out in support of this study is described by Sallenger et al. (1987). Here we focus on changes in seafloor elevation over the last 100 years as determined by bathymetric comparisons, and how this information may improve our understanding of the

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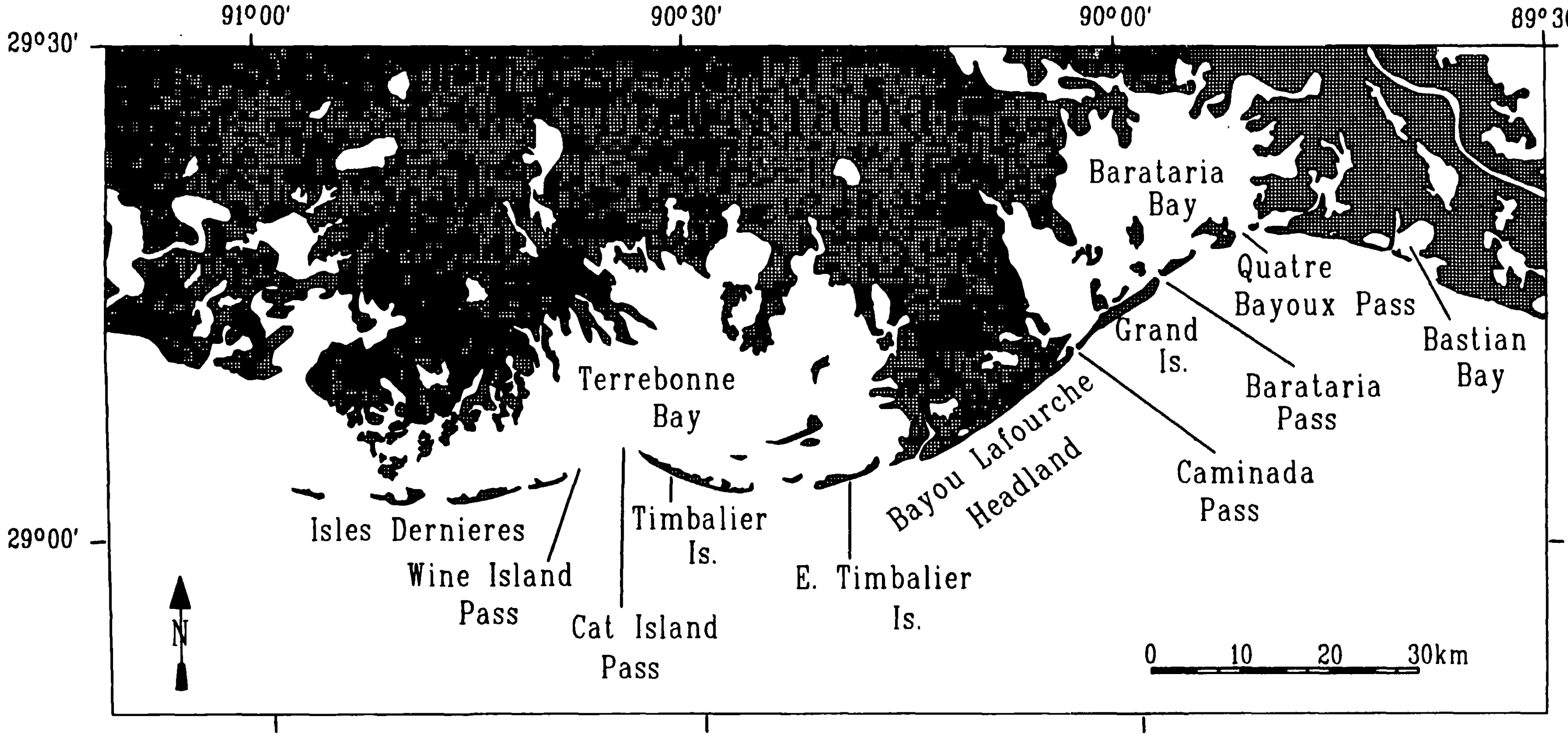

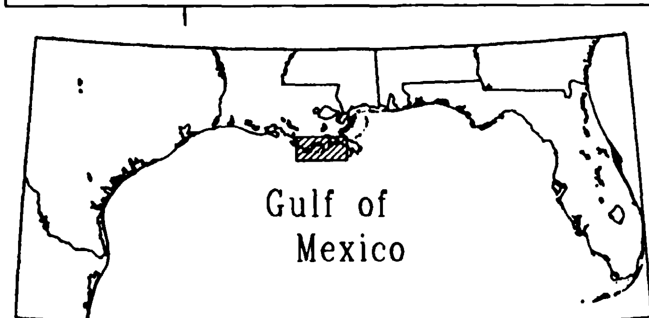

Figure 1. Index map showing geographic place names referred to in the text and the study area location in the Gulf of Mexico.

causes of past coastal erosion and the prediction of future changes.

The Louisiana barrier island coast (shown in Figure 1, exclusive of the Chandeleur Islands) consists of a series of headlands and flanking barrier islands formed by the re-working of abandoned Mississippi River delta complexes (Penland et al., 1988). Along much of the coast, especially along the Isles Dernieres and the Bayou Lafourche ("LaFOOSH") headland, the shorelines are receding at a long-term rate of 10-20 meters per year (m/yr). This extreme rate of erosion has commonly been hypothesized to be due to two main factors: the high rate of relative sea level rise of approximately 1 cm/yr (Ramsey and Moslow, 1987), and the lack of a major sand source in the eroding delta sediments which are composed largely of silts and clays.

The bathymetric comparisons presented here are a first-order representation of the long-term, averaged result of large-scale sediment transport processes occurring over the last 100 years. As such, they provide a crude, but invaluable, source of information that can be used with simple models (Bruun, 1962) to test these hypotheses of the causes of erosion. Our initial efforts and results following this approach are summarized below.

DATA PROCESSING

Bathymetric data covering the area shown in Figure 2 were obtained from different sources for three periods. Sounding data totaling 63,909 observations were digitized from U.S. Coast and Geodetic Survey (USCGS) hydrographic smooth sheets from 1878 to 1906. These surveys are referred to as the 1880s bathymetry. Sounding data in digital form totaling 315,856 observations were obtained from the National Geophysical Data Center for the years 1933 to 1936. These surveys, also conducted by the USCGS (now National Ocean Survey), are referred to as the 1930s bathymetry. Finally, the USGS collected, through contract surveys, digital sounding data totaling 232,289 observations for the period 1986 to 1989. These surveys are referred to as the 1980s bathymetry. An evaluation of data quality and maps showing data density can be found in Jaffe et al. (1988) and List et al. (1991).

These data sets were processed with standard commercial surface modeling software to yield grids of surface elevation (List et al., 1991). Figure 2 shows the depth contours representing the 1980s grid. After correcting for relative sea level rise during the study period (Jaffe et al., 1991), grids were numerically subtracted to yield the patterns of erosion and accretion. Figure 3 shows the sea-floor change between the 1930s and 1980s grids. Changes between 0.5 m of accretion and 0.5 m of erosion were considered within the error level inherent in this type of analysis, and were omitted from further consideration (List et al., 1991).

Shorelines corresponding to bathymetric survey years were digitized from historical USCGS topographic sheets, or obtained in

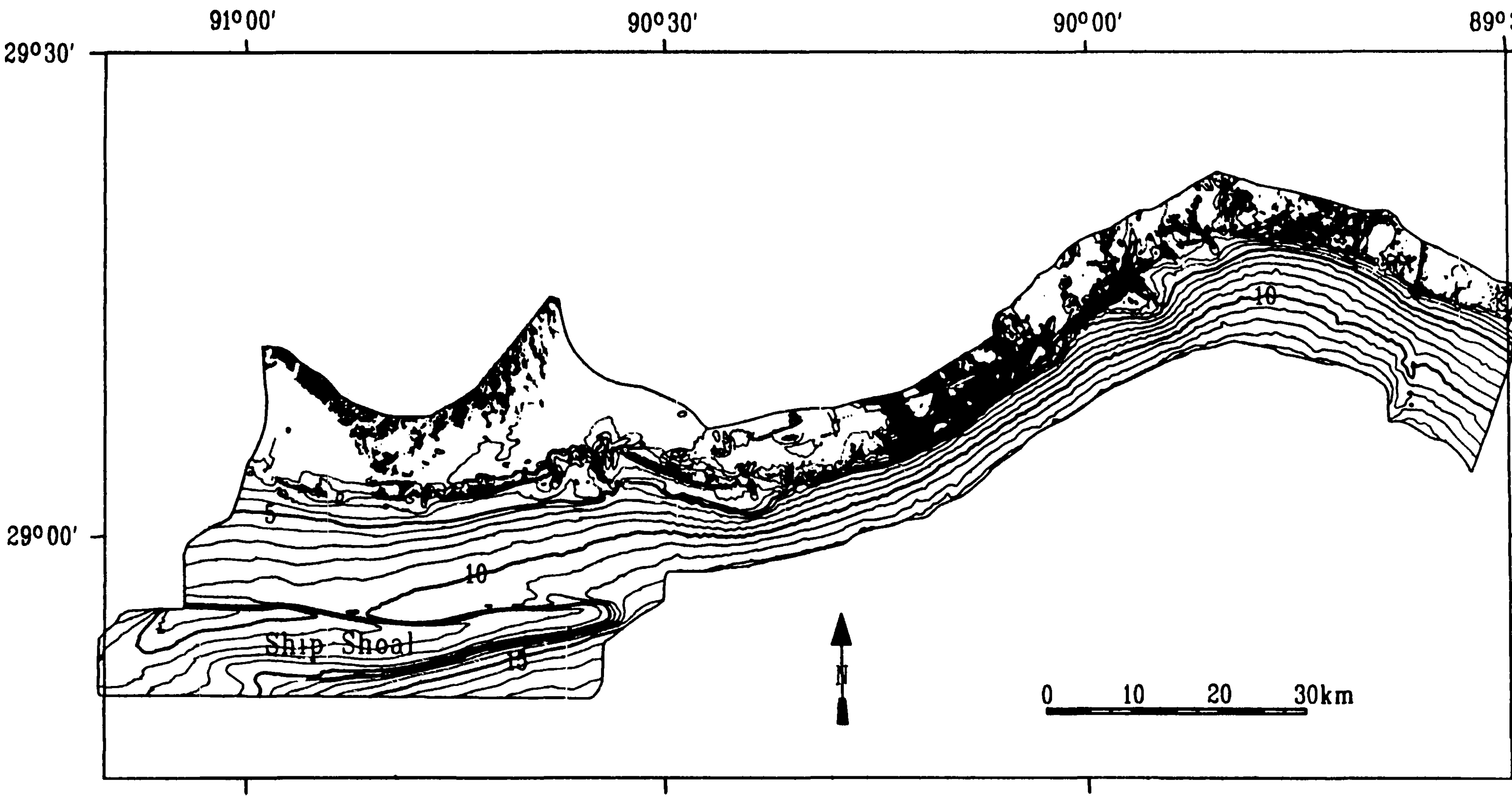

Figure 2. 1980s bathymetry from surveys conducted during 1986 to 1989. Contour interval 1 m. Vertical datum mean low water.

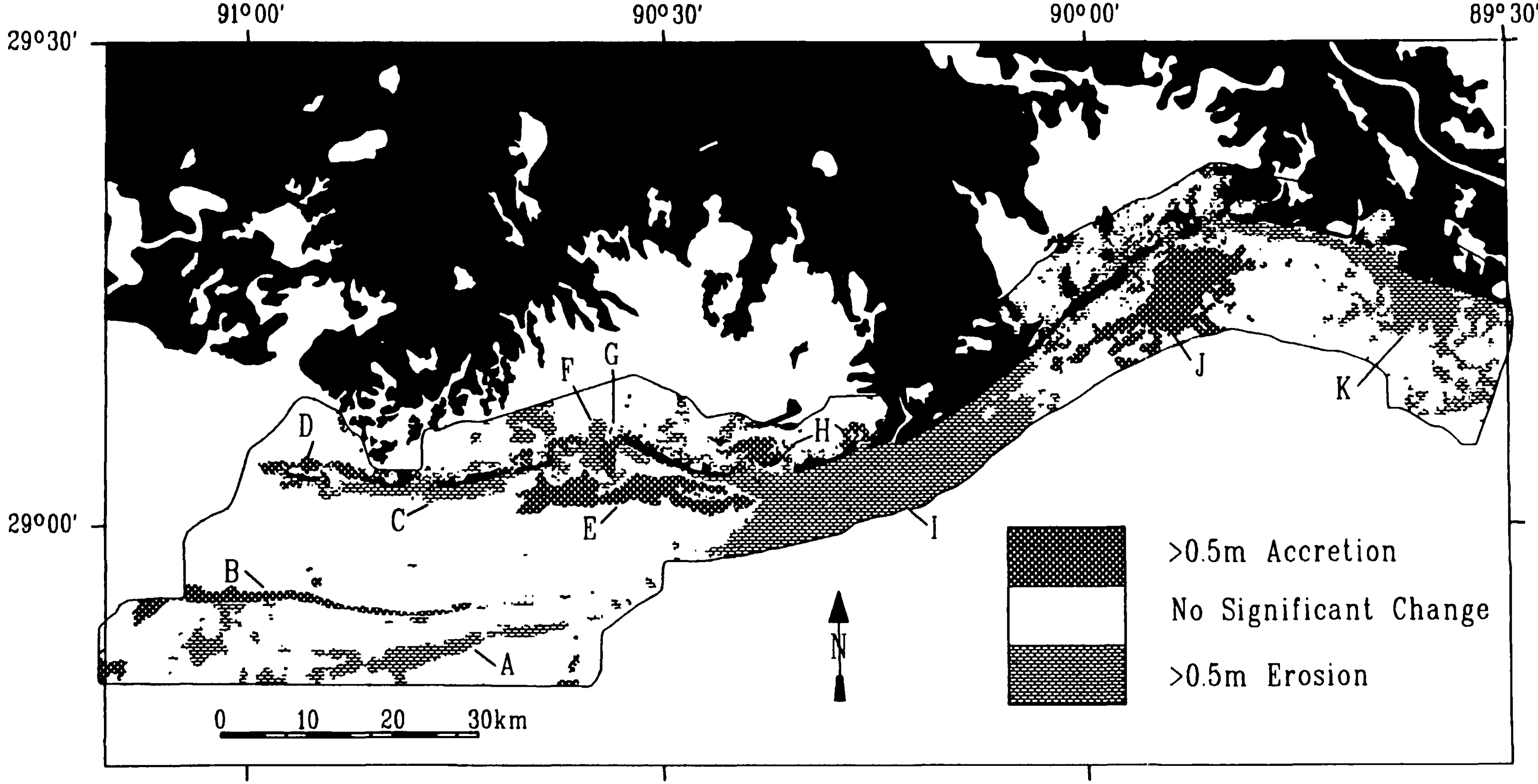

Figure 3. Bathymetric change between the 1930s and 1980s surface grids, corrected for relative sea level rise to yield the patterns of erosion and accretion. Letters indicate areas of erosion or accretion referred to in the text.

digital form from the Louisiana Geological Survey (see McBride et al., this volume).

PATTERNS OF SEA-FLOOR CHANGE

The patterns of erosion and accretion shown in Figure 3 are a unique representation of the large-scale transport of sediment over the last 50 years. Some of the changes were expected, based on our knowledge of historical shoreline changes, while some of the changes were entirely unforeseen, and suggest transport processes that warrant further investigation.

Overall, we observed only 35% as much deposition ($293x10^6 m^3$) as erosion ($-834x10^6 m^3$) throughout the study area shown in Figure 3. This may suggest that large depositional volumes were not identified because of wide dispersal or transport beyond the offshore limit of the 1980s survey (Figure 2). However, an examination of sediment cores indicates that the eroding deltaic headlands contain only about 1/3 sand-size material whereas the depositional bodies shown in Figure 3 tend to be composed mostly of sand. Thus we have some reason to believe the patterns of erosion and accretion represent a largely balanced system, with eroded fine material dispersed widely or removed from the study area. The following gives a brief description of the larger patterns observed, and our initial interpretations of the pathways of sediment transport. A more detailed description, including large-scale color maps, may be found in List et al. (1991).

Starting in the west, Ship Shoal (Figure 2) shows erosion on the seaward side (Figure 3, area A, $-62x10^6 m^3$) and deposition on the landward side (area B, $43x10^6 m^3$). This shoal, over 40 km in length, is thus behaving as a massive sand bar migrating landward. Landward of this shoal, the Isles Dernieres barrier island chain is experiencing shoreface erosion to a depth of 3-5 m (area C, $-50x10^6 m^3$), accompanied by shoreline retreat of 10-15 m/yr and the broadening of several inlets. The sand liberated by this retreat appears in small inlet channel deposits, spits, and narrow landward migrating barriers, with area D ($12x10^6 m^3$) being the largest such deposit. Overall, the total depositional volume ($18x10^6 m^3$) is about 1/3 of the total erosional volume ($-55x10^6 m^3$) for the Isles Dernieres. This suggests that the net export or import to the system was small considering the estimated percent sand in the eroded material (see above).

In the remaining study area toward the east, the patterns of erosion and deposition assume a much larger scale; these will be the primary focus of the remainder of this paper. The shoreface along E. Timbalier Island and the Bayou Lafourche headland has undergone massive erosion accompanied by a shoreline retreat of 10-20 m/yr. Figure 4 shows that over 6 m of vertical erosion has occurred near the shoreline, resulting in an eroded volume of $477x10^6 m^3$ (Figure 3, area I). The extreme depth of shoreface erosion was not anticipated; as a consequence, the 1980s survey was not extended into deep enough water to encompass the apparent closure depth of about 15 m (see Figures 3 and 4).

The patterns of accretion suggest several pathways of sand transport away from this rapidly eroding headland. Overwash and landward transport through shallow inlet areas has resulted in small deposits in area H ($24x10^6m^3$). Further west, longshore transport in the nearshore zone has resulted in the westward migration of Timbalier Island and the infilling and westward migration of Cat Island Pass. Area G ($34x10^6m^3$) represents this spit deposition and inlet filling while area F ($-15x10^6m^3$) represents the erosion due to channel relocation.

Another depositional body which appears to originate from the Bayou Lafourche headland erosion through longshore transport to the west is area E ($60x10^6m^3$), perhaps the most unexpected and unexplained feature of this bathymetric comparison. Also described by Jaffe et al. (1989), this deposition occurs at shoreface depths (4-8 m), and appears to be a means by which sand is bypassing a broad inlet system (Cat Island and Wine Island Passes). Understanding the processes responsible for this shoreface transport and concentrated deposition will require a major research effort, perhaps involving modeling the transport gradients associated with storm-driven coastal jets in the presence of a turning coast. Sediment cores within area E provided some clues, showing alternating laminations of sand and mud in the eastern half, suggesting episodic storm deposition, and pure, massive sand in the western half, suggesting a reworking and storage of sand in the ebb-tidal deltas associated with Wine Island and Cat Island Passes.

To the east of the Bayou Lafourche headland, area J ($112x10^6m^3$) represents another major depositional body at shoreface depths, occurring midway between the Bayou Lafourche shoreface erosion and similarly massive shoreface erosion in area K ($-131x10^6m^3$). Depositional area J represents a mostly sand-sized accumulation in the form of coalesced ebb-tidal deltas between Caminada Pass and Quatre Bayoux Pass. This deposit of sand is far too large to have been derived from adjacent shoreline erosion and inlet deepening (a total liberated volume of only $23x10^6m^3$). We conclude that sand deposited in area J was derived from the erosion of adjacent shorefaces in areas I and K, again through shoreface-depth processes which are poorly understood.

Overall, the patterns of erosion and accretion in the eastern 3/4 of the study area appear to follow a conceptually simple coastal straightening model, with erosion of headlands and deposition in embayments. However, except for along Timbalier Island, the transport occurred in water too deep to evoke traditional littoral processes as the responsible mechanism. Much more needs to be understood about shoreface-depth processes before the above conclusions on transport directions can be elevated above the conjecture level.

At this point we turn our focus to the question of how this sea-floor change information can be used to explain rates of shorelines erosion, assuming we have made correct interpretations of the transport pathways. We will focus on the erosion of the

Bayou Lafourche headland, the most erosive shoreline in the study area.

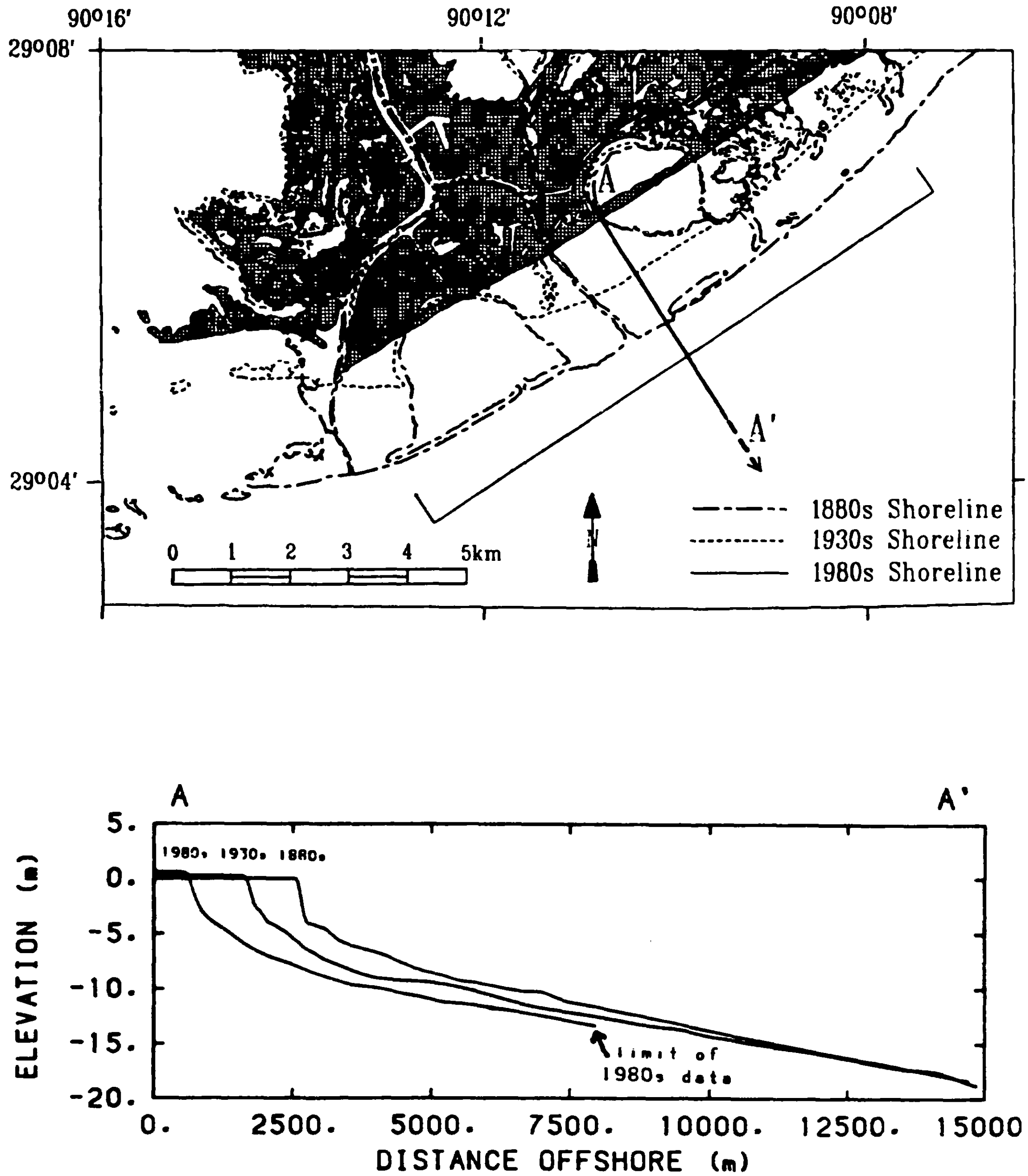

Figure 4. Top: map showing historical shoreline recession in the western part of the Bayou Lafourche headland. The 10 km section of coast used for profile averaging is marked by the coast parallel bracket. Bottom: historical profile changes along A-A'.

HINDCASTING SHORELINE RETREAT

The Bruun rule states that the horizontal shoreline retreat, s, should be related to the sea level rise, a, by

$$s = al/h \qquad (1)$$

where l is the length and h is the depth of the shoreface profile out to the limit of the active zone (closure depth). As noted by Bruun (1983), equation (1) only applies to a two-dimensional, sandy-coast (no longshore export or import of sand), where there is an equilibrium profile that moves upward and landward to maintain a constant elevation relative to sea level. Everts (1985) extended equation (1) in a numerical approach that accounted for gradients in longshore transport and a limited fraction of sand in the eroding portion of the shoreface. (It is assumed that only sand can contribute to maintaining a materials balance.) Everts finds solutions to the materials balance equation,

$$kV_1 + V_o - (V_g + V'_g) = 0 \qquad (2)$$

where k is the fraction of sand in the erosive portion of the shoreface, V_1 is the volume of sediment liberated by shoreface retreat, V_o is the net import or export of sand to the profile mainly through longshore transport, V_g is the volume of sand deposited onshore through overwash (and other) processes and V'_g is the volume of sand deposited offshore maintaining the profile's elevation in relation to sea level rise. For Louisiana's barrier islands, equation (2) can be simplified with $V_g=0$; observations of beach, dune, and overwash deposits (Ritchie and Penland, 1988) suggests a conservation of sand during the transgression of this subaerial complex over accreting marsh deposits.

Before calculating shoreline retreat rates based on equation (2), it was necessary to verify the equilibrium profile assumption central to the Bruun Rule, as well as the approach of Everts (1985). This was accomplished in a preliminary manner here by comparing the 1880s, 1930s and 1980s profiles averaged for each period along the 10 km section of coast shown in Figure 4. Although the coast has retreated almost 2 km during the last 100 yrs, the averaged profiles, adjusted to a common shoreline position, were nearly identical suggesting the equilibrium profile assumption is valid. A profile representative of the western part of the Bayou Lafourche headland was then found as the profile average from all three years. Using Everts' (1985) method, this profile was used to numerically solve the material's balance equation, (2), under different scenarios of sea level rise, percent sand in the eroding shoreface, and longshore rate of sand removal.

Figure 5 shows the results of three such calculations for a 50 year time period, with $h=-15$ m, $l=9600$ m, and a sea level rise of $a=0.50$ m (1 cm/yr). The case of 100% sand and no longshore removal of sand is shown in Figure 5A. This case predicts $s=326$ m, or very close to the Bruun Rule prediction of equation (1). The actual shoreline retreat for this section of coast averages about 916 m

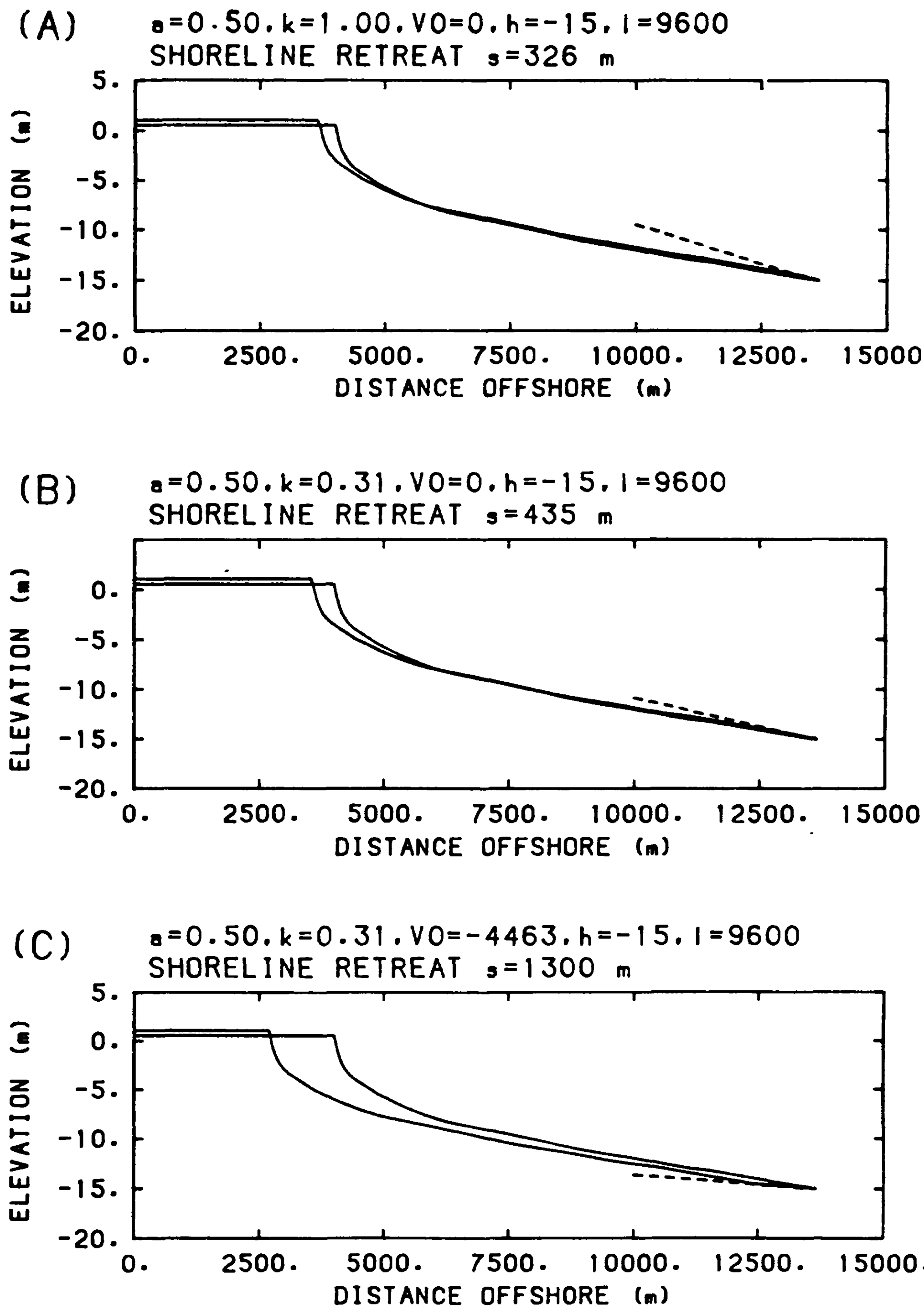

Figure 5. Shoreline retreat calculations for the averaged Bayou Lafourche profile over a 50 yr time period. Scenarios (A) basic Bruun Rule, (B) Bruun Rule with 31% sand in eroding shoreface, (C) Bruun Rule with 31% sand in eroding shoreface and a longshore sand removal rate of -4463 m^3/m 50 yr.

for 50 years (Figure 4), indicating that the basic Bruun Rule is inadequate here. Even taking into account the uncertainty in the sea level rise estimate (Ramsey and Moslow, 1987) and using a maximal rate of 1.2 cm/yr, less than half the observed shoreline retreat can be predicted from sea level rise alone (392 m).

Next, the effect of assuming a limited fraction of sand in the eroding shoreface is shown in Figure 5B. Through an evaluation of 14 cores within the erosional region I (Figure 3), it was estimated that 31% of the eroding delta sediment is of sand-size (k=0.31). The predicted shoreline retreat increases to 435 m, still far short of the observed retreat. Uncertainties in the estimate of k cannot account for this difference either.

Figure 5C makes one additional modification to the basic Bruun Rule: the removal of sand from the profile through longshore transport (V_o). To estimate this removal rate, we summed the sediment volumes in the deposits assumed to be derived from the erosional shoreface, including volumes E, G, H, and half of J (Figure 3). This total depositional volume was then divided by the length of erosional shoreface, 39 km, to give an overall V_o estimate of -4463 +/- 2170 m^3/m 50 yr. The large error associated with this estimate includes uncertainties in each area's volume and the assumption that half of volume J was derived from erosional volume I. Nevertheless, this estimate is likely to be far better than one made without the bathymetric change information.

Using this V_o estimate, the predicted shoreline change is 1300 m, or 384 m larger than the measured value. However, the observed value of s can be predicted with a V_o of -2700 m^3/m 50 yr, a value well within the V_o uncertainty. Thus the longshore removal of sand appears to be a critical factor in explaining the Bayou Lafourche shoreline retreat with an equilibrium profile concept. Sea level rise alone, even with a small k, predicts less than half the observed erosion.

FUTURE CONDITIONS

Predicting the long-term evolution of a coastal region, such as in Figure 1, is a difficult goal that can be approached on several different levels. On the simplest level, historical rates of shoreline change can be statistically projected into the future. This has the disadvantage of precluding predictions based on changing conditions, such as an accelerated sea level rise. On the other end of the spectrum are numerical models based on physical principles (or parameterizations of these principles), which predict changes in shoreline position based on wave information (e.g. deVriend and Ribbernick, 1989, Hansen and Kraus, 1989). While this approach may eventually be the most promising, at present it is limited by our knowledge of sediment transport processes. Also, these models generally involve currents and transport induced by breaking waves, which in our example would be inadequate in that much of the important sediment redistribution occurs at shoreface depths.

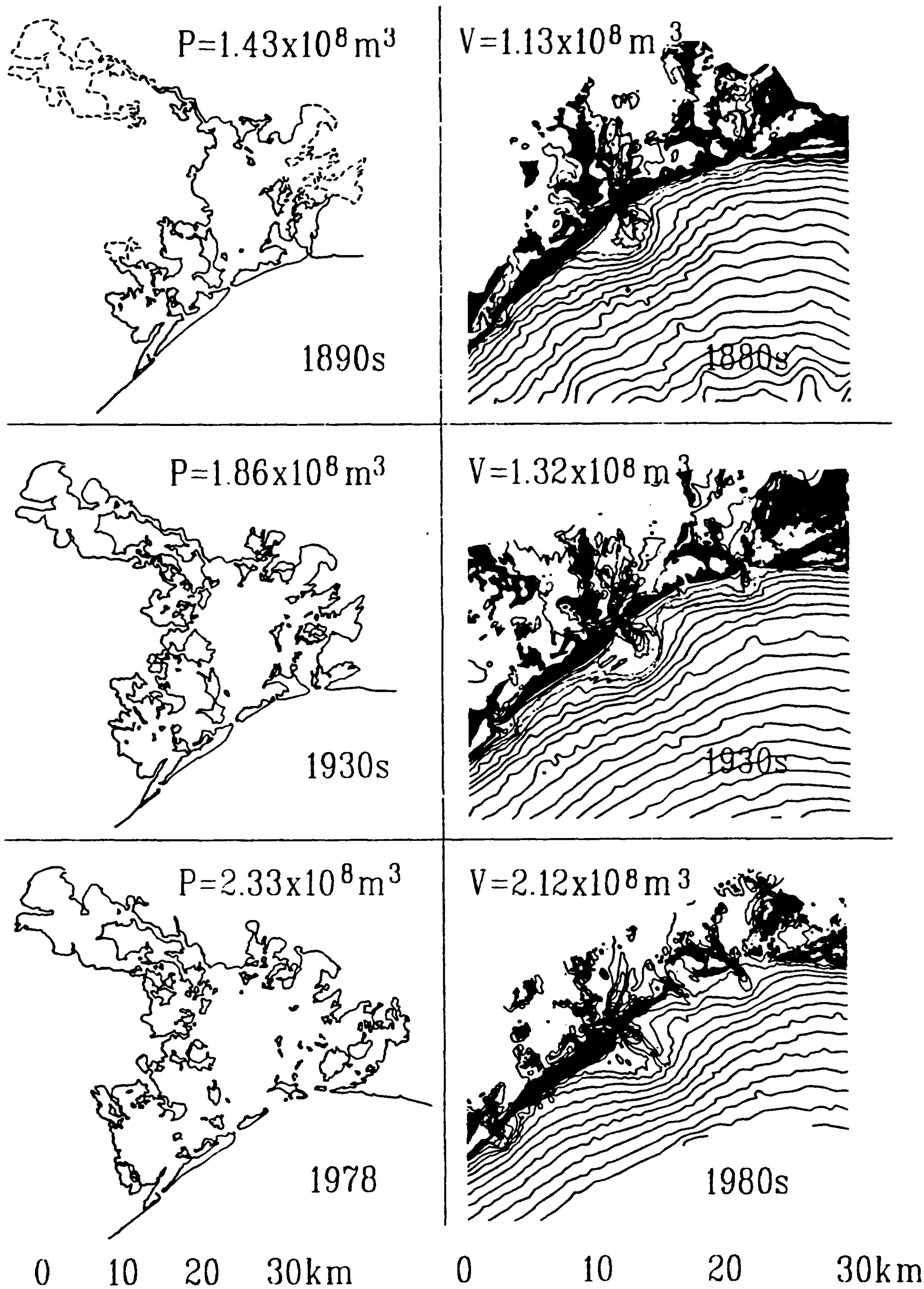

Figure 6. Co-evolution of Barataria Bay tidal prism (P) and adjacent ebb-tidal delta volume (V). The rapid marsh deterioration and expansion of Barataria Bay is likely due to relative sea level rise in a sediment-deficient system.

Falling somewhere in between these two extremes, the equilibrium profile assumption combined with long-term observations of sea-floor change is an approach which gives some insight into the processes controlling erosion, and allows the prediction of future changes under varying conditions. For example, this method predicts that a 100% increase in the relative sea level rise along the Bayou Lafourche headland would increase the shoreline erosion by only about 35%. This result could not have been obtained by either a shoreline change analysis nor process-based models in their present state.

Nevertheless, the continued improvement of process knowledge is critical for increasing the reliability of predictions based on the equilibrium profile concept. In our example above, it was assumed that the rate of longshore removal remained the same under the condition of an accelerated sea level rise. Without a better understanding of shoreface depth processes, this is difficult to assess. However, some potentially useful information on future changes to the longshore removal rate may be obtained by considering shoreface deposits as ebb-tidal deltas whose size is dependent on the adjacent bay's tidal prism. Figure 6 shows the co-evolution of Barataria Bay tidal prism, P, and the volume of sediment, V, stored in the coalesced ebb-tidal deltas seaward of Caminada, Barataria, and Quatre Bayoux Passes (method of Dean and Walton, 1973). The relation between P and V closely follows the relation found by Walton and Adams (1976), suggesting that depositional area J (Figure 3) may be an ebb-tidal delta deposit that will continue to grow as sea level rises and Barataria Bay continues to expand. Given the ability to predict increases in tidal prism under a scenario of accentuated sea level rise, we may therefore estimate the associated changes in the longshore removal rate. Naturally, this assumes a processes link between ebb-flow and ebb-delta volume corresponding to the observed empirical relation between tidal prism and ebb-delta volume. For the shoreface-depth transport observed here, this link is unclear, but may be related to the "dynamic diversion" process introduced by Todd (1968).

DISCUSSION

Thus far we have focused only on the erosion of the Bayou Lafourche headland. In order to predict the evolution of the entire coastal reach shown in Figure 1, the equilibrium profile approach used here must be adopted to other sections of coast. Preliminary investigation indicates that the method works well in other erosional areas, such as along the Isles Dernieres, but does not work where deposition occurs on the shoreface, such as between Grand Isle and Quatre Bayoux Pass (still an erosional coast).

At least along the erosional coastal sections, our initial results suggest that sea level rise is not the primary cause of shoreline retreat. However, this result must be tempered by the possibility that sea level rise also has some control over the longshore removal rate, at least in the example given above. Further processes research is clearly needed in this area.

CONCLUSIONS

1. Comparisons between historical and recent bathymetry along the Louisiana barrier island coast reveal patterns of erosion and deposition that could not have been anticipated from shoreline change alone. These patterns suggest transport gradients driven by shoreface-depth processes that are poorly understood.

2. The bathymetric change information can be used in conjunction with an equilibrium profile assumption to identify the relative importance of factors relating to shoreface retreat. Along the Bayou Lafourche headland, the longshore removal of sand appears to be the primary factor, even though the relative sea level rise rate is extremely high in the area.

3. Empirical evidence suggests that shoreface deposits adjacent to Barataria Bay are coalesced ebb-tidal deltas which are likely to continue being a sand sink as sea level rises. This may be one means of predicting future changes in the longshore removal rate given a particular scenario of sea level rise.

ACKNOWLEDGEMENTS

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(p. 407 follows)

RECENT GEOLOGIC DEVELOPMENT OF THE EASTERN LOUISIANA CONTINENTAL SHELF

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The eastern Louisiana continental shelf (Fig. 1) has been the site of extensive sediment accumulation during the Holocene. The St. Bernard Delta, previously described as the first of the Holocene sea-level highstand deltas, was actively depositing large quantities of sediments on the shelf from approximately 4-1 ka. With the abandonment of the delta, through the process known as delta switching, relatively little deposition has occurred since that time on the shelf. The topic of this paper is to discuss the processes and controls governing the Holocene development of the east Louisiana continental shelf, and to what extent the abandoned St. Bernard Delta influences the modern shelf configuration.

Over 6700 line-km of seismic reflection data and 77 vibracores were collected in order to determine the geologic development of the area. Initial data analysis has been completed; detailed analyses are continuing.

The base of the Holocene sediment package is a highly irregular, dissected seismic reflector representing an erosional unconformity (Fig. 2). This surface has been correlated throughout the study area and is interpreted to represent a sea-level lowstand erosional surface formed by subaerial processes.

Overlying this basal erosional surface is a relatively thin (few meters) unit with an extremely flat reflection surface (Fig. 2). Internal reflectors are dominantly parallel and continuous. Sediments consist primarily of relatively clean, fine-grained quartz sands exhibiting various degrees of bioturbation. This unit, also correlated throughout most of the study area, is interpreted to represent a transgressive sand sheet (Fig. 3) deposited during early flooding by the most recent sea-level rise.

Overlying the transgressive sand sheet is a thick (several meters to a few 10s of meters), seaward prograding, coarsening upward wedge of sands and muds containing vertically stacked units of deltaic succession (Fig. 2 and 3). A

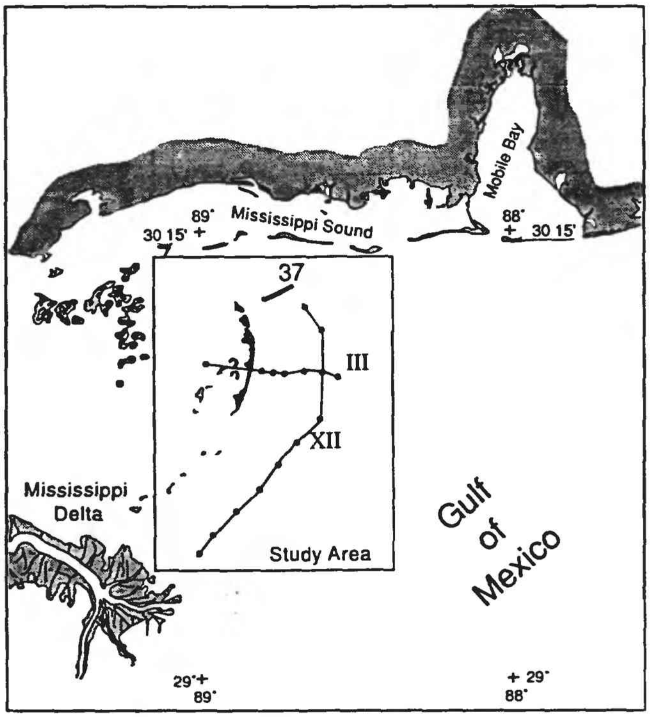

Figure 1. Location map showing study area. Black lines with roman numerals denote core cross sections shown in Figure 3; closed circles denote location of cores used to construct cross sections; bold line denotes location of seismic line shown in Figure 2.

variety of seismic facies have been identified, but a general pattern of parallel and continuous reflectors in lower sections, overlain by channelized, cut and fill structure, persists. Sediments consist dominantly of homogeneous or thinly laminated prodelta muds at the base, overlain by slightly burrowed, delta fringe sandy muds exhibiting a variety of structures including lenticular bedding and ripple cross stratification. Overlying delta fringe sediments, is the channelized section consisting of alternating layers of burrowed sands and muds exhibiting lenticular, wavy and flaser bedding. This unit is interpreted to represent the distributary facies of the delta and reflects the seaward most progradation of the delta proper.

Surficial sediments consist of a combination of sands and muds (Fig. 3), the distribution of which is a reflection of the underlying, abandoned St. Bernard Delta. The north-central portion of the study area is dominated by well-sorted, shelly, quartz sands, a product of reworking of underlying St. Bernard Delta distributary channel sands. The central shelf in this region is occupied by the St. Bernard Shoals representing the most active portion of the delta distributary.

Flanking the north-central, mid-shelf reworked distributary surface sands are heavily bioturbated shelly muds and sandy muds, found most extensively in the north-west portion of the study area. Surficial mud-rich sediments are a

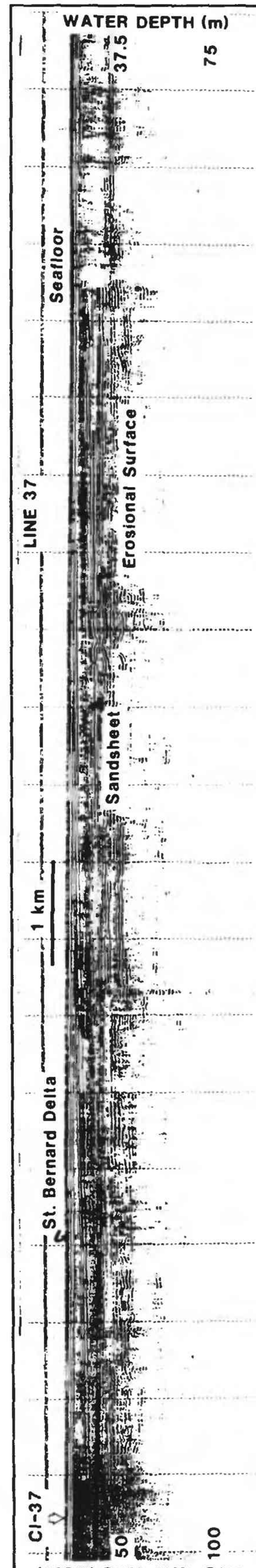

Figure 2. Portion of seismic line 37 showing erosional unconformity, transgressive sand sheet and overlying St. Bernard Delta sediments pinching out to the east. Refer to Figure 1 for the location.

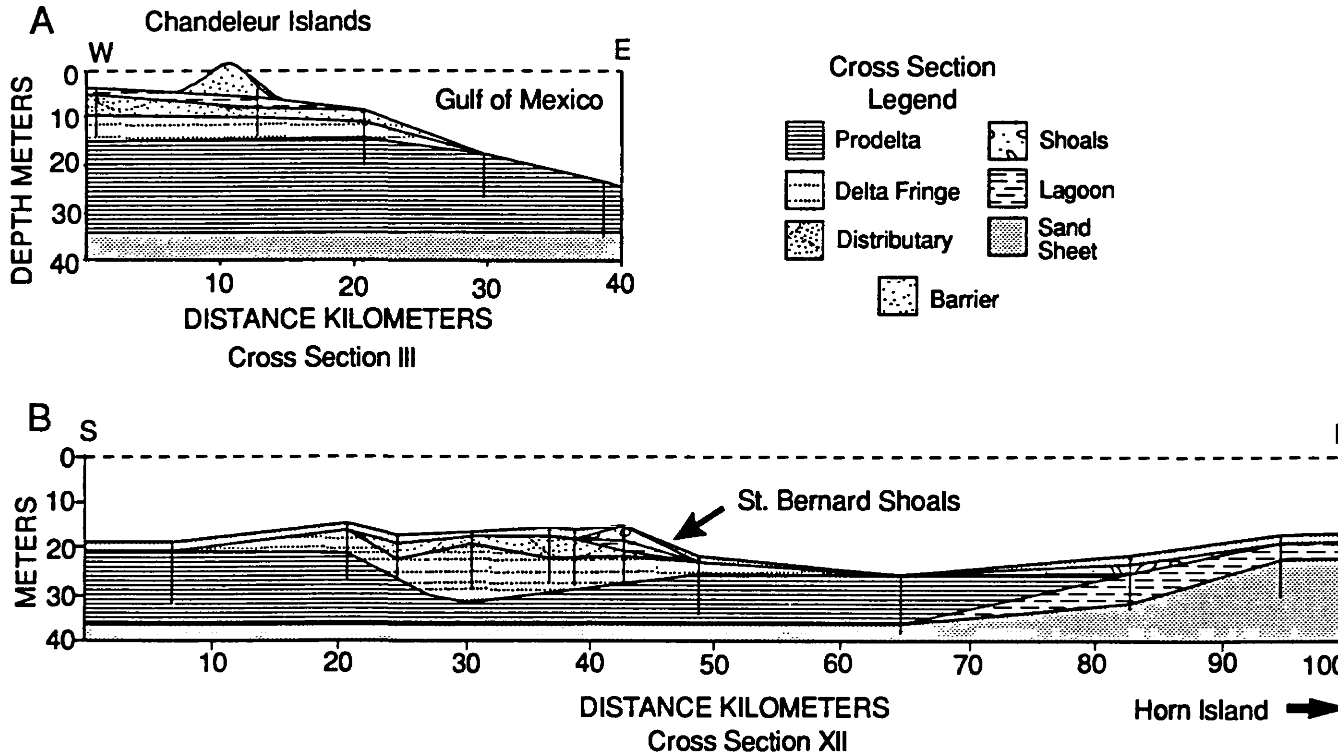

Figure 3. Core cross sections III (a) and XII (b) showing the distribution of sediments in the study area. Refer to Figure 1 for locations.

product of reworking of prodelta and delta fringe deposits and represent the margins of the delta where the distributary was least active.

Surficial sands in the northeast region are not reworked delta sediments, but originate from outside the study area to the east. Sands are prograding westward, possibly in response to long-shore current processes, where they are actively burying deltaic surficial muds. This northeast surficial sand sheet is the only surficial unit resolved on seismic profiles, represented as a westward thinning wedge pinching out against St. Bernard delta muds.

Holocene development of the shelf has been controlled by sea level and deltaic construction/destruction processes. During the most recent sea level lowstand, approximately 18 ka, the shelf surface was eroded by subaerial processes. The ancestral Mississippi river dissected the shelf on its way to the sea. It is during this time period that a lowstand sediment wedge was deposited on what is now the upper continental slope. During early flooding by the ensuing sea-level rise, a thin transgressive sand sheet was deposited over the lowstand erosional surface. During the late transgression, as sea level reached near its present position, the St. Bernard Delta began to develop. The delta was active for approximately 3,000 years as it prograded eastward depositing large quantities of sands and muds on the shelf surface.

The modern configuration of the shelf is controlled principally by the underlying St. Bernard Delta. Although the delta was active for a relatively short segment of the Holocene, it has had a profound effect on the modern configuration. With abandonment of the delta approximately 1 ka began the destructional phase of the delta cycle. Reworking of delta sediments by shallow marine biological and physical processes is slowly concealing the influence of the delta. The lack of significant modern sediment accumulation in the study area, however, has helped to preserve the imprint of the underlying delta.

(p 411 follows)

THE MISSISSIPPI DELTA PLAIN'S LEVEES, CREVASSES, AND SEDIMENTS

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ABSTRACT

From its inception, New Orleans was an "island city" surrounded by water. When it was surveyed in 1720, each block was circled with drainage ditches. These small channels established New Orleans' dependence on a levee/drainage network. Levee construction began as early as 1718. By 1727, a hand-made embankment protected the earliest city– the "Vieux Carre." With time the initial levee extended along the Mississippi River for a total of 67.6 km. The first artificial levee built to protect New Orleans was in place, but it was neither high enough nor wide enough. By the 1850s, intermittent dikes flanked most of the lower Mississippi River.

After the devastating flood of 1927, the Mississippi River was locked into a conduit framed by artificial levees. The river can no longer inundate its historic flood plain. Sediments are channeled away from the wetlands. Loss of these sediments deprives the coast of the material necessary to build new land at a rate slightly greater than subsidence. There is nothing available that can offset the rapid rate of wetland loss. Consequently, to exist in this dynamic and sometimes inhospitable physiographic province, the population had to develop and utilize innovative engineering techniques, unconventional wisdom, and unique cultural occupancy patterns.

INTRODUCTION

> The ground on which New Orleans is situated, being an earth accumulated by the ooze . . is a good quality for agriculture... This land being flat, and drowned by the innundations [*sic*] for several ages, cannot fail to be kept in moisture, there being, moreover, only a mole or bank to prevent the river from overflowing it; and would be even too moist, and incapable of cultivation, had not his mole been made, and ditches, close to each other, to facilitate the draining off the waters: by this means it has been put in a condition to be cultivated with success. – M. Le Page du Pratz, *Histoire de la Louisiana*, 1758, p. 158.

Transgression, sea-level rise, subsidence, vibracores, seismic profiles, and sediment loading are part of the lexicon of coastal geology. These terms and others are used to describe the fluvial and regional history of Louisiana's delta plain. The descriptive techniques employed are used to unravel the sequential history of the Mississippi's sedimentary patterns. More than 10,000 years of geomorphic history has been analyzed in producing the contemporary map of deltaic history. Superimposed on this natural sequence of deltaic events are the engineering structures that have harnessed and trained the Mississippi River's 54 tributaries to follow a designated route. The river can no longer overflow at random; it must follow a course framed by levees constructed to control spring floods. After the record deluge of 1927, under the direction of Congress, the United States Army Corps of Engineers went into the levee business, but levees have been a part of the Mississippi River's history since New Orleans was settled in 1718.

LEVEES ALONG THE RIVER

Flanking the Mississippi River are natural levee ridges, that along its lower channel rarely exceed 10 m above sea level. The crest of this natural levee is near the stream bank and the backslope is so slight it is not recognized easily. The height and width of these topographic elements are directly proportional to the size of the river, stream, or bayou that created them. Stream patterns are complex and so are the associated guide levees. Within the distributary networks that shaped the delta plain, are natural levee configurations that can be utilized to distinguish and classify, by time periods, a stream's history. Some of these levees are not continuous; local subsidence has disrupted their continuity to create isolated levee segments. Others disappear beneath the wetland surface. Regardless, these features furnished the essential "high ground" for colonization. In the delta plain, elevations above sea level are not great. Differences are slight but vital from the standpoint of human occupancy. Further floods were a perpetual dilemma that had to be endured.

Annual floods renourished the land, but were an aggravating part of living within the river's flood plain. To neutralize these seasonal disasters, natural levees were augmented by engineered structures high enough to counteract flood wat.. or at least minimize its effects. Actually, artificial levees are the only practical technique that can be implemented to resolve flood-control problems.

From the first explorers to the present, there has been widespread interest in the Mississippi River. It was explored, claimed, and exploited by the English, French, and Spanish. In 1543, De Soto's expedition observed the Mississippi overflowing its banks for about 80 days (Elliott, 1932). Garcilaso de la Vega wrote "the inundated areas extended for 20 leagues on either side of the river" (Elliott, 1932, p. 105). LaSalle in 1684 also found the Lower Mississippi out of its defined channel.

To these explorers, control of the Mississippi was paramount but not in the sense of building a massive levee system to channelize its flow. Political jurisdiction was deemed imperative; for over 150 years free navigation was critical. The sentiment was so strong Thomas Jefferson was determined to gain authority over at least the river's east bank. Through the Louisiana Purchase in 1803, the U. S. acquired over 2,590,000 km^2, including most of the Mississippi's drainage basin. The river was under the jurisdiction of one government that began to exhibit an interest in the connectivity between flood management and navigation.

Flood control was not a new issue; there is ample evidence to suggest flooding problems extended back to the earliest settlements. From the beginning, the New Orleans learned to endure the hardships that accompanied the river's annual floods. The site the explorer Bienville selected was over the objection of de la Tour, his chief engineer, who felt the area would be flooded periodically. The new colony was above the surrounding terrain but could not be built until the water receded from the 1717 flood (Martin, 1882; Elliott, 1932). This was an omen of things to come. Flooding occurred in 1735, 1775, 1785, 1791, 1799, 1816, 1823, 1844 (at Algiers, opposite New Orleans), 1849, and 1927 (Elliott, 1932). New Orleans flooded often, so much so it became a walled city. Levees formed the protective barriers; without them the river would easily engulf North America's premier below-sea-level city. Water was pushed often over the levee crests into the city's reclaimed land. When this happened, a second reclamation effort was initiated to pump the flood water out of the holding basin. Even though the area is drained, the natural system has been superseded by an artificial one, that, at times, cannot accommodate the torrential rain storms of the summer months. While the situation in New Orleans was bad, other settlements fared even worse. "They were almost destroyed by the mighty floods that came sweeping down upon them in early spring" (Frank, 1930, p. 14).

Europeans and others constructed levees to protect their communities from flood water along the Nile, Po, Danube, Rhine, Rhone, and Volga rivers. Prior to the establishment of New Orleans, this technology was widely used, accepted, and understood in Europe. The new immigrants knew the solution to the flooding problem and needed only to implement it. Consequently, immediately after New Orleans was founded, de la Tour began to construct a riverfront levee. Initially, a 1.5 km long earthen mound was created to defend the city from floods. Completed in 1727, the embankment was 1649 m long, .9 m high, with a crown width of 5.4 m. With time it expanded as settlements migrated along the river's lower reach (Elliott, 1932). Two hundred years later a flood of major proportions would result in a levee construction strategy that would permanently alter the Mississippi River's natural geometry. De la Tour effectively gave birth to the Mississippi River's levee system. Small by contemporary standards, but nevertheless, it was the beginning of an engineered rampart designed for flood control.

By 1735 the protective bulwark was 28.9 km long. When Louisiana became a state in 1812–nearly 100 years after construction of New Orleans' first levees–the de la Tour embankment extended 249 km on the east bank and 297 km on the west bank (Frank, 1935). Early on, Louisiana's citizens were mandated by law, if they lived within 11.2 km of the river, to work and maintain the levees. Spanish Governor Alexandro O'Reilly passed an ordinance in 1743 that required property owners to complete their levees by January 1, 1744, or forfeit their land as a penalty for their negligence (Frank, 1930). He further required every family settling in the province to construct, within three years, a levee and finish a highway with parallel ditches toward the levee (Martin, 1882). O'Reilly wanted Louisiana to become a self-sufficient, agriculturally based, exporting colony and recognized the need for adequate drainage and flood control.

While flooding was of local and regional concern, the national interest in the first half of the 19th century was focused on enhancing river navigation. Protection against flooding attracted little legislative attention. However, in 1822 a survey by Bernard and Totten concluded the only way to reduce the number of snags in the Mississippi's main channel was to construct levees. It was believed these features would prevent the lateral currents responsible for the snags and enhance navigation (Frank, 1930). The connection was thus made that levee construction improved navigation.

Nationally, improvement of navigation was the center of appropriation debates. As late as 1855 there was no mention of levees to defend against floods–only to augment navigation. Merchants and the business community successfully lobbied for navigational improvements. The agricultural and urban communities said practically nothing. In 1835 Henry Clay suggested to the Secretary of the Treasury the government should study carefully the cost of raising a levee on the Mississippi's west bank. "The resolution also called for an estimate of the probable effects upon the health and prosperity of the country in which any such works may be constructed" (Frank, 1930, p. 20). The suggestion fell on deaf ears.

Flood control may not have been a concern at the national level, but the interconnecting levee network increased in length and strength through the efforts of local governments and individual riparian property owners. Planters using slave labor extended their levees during the seasons when these farm hands were not in the fields.

By current standards, these levees were small; their average height was about .9 m (Elliott, 1932; Waddill, 1945). All levees built during this period were insufficient in height and cross-sectional profile. An indication of the levee's deficiency is the number of crevasses identified with each flood (Table 1). Numerous gaps were present–although in 1851 the Baton Rouge-to-Pointe-a-la-Hache levee segment was continuous with a mean height of 1.37 m (Elliott, 1932). Many of these levees were, nevertheless, too close to the river. They were inefficient and failed because of overtopping, crevassing, seepage, and bank collapse or caving. It was a weak system, easily breached creating crevasse-induced flooding.

Table 1. Crevasses on the Mississippi, principally in Louisiana

Flood	Crevasses	Kilometers of Levee breached	Flood	Crevasse	Kilometers of Levee breached
1850	8		1893	17	5.2
1851	8		1897	37	14.00
1858	45		1903	6	3.5
1859	32		1912	15	21.6
1874	43*	33.8	1913	8	4.9
1882	284	95.1	1916	1	.5
1883	224	54.9	1922	4	2.1
1890	53	10.9	1927	13	8.0
1892	31	3.7			

* Water from two of these crevasses flowed through an 8 km opening for seven years.

From Vogel, 1930; Elliott, 1932; and Waddill, 1945

FLOODING FROM CREVASSES

In the fall, winter, and spring of 1858 and 1859 occurred "the worst flood in the history of the Mississippi valley" (Frank, 1930, p. 27). Numerous crevasses ripped through the levees and devastated the Mississippi flood plain's bottom lands. More than 40.2 km of crevasses inundated this valuable agricultural property (Frank, 1930). The magnitude of this flood convinced levee builders their construction design was inadequate.

When the levee was breached, the associated crevasse furnished a pathway for water and sediments to be discharged into the backswamps and interdistributary basins (Kesel, 1989). Before construction of artificial levees, crevasse splays were a common occurrence that directed sediments out of the main channel and reduced flood stage down river. Archaeological evidence suggests these geomorphic features are a natural phenomenon that often remained open and functional for several hundred years (Gagliano and Van Beek, 1970). Vogel (1930) shows a crevasse splay will encompass an average of about 1675 km^2–the largest involved 5600 km^2, while the smallest was about 550 km^2.

It is important to note once a large crevasse opens, closure is difficult. The breach cannot be repaired until the flooded areas influenced by the crevasse splay are sufficiently inundated to materially reduce current flow through the break. Once the flow is no longer a raging torrent, closure procedures can be initiated to seal the fissure. This is such an acute problem the utmost precautions must be taken to prevent crevasses, because once they are present, they flow at will. For example, in 1849 a crevasse at Fortier's plantation, about 24 km above New Orleans on the river's west bank, inundated the upper Barataria basin, between the Mississippi and Bayou Lafourche, to a depth of 1.2 m–depositing a thin sheet of new sediments onto the affected sugar and rice plantations (Humphreys and Abbot, 1861). In that same year the Sauve's crevasse submerged New Orleans for 48 days (Humphreys and Abbot, 1861).

Literature from the period reports in many instances these crevasses were due wholly to defective rice flumes placed in the levee. The 1884 Davis crevasse in St. Charles Parish, about 33.7 km above New Orleans, was directly attributed to an old rice flume. The waters from this break overflowed into St. Charles and Jefferson parishes (Territory submerged by ... 1884). This experience led to the conclusion "that rice flumes are the great crevasse makers, and that they should be abolished" (Ewens, 1885, p. 108). In the floods of 1897, rice flumes were responsible for 13 crevasses in the vicinity of New Orleans (Gillespie *et al.*, 1897). The warning of 1884 was not heeded.

Between 1850 and 1927, 829 crevasses punctured a levee built for an effective life "of at least 20 years" (Waddill, 1945, p. 6). Each of these floods and related crevasses, particularly those that developed after formation of the Mississippi River Commission, resulted in the alteration of the levee design. The 1922 flood is particularly notable since it threatened New Orleans. To reduce the danger a relief outlet was constructed at Pointe-a-la-Hache 72.4 km south of New Orleans–initiating the first of many spillways.

Early Louisiana records attest to the connectivity between floods and crevasses:

* The water was so high in 1735 and 1775 crevasse waters inundated New Orleans.

* The flood of 1782 "rose to a greater height than was remembered by the oldest inhabitants ... the inundation was extreme. The few spots which the water did not reach were covered with deer" (Humphreys and Abbot, 1861, p. 168).

* In 1785, 1791, 1799, and 1816 New Orleans was flooded by high water from various crevasses.

* Several crevasses occurred between Baton Rouge and New Orleans from the 1832 flood. One of these, 32.1 km up river from New Orleans, increased flooding within the city.

* A crevasse in 1847 at Algiers caused extensive damage to the communities on the river's west bank.

* A large crevasse in 1849 flooded the country between the Mississippi River and Bayou Lafourche to a depth of 1.2 m. On the east bank a crevasse 28.9 km above New Orleans flooded the city.

* In 1850 a crevasse, 2 km wide, broke through the levee at Bonnet Carre and flowed for more than six months (Elliott, 1932). From 1849 to 1874 this crevasse overflowed five times. The 1874 break remained open until 1883–ten years. The natural crevasse was replaced by the Bonne Carre Spillway in 1931. Actually, an artificial or controlled crevasse was constructed to protect New Orleans by diverting flood water away from the Mississippi River into Lake Pontchartrain.

* In 1867 flood water opened four old crevasses and twelve new ones.

* On the lower Mississippi River, crevasses in conjunction with the 1874 flood had an aggregate length of 230 km, 7.56 km in Louisiana. From 1866 to 1874 more than 160.9 km of Louisiana's levees collapsed into the main channel.

* The most destructive flood to be recorded on the Mississippi River occurred in 1882. At New Orleans flood stage lasted 91 days.

* The flood of 1890 was adopted as the standard project flood on which the levee grades were to be referenced (Elliott, 1932).

* In 1920 the levees constructed by the Federal government sustained little damage. The only problems were two breaks south of New Orleans totaling 144.7 m.

Bayou Lafourche: A Distributary in Flood

Crevasses and the flooding dilemma were not confined to the Mississippi. Along Bayou Lafourche–the river's last outlet–levees were erected by plantation owners. These slave levees were 1.06 m high at Donaldsonville and increased to 2.43 m at Lockport. By 1859 they extended south from Donaldsonville 133.5 km. Levees along the bayou's lower reach were raised because the high water level was increasing constantly (Humphreys and Abbot, 1861).

In 1858, the Bell and LaBranche crevasses south of Lockport easily overflowed the relatively small levee (Humphreys and Abbot, 1861). It was apparent the artificial levees were not high enough to protect against overflow. Because they were poorly engineered, they could not keep flood water confined to the main channel. This was also evident in 1854 when a levee in front of an old rice mill at Lockport created a crevasse that inundated the surrounding property and remained open for five months (Crevasse at Lockport, 1854; All hopes of ... 1854). In 1874 fourteen plantations were flooded by a crevasse splay (Crevasse on Lafourche, 1874). Ironically, the year before a levee ordinance was enacted by the Lafourche Parish Police Jury that mandated levees were to be constructed according to a strict ratio of height to base (.3 m to 1.5 m; .3 m to 1.8 m; .3 m to 2.1 m) predicated by the bayou's flow regime (Levee ordinance, 1853).

These early embankments were narrow–scarcely wide enough for a foot or bridle path. When water came to within a few cm of the top, they caved in creating a crevasse that could lower the surface .6 m to .9 m (Humphreys and Abbot, 1861). These levee breaks were often less than 152 m wide, but scoured a channel 2.7 m to 3.0 m below the top of the levee.

South of the termination point of these levees, the bayou discharges freely into the surrounding swamps and marshes. This lateral discharge was estimated by Humphreys and Abbot (1861) to extend for 32 km to 48 km adding valuable sediments to the wetlands–contributing substantially to the accretion process.

GOVERNMENT INTERVENTION AND THE 1927 FLOOD

From 1840 to 1860 a series of harsh and injurious floods made it apparent the flooding problem was too large to be handled at the local level. It was a national issue. Much of the unprotected/unoccupied land was in the public domain. If reclaimed and protected against overflow, it would become an economic asset (Waddill, 1945). Two severe floods in 1849 and 1850 convinced the Federal government to provide financial assistance to construct a continuous levee system; one without gaps fronting unoccupied lowlands.

The period from 1812 to 1860 saw the country's land reclamation projects frequently flooded. In Louisiana there were 2253 km of privately built levees, providing flood protection for more than 1.2 million ha. To expand this network major financing was required. The Federal government recognized the problem and enacted the Swamp Land Act of 1849 (Tomlinson, 1926). It applied only to Louisiana, while the Swamp Land Act of 1850 extended to other states ownership of wetlands within their borders (Schneider, 1952).

Through these Acts Congress granted/gave states the swamp and overflowed lands within their boundaries. The understanding was this land was to be sold with the proceeds used for: 1) levee construction, and 2) reclamation projects required to make the land fit for cultivation and settlement.

In the early 1800s, it was believed by properly managing rainwater runoff, and high water "the whole of this country [south Louisiana] may be reclaimed and made in the highest degree productive" (Graham, 1929, p. 614).

Louisiana, Mississippi, Alabama, and Missouri organized offices to sell these newly acquired swamp lands. Lack of coordination and cooperation between states prevented construction of an effective levee system. The Swamp Land Act was intended to build a contiguous levee; it was a failure. In the strictest sense the Act was not a flood-control measure, but did mark the beginning of Federal participation in flood-related issues.

While the Federal government was deciding the merits of flood control, the states created levee districts and levee boards. These quasi-public corporations were empowered to construct the drains necessary to reclaim the swamps and overflowed lands. They were empowered to fight the battle against floods. With these boards and the Federal government working together there were by 1858 more than 3218 km of 2.4 m to 3.0 m high (with a base of 15.2 m to 21.3 m) levees outlining the Mississippi. By 1927 from Cape Girardeau to New Orleans there were 28 of these boards who were working on a two to one match. For every two dollars spent by the Federal government the local district would have to spend one dollar (Simpich, 1927).

Floods in 1862, 1865, 1867, 1874, 1882, 1883, and 1884 penetrated the levees, thus demonstrating the necessity for raising and strengthening their height and base. Flood water went through and over them without restraint. Both armies of the Civil War had done their jobs well; the levee system was destroyed, neglected or in disrepair (Waddill, 1945). Crevasse after crevasse further helped destroy the post-War levees. By 1878 "hundreds of miles [km] of the main line had disappeared or had been destroyed" (Frank 1930, p. 30). The problem was so severe, some seriously considered abandoning the levees and allowing the river to overflow its banks and flood the formerly protected fields. The people were losing to the river, but the Federal government was taking an interest. The detailed and scholarly Delta Survey conducted by Humphreys and Abbot was published in 1861. In 1865 the Secretary of War, Edwin M. Stanton, commissioned General A.A. Humphreys to investigate the status of the Mississippi River's levees. In 1866 Congress wanted to know what it would cost to repair the levees after Humphreys determined their status. President Johnson urged Congress to pass the necessary legislation to rebuild the levees of the Mississippi River.

Lack of enthusiasm during reconstruction killed the momentum. Reconstruction was a period of inactivity. Planters were financially unable to push into the backlands. Levees needed to be repaired, but funds were unavailable. For a time, the river regained control. Natural processes dominated. Suitable habitation and agricultural land was nothing more than the natural levee. Interest in reclamation and flood protection waned, but was not terminated.

Floods in 1868 and 1874 rekindled the issue. Congress began to move off center to support flood-control legislation, particularly after the 1874 flood when it was reported "gaps in the levees equaled from one-third to one-half of the entire length of the levees" (Frank, 1930, p. 39). After this flood a board of engineers was convened, called the "Levee Commission" (Waddill, 1945, p. 3). Five years later the Mississippi River Commission was created by an Act of Congress (approved June 28, 1879) and immediately put the United States into the flood-control business. In 1882 the Commission adopted a levee policy based on "the theory that confinement of flood water would periodically flush out the channel, thus removing obstructing bars and preventing the formation of new obstructions" (Waddill, 1945, p. 5).

Creation of the Commission marked the end the non-systematic approach to levee construction, based on the gradual extension of the system through the cooperative efforts of interested landowners. The levees were inadequate. They were built without effective supervision from a central authority. This era of uncontrolled, unstructured, and unsupervised construction was over. It was no longer acceptable to build levees around the premise that the whole is no stronger than its weakest link. Under this principle the levees were defective.

With establishment of the Mississippi River Commission levee construction was altered. Early levee specifications called for the right-of-way to be carefully cleared. A muck-ditch was used to close all root holes. These levees were constructed by excavating parallel drain ditches whose spoil was utilized to build the embankment. "Station men" using wheelbarrows contracted to work 30.4 m of levee (Fig. 1). As the levee increased in height and volume, mules and scrapers were added to the construction effort. With time, mules were replaced by machines that required coal, gasoline, diesel, fuel oil or electricity (Waddill, 1945). Once completed, these levees often were set back and raised in order to maximize high-water protection.

The 1927 flood

> At noon the streets . . . were dry and dusty. By 2 o'clock mules were drowning in the main streets . . . faster than they could be unhitched from wagons. Before dark the homes and stores stood six feet [1.8 m] deep in water. – F. Simpich, *The Great Mississippi Flood of 1927*, 1927, p. 256.

The flood of 1927 (Fig. 2) was considered the "greatest peacetime disaster in our history" (Simpich, 1927, p. 245). It was the product of abnormally high rainfall falling over the 31 states and two Canadian provinces that comprise the Mississippi's drainage basin. Deluge after deluge increased the Mississippi's discharge rates. Thirteen crevasses

Figure 1. Levees were constructed with mule teams and drags, a system that was discontinued, but used to construct this Jefferson Parish levee, *ca.* 1908 (photograph courtesy of the U.S. Army Corps of Engineers, New Orleans District).

Figure 2. The 1927 flood required a herculean effort to try to prevent any breaks in the levee (photograph courtesy of the U.S. Army Corps of Engineers, New Orleans District).

breached the levees of the Lower Mississippi, siphoning off enough flow to reduce the flood stage down reach. Nevertheless, parts of seven states were submerged. More than 8 km of levee was breached. The current was so strong small homes were often tied to trees with wire or ropes to hold them fast. Many floated off their foundations, often lodging kilometers away from their original sites. It was apparent the levees needed to be strengthened.

Figure 3. Throughout the Mississippi River's flood plain homes were destroyed by high water associated with the 1927 flood (photograph courtesy of the U.S. Army Corps of Engineers, New Orleans District).

Approximately 800,000 individuals were driven from their homes (Fig. 3) and housed in tents, warehouses, schools, churches, and other shelters–a number nearly equal to the 1927 population of Washington, D.C. (Simpich, 1927). Over 500,000 people were vaccinated for infectious diseases, since the flood was considered "the most extensive health hazard ever experienced in America" (Simpich, 1927, p. 265). About 59,570 km^2 were inundated.

To reduce the flood water's height, 1500 pounds of dynamite were used to blow up the levee at Caernarvon creating a 979.3 m wide artificial crevasse, removing 9204 cu m/sec from the main channel and thus relieve the pressure on the levee at New Orleans (Simpich, 1927). The 1882 and 1927 floods submerged 149,184 km^2–an area larger than Delaware, Connecticut, Hawaii, Massachusetts, Maryland, New Hampshire, New Jersey, Rhode Island, and Vermont combined (Fig. 4) (Elliott, 1932).

The severity of the 1927 flood resulted in passage of the 1928 Flood Control Act. This comprehensive legislation began the process of locking the Mississippi into a conduit with spillways constructed along its course to protect against severe flooding. These spillways proved their worth during the 1937 flood.

SUMMARY AND CONCLUSIONS

After the devastating 1927 flood, the U.S. Army Corps of Engineers began to construct the Mississippi's "guide levees." Today this levee network protects cities, towns, villages, farmland, and industrial complexes. In retrospect, they had a dramatic impact on the general ecology of the wetlands, and modified the orderly distribution of fresh water out of the river into the marsh-estuary complexes. Natural wetlands processes, interlevee-basin drainage regimes, and vegetation patterns were permanently altered. Engineers brought about these changes through their use of levees, internal drains, and pumps. Through time, the Mississippi's levees were strengthened, eliminating overbank flooding and the systematic sediment recharge to Louisiana's subsiding coastal lowlands. Sediment flow was effectively shut off. Natural accretion, derived from overbank flooding, was terminated. An artificial levee system is responsible. Engineered to protect the population living within the river's alluvial valley, this levee also altered directly and indirectly the region's natural topography.

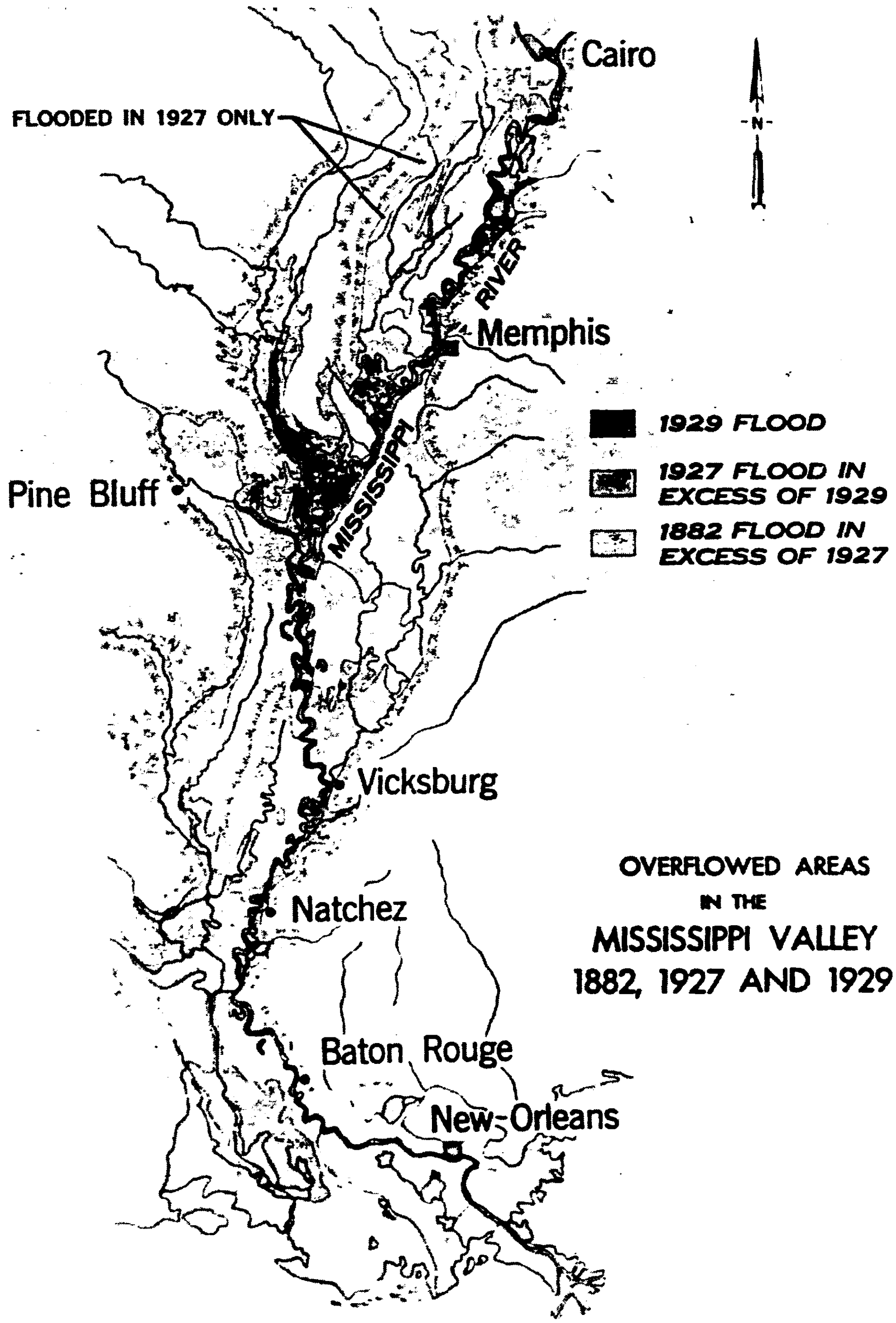

Figure 4. Areas overflowed by the Mississippi (map courtesy of the U.S. Army Corps of Engineers, New Orleans District).

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MORPHODYNAMICS OF THE ISLES DERNIERES BARRIER SHORELINE, LOUISIANA: 1984-1989

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ABSTRACT: An aerial videotape mapping system was used to monitor spatial and temporal variability of the coastal morphology along the Isles Dernieres barrier shoreline. Between 1984 and 1989, nine sequential annual and post-hurricane aerial videotape surveys were flown covering periods of prolonged fair weather, hurricane impacts, and subsequent post-storm recovery. Morphologic time series were developed to depict spatial and temporal geomorphic changes along the Isles Dernieres low-profile transgressive barrier island system. The net effect of Hurricanes Danny and Juan, in 1985, was the transformation of a high relief landscape dominated by well-vegetated dunes, dune terraces, and washover terraces to one dominated by partially-vegetated washover terraces and unvegetated washover flats. In 1988, Hurricane Gilbert caused extensive geomorphic changes in the central Isles Dernieres where the low-relief, less-vegetated islands were more susceptible to storm-surge processes. Post-storm island morphodynamics were characterized by a gradual build up of the low-relief landforms to high-profile features. The greatest post-storm recovery consistently occurred in areas of greater island width and relief. In addition, the rate of post-storm recovery was controlled by the regional setting of individual islands relative to sand supply. The degree of post-storm recovery was consistently greater in areas where hurricane impact had caused greatest geomorphic change.

INTRODUCTION

Louisiana is faced with the highest rates of coastal erosion and wetland loss in the United States. The barrier islands, which protect the Louisiana wetlands and bays, are migrating landward, eroding rapidly, and decreasing in area (Penland et al, 1990). A better understanding of the processes that contribute to barrier island erosion is needed for successful management of our coastal resources. Hurricanes, tropical storms, and cold fronts all contribute to the erosion of Louisiana's barrier islands (Dingler and Reiss, 1990; Ritchie and Penland, 1988). One of the goals of the five-year U.S. Geological Survey/Louisiana Geological Survey (LGS) barrier island erosion and land loss study was to analyze the effects of these storms through a qualitative and quantitative investigation of their impact on the geomorphology along Louisiana's outer coast (Sallenger and Williams, 1991).

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Between 1984 and 1989 three hurricanes, ranging in strength from 1 to 5 on the Saffir-Simpson scale (Saffir, 1977), severely eroded Louisiana's shoreline surrounding the Mississippi River delta plain (figure 1). Hurricanes Danny and Juan made landfall in Louisiana in 1985 and produced significant geomorphic changes on the Isles Dernieres barrier islands. Although Hurricane Gilbert (1988) made landfall at the Texas/Mexico border, the severity of this storm resulted in beach erosion and storm surge flooding in Louisiana. Data from aerial videotape surveys were used to examine the geomorphic response of the Isles Dernieres barrier island arc to multiple hurricane impacts and to assess post-storm response characteristics. The results of this study contribute to a better understanding of landform dynamics for coastal scientists and managers (Sallenger et al, 1987).

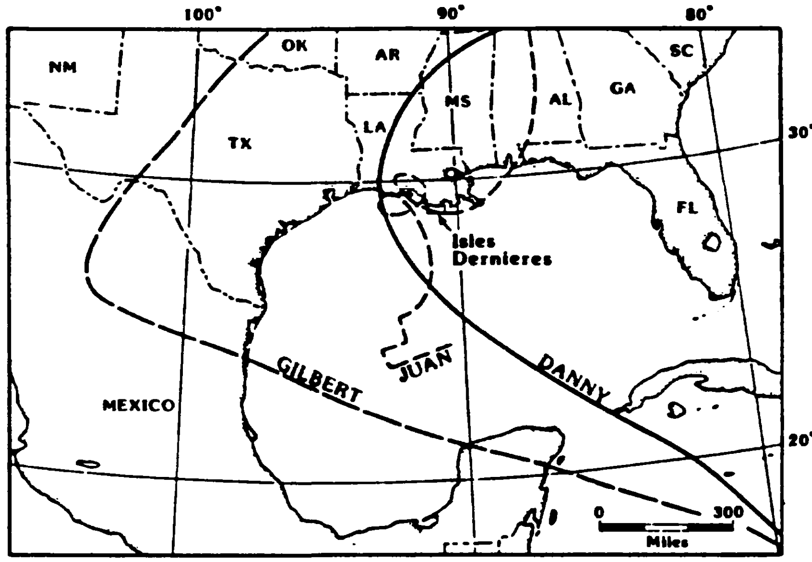

Figure 1. Storm tracks of the 1985 and 1988 Gulf of Mexico hurricanes (data from the National Hurricane Center).

DATA BASE AND METHODOLOGY

Wind, wave, and tidal process data and aerial videotape imagery were used to interpret the spatial and temporal morphologic variability of the Isles Dernieres and the morphodynamic signature of the 1985 and 1988 hurricanes. Information on wind, rain, and atmospheric pressure was supplied by the National Hurricane Center, National Climatic Data Center, National Weather Service, and the Office of the State Climatologist at Louisiana State University. Information on water levels was acquired from the National Ocean Survey, the U.S. Army Corp of Engineers District, New Orleans, and the Coastal Engineering Research Center. For each hurricane, we used these data sets to produce (1) a storm trackline map, (2) a storm history statistics table, (3) a wind-pressure history, (4) representative surface weather maps, (5) rainfall distribution patterns, and (6) regional storm-surge maps and hydrograph time series for specific stations (Penland et al, 1989c). Between 1984 and 1989, the LGS flew nine videotape surveys from a helicopter at an altitude of 100 meters (m) and a speed of 40-50 knots. Geomorphic data were obtained from this color oblique imagery which covered periods of prolonged fair weather, hurricane impacts, and post-storm recovery (Debusschere et al, in press).

The LGS developed a coastal geomorphologic classification system for shorelines surrounding the Mississippi River Delta and Chenier Plains based on 10 years of shoreline monitoring, analysis of aerial photography for the period between 1940 and 1989, and numerous field surveys (Debusschere et al, in press). The coastal morphology is classified to quantify the longshore and cross-shore geomorphic, sedimentologic, and vegetative character of Louisiana's shoreline systems. The classification system divides shorelines into two broad classes: natural and altered. Each class consists of several genetically linked categories of shorelines. Each category is further subdivided into morphologic types on the basis of landform relief, elevation, habitat type, vegetation density and type, and sediment characteristics. Sixteen coastal morphologic types can be identified in the Isles Dernieres (table 1).

Table 1. Morphologic types present on the Isles Dernieres barrier islands

1. Intertidal Flat	9. Marsh Platform
2. Washover Flat	10. Scarp
3. Washover Terrace	11. Barrier Restoration
4. Dune Terrace	12. Spoil Bank
5. Continuous Dune	13. Dredge Spoil
6. Tidal Inlet	14. Dune Fencing
7. Major Washover Channel	15. Flood Tidal-Delta
8. Minor Washover Channel	16. Pipeline Landfall

All morphologic types identified in the system can be used at any of three descriptor levels; this gives the classification scheme greater flexibility. The three levels are (1) primary morphology, (2) modifier, and (3) variant. The primary morphology descriptor defines the dominant longshore morphologic type per unit length of shoreline and is mapped on a 1:24,000 base map, with a unit length no smaller than 10 m. The modifier describes secondary longshore features on the foreshore and backshore, whereas variants are important features that can be located and counted but are less than 10 m long (figure 2). The arrow and triangle in figure 2 are examples of variant features and their position in relation to the subaerial beach. A maximum of three modifiers and two variants, in addition to the primary morphology, can be allocated to each unit.

Comparative analyses of individual surveys were performed to identify temporal and spatial coastal changes in geomorphology for the Isles Dernieres barrier system. For each aerial video survey, the geomorphology is described by total unit length of shoreline. Next, this barrier island arc is subdivided into its four individual elements, Raccoon Island, Whiskey Island, Trinity Island, and East Island. Morphologic time series were developed for each island and for the total shoreline length to depict spatial and temporal geomorphic changes.

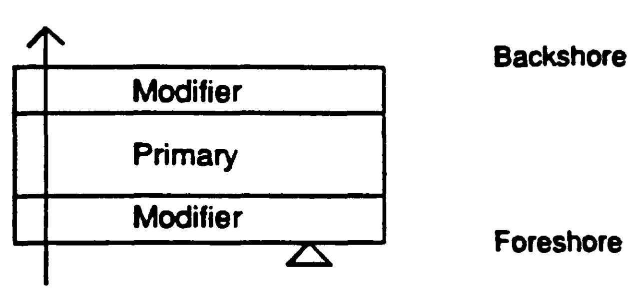

Figure 2. Framework for coastal geomorphic mapping technique.

HURRICANE IMPACT PROCESSES

Hurricane Danny

In 1985, Hurricane Danny was the first hurricane to directly impact the Louisiana barrier islands since Hurricanes Bob and Frederic made landfall in the northern Gulf of Mexico in 1979 (Ritchie and Penland, 1985). The center of Hurricane Danny made landfall southeast of Lake Charles, Louisiana, around noon on August 15, and then quickly weakened to tropical storm strength as it moved inland (figure 1) (National Hurricane Center, 1985a). Hurricane Danny was a hurricane for only 24 hours. Maximum sustained wind at time of landfall was reported at 80 knots. The highest tides occurred 50 km east of the eye of hurricane Danny at Intracoastal City, where the storm surge was recorded at 2.4 m (Penland et al, 1989b). The storm surge was greater than a meter above the National Geodetic Vertical Datum (NGVD) 300 km east of the storm center and 100 km to the west. In the vicinity of the Isles Dernieres, the storm surge was about 1.25 to 1.75 m. The tide gage at Eugene Island was on the east side of the storm and recorded a maximum surge of 1.88 m NGVD. To the west of the storm track at Cameron, the winds were predominantly offshore, helping to dampen the storm surge, which reached a maximum of only 0.88 m NGVD. At landfall, the water levels at Cameron were depressed 0.25 m below NGVD by strong offshore winds.

Hurricane Juan

Two months following Hurricane Danny, Hurricane Juan made two cyclonic loops over the south-central Louisiana coast, making its initial landfall on October 29 near Morgan City, Louisiana (National Hurricane Center, 1985b). Juan made a second landfall on October 31 just west of Pensacola, Florida (figure 1). Hurricane Juan maintained hurricane status for 42 hours. Maximum sustained wind reported by reconnaissance aircraft was 75 knots on the morning of October 28, 1985. Storm surge associated with Hurricane Juan was unusually long, lasting three days as the storm looped twice across coastal Louisiana. Maximum water level was associated with the initial landfall at Chenier Au Tigre, Louisiana (Penland et al, 1989b). The storm surge peaked at an elevation of 2.19 m 30 km west of the storm track and more than a meter as far east as Pensacola, Florida. West of the storm track, surge levels measuring more than a meter reached as far as Galveston, Texas .

Hurricane Gilbert

Hurricane Gilbert was the first category 5 hurricane on the Saffir-Simpson scale to make landfall in the western hemisphere since Hurricane Camille in 1969 (National Climatic Data Center, 1988). Hurricane Gilbert made its first landfall at Jamaica on September 12 as a category 3 hurricane and made a second landfall on the northeast Yucatan Peninsula as a category 4 hurricane on September 14 (Lawrence, 1989; National Hurricane Center, 1988). Gilbert made its final landfall as a category 3 hurricane on September 16 in northeast Mexico and then quickly weakened as it moved inland over Texas and into Oklahoma (figure 1). Gilbert was a hurricane for 150 hours. The strongest sustained wind at flight level was recorded at 160 knots (category 5) by a NOAA aircraft. Maximum sustained surface winds were estimated at 147 knots over the Yucatan Peninsula and recorded as 101 knots at Kingston, Jamaica. The highest reported surge levels are associated with Gilbert's second landfall; surge levels were reported to be at least 5.9 m NGVD. Storm surge was 3.0 m NGVD near Kingston, Jamaica, 1.6 m NGVD at Grand Cayman Island, and 2.0 m NGVD at South Padre Island, Texas. Storm surge levels of 1.3 m NGVD were reported at Port Arthur, Texas, 325 km to the west of the Isles Dernieres.

DISCUSSION AND SUMMARY

Regional Morphology

During non-hurricane years, vegetative cover and eolian deposition increases allowing development of greater island relief and elevation as well as greater habitat diversity (Ritchie and Penland, 1988). The Isles Dernieres had not been impacted by hurricanes since 1979, and by 1984-85, the islands were characterized by high-relief morphologies, including continuous dunes, dune terraces, and washover terraces (figures 3, 4, 5, 6, and 7; table 2). The data show a slight decrease in percentage of high-relief forms between these two years as a result of minor winter storms in 1984 (Ritchie and Penland, 1988). Overall elevation of island morphologies rarely approach 3 m above mean sea level. The central Isles Dernieres (Whiskey Island and Trinity Island) exhibit the lowest relief and are dominated by washover flats and washover terraces. The ends of the Isles Dernieres (Raccoon Island and East Island) are higher in relief, diversity, and elevation; the morphologies of these islands are dominated by washover terraces, dune terraces, and continuous dunes. The higher and more diverse morphologies of the Isles Dernieres are characterized by well established vegetative cover, slower shoreline retreat rates, and an updrift supply of sediment. Lower morphologies are associated with rapidly eroding, poorly vegetated shorelines (Ritchie et al, 1989).

Hurricane Danny Impact

Hurricane Danny resulted in a typical force-1 shore-normal hurricane impact. The greatest changes in primary morphology occurred at Raccoon Island and Trinity Island (figures 4, 5, 6, and 7; table 2). Storm-surge overwash reduced the morphology of Trinity Island to predominately washover flats and terraces and resulted in a major increase in exposed marsh platform. At Raccoon Island, dune terraces were converted to washover terraces, and the exposure of marsh platform on the beach face increased dramatically; however, the overall relief of the island remained relatively high. Whiskey Island and East Island had the fewest changes in primary morphology. Whiskey Island is characterized by low-relief morphologies, such as washover flats, intertidal flats, and marsh platforms, with washover flats remaining the dominant morphology. Like Raccoon Island, East Island underwent a general reduction in relief, but the overall relief remained high relative to the other islands. The major impact of Hurricane Danny was a general flattening of the island profile and scarping of the high-relief landforms.

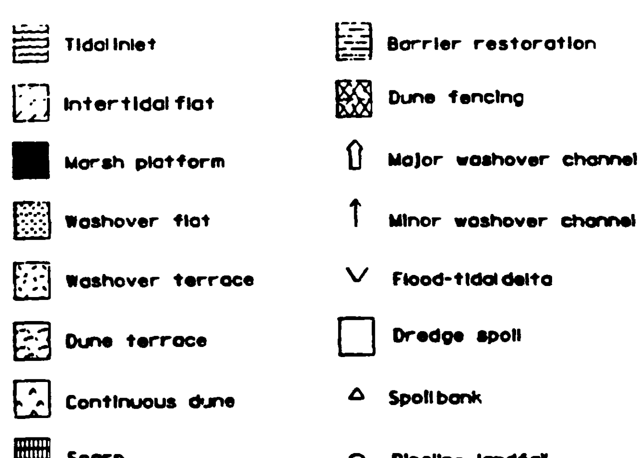

Figure 3. Classification patterns for morphologic types present on the Isles Dernieres. This figure functions as a legend for figures 4, 5, 6, and 7.

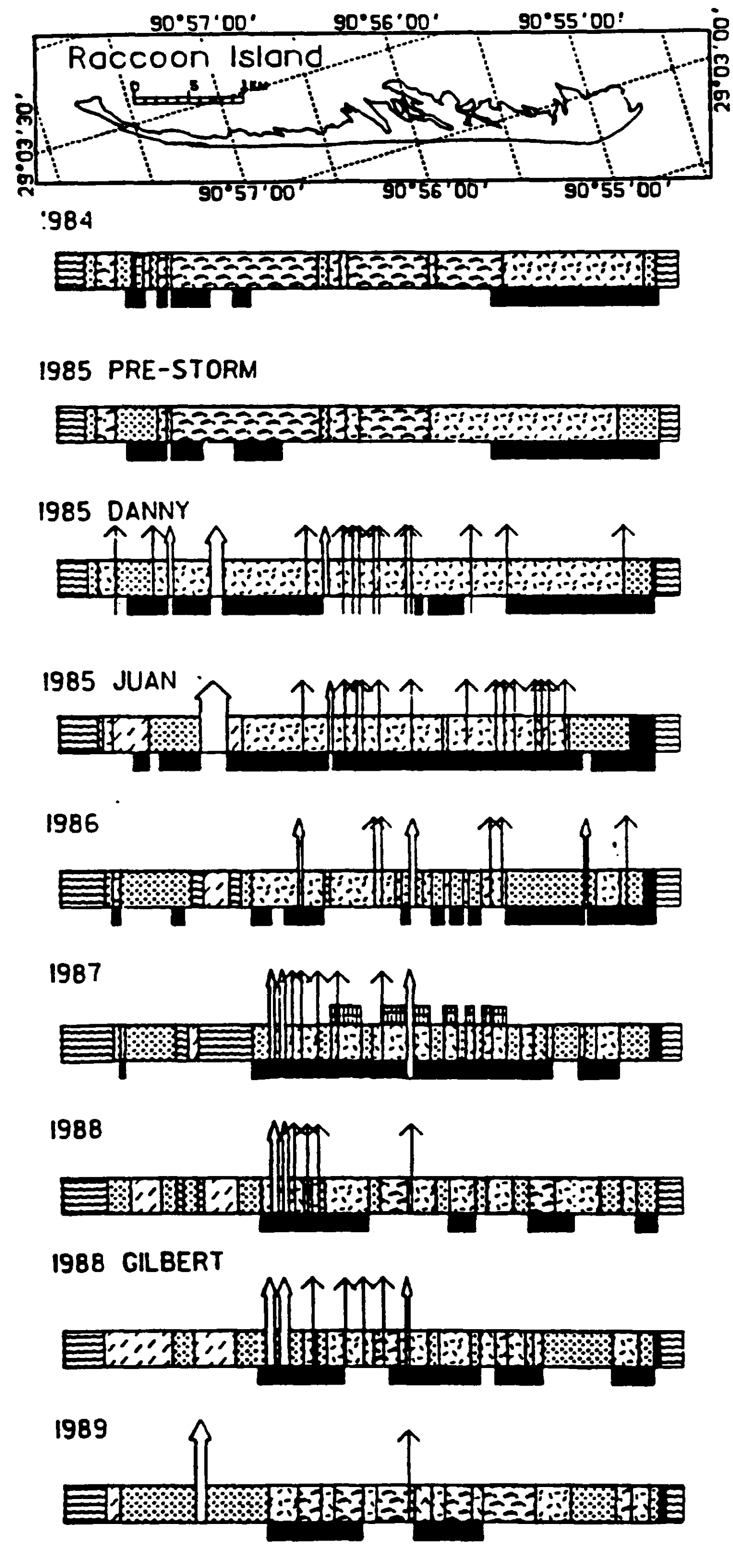

Figure 4. Racooon Island geomorphic changes, 1984-1989

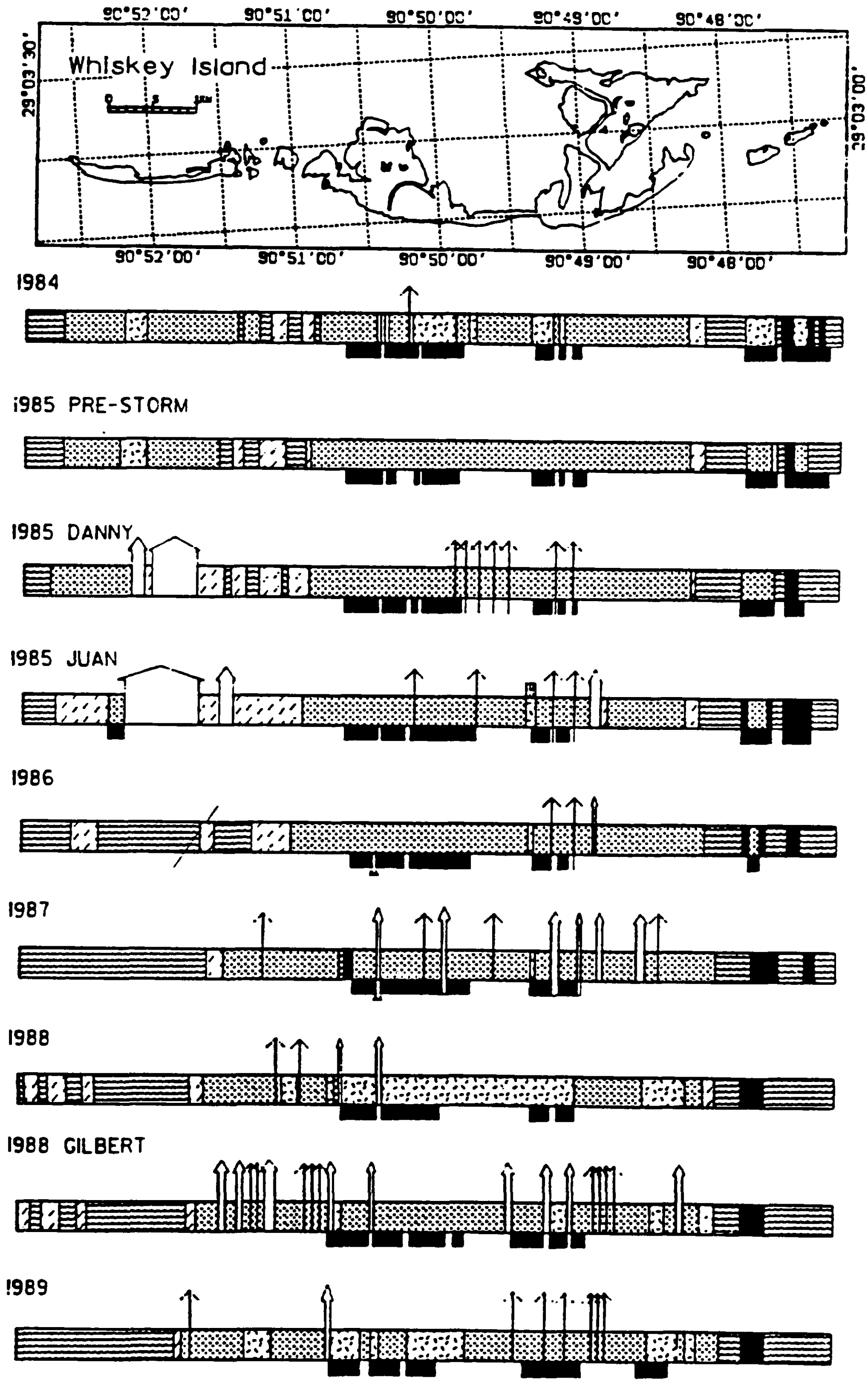

Figure 5. Whiskey Island geomorphic changes, 1984-1989.

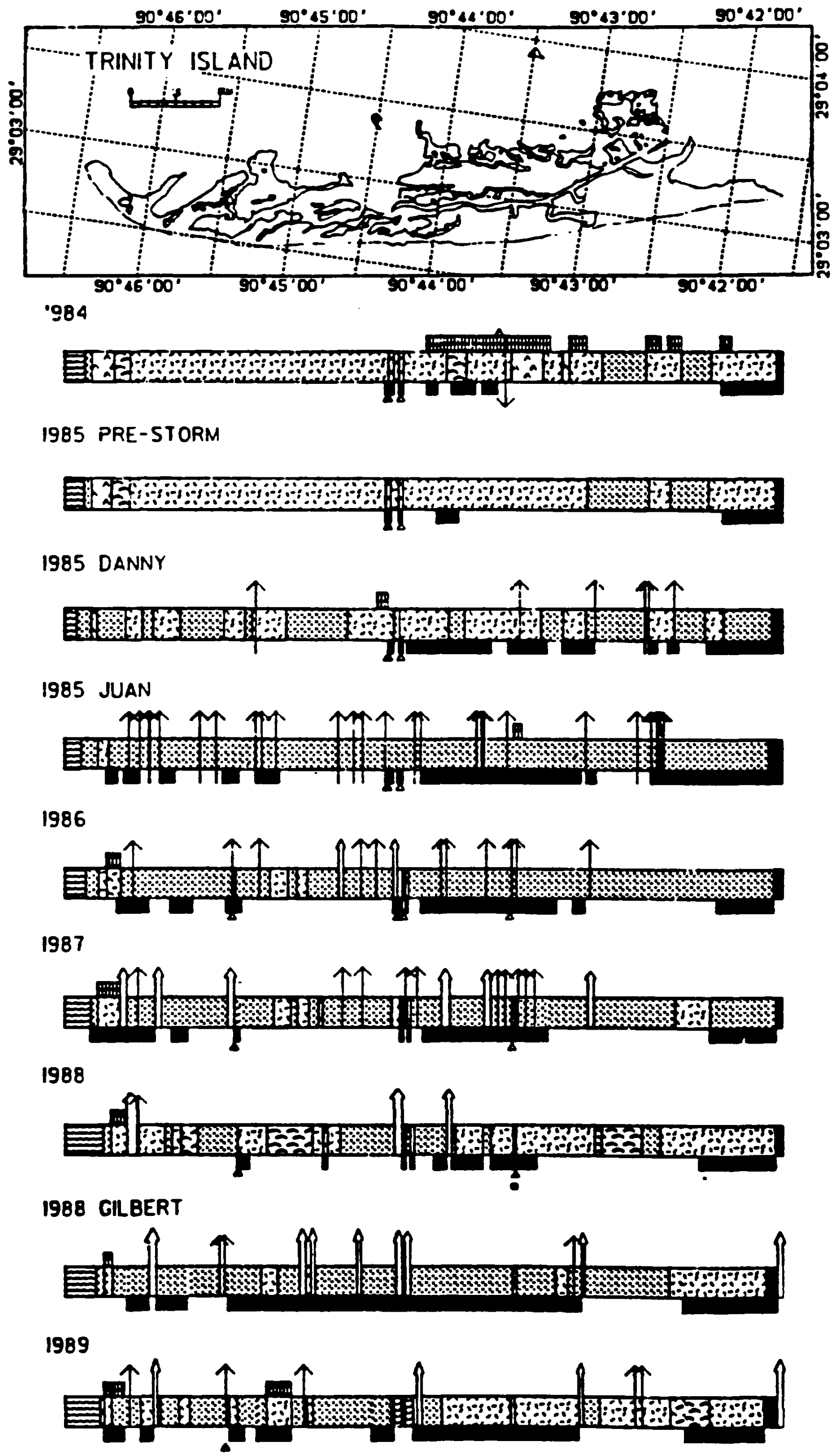

Figure 6. Trinity Island geomorphic changes, 1984-1989.

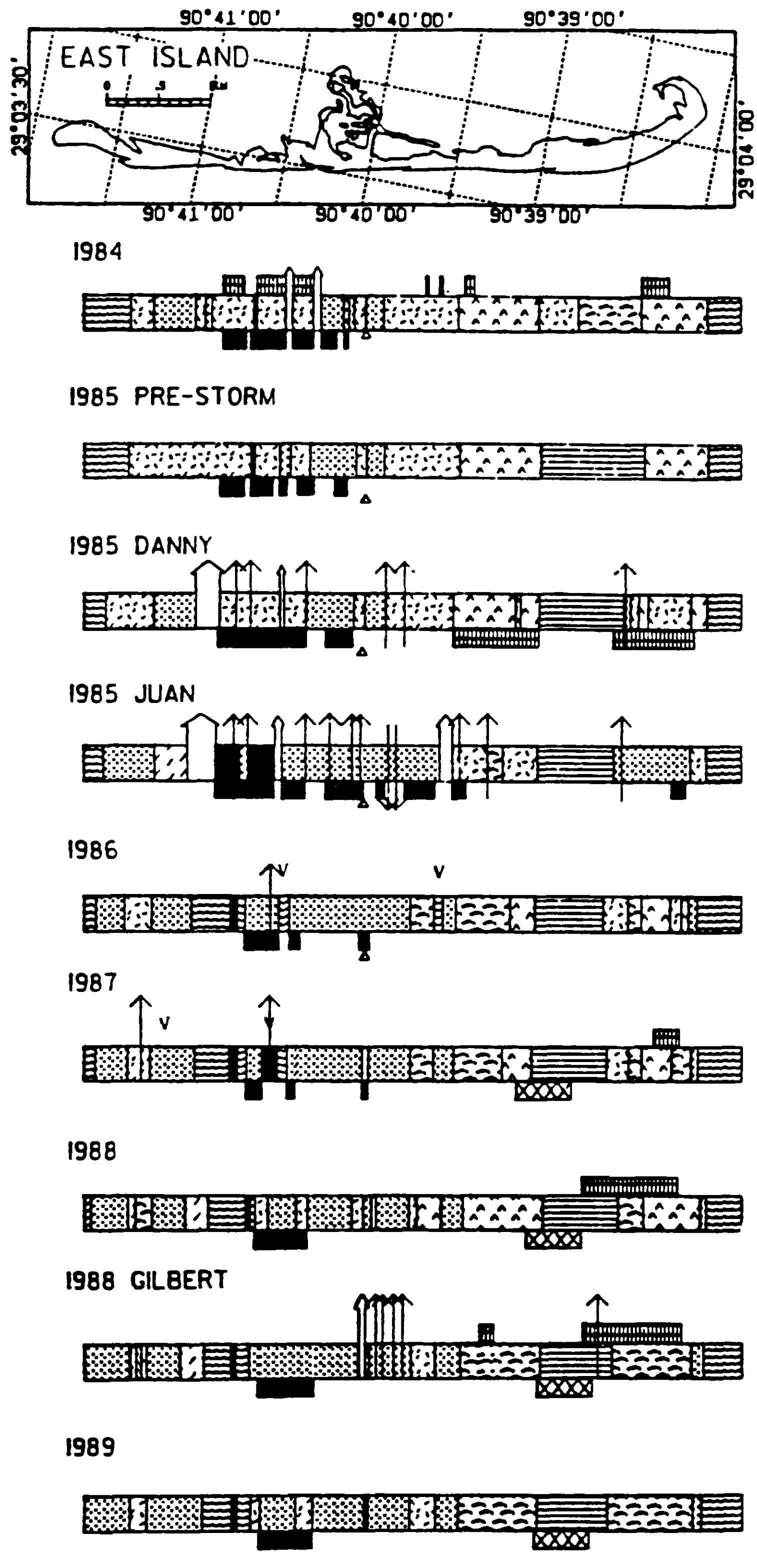

Figure 7. East Island geomorphic changes, 1984-1989.

Table 2. Morphologic units in the Isles Dernieres, as percentages of total shoreline length.

All Islands	TI*(%)	MWC*(%)	IF*(%)	MP*(%)	WF*(%)	WT*(%)	DT*(%)	CD*(%)	BR*(%)	DS*(%)
1984 July	21.7	0.3	1.6	0.9	22.6	33.8	12.9	6.2	0.0	0.0
1985 July	22.5	0.0	2.2	0.5	27.3	31.8	8.0	4.8	3.0	0.0
1985 Danny	21.7	3.4	3.3	0.8	33.7	31.6	0.0	2.9	2.5	0.0
1985 Juan	20.6	5.6	7.8	3.7	47.9	11.7	0.5	0.0	2.2	0.0
1986 July	28.5	0.8	3.6	1.6	48.6	8.9	3.9	1.6	2.0	0.4
1987 July	28.9	2.9	1.1	2.7	46.4	10.2	3.3	1.7	2.2	0.6
1988 July	25.9	1.3	4.8	1.1	24.3	29.0	6.2	4.8	2.2	0.4
1988 Gilbert	24.0	4.2	5.9	1.4	43.7	12.5	5.9	0.0	2.1	0.3
1989 July	25.8	1.0	0.8	1.7	34.1	22.5	11.3	0.4	2.1	0.3
Raccoon Island										
1984 July	0.0	0.0	0.0	0.0	11.4	26.9	61.7	0.0	0.0	0.0
1985 July	0.0	0.0	0.0	0.0	19.4	34.9	45.7	0.0	0.0	0.0
1985 Danny	0.0	4.1	0.0	0.6	13.7	81.6	0.0	0.0	0.0	0.0
1985 Juan	0.0	6.0	9.7	4.3	21.9	58.1	0.0	0.0	0.0	0.0
1986 July	5.4	2.7	4.8	2.3	44.8	37.3	2.7	0.0	0.0	0.0
1987 July	12.2	3.1	1.7	1.9	41.3	38.4	1.5	0.0	0.0	0.0
1988 July	2.5	2.1	11.5	0.0	34.4	40.2	9.4	0.0	0.0	0.0
1988 Gilbert	0.0	4.0	19.2	1.0	33.5	34.1	8.1	0.0	0.0	0.0
1989 July	0.0	1.8	2.7	1.2	33.9	23.9	33.7	2.9	0.0	0.0
Whiskey Island										
1984 July	12.0	0.0	6.0	2.8	58.8	20.3	0.0	0.0	0.0	0.0
1985 July	15.1	0.0	8.3	1.1	71.3	4.3	0.0	0.0	0.0	0.0
1985 Danny	12.0	8.2	12.9	1.4	65.5	0.0	0.0	0.0	0.0	0.0
1985 Juan	7.9	13.3	21.0	4.7	52.1	1.1	0.0	0.0	0.0	0.0
1986 July	27.6	0.5	11.7	3.3	56.2	0.8	0.0	0.0	0.0	0.0
1987 July	11.2	5.6	2.7	7.1	72.6	0.8	0.0	0.0	0.0	0.0
1988 July	20.0	1.1	9.7	3.0	27.0	39.2	0.0	0.0	0.0	0.0
1988 Gilbert	20.6	7.6	8.7	3.2	54.6	5.4	0.0	0.0	0.0	0.0
1989 July	3.7	0.8	1.2	3.9	62.7	27.6	0.0	0.0	0.0	0.0
Trinity Island										
1984 July	0.0	0.0	0.0	0.8	11.6	72.5	6.6	8.5	0.0	0.0
1985 July	0.0	0.0	0.0	1.0	15.3	76.8	4.3	2.6	0.0	0.0
1985 Danny	0.0	0.0	0.0	1.3	49.3	49.3	0.0	0.0	0.0	0.0
1985 Juan	0.0	0.0	0.0	1.6	97.2	1.2	0.0	0.0	0.0	0.0
1986 July	1.4	1.2	0.0	1.2	85.8	7.4	1.6	0.0	0.0	1.4
1987 July	1.4	4.8	1.0	1.2	76.5	13.7	0.0	0.0	0.0	1.4
1988 July	0.7	2.8	2.7	0.9	31.2	45.2	15.3	0.0	0.0	1.2
1988 Gilbert	0.0	5.4	2.6	1.4	70.9	18.9	0.0	0.0	0.0	0.8
1989 July	2.1	2.2	0.5	2.1	43.2	43.9	5.1	0.0	0.0	0.9
East Island										
1984 July	0.0	2.1	0.0	0.0	16.9	44.6	10.9	25.7	0.0	0.0
1985 July	0.0	0.0	0.0	0.0	13.4	43.5	0.0	25.2	17.9	0.0
1985 Danny	0.0	4.2	0.0	0.0	18.8	45.3	0.0	17.1	14.6	0.0
1985 Juan	0.0	7.7	5.4	8.8	48.5	14.2	2.7	0.0	12.6	0.0
1986 July	6.0	0.0	0.0	1.3	36.5	7.8	22.3	11.4	14.7	0.0
1987 July	4.0	0.0	0.0	4.7	34.7	4.7	22.0	12.5	16.0	1.3
1988 July	0.9	0.0	0.0	0.7	31.0	9.6	5.7	35.1	16.4	0.7
1988 Gilbert	3.1	1.3	0.0	0.7	40.2	5.1	33.3	0.0	15.3	0.9
1989 July	2.9	0.0	0.0	1.1	34.5	11.1	34.5	0.0	15.1	0.7

*TI = Tidal Inlet
MWC = Major Washover Channel
IF = Intertidal Flat
MP = Marsh Platform
WF = Washover Flat
WT = Washover Terrace
DT = Dune Terrace
CD = Continuous Dune
BR = Barrier Restoration
DS = Dredge Spoil

Seven major washover channels were cut through the Isles Dernieres. All of these major channels breached locations where the islands were very narrow, low in profile, and not backed by backbarrier marsh. Hurricane Danny cut 32 minor washover channels through the Isles Dernieres, and, as with the major washover channels, there was no preferred regional zone of development. Development of minor washover channels was confined to the low-relief morphologies--washover flats and terraces. Erosional scarps were associated with washover terraces, continuous dunes, and the barrier island restoration project on East Island. Overall, Hurricane Danny was sufficient to alter the high-relief landforms of the Isles Dernieres; dune terraces on Raccoon Island were reduced to washover terraces, and extensive scarping of high-relief landforms occurred on East Island. However, the overall relief of these islands remained relatively high. Process-response characteristics of the Isles Dernieres to Hurricane Danny illustrate the effects of a minor hurricane making a rapid shore-normal landfall.

Hurricane Juan Impact

Like Hurricane Danny, Hurricane Juan was a minor storm in terms of wind speed and pressure; however, in terms of storm-surge duration and storm track, this storm was different. The storm surge lasted three days, instead of several hours, as Hurricane Juan wandered across coastal Louisiana. As a consequence, the landscape of the entire Isles Dernieres was extensively changed. The low-profile and less-vegetated central Isles Dernieres responded dramatically to Hurricane Juan. At Whiskey Island, washover flat morphology persisted, and many areas were further reduced in profile to intertidal flats (figures 4, 5, 6, and 7; table 2). Washover channel development continued with the formation of new minor channels and the consolidation of major channels. The primary morphology of Trinity Island was reduced from scattered washover terraces and flats to a continuous washover flat. Many new minor washover channels were cut in areas where high-relief washover terraces were reworked into washover flats.

On the high-relief areas of the Isles Dernieres, continuous dunes were extensively eroded. The East Island dunes were converted to dune and washover terraces, washover flats, and marsh platform. Dunes flanking the barrier island restoration project were converted to dune and washover terraces, but the project itself had only minor overwash and localized scarping of the artificial dune front. New major and minor washover channels breached East Island. To the west, Raccoon Island underwent the fewest primary morphological changes of the Isles Dernieres. The washover terrace morphology of Raccoon Island remained almost unchanged after Hurricane Juan; major storm effects were development of more major and minor washover channels and exposure of more marsh platform along the shoreline.

Hurricane Juan further lowered the already-weakened profile of the Isles Dernieres, enlarged major washover channels, and increased the number of minor washover channels. After Hurricane Juan, the entire island chain was breached by 57 minor and 8 major washover channels. Geomorphic changes associated with Hurricane Juan likely reflect the impact of duration of the storm surge rather than its magnitude.

Post-storm Recovery: November 1985 - July 1988

The 1985 hurricane season was followed by three consecutive non-hurricane years during which the Isles Dernieres were characterized by a restoration of island relief and elevation as well as development of greater habitat diversity. The cumulative impact of Hurricanes Danny and Juan, within two months of each other, had produced extensive landscape changes on the Isles Dernieres between July 1984 and November 1985 (Penland et al, 1989a). The net effect of the storms had been a transformation of a relatively high-relief landscape dominated by well-vegetated dunes, dune terraces and washover terraces to one dominated by partially vegetated washover terraces and unvegetated washover flats. Between November 1985 and July 1988, the island morphology was characterized by a gradual build up of low-relief landforms to high-profile features (figures 4, 5, 6, and 7; table 2).

Each island of the Isles Dernieres chain had a distinctive geomorphic response to the 1985 hurricane impacts and a distinctive subsequent recovery. The 1985 hurricanes had completely destroyed the extensive dune terrace system on Raccoon Island and had converted it to predominately washover terraces, washover flats, intertidal flats, and major washover channels. Post-storm recovery was very slow on this island. Initially a further overall lowering of the island profile occurred. By July 1986, the continuous washover terrace was reduced to scattered washover flats and terraces. In subsequent non-hurricane years, the morphology of Raccoon Island was characterized by an increase in high-relief landforms. Post-storm recovery was initially concentrated on the central and east side of the island where washover terraces and dune terraces developed concurrent with a decrease in exposed marsh platform on the beach face. On the west side of the island, the impacts of Hurricanes Danny and Juan had resulted in island breaching and development of a tidal inlet. Post-storm recovery occurred at a slower rate in this low-relief area than on the eastern high-relief portion of the island. By July 1988, the primary morphology in this area consisted of predominantly intertidal and washover flats, leaving only two small tidal inlets.

Post-storm recovery was relatively analogous in the central Isles Dernieres. At Whiskey Island, between July 1984 and November 1985, the pattern of landscape change had been a conversion of washover terraces into marsh platform, intertidal flats, major washover channels, and washover flats. The 1985 hurricanes also had been responsible for converting washover flats into other low-relief morphologies. Washover flats persisted throughout most of the non-hurricane period. Between July 1987 and July 1988, significant geomorphic changes occurred; the majority of washover flats evolved into washover terraces. By July 1988, Whiskey Island attained an island relief and elevation that exceeded pre-storm morphology. An anomaly in the trend of increased high-profile landforms is the presence of a high percentage of the tidal inlets in all three non-hurricane years at Whiskey Island. The impacts of both Hurricanes Danny and Juan had resulted in major washover channel formation on the west side of Whiskey Island. These washover channels consolidated and remained open throughout the following years, thus becoming a tidal inlet. Post-storm recovery, characteristic for the majority of the island, and as observed at the tidal inlet on Raccoon Island, did not occur on the west side of the island.

As was the case for Whiskey Island, the geomorphology of Trinity Island was dominated by extensive washover flats subsequent to the 1985 hurricane impacts. The following three non-hurricane years were characterized by a gradual increase in island relief. By July 1988, only a third of the near continuous washover flats, which marked the post-Juan morphology in this area, remained, and 60% of the longshore morphology consisted of high-relief washover terraces and dune terraces. However, overall relief of the island remained drastically lower relative to the pre-storm conditions.

At East Island, the cumulative impact of Hurricanes Danny and Juan had resulted in a conversion of extensive dune and washover terrace morphologies to washover flats, marsh platforms, intertidal flats, and major washover channels. Dunes flanking the barrier island restoration project on the east end of the island had been converted to dune and washover terraces, but the project area had only minor overwash and localized scarping of the artificial dune front. Unlike the other islands, post-storm recovery occurred relatively fast at East Island. Between November 1985 and July 1986, a complex of continuous dunes and dune terraces flanked the barrier island restoration project, and by July 1988 this dune complex was converted into, predominately, continuous dunes. On the west side of the island, increase in island relief was associated with natural closing of the tidal inlets. The two tidal inlets closest to the restoration project were completely closed by July 1988. The third breach persisted throughout this period but decreased in size.

Although the result of this non-hurricane period was a general restoration of morphology along the Isles Dernieres, overall island relief did not recover to its pre-storm status by July 1988.

Post-storm recovery was consistently more extensive in areas of greater island width and relief. In addition, the rate of post-storm recovery was controlled by the regional setting of the individual islands. Post-storm recovery occurred at a more rapid rate on East Island. The eastern Isles Dernieres are subject to a relatively high sediment supply resulting from sediment bypassing at Cat Island Pass (Jaffe et al, 1989; Suter and Penland, 1987). This sediment supply reduces shoreface erosion, nourishes the eastern Isles Dernieres, and potentially aids post-storm recovery.

Hurricane Gilbert Impact

Hurricane Gilbert was a severe storm (category 5) in terms of wind speed, pressure, and surge characteristics. Even though Gilbert made landfall considerably south of the Isles Dernieres, the severity of the storm caused storm surge flooding and beach erosion along the Isles Dernieres. The low-profile and less-vegetated central Isles Dernieres responded dramatically to Hurricane Gilbert (figures 4, 5, 6, and 7; table 2). At Whiskey Island, storm-surge overwash converted washover terraces to washover flats, and seven new major washover channels were formed. At Trinity Island, dune and washover terraces were reduced to an almost continuous washover flat, breached by five new major washover channels. As was the case with the 1985 hurricanes, hurricane impact in 1988 was associated with an increase in exposed marsh platform on the beach face. On high-relief, vegetated areas of the Isles Dernieres, continuous dunes were eroded. The dune complexes on East Island were converted to dune terraces and storm-surge overwash reduced the washover terraces to washover flats. Washover channels breached the lower western portion of the island and one minor washover channel was cut through the barrier island restoration project. Raccoon Island experienced very little change; major storm effects were a slight reduction in overall island relief, breaching of minor washover channels, and a slight increase in exposed marsh platform.

After Hurricane Gilbert, a total of 21 major and 21 minor washover channels remained. As was the case in 1985, all major washover channels breached locations where the islands were narrow, low in profile, and not backed by backbarrier marsh. However, a preferred regional zone of development existed; the majority of major washover channels were cut through the low-relief, central Isles Dernieres. Development of minor washover channels was again confined to low-relief morphologies--washover flats and terraces. The impact of Hurricane Gilbert resulted in a general lowering of the Isles Dernieres morphology. The low-relief and less-vegetated central Isles Dernieres were more susceptible to storm-surge processes associated with the hurricane. Although extensive erosion of continuous dunes occurred on East Island, the overall relief of the island remained relatively high. The geomorphology on Raccoon Island showed the least amount of change due to hurricane impact.

Post-storm Recovery: October 1988 - July 1989

In contrast to the post-storm recovery period prior to the 1988 hurricane season, the Isles Dernieres recovered at a rapid rate following Gilbert's impact. In less than one year after hurricane impact, considerable geomorphological reconstruction occurred on the islands (figures 4, 5, 6, and 7; table 2). Between October 1988 and July 1989, low-relief morphologies decreased while continuous dunes, dune terraces, and washover terraces increased substantially. Each island of the Isles Dernieres had a distinctive response to this non-hurricane period. The degree of post-storm recovery was consistently greater in areas where hurricane impact had caused greatest geomorphic change. The greatest post-storm recovery occurred in the low-relief central Isles Dernieres where the 1988 hurricane impact had caused extensive changes in island morphology. At Trinity Island, washover flats were converted to washover terraces, and a dune terrace complex developed on the eastern end of the island in less than a year. Exposed marsh platform on the beach face decreased drastically. At Whiskey Island post-storm recovery was less extensive. Although high-relief washover terrace morphology increased and areas of island breaching were converted to washover flats, the island continued to be dominated by washover flats. On both islands, post-storm recovery was predominately concentrated in areas of greater island width.

The morphologies of the high-relief areas of the Isles Dernieres had been least affected by Hurricane Gilbert. Although continuous dunes at East Island had been reduced to dune terraces, overall relief of the island had remained relatively high. No significant change in geomorphology occurred during the non-hurricane period between 1988 and 1989. Post-storm recovery was restricted to a minimal conversion of washover flats to washover terraces and slight increase in terrace morphology. Raccoon Island had illustrated the least amount of change as a result of hurricane impact. Subsequent post-storm recovery occurred rapidly, and by July 1989 island relief and elevation far exceeded pre-hurricane conditions. In 1989, dune terraces, washover terraces and continuous dunes dominated island morphology. The primary morphology on the western end of the island persisted as low-relief landforms. The rapid increase in high-relief morphologies on Raccoon Island in less than a year also indicates the minimal impact of Hurricane Gilbert. The morphodynamics of this island between October 1988 and July 1989 are more representative of a long term post-storm recovery period and are probably an extension of the post-storm response to Hurricanes Danny and Juan in 1985.

CONCLUSIONS

The morphodynamics of the Isles Dernieres are controlled by hurricane impacts and subsequent periods of non-hurricane years. The cumulative impact of Hurricanes Danny and Juan in 1985 caused significant landscape changes in the Isles Dernieres. The net effect of the storms was a transformation of a relatively high-relief landscape dominated by well-vegetated dunes, dune terraces, and washover terraces to one dominated by partially-vegetated washover terraces and unvegetated washover flats. The central Isles Dernieres exhibited the most drastic geomorphic changes as a result Hurricane Gilbert (1988). The low-profile, rapidly eroding central Isles Dernieres are more sensitive to variations in high-energy waves and overwash conditions than are the high-profile and slower-eroding islands at the ends of the chain. During non-hurricane years, the Isles Dernieres are characterized by a restoration of island relief and elevation as well as greater habitat diversity. Greatest post-storm recovery occurred in areas of greater island width and relief. The rate of post-storm recovery was controlled by the regional setting of the individual islands relative to sand supply. The degree of the post-storm recovery was greater in areas where hurricane impact had caused greatest geomorphic changes. Between 1984 and 1989, the rate of shoreline change and sediment supply controlled the spatial morphologic variability in the Isles Dernieres; the frequency, magnitude, and duration of hurricane impacts controlled the temporal morphologic variability.

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MORPHODYNAMIC SIGNATURE OF STORM IMPACT PROCESSES AT THE ISLES DERNIERES BARRIER ISLAND ARC: 1984-1989

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Between 1984 and 1989 three hurricanes, ranging in strength from 1 to 5 on the Saffir-Simpson scale (Saffir, 1977), impacted Louisiana's shoreline surrounding the Mississippi River delta plain. Hurricanes Danny and Juan made landfall in Louisiana in 1985 and produced significant geomorphic changes on the Isles Dernieres barrier islands. Although Hurricane Gilbert (1988) made landfall at the Texas/Mexico border, the severity of this storm resulted in beach erosion and storm surge flooding in Louisiana. Data from aerial videotape surveys were used to examine the geomorphic response of the Isles Dernieres barrier island arc to multiple hurricane impacts and to assess post-storm response characteristics. Morphologic time series were developed to depict spatial and temporal geomorphic changes along the Isles Dernieres low-profile transgressive barrier island system.

The net effect of Hurricanes Danny and Juan, in 1985, was the transformation of a high-relief landscape dominated by well-vegetated dunes, dune terraces, and washover terraces to one dominated by partially-vegetated washover terraces and unvegetated washover flats. In 1988, Hurricane Gilbert caused extensive geomorphic changes in the central Isles Dernieres where the low-relief, less-vegetated islands were more susceptible to storm-surge processes. Post-storm island morphodynamics were characterized by a gradual buildup of the low-relief landforms to higher-profile features. The greatest post-storm recovery consistently occurred in areas of greatest island width and relief. In addition, the rate of post-storm recovery was controlled by the regional setting of individual islands relative to sand supply. The degree of post-storm recovery was consistently greater in areas where hurricane impact had caused greatest geomorphic change.

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MORPHODYNAMIC SIGNATURE OF THE 1985 HURRICANE IMPACTS ON THE NORTHERN GULF OF MEXICO

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ABSTRACT

Three hurricanes hit Lousiana (LA), Mississippi (MS), Alabama (AL), and the Florida (FL) panhandle in 1985, producing dramatic geomorphic changes in a wide variety of coastal environments. The impact zone for hurricanes Danny, Elena, and Juan stretched 1000 km between the Sabine River in LA to the Apalachicola River in FL. Barrier shorelines experienced repeated intense overwash events, producing beach and dune erosion exceeding 30 m, as well as producing classic examples of storm surge deposits. Pre- and post-storm airborne videotape surveys, sequential vertical mapping photography, and field surveys provide the data base for this regional hurricane impact assessment on the northern Gulf of Mexico.

Hurricane Danny hit the chenier plain in SW LA, depositing fluid mud washover features and wide mudflat accumulations along the shoreline. East of the landfall, strong onshore washover conditions severely breached and eroded the low-profile MS delta barrier shorelines.

In LA hurricane Elena generated an offshore directed overwash surge, which extensively breached the Chandeleur Islands, depositing washover fans into the surf zone. Along the high-profile MS-AL and Santa Rosa barrier shorelines, extensive dune erosion and intradune washover fan sedimentation predominated. The Pleistocene marine terrace cliffs west of Panama City beach were undercut, resulting in extensive slope failures and retrogressive slumping. In LA hurricane Juan produced spectacular high flow velocity washover features along the MS delta barrier shorelines before making its final landfall at Pensacola Beach, FL.

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Hurricane impacts on the low-profile and high-profile barrier shorelines, as well as on the marine terrace cliffs, were systematic and predictable. Controlling the direction of overwash flow and the impact distribution pattern is the relationship among shoreline orientation, hurricane storm track, and regional wind field. The relationship between shore-zone geomorphology and storm surge overwash controls the impact response.

INTRODUCTION

In 1985, hurricanes Danny, Elena, and Juan caused severe shoreline erosion and spectacular geomorphic changes in LA, MS, AL, and the FL panhandle (figure 1). With strengths between Saffir-Simpson scale 1 and 3 the storms produced spectacular coastal geomorphic changes (Saffir, 1977).

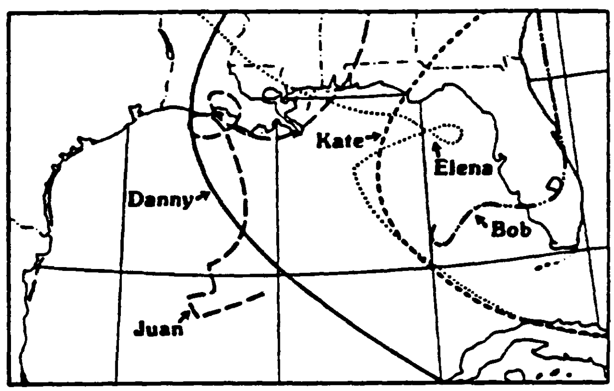

Figure 1. Storm tracks of the 1985 Gulf of Mexico hurricanes.

Prior to the storms, the average annual erosion conditions of the northern Gulf Coast had been driven primarily by relative sea level rise and cold front impacts. Vegetated dune and terrace systems had developed under these conditions, and the robust morphology reflected the influence of constructive aeolian and overwash processes. Island profiles were higher and more storm resistant because of extensive vegetative cover. The 1985 hurricane impacts provided an opportunity to examine the geomorphic responses of different types of coastal systems to multiple hurricane impacts. This examination will provide the reader with a better understanding of landform dynamics and hurricane impact processes on the northern Gulf Coast.

REGIONAL GEOMORPHOLOGY

The northern Gulf Coast stretches 1000 km between Sabine Pass, TX, and Panama Beach, FL (figure 2). The Mississippi River delta plain dominates this region by extending over 150 km to the south of the adjacent coastal plains (Frazier, 1967; Coleman, 1988). This delta plain consists of a series of four low-profile, transgressive barrier shorelines associated with abandoned delta complexes and two active delta complexes (Penland et al., 1988). The Balize and Atchafalaya delta complexes are active, and the barrier

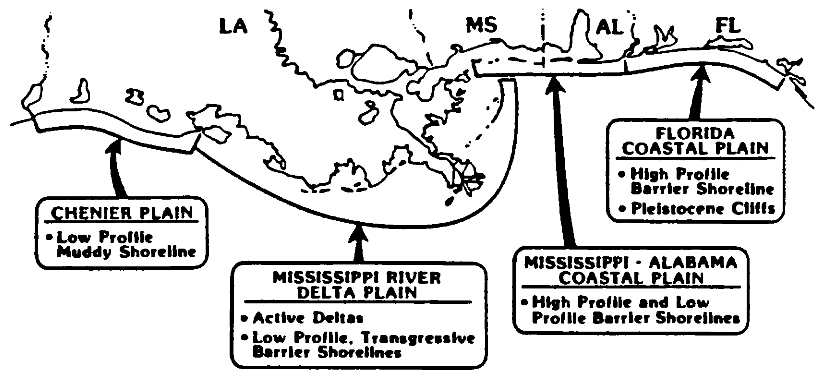

Figure 2. Coastal geomorphology of the northern Gulf of Mexico between Sabine Pass, TX, and Panama Beach, FL.

shorelines are the Isles Dernieres, Lafourche, Plaquemine, and Chandeleur Islands. To the west is the Mississippi River chenier plain, a downdrift accumulation of mudflats separated by low-profile, transgressive shorelines, which are associated with distributary switching events in the delta plain (Gould and McFarlen, 1959). The area between Chenier Au Tigre and the Calcasieu River mouth is a true stratigraphic chenier plain of alternating mudflats and ridges. However, the area between the Calcasieu and Sabine rivers is an ancient erosional headland of an ancestral Calcasieu river. On this coast one finds a low-profile transgressive shoreline flanked by regressive beach-ridge plains. To the east of the Mississippi River delta plain lie the MS-AL and FL coastal plains (Shepard and Wanless, 1971). The MS-AL barrier island system represents a combination high-profile and low-profile shoreline. These islands over the last 100 years have experienced lateral migration to the west by updrift erosion, downdrift spit accretion, and island fragmentation followed by island welding. From east to west, Cat Island, Ship Island, Horn Island, Petit Bois Island, Dauphin island, and the Morgin Peninsula make up this barrier island system. The FL coastal plain consists of a continuous high-profile barrier shoreline from Perdido Key to Santa Rosa Island (Martens, 1931). From East Pass to Gulf Lagoon Beach, high eroding Pleistocene terrace cliffs supply sediment to the downdrift high-profile barrier shorelines.

1985 HURRICANE IMPACT PROCESSES

Hurricane Danny

A tropical depression moved NW over the extreme western tip of Cuba and into the southeastern Gulf of Mexico on August 13 (figure 1). This tropical depression went from minimal tropical storm strength to hurricane strength in a 24-hour period (National Hurricane Center, 1985a). Named Danny, the hurricane continued NW before turning on a more northerly course during the morning hours of August 15 off the LA coast. The center made landfall SE of Lake Charles, LA, near noon on August 15. Hurricane Danny quickly weakened to tropical storm strength as it moved inland (figure 3).

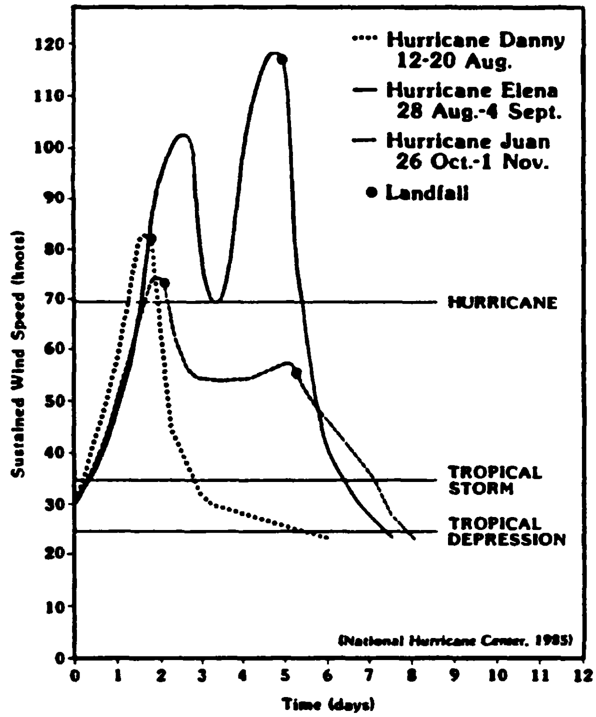

Figure 3. Wind speed and barometric time-series for hurricanes Danny, Elena, and Juan in 1985 (National Hurricane Center 1985a, 1985b, and 1985c).

The highest tides occurred 50 km east of the eye of hurricane Danny at Intracoastal City, where the storm surge was recorded at 2.4 m (figure 4). The storm surge was

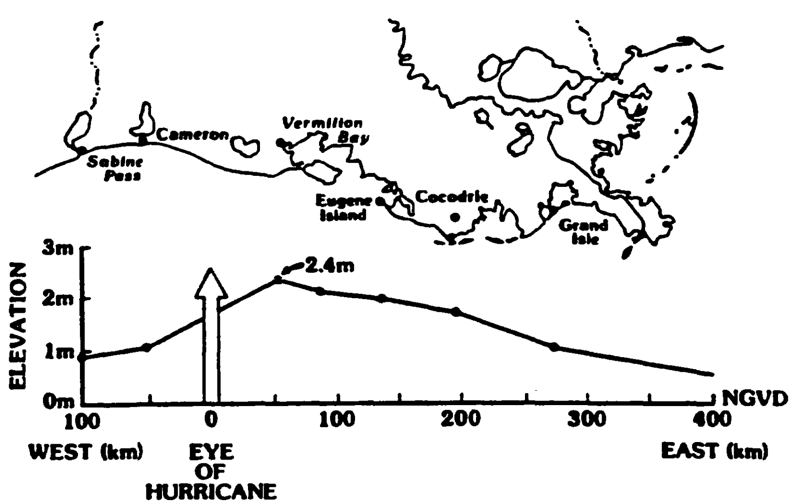

Figure 4. Maximum storm-surge elevation map for the tide gage stations between Sabine Pass, TX, and Pensacola, FL.

greater than a meter above NGVD 300 km east of the storm center and 100 km to the west. In the vicinity of the Isles Dernieres the storm surge was about 1.25-1.75 m. The tide gage at Eugene Island was on the east side of the storm and recorded a maximum surge of 1.88 m NGVD (Figure 5). A review

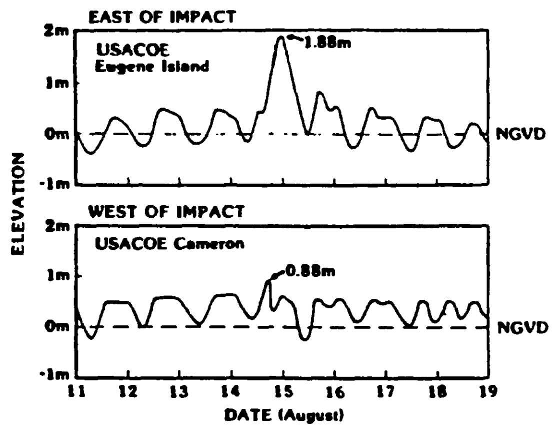

Figure 5. Water level time-series for the USACE Eugene Island, LA tide gage and for the USACE Cameron, LA tide gage.

of the tide gage record indicates the storm surge preceded landfall by about 12 hours, with water levels rapidly rising from -0.15 m NGVD at 1200 August 19 to 1.88 m at 0000 August 15. This is a 2 m rise in 12 hours. By 1200 August 15, the storm surge had receded 2 m. To the west of the storm track at Cameron the winds were predominately offshore, helping to dampen the storm surge, which reached a maximum of only 0.88 m NGVD. At landfall, the water levels in Cameron were depressed -0.25 m below NGVD by strong offshore winds.

Hurricane Elena

Tropical storm Elena was named on August 28, when its center was over central Cuba and reconnaissance aircraft measured winds 45-50 kn N (National Hurricane Center, 1985b). After moving into the Gulf of Mexico, Elena strengthened to a hurricane on August 29 (figure 1). The center of Elena made landfall near Biloxi, MS, on the morning of September 2. Maximum winds recorded on the coast were at Dauphin Island, AL, with sustained winds of 92 kn and gusts up to 118 kn. The lowest pressure observed on the coast was 953 mb at Pascagoula, MS. Lowest pressure observed by NOAA reconnaissance aircraft at the time of landfall was 959 mb (National Hurricane Center, 1985b). The left oblique storm track to the shoreline produced a skewed wind field oriented NW/SE. North of hurricane Elena's storm track, maximum winds were from E/NE, and south of the storm track winds were from the NW (figure 6). The strongest zone of 110 kn NE winds impacted a narrow zone between Biloxi, MS, and Dauphin Island, AL. A broader zone of 90 kn wind about 30-50 km wide stretched from Gulf Shores, AL, to Pearl River, MS. The 70 kn wind zone stretched farther from Pensacola, FL, to McComb, MS, and was 80-100 km wide. From the damage maps of hurricane Elena it is evident the barrier islands east of the storm track were impacted by strong onshore wave and storm surge conditions. South of the storm track, the barrier islands were impacted by strong offshore wind and overwash conditions. In the vicinity of the Chandeleur Islands, the winds were directed offshore at 50-70 kn.

The highest storm surge levels in the study area were recorded in Pascagoula, MS, and Dauphin Island, AL (figure 7). An inside high water measurement was made in Dauphin Island at 2.65 m, and the maximum outside measurement of wave height run-up was 3.93 m (Garcia and Hegge, 1987). On the

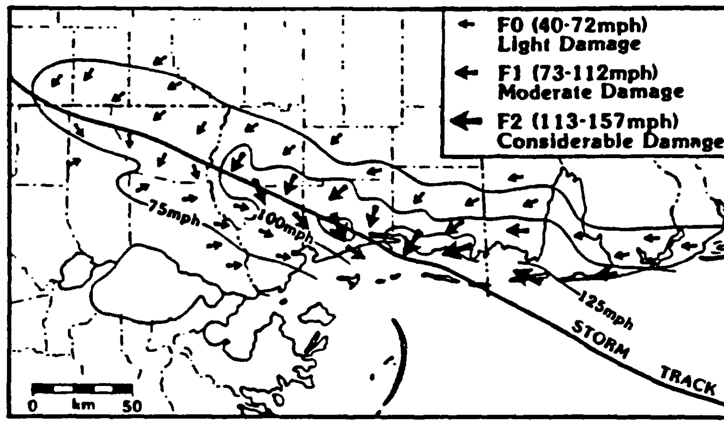

Figure 6. Diagram of the hurricane Elena maximum wind field distribution map (National Hurricane Center 1985c).

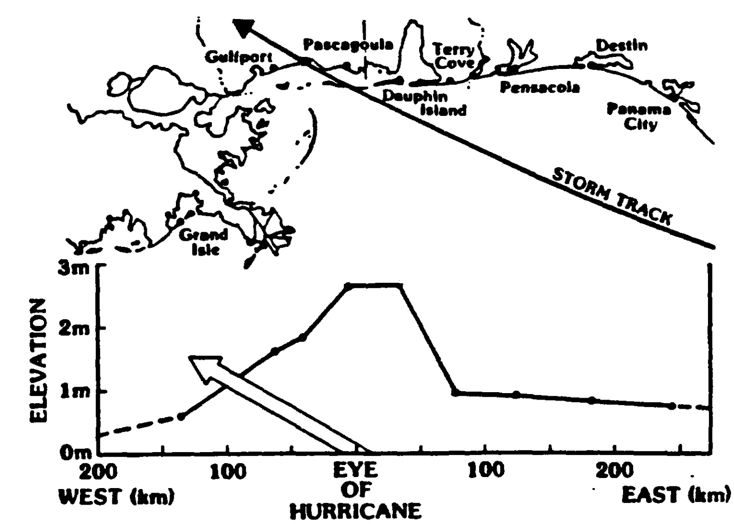

Figure 7. Maximum storm-surge elevation map for the hurricane Elena impact zone.

mainland at Pascagoula, MS, the maximum inside high water measurement was 2.65 m, and the maximum strong surge exceeded one meter as far as Port Eads, LA. At Grand Isle, LA, the storm surge was less than a meter.

Figure 8 illustrates the time-series hydrograph for Cadet Point, MS, on the north side of hurricane Elena's storm track, and for Frenier Beach, LA, on the south side. Both records indicate sea levels depressed below 0.0 m NGVD prior to landfall. The regional wind field shown by synoptic weather charts was offshore directed. Water levels at the Cadet Point gage were depressed more than 70 cm below NGVD before rising in a 4 hour period to a maximum level of about 2.3 m. This is opposite of the pattern observed during the hurricane Danny impact, when maximum water levels were followed by a set-down. The Frenier Beach gage did not

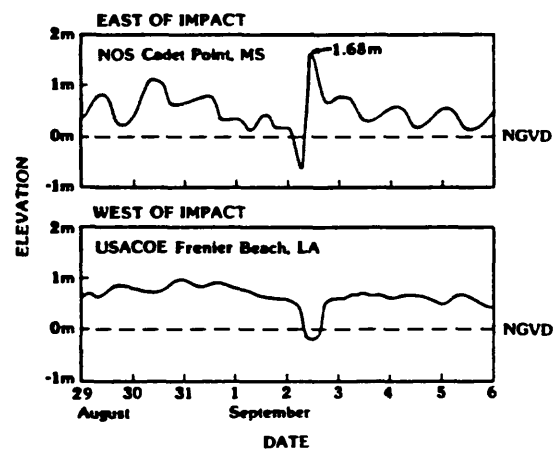

Figure 8. Water level time-series for the NOS Point Cadet, MS tide gage for the passage of hurricane Elena in 1985 and for the USACE Frenier Beach, LA tide gage.

record any major water level set-up south of the storm track because of strong N/NW winds blowing offshore. The Frenier Beach gage recorded a set-down of only about 60 cm to a low of -0.20 m NGVD.

Hurricane Juan

Hurricane Juan moved on a very erratic course throughout its development. Initially, reconnaissance aircraft reported the center to be a wide area of light and variable winds. As the storm became better organized, it began moving NE around 10 kn early October 27. That afternoon the storm turned NW at 15 kn and attained minimal hurricane strength. Hurricane Juan's speed dropped to less than 5 kn by early October 28, and during the next 24 hours it made a cyclonic loop off the south-central LA coast. Early October 29 Juan hit near Morgan City, LA, and on the following day made a another cyclonic loop around Lafayette, LA, before emerging over Vermilion Bay. On October 30, hurricane Juan was downgraded to a tropical storm with gale force winds confined to the waters of the northern Gulf of Mexico. After moving offshore the storm became better organized as it passed the LA coast and then moved across the mouth of the Mississippi River near Burwood and was upgraded to a hurricane again. In the morning hours of October 31, heading NE at 15 kn, hurricane Juan made a second landfall just west of Pensacola, FL, at midday. Hurricane Juan turned northward and gradually lost strength before finally becoming classified as an extratropical storm on November 1 (National Hurricane Center, 1985c). The maximum sustained wind reported by reconnaissance aircraft was 75 kn in the morning of October 28, 1985 (National Hurricane Center, 1985c). Storm rainfall totals ranged from 10-20 cm with some local amounts of 40 cm over LA (figure 9).

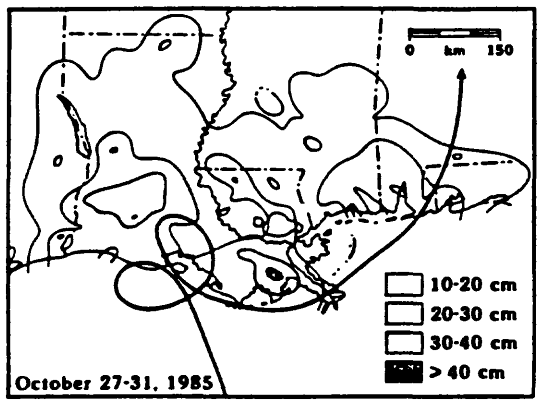

Figure 9. Distribution map illustrating the total cumulative rainfall pattern for the passage of hurricane Juan in 1985 (National Hurricane Center, 1985c).

The storm surge of hurricane Juan was unusually long, lasting three days as the storm looped twice across coastal LA. The maximum water level was associated with the initial landfall of hurricane Juan at Chenier Au Tigre, LA. The storm surge peaked at an elevation of 2.19 m 30 km west of the storm track and more than a meter as far east as Pensacola, FL (figure 10). West of the storm track, surge

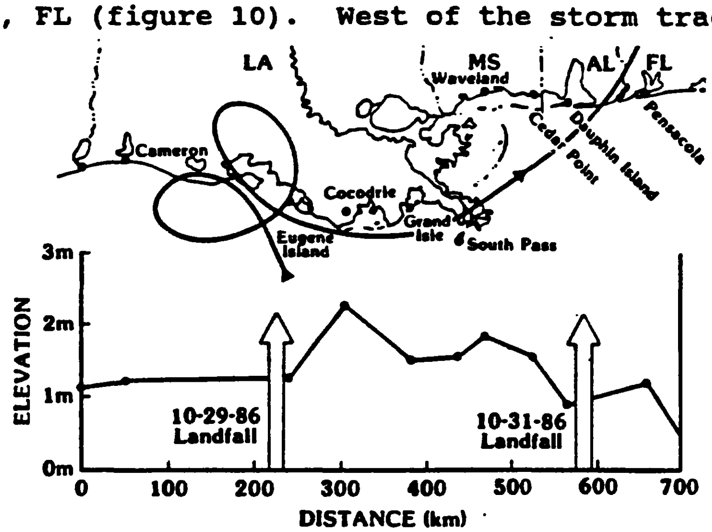

Figure 10. Water level time-series for the USACE Cocodrie tide gage station for hurricane Juan in 1985.

levels measuring more than a meter reached as far as Galveston, TX. The Cocodrie USACE tide gage station recorded the water level time-series for hurricane Juan (figure 11). The water level pattern was again different from both hurricanes Danny and Elena. This gage recorded a single storm surge set-up with no set-down before or after the passage of hurricane Juan. The water level initially reached its maximum elevation of 2.19 m, then subsided to a level of about 1.50 m for the next three days.

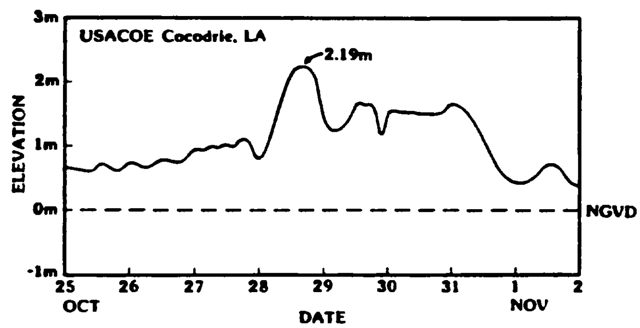

Figure 11. Maximum storm-surge elevation map for the hurricane Juan impact zone.

MORPHODYNAMIC RESPONSE PATTERN

Hurricane Danny Impact Zone

The hurricane Danny impact stretched 350 km between Sabine Pass and the Chandeleur Islands. Landfall was in the Rollover Bayou area of the chenier plain. Figure 12 illustrates the regional process-response pattern for the

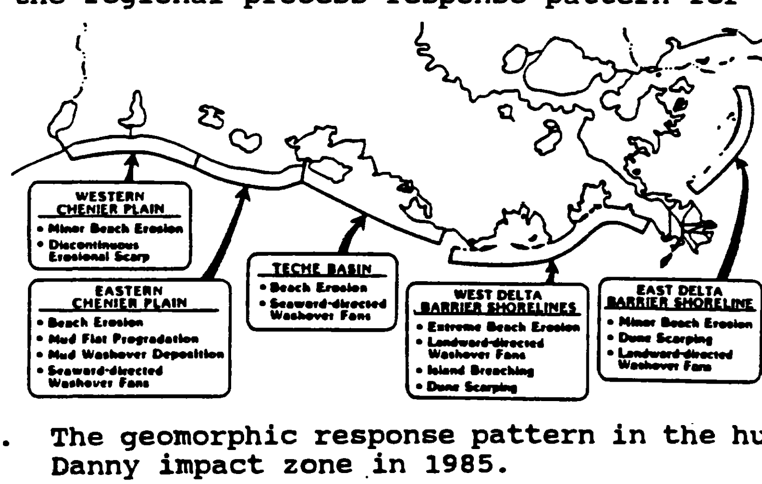

Figure 12. The geomorphic response pattern in the hurricane Danny impact zone in 1985.

hurricane Danny impact. Located on the eastern side of the storm track, the area hardest hit was the west delta barrier shorelines, the Isles Dernieres and Bayou Lafourche systems. Extreme beach erosion occurred, in some areas exceeding 40 m. The storm surge produced landward-directed overwash channels and barrier island breaches (figure 13). In localized areas where relatively higher dunes occurred, erosion scarping of these dunes was predominant. The eastern chenier plain and the Teche basin, also located in the NE storm quadrant, were the areas next hardest hit. Beach erosion was moderate, around 10-15 m. The storm surge produced spectacular seaward-directed overwash channels by water flooding the mainland being driven seaward by the hurricane wind shift (figure 13B). In the eastern chenier plain, beach erosion and seaward-directed overwash channels were similar to those of the Teche basin; however, the major mudflat accumulation and mud overwash fan deposition differed from those of Teche Basin (figure 13C and 13D). The area between Lake Constance

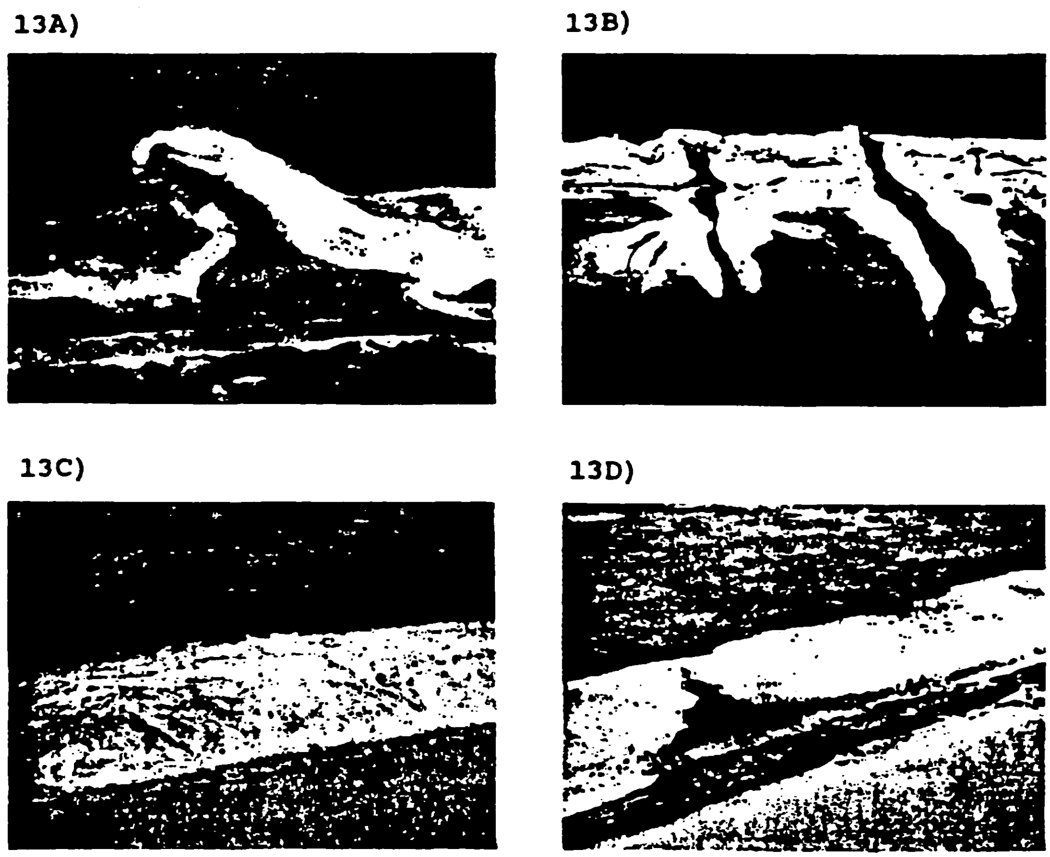

Figure 13. A) Landward oriented washover fan in the Isles Dernieres; B) seaward directed washover fan in the LA chenier plain; C) mudflat in the LA chenier plain; and D) mud washover fan in the LA chenier plain.

and Freshwater Bayou was the primary zone of accumulation, in some areas the coast prograding more than 50 m. The areas least impacted were the western chenier plain and the east delta barrier shoreline. The western chenier plain was located west of the storm track where hurricane conditions were minimal. The beaches experienced minor beach erosion of 5-10 m, and along higher areas a discontinuous erosional scarp developed. The east delta shoreline was on the eastern fringe of hurricane Danny; the barrier islands experienced minor beach erosion, dune scarping, and in some areas landward-directed overwash fans developed. Overall, the regional process-response pattern of the hurricane Danny landfall was representative of a direct, shore-normal impact.

Hurricane Elena Impact Zone

The hurricane Elena impact zone stretched 300 km between the west delta barrier shorelines to the FL Pleistocene cliffs. Landfall was in the MS-AL barrier islands. Figure 14 illustrates the regional process-response pattern for the hurricane Elena impact. The areas hardest hit appeared to be

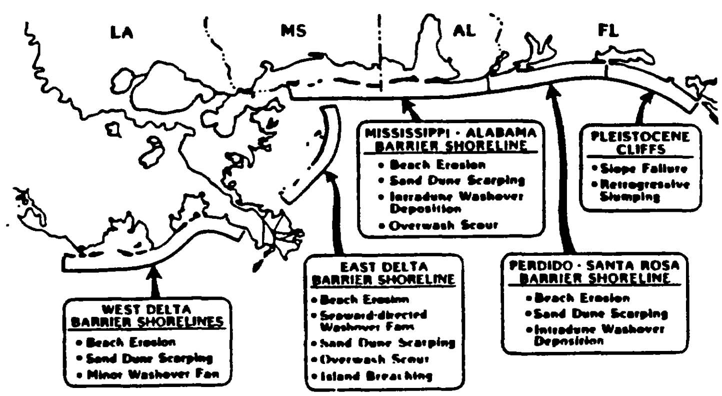

Figure 14. The geomorphic response pattern in the hurricane Elena impact zone in 1985.

the MS-AL barrier shoreline and the east delta barrier shoreline of the Chandeleur Islands. From east to west across the impact zone, the west delta barrier shorelines of the Isles Dernieres, Lafourche, and Plaquemines experienced minor beach erosion, sand dune scarping, and washover channel development. The Chandeleur Islands experienced major beach erosion exceeding 20-30 m, major sand dune scarping, and overwash scour. An interesting geomorphic response pattern took place in the Chandeleur Islands; the major washover channels and island breaches were produced by seaward-directed hurricane overwash (figure 15A). Orientation of the shoreline and strong offshore winds on the south side of the hurricane Elena storm track generated a seaward-directed overwash flow from Chandeleur Sound across this barrier island arc into the Gulf of Mexico (figure 15B). The MS-AL barrier shoreline experienced major beach erosion and dune scarping. In high-profile areas, storm overwash produced intradune washover deposition; where the islands were narrow, washover fans were deposited in Mississippi Sound (figures 15C and 15D).

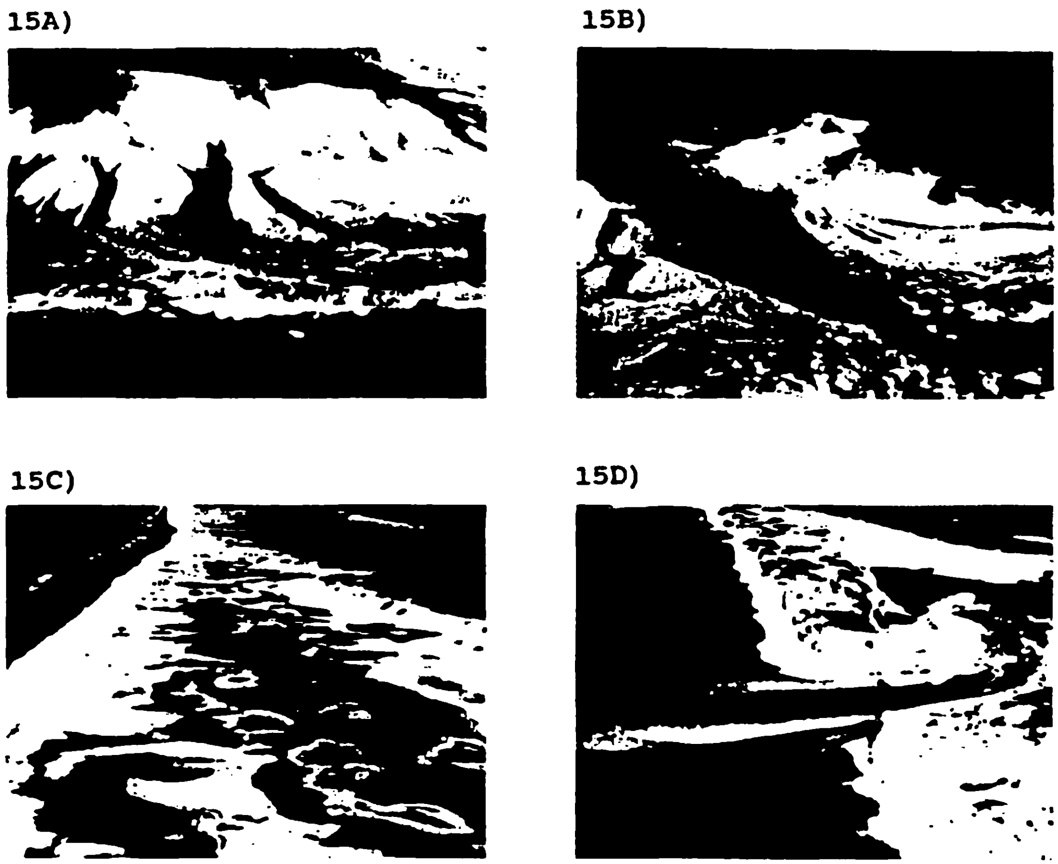

Figure 15. A) Overwash scour and seaward-oriented overwash channels at Curlew Island; B) seaward-oriented washover fan in the northern Chandeleur Islands; C) intradune washover deposition at Horn Island; and D) washover fan on Petit Bois Island.

On lower-profile areas, the storm surge produced overwash scour features (Nummedal et al., 1980; Penland et al., 1980), particularly at Dauphin Island, AL, or at the ends of the other barrier islands (figure 16A). In populated areas, such as Dauphin Island, flying debris was a major hazard to life and property (figure 16B). The Perdido-Santa barrier shoreline experienced minor beach erosion and regional dune scraping. Within the high-profile dunes, intradune washover deposition was common. The Pleistocene cliffs were undercut by beach erosion, causing localized slope failures and retrogressive slumping. Overall, the regional process-response pattern was representative of a left-oblique hurricane impact (Penland and Suter, 1984).

16A)

16B)

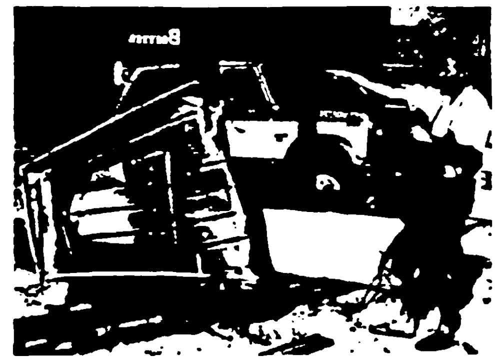

Figure 16. A) Washover sedimentation and backbarrier scour features at Dauphin Island; and B) example of wind blown debris at Dauphin Island.

Hurricane Juan Impact Zone

The hurricane Juan impact zone stretched 400 km between Sabine Pass, TX, and East Pass, FL. Hurricane Juan was very erratic, crossing the LA coast three times before making landfall in FL. Figure 17 illustrates the regional process-response pattern in the hurricane Juan impact zone.

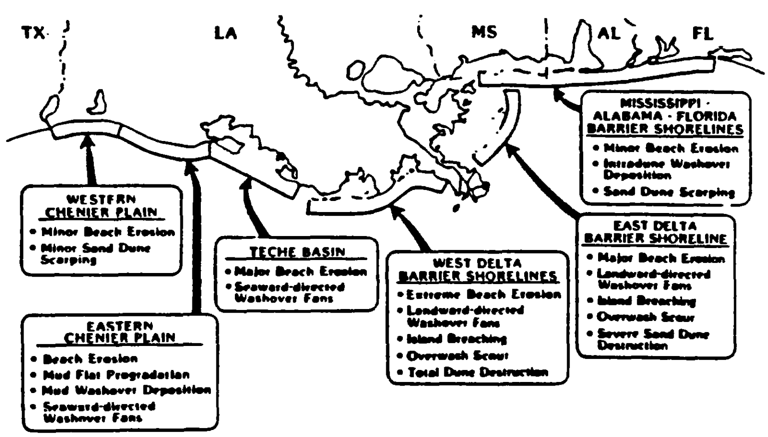

Figure 17. The geomorphic response pattern in the hurricane Juan impact zone in 1985.

The western chenier plain experienced minor beach erosion and scarping of the shoreline on the western side of hurricane Juan. In the eastern chenier plain and Teche basin, major beach erosion occurred along with seaward-directed washover fans. At the Rollover Bayou area in the eastern chenier, mud washover and mudflat accumulation took place again as they had during hurricane Danny. The west delta barrier shorelines of the Isles Dernieres, Lafourche, and Plaquemines were the hardest areas hit. Extreme beach erosion and overwash scour occurred. Landward-directed washover channels and breaches dissected these barrier islands. Due to the prolonged storm surge, all of the major dune fields were destroyed. In the Chandeleur Islands east of the delta, the beaches experienced major erosion and overwash scour. The pattern of island breaching and washover channel development was landward-directed. The sand dune fields in the Chandeleur Islands, the largest in LA, experienced severe destruction. Due to their higher profile, the MS-AL-FL barrier shorelines experienced minor beach erosion, intradune washover deposition, and sand dune scraping. The overall impact pattern for hurricane Juan was not typical because of its erratic and prolonged landfall.

CONCLUSIONS

1.Geomorphic response to hurricane impacts is predictable.

2.Relationships among shoreline orientation, hurricane storm track, and regional wind field control the storm surge distribution, the overwash flow direction, and the impact distribution pattern.

3.Relationship between shore-zone geomorphology and storm surge overwash controls the type of impact response.

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ENVIRONMENTAL ISSUES IN THE GULF OF MEXICO: STIMULUS FOR RESEARCH

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The Gulf of Mexico has provided the abundance of hydrocarbons, fisheries resources, transportation, and recreation opportunities that fed the post-World War II economic and population boom in the region from Florida to Texas. The Gulf has also brought the hurricanes and coastal erosion that combine with the effects of man's use of Gulf resources to cause many of the environmental problems that have spurred regulations and initiatives to deal with them. If we examine the list of environmental problems facing the Gulf, we find a complex of interacting processes at work. If the premise is valid that effective solutions depend on a clear understanding of the problem, it becomes evident why we are still struggling with these issues: we simply don't have a good understanding of the conditions and processes causing the environmental problems.

An understanding of the geologic framework and of natural geologic processes is fundamental to any attempts to deal systematically with the most spectacular changes affecting the borders of the Gulf, namely wetland loss and shoreline erosion. While it may be obvious to geologists that the cyclic behavior of the Mississippi delta results both in accretion and subsidence-induced wetland loss, many life scientists and environmental activists pass over this lightly and look exclusively for human villains. The need to understand the processes and sediment budget factors that determine the rates of shoreline and barrier-island retreat before planning restoration is not widely understood by planners and engineers, nor is the utility of understanding the surficial and shallow subbottom geology of the continental shelf in locating sand for beach nourishment, if, in fact, nourishment is justified. Man's imprint on the coastal zone through the construction of levees, dredging of canals, placement of dredged material, and alteration of shorelines has to be viewed in light of the natural processes and in terms of how it has modified them.

There are many human activities that result in the degradation of the quality of Gulf and adjacent coastal waters. Raw sewage and effluent from sewage treatment, pesticides and fertilized from agricultural lands, produced waters from oil and gas operations, spillage of oil and chemicals from ships and barges, and waste streams from industrial facilities are among the things that man adds to a system that is already stressed at times by naturally occurring anoxic conditions. The transport of these materials in solution and attached to sediments must be understood if we are to comprehend the severity and distribution of the effects they produce. The circulation patterns that operate in the Gulf interact with the large plumes of water, sediment, and solution load delivered by the Mississippi River and other rivers, complicating the sorting out of where pollution problems originate and where the effects will be concentrated.

It is a sobering experience to contemplate the complexity of the system that must be understood and the diversity of the research capabilities that must be brought to bear. The breadth and diversity of the elements of the EPA Gulf of Mexico Initiative are a good indication of what is involved in just trying to identify the problems and the status of our understanding of them. Yet the positive effects of tackling these complex systems can be appreciated as we see maps and reports from the U.S.G.S./Louisiana Geological Survey cooperative barrier island project being used in coastal restoration planning and Minerals Management Service-funded studies of produced waters used in developing discharge regulations. The research community actively investigating environmental issues in the Gulf is growing as federal and state agency interest and funding increase. The need to integrate studies and manage data useful to all through geographic information systems is becoming more appreciated resulting in more cooperative efforts and greater sharing of information. The rising tide of research and application of results must continue if the environmental problems of the Gulf are to be dealt with before they so diminish the resources that characterize the region that the economic base is destroyed. Geoscientists have a vital role to play and should look to the Gulf for exciting research challenges that have important beneficial applications.

(p. 457 follows)

NEARSHORE HOLOCENE STRATIGRAPHY, NORTHERN GULF OF MEXICO: INTEGRATION OF REGIONAL GEOLOGIC STUDIES

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ABSTRACT

Late Quaternary geology of the Mississippi-Alabama Shelf Province has been intensely investigated through various cooperative federal and state projects. Goals of the individual projects were diverse but required basic description of the geologic framework and stratigraphy. A large data base has been accumulated including high-resolution single-channel seismic reflection data (>7,000 km) (Kindinger *et al.*, 1982; Kindinger, 1989a) and vibracores (>100) (Fig. 1).

The Mississippi-Alabama Shelf Province encompasses eastern Louisiana barrier islands and shelf, Mississippi-Alabama barrier islands and shelf, Mississippi Sound and Mobile Bay. The morphology and stratigraphy of the eastern Louisiana barrier islands and adjacent shelf are dominated by the Mississippi River plain. Removed from the direct influence of the Mississippi River, Mississippi Sound and Mobile Bay are estuarine systems which have evolved differently. Mississippi Sound, initially a shallow open marine coast, has been restricted by a westward migration of barrier islands. Mobile Bay is a classic drowned river valley, incised most recently during the last lowstand and infilled with a 10 m thick section, consisting primarily of lagoonal sediments.

As the most recent sea-level rise flooded the shelf, very little deposition occurred on the Mississippi-Alabama shelf until the Holocene progradation of the St. Bernard delta complex (Kindinger, 1988). Deposition began in the northwest corner of the inner shelf and has accumulated an

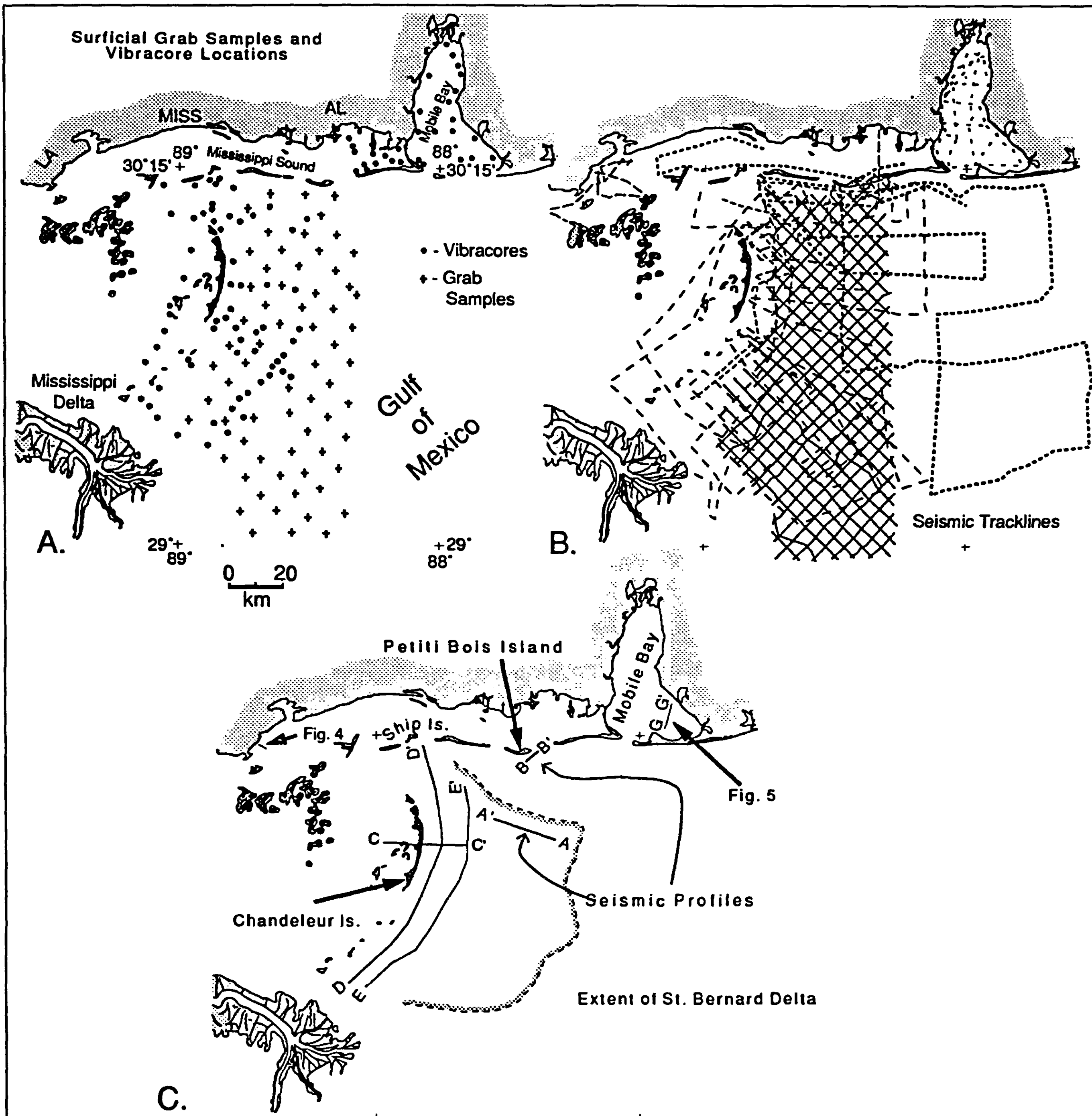

Figure 1. Study area including locations of samples, tracklines, figures and cross sections: A, location of surficial grab and vibracore samples; B, seismic survey tracklines; and C, locations of seismic profiles and cross sections shown in Figures 2, 3, 4, and 5.

average prodelta thickness of 4 m (Kindinger *et al.*, 1982). The St. Bernard delta complex systematically thins from the northwest to the southeast. Seismic profiles reveal little internal structure for those which characterize filled distributary channels (Fig. 2) and low-angle clinoforms near the seaward pinchout. Distributaries are the primary conduit for sediment transport to the coast and continental shelf. This delta complex, which ceased its progradational phase approximately 1,200 yrs BP (Frazier, 1967), is now in the destructional phase of the deltaic cycle (Penland *et al.*, 1985).

Vibracores have been analyzed correlated with seismic

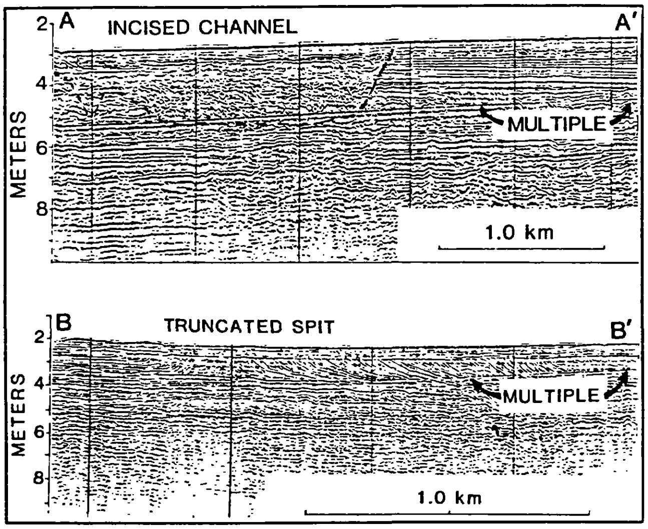

Figure 2. Seismic profile A-A' is an example showing a buried incised channel or valley. Profile B-B' is a truncated sand ridge or spit, located off Petit Bois Island and is the eastern remnant of Petit Bois Island. Locations of profiles are shown in Figure 1C.

profiles to produce a series of cross sections constructed from the results (Fig. 3; modified from Brooks *et al.*, 1991). Figure 3 C-C' is a west to east cross section from Chandeleur Sound across the Chandeleur Islands onto he shelf. Deltaic facies identified from the vibracores, including prodelta, delta fringe, distributary, and lagoonal deposits overlain by the transgressive Chandeleur Islands. The sands of the Chandeleur Islands were deposited in the form of distributary as mouth-bar sands (Penland *et al.*, 1985). These sands

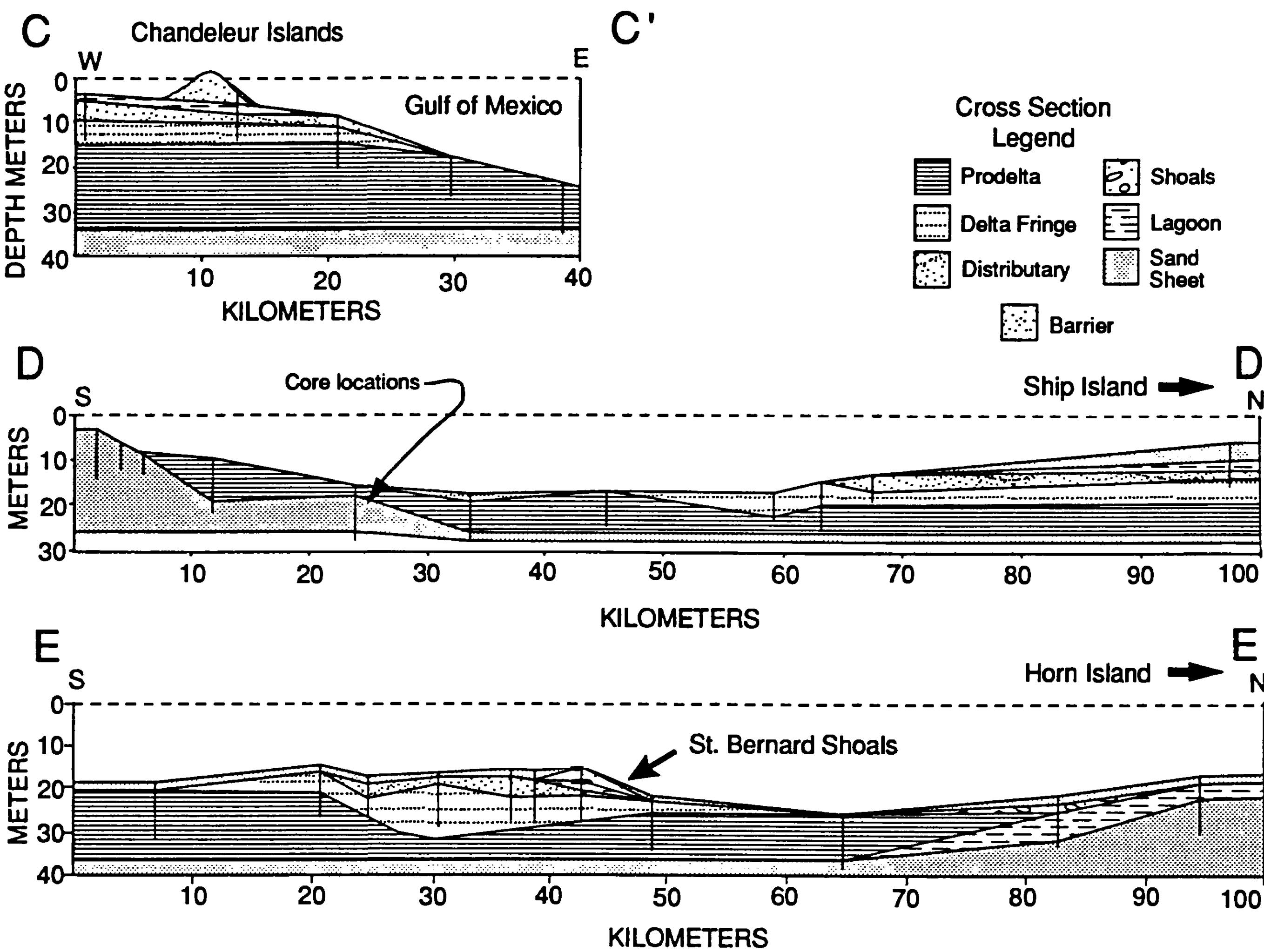

Figure 3. Cross sections C-C', D-D', and E-E' constructed using vibracores from the Mississippi-Alabama shelf; locations of cross sections are shown on Figure 1C.

were reworked and have been transgressed shoreward over the lagoonal deposits that were originally behind the mouth-bar sands. Organic samples from this lagoonal facies have given radiocarbon dates of <2000 yrs BP.

South to north cross sections demonstrate sedimentary facies changes with increased distance from the Chandeleur Islands (Fig. 3 D-D' and E-E'). The cross sections also give dip view of facies from the Mississippi-Alabama barrier island chain. Figure 3 D-D' primarily shows the distribution of the prodelta and delta fringe facies of the St. Bernard Delta. St. Bernard Shoals is shown in Figure E-E'. Also shown is the prodelta facies overlain by a delta fringe facies that has been incised by a distributary. The distributary channel supplied sands for the formation of the St. Bernard Shoals (Penland *et al.*, 1989). Data show that the St. Bernard Shoals and Chandeleur Islands have formed in much the same way.

The Mississippi-Alabama inner shelf has been repeatedly subjected to coastal and fluvial processes. Shoreline migration and coastal processes, such as longshore transport and shoaling, have reworked the sands and winnowed much of the finer sediments delivered by fluvial transport out of the Mississippi Sound barrier island area. An example of the effects of these processes is a sand ridge truncated by the ravinement surface (Fig. 2). Also truncated by the ravinement surface are shingled reflectors that may be associated with the sand ridge at the east end of Petit Bois Island.

Late Quaternary deposits of western coastal Mississippi Sound display a variety of complex stratigraphic patterns representing local fluvial-deltaic processes and distal Mississippi River deposition (Fig. 4). Considerable channeling reflects incision during lowstands, possibly a combination of fluvial, tidal, and distributary processes. These depositional sequences extend landward beneath the present shoreline, suggesting overall progradation of the coastline during the late Quaternary. Sequence I, (Holocene?) is comprised primarily of acoustically reflection-free fill over an irregular Pleistocene surface. Faint parallel reflections in the southwest area of sequence I are distal deltaic deposits which onlap from the south-southwest and do not extend closer than ~10 km from the present shoreline.

Mobile Bay is a classic drowned river valley, incised most recently during the last lowstand and filled primarily with lagoonal sediments thinning from 10 m in the center to the perimeter (Kindinger *et al.*, 1991) (Fig. 5 and 6). Overlying the Pleistocene-Holocene contact is this Holocene section that thickens toward the center of the bay from a bay-head delta system in the north. This section is transitional from clayey prodelta to lagoonal facies composed of sediment supplied by the Tombigbee and Alabama rivers into the Mobile River to the bay-head delta. The bay-head delta has reportedly filled ~65 km of Mobile Bay in the last 3,000 yrs (Smith, 1981). The Holocene section in the lower bay is transitional with the prodelta facies interfingering with sandy deposits from the large spit known as Morgan Peninsula. Within the Holocene section of the bay are several filled incised stream channels including Dog and Fowl rivers.

Cross section I-I' (Fig. 6) had several samples from which radiocarbon dates were attained. An oyster biostrome in Core 12 yield radiocarbon dates of 1,700 and 4,000 yrs BP. The Holocene basal unconformity has been dated as 35,000 yrs BP.

Holocene deposition on this shelf has occurred in several stages. The St. Bernard delta complex began its initial deposition at the end of the Holocene transgression. These deltaic sediments were reworked and winnowed to form sandy shoals that developed into islands. Sea level rise also drowned the fluvial valley of the Mobile River concurrently. Deposition in Mobile Bay has been relatively rapid due to the influx of sediment from the Mobile drainage basin. As sea level rise approached present levels, the central portion of Mississippi Sound was originally a shallow, open-marine coast and then was formed by the westward migration of barrier islands broken by natural tidal inlet system such as Petit Bois Pass. Lagoonal sediments are now being deposited within the restricted Mississippi Sound.

Holocene development of the region has been intricately linked to sea level rise since the late Wisconsinan. Deposition and erosion have occurred penecontemporaneously on various areas of the post-Pleistocene shelf.

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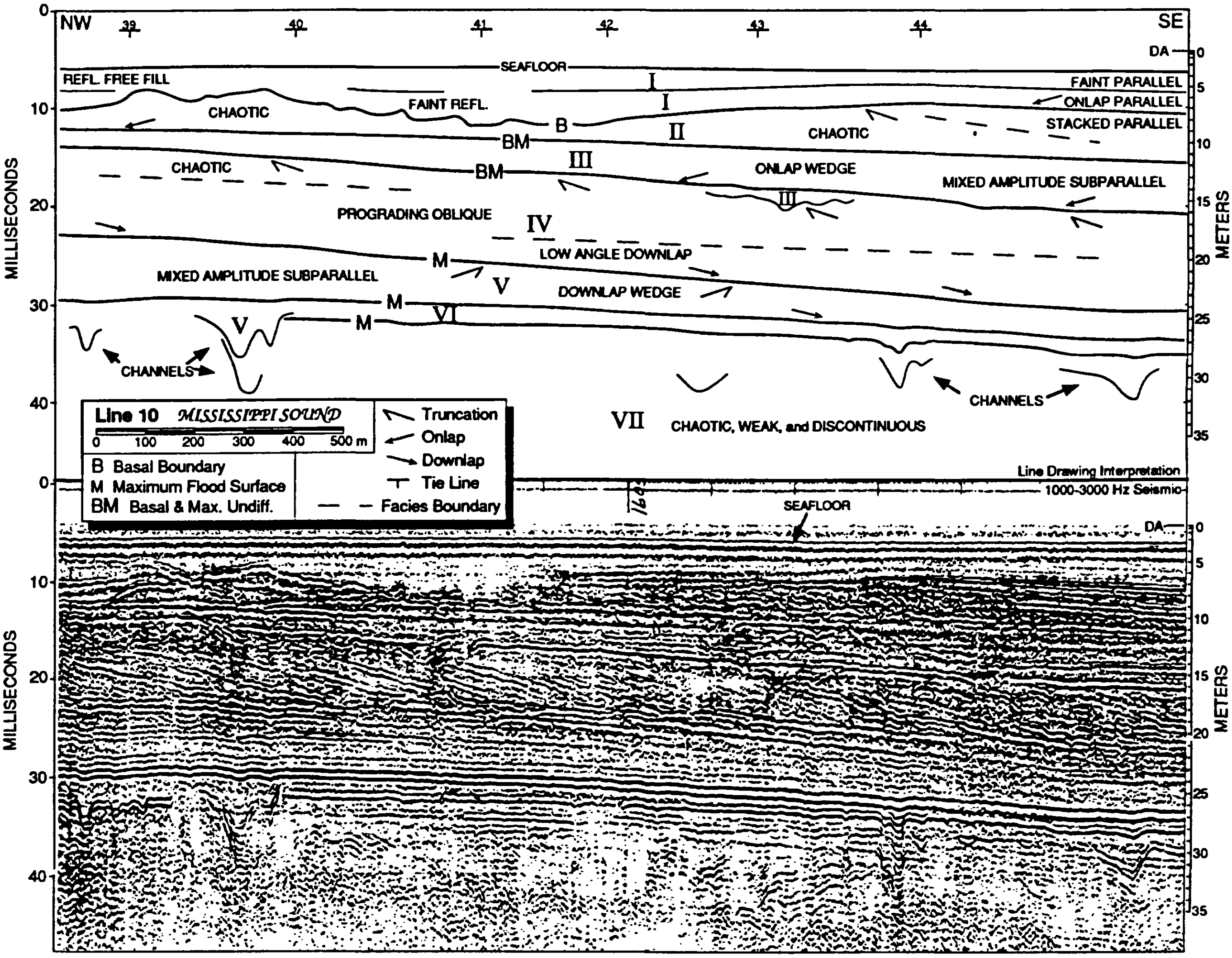

Figure 4. Seismic profile F with line drawing interpretation from nearshore Hancock County, Mississippi; location of profile shown on Figure 1C.

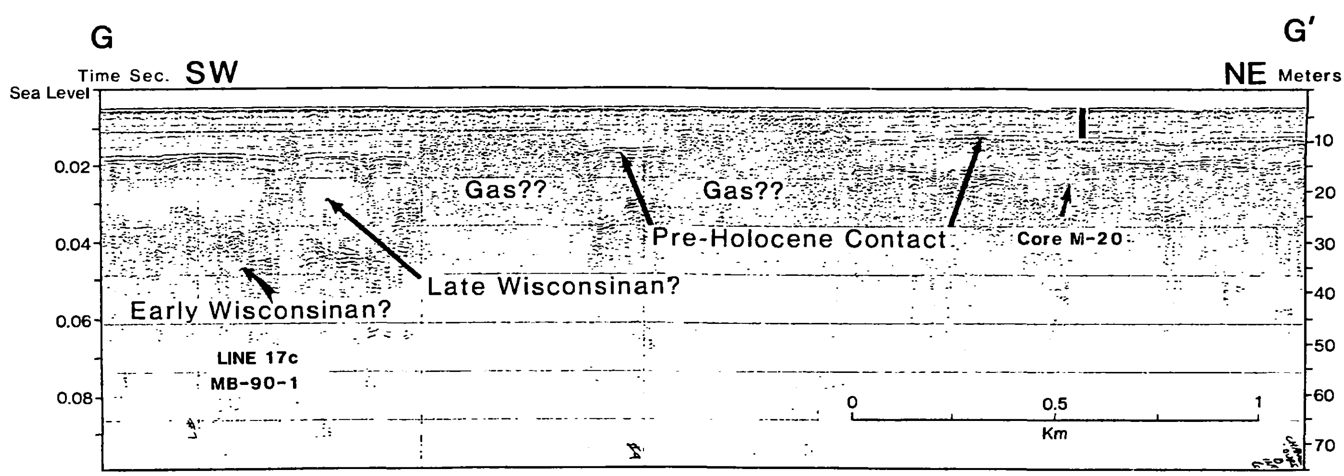

Figure 5. Seismic profile G-G' from Mobile Bay shown Pre-Holocene Contact overlain by ~10 m of Holocene lagoonal sediments in the bay center (SW) thinning to the bay margin (NE). Location of profile is shown on Figure 1C.

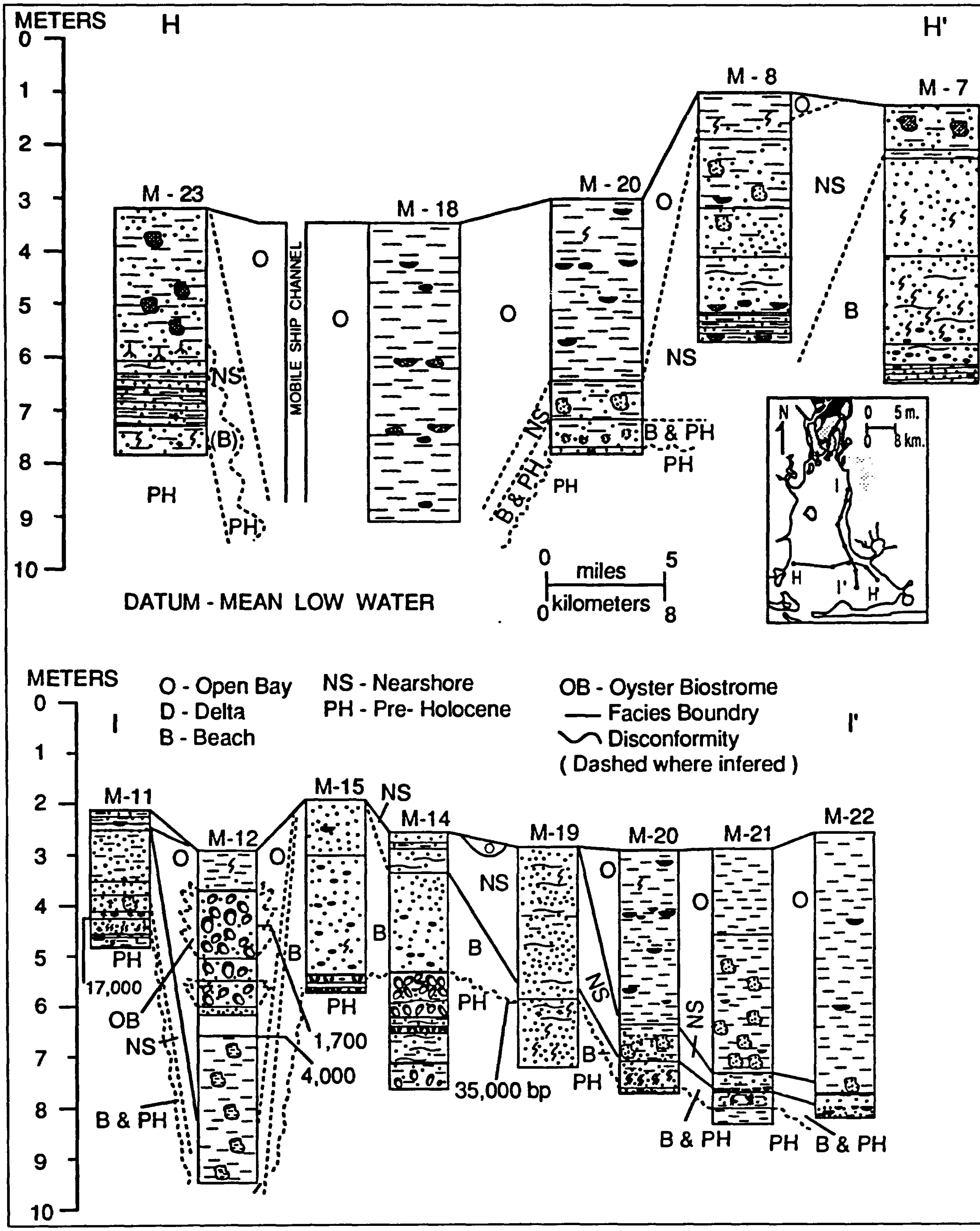

Figure 6. Cross sections constructed from Mobile Bay vibracores. Section H-H' transects the middle of Mobile Bay showing the thickness of lagoonal sediments found in the central portion of the bay. Section I-I' shows bay margin deposits and lower bay lagoonal deposits. Radiocarbon dates similar to those from the oyster biostrome in Core M-12 were used to identify Holocene sections in seismic profiles. Core M-20 in both sections H-H' and I-I' is seen on seismic profile in Figure 5.

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(p. 465 follows)

HOLOCENE DEVELOPMENT OF SHELF-PHASE MISSISSIPPI RIVER DELTA PLAINS

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ABSTRACT

Early delta plain scientists emphasized the concept of the Mississippi River building a single delta plain at the end of the Holocene transgression beginning about 3000-4000 yBP. Their work suggests that during the Holocene transgression the rate of relative sea level rise was sufficient enough to prevent delta plain development and as a consequence, the Gulf of Mexico flooded the alluvial valley until the end of the Holocene transgression. Using new geophysical, geotechnical, and radiometric techniques, recent geologic studies of the Mississippi River delta plain and continental shelf reveal the occurrence of several relative sea level stillstands during the last stages of the Holocene transgression. Three shelf-phase delta plains have been identified to date, each separated by a regional transgressive surface of erosion produced by a rise in relative sea level. Sequence stratigraphic relationships suggest that whenever relative sea level rise rates exceed 2 cm/yr for several centuries, the delta cycle process of the Mississippi River stops, and the shelf-phase delta plain undergoes regional submergence and transgression. In contrast, it appears that whenever relative sea level rise rates drop below 2 cm/yr, the delta cycle process operates building a new shelf-phase delta plain.

INTRODUCTION

Geologic studies of the Mississippi River delta plain and continental shelf reveal the occurrence of several relative sea level stillstands during the last stages of the Holocene transgression. During periods of rapid relative sea level rise, delta plains undergo coastal submergence and land loss as their lower alluvial valleys fill with transgressive sediments. During periods of relative sea level stability, this trend of transgression and submergence is reversed. The river begins to fill its lower alluvial valley with lacustrine delta complexes behind the high-stand shoreline. With time, bayhead deltas build out into shallow coastal bays forming delta complexes that evolve into shelf-phase delta plains on the continental shelf. The timing of delta formation is tied to sea level stillstands when the rate of rise dropped below a critical threshold valve that allow river delta development. In the Gulf of Mexico, one can observe river deltas in all stages of evolution, since sea level reached the current highstand about 3,000 years ago (Curray, 1960). The lacustrine and bayhead delta complex stage can be observed in the Atchafalaya basin in Louisiana (Van Heerden and Roberts, 1988, Tye and Coleman, 1989). Other examples of bayhead deltas can be found at the Trinity River in Texas, the Pascagoula River in Mississippi, the Mobile River in Alabama, and the Escambia River in Florida. In contrast, the Mississippi River has filled its alluvial valley and built a large shelf-phase delta plain composed of a series of delta complexes (Fisk, 1944, Kolb and Van Lopik, 1958, Frazier, 1967).

The objective of the paper is to examine the Holocene history of the Mississippi River delta plain and continental shelf in light of trying to understand the relationship between sea level change and coastal evolution. The continental shelf of the Mississippi River delta plain contains an 18,000-year record of sea level changes and coastal evolution. By examining high resolution seismic profiles, deep cores, and shallow vibracores combined with new radiocarbon dating results, it is our intent to develop a better understanding of the sea level change thresholds required to drive the development of different styles of coastal evolution observed in the Mississippi River delta plain.

HOLOCENE GEOLOGIC FRAMEWORK

Mississippi River sediment accumulates in deltaic depositional sequences consisting of a regressive, or constructional phase followed by a transgressive or destructive phase (Russell, 1936, Bernard and LeBlanc, 1965, Coleman, 1988). Scruton (1960) used the term *delta cycle* to refer to those alternating phases of deltaic evolution. The delta-building process consists of prodelta platform formation, followed by distributary progradation and bifurcation, which results in delta plain establishment during the regressive phase of the delta cycle. This process continues until the distributary course is no longer hydraulically efficient. Abandonment occurs in favor of a more efficient course, initiating the transgressive phase of the delta cycle. The abandoned delta complex subsides, and coastal processes rework the seaward margin, generating a sandy barrier shoreline backed by bays and lagoons. Each transgressive depositional system is derived from a single abandoned delta or delta complex (Penland *et al.*, 1988). The term *delta plain* delineates a *systems tract* comprised of a set of delta complex *parasequences* deposited during a period of relatively stable sea level (Boyd *et al.*, 1989, McBride *et al.*, 1990). The term *delta complex* delineates a *parasequence* comprised of a set of smaller delta lobes that are tied to a common distributary and are built by the delta-switching process.

Fisk (1944) produced the first depositional model of the Mississippi River delta plain. This model depicts the single Holocene delta plain concept which was 4250 years old consisting of five delta complexes. From oldest to youngest, these are Maringouin, Teche, Lafourche, St. Bernard, and Modern Mississippi. Within these delta complexes, Fisk (1944) identified 20 individual stages. Kolb and Van Lopik (1958) presented the next single Holocene delta plain model showing the Mississippi River delta plain is 5400 years old consisting of seven delta complexes: the Sale-Cypremort, Cocodrie, Teche, St.Bernard, Lafourche, Plaquemines, and Balize, in order of decreasing age. The most recent depositional model of the Mississippi River delta plain is by Frazier (1967), and it depicted a single Holocene delta plain estimated to be 7250 years old and consisting of sixteen separate delta lobes organized into five delta complexes. From oldest to the youngest, these are the Maringouin, Teche, St. Bernard, Lafourche, and Plaquemines- Modern delta complexes. The major theme expressed by all three depositional models is the single Holocene delta plain concept. Each model suggests that during the Holocene transgression, which began about 18,000 years ago, relative sea level rise rates were sufficient enough to overwhelm Mississippi River sedimentation, transgress the lower alluvial valley, and prevent the development of a shelf-phase delta plain onto the continental shelf. The coastal zone was displaced more than 100 km landward under the effects of relative sea level rise during the Holocene transgression. It was not until the later stages in the Holocene transgression that relative sea level rise dropped below a threshold rate that allowed the Mississippi River *delta cycle* process to operate and build a delta plain sometime after 3,000 yBP. These models also suggested that the rise of sea level during the Holocene transgression was somewhat constant, producing a smooth sea level curve at rates above the threshold for regional submergence and transgression.

COASTAL EVOLUTION

New research results show relative sea level during the late Wisconsinan lowstand fell to depths of 130 m below present sea level in the northern Gulf of Mexico exposing the continental shelf and producing a set of shelf margin deltas representing lowstand system tracts. During the lowstand, the Mississippi River incised an alluvial valley across the continental shelf and, together with tributary streams and subaerial weathering processes, produced an erosional unconformity on the Pleistocene Prairie terrace marked by a widespread oxidation surface (Fisk, 1944). Sediments were largely restricted to infilling the Mississippi River alluvial valley and submarine canyon prior to 18,000 yBP. By 9000 yBP, the Mississippi River was no longer totally confined to the canyon and proceeded to develop a series of shelf-phase delta plains on the continental shelf during the Holocene transgression (Boyd *et al.*, 1989; Penland *et al.*, 1991). Individual shelf- phase delta plains were coupled with each stillstand, and backstepped landward in the form of transgressive system tracts, filling the lower alluvial valley of the Mississippi River. Each transgressive systems tract is built of a set of lacustrine, bayhead, and shelf- phase delta complexes organized into a delta plain truncated by a transgression surface of erosion and overlain by a major marine sand body.

This pattern of sea level change during the Holocene transgression corresponds very closely to the sea level curves and history for the Gulf of Mexico by Curray (1960), Coleman and Smith (1964), Nelson and Bray (1970), Frazier (1974), and Thomas and Anderson (1988; 1989). All the Holocene sea level curves show a sea level highstand about 3,000 years ago (Fig. 1). Maximum withdrawal estimates range between 90 m and 130 m respectively (Curray, 1960; Frazier, 1974). The earliest sea level curve by Curray (1960) indicates sea level stillstands at -60 m about 10 - 12,000 yBP and at -20 m about 8 - 10,000 yBP. The Nelson and Bray (1970) curve closely match Curray's (1960) sea level stillstands at -20 m about 7 - 9,000 yBP and -5 m about 3 - 6,000 yBP. Frazier's (1974) curve identified a similar pattern of Holocene sea level stillstands at slightly different levels and ages. Frazier (1974) recognized sea level stillstands at -20 m about 7 - 9,000 yBP and -5 m about 4 - 6,000 yBP. The pattern of Holocene sea level changes recognized by our investigation represents a hybrid curve of Curray (1960), Coleman and Smith (1964), Nelson and Bray (1970), and Frazier (1974). This Holocene curve recognizes three relative sea level stillstands in the last 10,000 years and each is identified by a major transgressive sandbody (Penland *et al.*, 1989). The Outer Shoal is associated with an early Holocene stillstand. Ship Shoal and Trinity Shoal are associated with a later Holocene stillstand below present. The transgressive barrier islands surrounding the delta plain are associated with the current sea-level stillstand. The Outer Shoal stillstand occurred about 7 - 9,000 yBP, the Trinity-Ship Shoal stillstand occurred about 4 - 6,000 yBP, and the Modern stillstand occurred 3,000 yBP (Fig. 2). The occurrence of these shoals indicates that a threshold value for relative sea level rise exists, at which a particular rate of rise produces either coastal retreat or progradation. Within the Modern delta plain, subsidence ranges from >0.50 cm/yr for young sediments to <0.10 cm/yr for older sediments based on data from the Terrebonne coastal region (Penland *et al.*, 1987). Under these conditions, the Mississippi River has built a delta plain of four smaller delta complexes over the last 3,000 years. The timing of these stillstands is based on previous work by Curray (1960), Nelson and Bray (1970), and Frazier (1974). Coleman and Smith (1964), McFarlan (1961), and Gould and McFarlan (1959) all suggest the current stillstand started 3,000 yBP. The recognition of regional transgressive surfaces, the Teche shoreline and ravinement surface, separating the individual delta plains and the stratigraphic relationships between overlying shoals and underlying delta plains indicate several hiatuses in delta plain development occurred during the Holocene transgression. Anderson and Thomas (1991) suggest marine ice sheet decoupling as a potential mechanism for rapid, episodic rises in relative sea level during the Holocene transgression.

Because three major stillstands took place between 3,000 and 10,000 yBP, less time was available for sea level

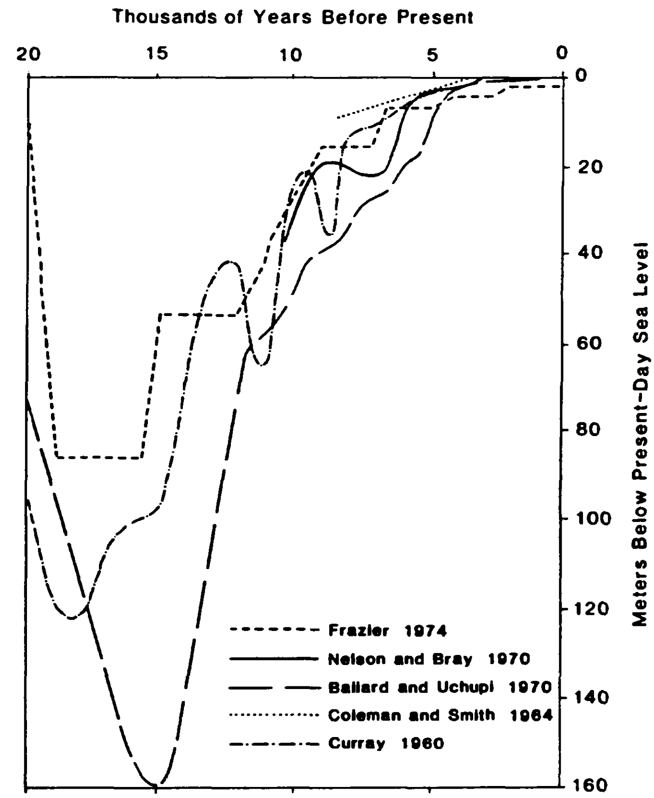

Figure 1. Holocene sea level curves for the Gulf of Mexico.

to rise 20 m; therefore the rate of rise must be higher than the average rate indicated for the Holocene transgression. During the period 3,000-10,000 yBP, a 20 m rise in sea level occurred incorporating two periods of rapid relative sea level rise. Assuming the early (7,000-9,000 yBP) and late (4,000-6,000 yBP) Holocene stillstands each lasted 2,000 years, this allows only 2,000 years available to accomplish a 20 m rise in sea level, at a rate of 1 >cm/yr or greater. If

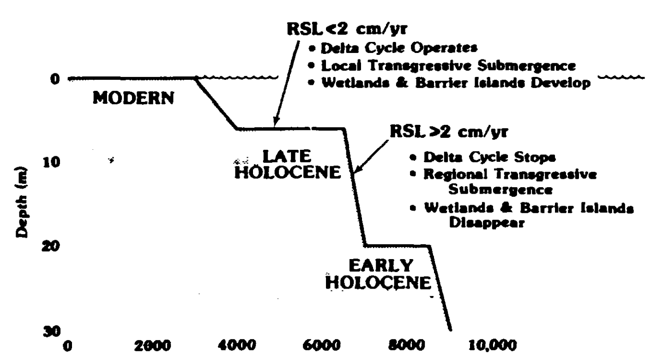

Figure 2. Relationship between sea level history and coastal stability. This curve represents a hybrid of Curray (1960), Nelson and Bray (1970), and Frazier (1974) combined with new seismic, vibracore, and radiometric data from the U.S. Geological Survey and Louisiana Geological Survey.

these transgressive events are only 500 years in duration, as some radiometric data suggest, the sea level rise rates would increase to >2 cm/yr. These relative sea level rise rates suggest that the threshold value for the regional submergence and transgression of a shelf-phase delta plain is probably at rates greater than 2 cm/yr.

CONCLUSION

Geologic studies of the Holocene evolution of the Mississippi River delta plain led to the recognition of multiple shelf-phase delta plains and the identification of a relative sea level rise threshold rate for regional submergence and transgression to take place. The Holocene transgression filled the lower Mississippi River valley with a series of backstepping, transgressive system tracts deposited during periods of relative sea level stability. Each transgressive system tract represents a shelf-phase delta-plain separated by a transgressive surface of erosion. The sequence stratigraphic relationships of the transgressive system tracts, filling the lower alluvial valley, indicate the threshold rate for the regional transgression and submergence of a single shelf-phase delta plain to take place is about 2 cm/yr for a sustained period of centuries. It also appears that whenever the rates of sea level rise drop below 2 cm/yr and achieve relative stability for a sustained period of centuries, the lower alluvial valley fills with lacustrine delta complexes behind a highstand shoreline. Once the lower alluvial valley is filled, bayhead delta complexes develop and evolve into shelf-phase delta plains.

Acknowledgments

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HOLOCENE GEOLOGIC FRAMEWORK OF THE TRINITY SHOAL REGION, LOUISIANA CONTINENTAL SHELF

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ABSTRACT

The geologic framework and sand resources of Trinity Shoal were assessed for their suitability as construction aggregate and beach replenishment material. The study of Trinity Shoal was conducted in two phases. First, potential sand deposits on Louisiana's continental shelf were identified from published nautical charts and bathymetric maps. A regional seismic survey was then conducted in the area, in which about 800 line-km of high-resolution seismic profiles were acquired and interpreted. The second phase of the study involved acquisition of vibracores. The vibracore locations were chosen from preliminary interpretation of the seismic data, and through analysis of historical and current coastal geomorphology.

From analysis of the seismic and core data, an isopach map, geologic cross-sections, and grain texture analyses were made. Texture, primary physical structures, and sequence associations were used to characterize sediment facies. Six depositional environments were delineated from the core and seismic data. The regressive depositional environments include: (1) prodelta; (2) delta fringe; and (3) distributary channel. The transgressive depositional environments include: (1) lagoon; (2) barrier; and (3) shoal. The shoal environment is represented by the marine sand body that caps Trinity Shoal, and is derived from reworking the underlying barrier facies. In contrast, the barrier environment is comprised of recurved spit, tidal inlet, washover, and sand sheet sub-environments.

Seismic profiles and core logs were integrated to calibrate the seismic facies with shoal and barrier environments interpreted from core analysis. The geologic cross-sections and the isopach map show the shoal and barrier sand thickness trend thinning in a general west to east direction across the study area. Shoal and barrier sand thickness exceed 8 m on the southern or seaward flank of Trinity Shoal. The shoal's transgressive sand facies offer the best source of material for coastal erosion control projects in terms of volume and quality, with a calculated volume of about 2 billion m^3.

INTRODUCTION

In 1983, the Louisiana Geological Survey (LGS) began a cooperative study with the U.S. Geological Survey (USGS) to inventory and map known sand resources on the Louisiana continental shelf. These offshore sand deposits were targeted for study in an effort to help mitigate Louisiana's severe coastal erosion problem (Penland *et al.*, 1990; McBride *et al.*, 1991). An inner-shelf shoal group of Holocene age offshore of south-central and southeastern Louisiana were identified from published bathymetric and nautical

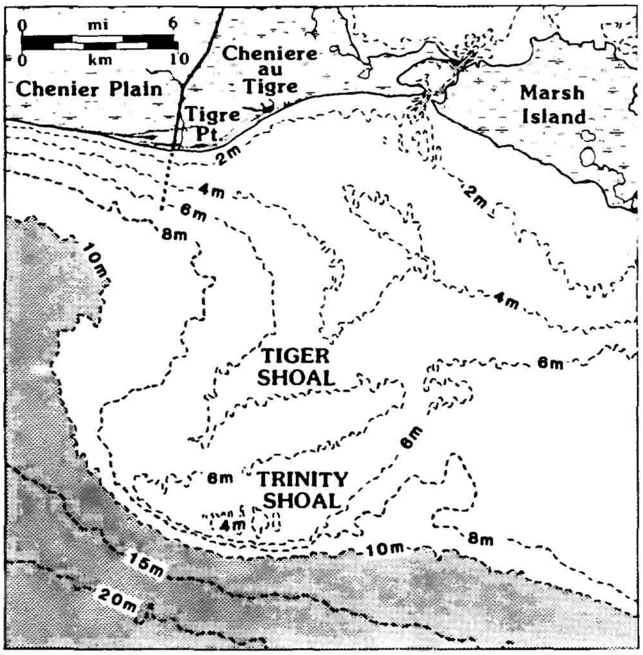

Figure 1. Study area showing the bathymetry of Trinity Shoal, Louisiana inner continental shelf.

charts. This paper describes the results of the study of Trinity Shoal and examines the Holocene geologic framework of this region.

Trinity Shoal is one of four major sand shoals that formed on the Louisiana continental shelf during the Holocene transgression, and is located about 40 km south of Marsh Island and the coastal communities of Freshwater Bayou, Intracoastal City, and Morgan City (Fig. 1). Trinity Shoal is a shore-parallel lunate shoal 30 km long and 5 to 10 km wide that formed in association with the Teche delta about 3500 years ago. The shoal lies in 7 to 10 m of water, and has a surface relief of 2 to 4 m.

METHODOLOGY

Exploration for suitable offshore aggregate resources in the Trinity Shoal region was conducted in two phases. First, two regional seismic surveys were conducted in the area during 1983 and 1985. A total of about 800 line-km of high-resolution seismic data were collected and analyzed for this study (Fig. 2). A Datasonics 3.5-kHz subbottom profiler was employed as the high-frequency tool; an ORE Geopulse–a uniboom-type system–was used to provide greater penetration. Vertical resolution of these two seismic systems is about 0.5 m and 1.5 m, respectively. Penetration averaged about 15 m for the 3.5-kHz device and 100 m for the Geopulse device in the Trinity Shoal area. The returning signals were split-traced on an EPC 3200 recorder at sweep rates of 1/8 sec for each channel, resulting in an effective display of 1/4 sec for the entire record. Filter settings for the ORE Geopulse were variable, depending upon the area surveyed. All data were recorded on a Hewlett Packard 4300 reel-to-reel magnetic tape machine for subsequent playback. Navigation data were recorded on magnetic tape on a Texas Instruments Silent 700 and processed into trackline maps by the U.S. Geological Survey in Corpus Christi, Texas and at Woods Hole, Massachusetts. Seismic interpretations were plotted onto the trackline charts on mylar overlays at a scale of 1:80,000.

The second phase of sand exploration involved acquisition of 30 vibracores, which were collected during 1986 (Fig. 2). Vibracoring, the preferred method of coring in unconsolidated sediment, uses a vibrating core barrel to achieve penetration into the sediment. The vibracoring technique usually preserves sedimentary structures contained within the core barrel better than other coring methods. Vibracore locations were chosen from interpretations of seismic data and through analysis of current and historical shoreline geomorphology.

The textural suitability of offshore sand deposits as borrow material was determined by grain size analysis of sediment samples obtained from the vibracores (Table 1). After completing vibracore descriptions and textural analysis, core data were integrated with the seismic profiles to calibrate the interpreted seismic packages. This procedure allowed a regional interpretation of the seismic facies in terms of the geologic setting and the depositional process. Isopach maps and geologic cross-sections were then produced to map thickness patterns and trends of sand resources throughout the study area.

TRINITY SHOAL GEOMORPHOLOGY

Trinity Shoal is the westernmost member of an inner-shelf shoal group offshore of south-central Louisiana (Fig. 3). Six north-south oriented bathymetric profiles across Trinity Shoal illustrate its terrace morphology (Fig. 4). The shoreface landward of Trinity Shoal represents a transitional zone between the Mississippi River delta plain to the east near Marsh Island and the chenier plain near Cheniere au Tigre to the west. The Marsh Island shoreface is erosional with *in situ* and reworked, intertidally exposed shell reefs, of *Crassostrea* sp. and *Rangia* sp. Slopes on the Marsh Island shoreface range between 1:300 and 1:400. The Cheniere au Tigre shoreface varies from zones of active mud accumulation derived from the Atchafalaya River, to zones of shoreface retreat. Slopes on the chenier plain shoreface range from 1:400 to 1:500.

The back shoal represents the zone between the crest of Trinity Shoal and the base of the Marsh Island shoreface. The landward slope of the back shoal is between 1:1800 and 1:2000. The crestline of Trinity Shoal is concave landward with seaward slopes of 1:1200 and 1:1400. The seaward slope of Trinity Shoal is relatively steep, with 1:800 to

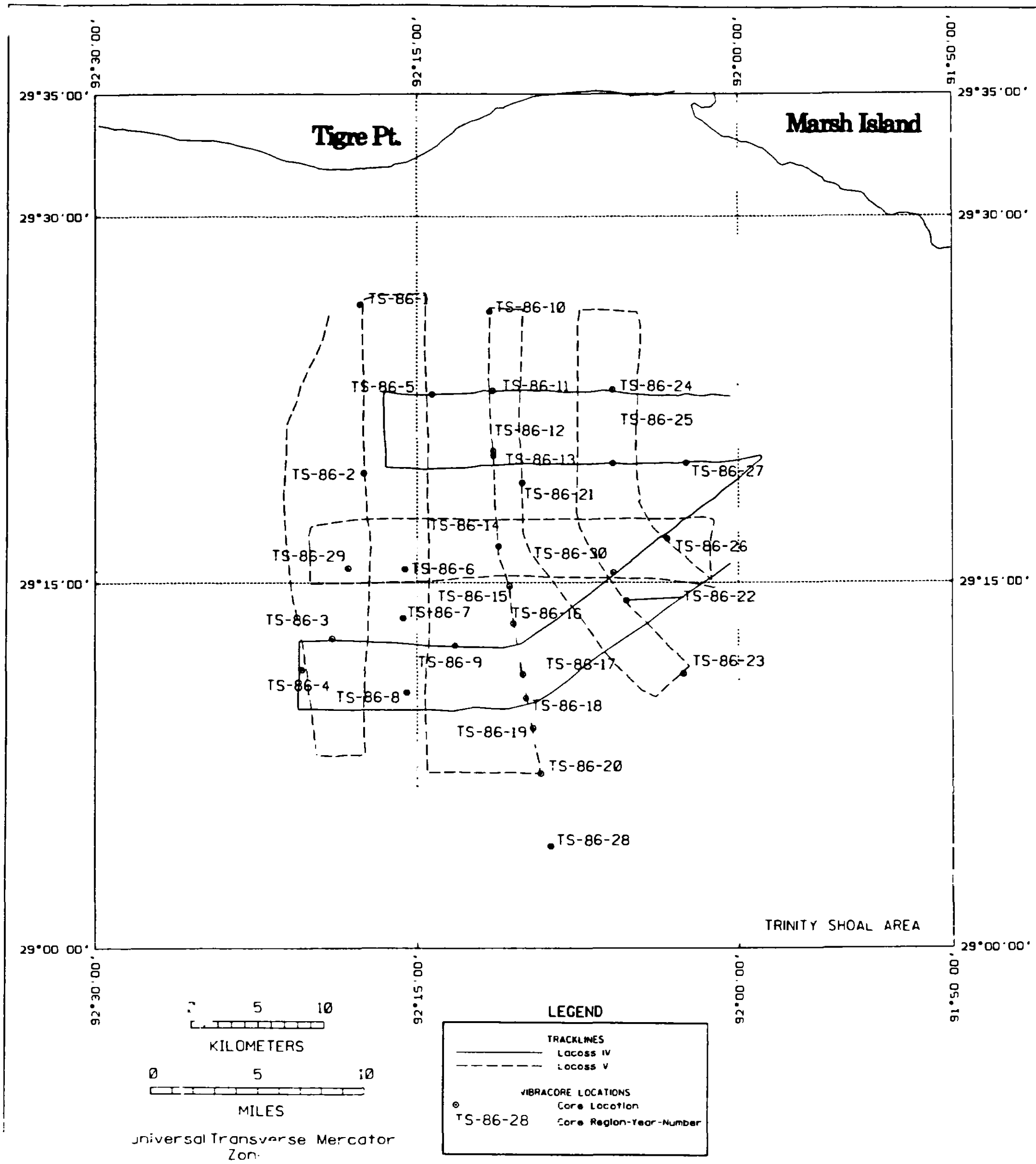

Figure 2. Seismic tracklines and vibracore locations, Trinity Shoal.

1:1000 slopes. Together, the back shoal, shoal, and ramp represent the shelf expression of a transgressed barrier shoreline associated with the abandoned Teche delta complex. A comparison of historical hydrographic surveys of Trinity Shoal indicates that landward shoal migration has occurred. Trinity Shoal appears to retreat landward by erosion of the seaward shoal ramp with deposition on the back shoal. Rates of shoal retreat between 1887 and 1932 are less than 5 m/yr.

Surficial sediment on Trinity Shoal was mapped as very fine-grained sand by Krawiec (1966). Frazier (1974) mapped the surface lithofacies of Trinity Shoal as 100%-75% sand. The median phi diameter for sand ranged from 3.4 phi to 3.8 phi with secondary amounts of shell and organic material. Krawiec (1966) concluded that Trinity Shoal is composed of sands from a transgressive barrier shoreline associated with an abandoned Mississippi River delta.

HOLOCENE GEOLOGIC FRAMEWORK

Four large sand shoals were formed in the retreat path of the Mississippi River delta plain during the Holocene transgression (Penland *et al.*, 1989) (Fig. 3). These sand bodies include Trinity Shoal, Ship Shoal, the Outer Shoal, and the St. Bernard Shoals, and represent former shoreline positions of deltas associated with lower stillstands in rela-

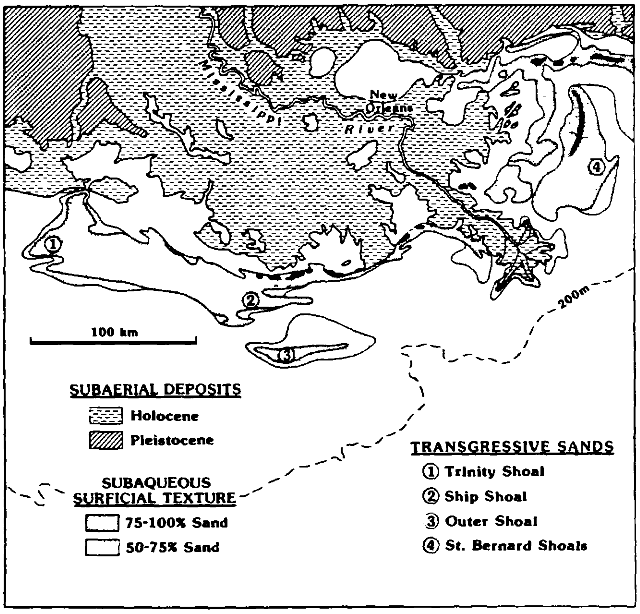

Figure 3. Location of the Holocene sand shoals offshore of the Mississippi River delta plain (modified from Frazier, 1974).

tive sea level. Short periods of rapid relative sea level rise led to the transgressive submergence of these shorelines, which today can be recognized at the -10 m and -20 m isobaths on the Louisiana continental shelf. Trinity Shoal and Ship Shoal comprise the -10 m Holocene shoreline trend. The Outer Shoal and the St. Bernard Shoals make up the -20 m earlier Holocene shoreline trend. These sand bodies provide tremendous potential as sources of aggregate for shoreline erosion control. Scientifically, the shoals provide insight into the processes that control coastal evolution and shelf sand development under the conditions of eustacy and subsidence.

Relative sea level in the northern Gulf of Mexico during the late Wisconsin lowstand fell to depths of -130 m below present sea level, exposing the continental shelf and producing a set of shelf-margin deltas (Berryhill, 1986; Berryhill and Suter, 1986; Kindinger, 1989). During the 18,000 yr B.P. lowstand, the Mississippi River incised a trench across the Louisiana continental shelf. Together with tributary streams and subaerial weathering processes, an erosional unconformity was formed on the Pleistocene Prairie terrace, which is marked by a widespread oxidation surface (Fisk, 1944). Between 20,000 to 10,000 yr B.P., sediment from the ancestral Mississippi River was restricted to infilling the Mississippi Canyon (Coleman *et al.*, 1983). Between 9000 and 3500 yr B.P. the Mississippi River was no longer confined totally to the canyon, which allowed a series of shelf-phase delta plains to form on the outer-to mid-continental shelf during the Holocene transgression (Fisk and McClelland, 1959; Boyd *et al.*, 1988). The establishment of individual delta plains, built of smaller complexes through the delta switching process, indicates the existence of several periods during which the rate of sea level rise increased. As rates of relative sea level rise increased, the earlier Holocene shelf-phase delta plains were transgressed and submerged, producing the large sand shoals from reworked distributary and barrier shoreline deposits, marking their former shoreline position.

Each shelf-phase delta plain lies on a transgressive surface of erosion, and consists of a regressive and transgressive component (Penland *et al.*, 1988). The regressive component is built by shallow water deltas, consisting predominantly of distributary sands encased in prodelta mud and capped by freshwater marsh deposits. The transgressive component consists of lagoonal deposits overlain by a barrier shoreline or shelf sand body (Fig. 5). Lying along the -10 m isobath, the Trinity Shoal and Ship Shoal trend represent the former shoreline of an earlier Holocene delta plain.

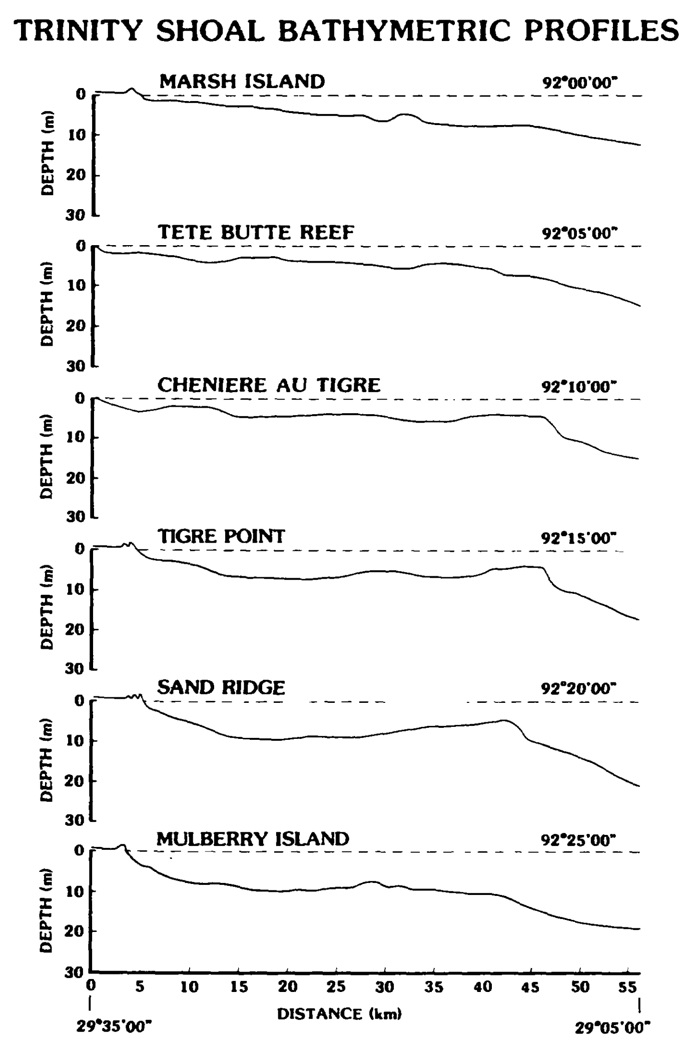

Figure 4. The terrace morphology of Trinity Shoal illustrated by north-south bathymetric profiles.

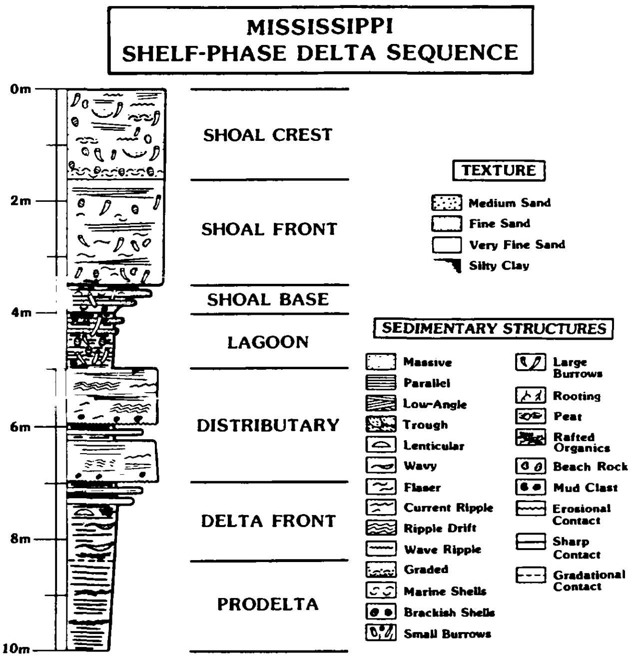

Figure 5. Generalized composite stratigraphic model for a transgressive Mississippi River shelf-phase delta plain (from Penland *et al.*, 1988).

TRINITY SHOAL GEOLOGY

Depositional Environments

Analyses of vibracores and seismic data resulted in the delineation of six distinct depositional environments. Texture, primary physical structures, and sequence associations were used to characterize the depositional environment and sediment facies. The regressive sediment environments include: (1) prodelta; (2) delta fringe; and (3) distributary channel. The transgressive sediment environments include: (1) lagoon; (2) barrier; and (3) shoal (Fig. 5 and 6).

The prodelta environment was interpreted from core analysis as fine-grained laminated clay deposits that form the platform upon which the distributary network prograded. The delta fringe environment is characterized by a coarsening-upward sequence of lenticular and wavy cross-beds of silt and sand with interbedded clay deposits. Distributary channel deposits are composed of channel fill and levee/overbank sand and silt, as well as the fine-grained fill that seals the channel.

The shoal environment is represented by the marine sand body that caps Trinity Shoal. Massive in appearance, the shoal environment is composed of a marine sand body derived from reworking the underlying barrier facies. This sand facies contains faint horizontal and planar bedding, mud-filled burrows, and shell fragments throughout. It is a more homogeneous sand body, with no inclusions of wavy

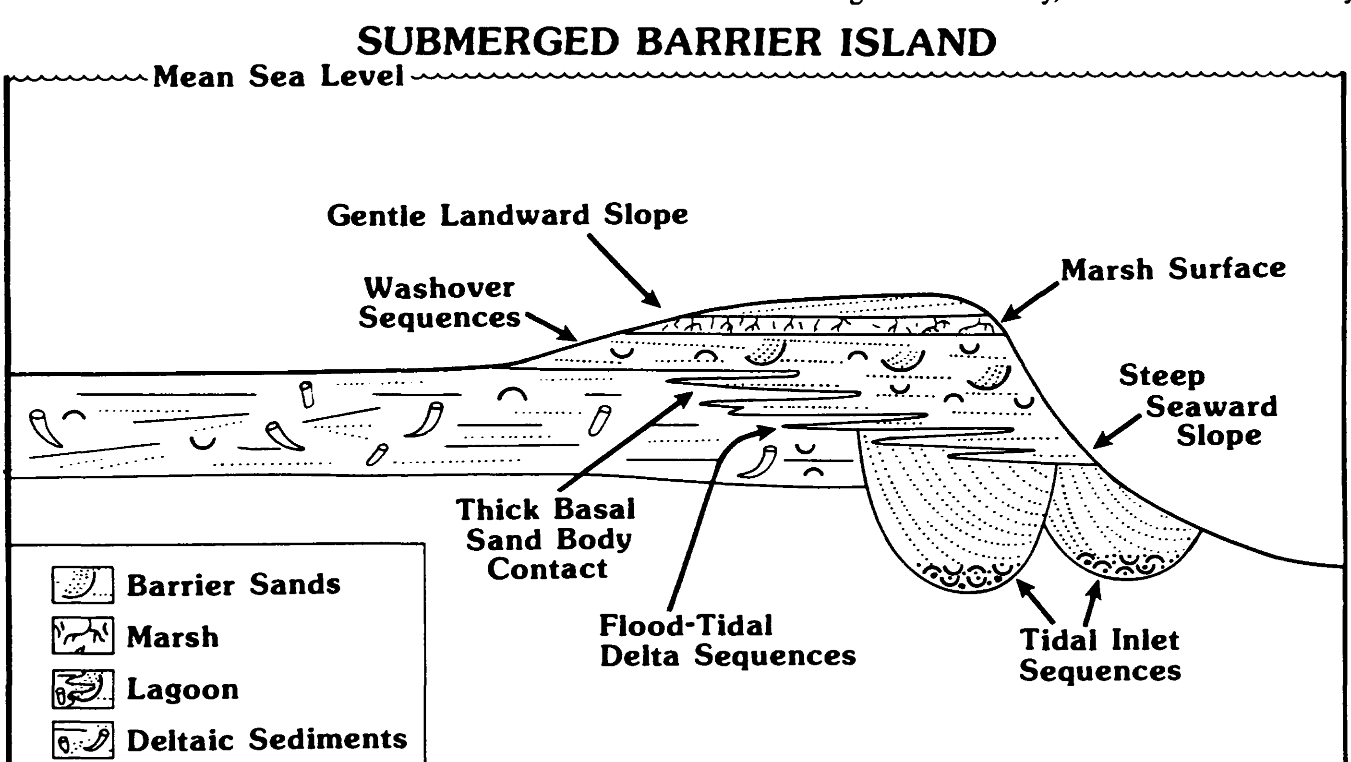

Figure 6. Schematic illustrating the sedimentary facies of submerged barrier islands.

Table 1. Grain texture analyses from the transgressive shoal and barrier deposits, Trinity Shoal.

VIBRACORE SAMPLE NUMBER	DEPTH IN CENTI-METER	CALCULATION OF MOMENT MEASURE STATISTICS				CALCULATION OF FOLK STATISTICS				CALCULATION OF INMAN STATISTICS				TEXTURAL STATISTICS			
		Mean Size	Sorting	Skewness	Kurtosis	Mean Size	Sorting	Skewness	Kurtosis	Mean Size	Sorting	Skewness	Kurtosis				
TS-86-03	10	3.41	.38	-.85	3.98	3.43	.34	.18	.83	3.46	.36	.19	.42	sand	v. well sorted	fine skewed	platykurtic
TS-86-03	300	3.62	.35	-1.48	5.48	3.61	.33	-.18	1.04	3.59	.34	-.22	.62	sand	v. well sorted	coarse skewed	mesokurtic
TS-86-04	10	3.80	.36	-.88	3.20	3.83	.37	.05	1.12	3.85	.36	.14	.77	muddy sand	well sorted	near symmetrical	leptokurtic
TS-86-04	250	3.58	.55	-1.46	2.68	3.61	.53	-.26	1.42	3.59	.45	-.19	1.28	muddy sand	mod. well sorted	coarse skewed	leptokurtic
TS-86-06	05	3.28	.54	-1.31	2.80	3.37	.49	-.06	1.56	3.40	.38	.20	1.54	sand	well sorted	near symmetrical	very leptokurtic
TS-86-06	325	3.75	.37	-1.91	7.32	3.78	.32	.00	1.47	3.78	.26	.07	1.45	muddy sand	v. well sorted	near symmetrical	leptokurtic
TS-86-07	10	3.38	.36	-1.04	4.92	3.40	.32	.23	.85	3.43	.34	.21	.40	sand	v. well sorted	fine skewed	platykurtic
TS-86-07	250	3.45	.35	-1.24	6.88	3.46	.32	.12	.75	3.48	.36	.12	.33	sand	v. well sorted	fine skewed	platykurtic
TS-86-08	05	3.35	.30	-.07	4.09	3.36	.29	.27	1.10	3.38	.30	.21	.54	sand	v. well sorted	fine skewed	mesokurtic
TS-86-08	305	3.32	.68	-1.30	.83	3.44	.60	-.33	1.50	3.42	.47	-.16	1.56	sand	mod. well sorted	v. coarse skewed	very leptokurtic
TS-86-09	100	3.19	.48	-.74	1.37	3.21	.49	-.10	1.17	3.20	.49	1.06	.68	sand	well sorted	coarse skewed	leptokurtic
TS-86-09	300	3.35	.45	-.76	.84	3.35	.46	-.16	.85	3.34	.49	-.13	.43	sand	well sorted	coarse skewed	platykurtic
TS-86-15	10	3.05	.44	-.63	2.61	3.05	.42	-.07	1.04	3.04	.40	-.12	.83	sand	well sorted	near symmetrical	mesokurtic
TS-86-17	10	3.27	.46	-.66	.61	3.28	.48	-.11	1.03	3.27	.49	-.05	.56	sand	well sorted	coarse skewed	mesokurtic
TS-86-17	280	3.55	.40	-1.98	6.68	3.57	.36	-.32	1.00	3.54	.36	-.25	.63	sand	well sorted	v. coarse skewed	mesokurtic
TS-86-18	10	3.53	.37	-1.35	4.89	3.54	.33	-.17	.76	3.52	.37	-.16	.34	sand	v. well sorted	coarse skewed	platykurtic
TS-86-18	180	3.45	.42	-1.65	4.47	3.49	.40	-.24	.97	3.47	.39	-.14	.73	sand	well sorted	coarse skewed	mesokurtic
TS-86-21	10	3.05	.32	-.29	2.27	3.04	.32	-.13	.76	3.03	.35	-0.13	.34	sand	v. well sorted	coarse skewed	platykurtic
TS-86-21	95	3.17	.40	-.29	2.70	3.15	.38	-.08	1.40	3.13	.34	-.21	1.02	sand	well sorted	near symmetrical	leptokurtic
TS-86-23	10	3.40	.53	-.64	1.42	3.45	.52	.13	1.26	3.49	.46	.27	1.11	muddy sand	mod. well sorted	fine skewed	leptokurtic
TS-86-23	230	3.53	.60	-1.24	1.07	3.54	.59	-.39	1.42	3.47	.52	-.39	1.08	muddy sand	mod. well sorted	v. coarse skewed	leptokurtic
TS-86-25	20	2.77	.85	.02	-1.12	2.76	.89	-.02	.73	2.74	.98	-.07	.35	sand	moderately sorted	near symmetrical	platykurtic
TS-86-29	10	3.35	.43	-1.14	4.21	3.39	.39	.09	1.24	3.43	.35	.24	.96	sand	well sorted	near symmetrical	leptokurtic
TS-86-29	250	3.48	.33	-.26	3.07	3.47	.33	.15	.75	3.49	.36	.14	.33	sand	v. well sorted	fine skewed	platykurtic
TS-86-30	05	2.94	.54	-.59	.32	2.94	.54	-.35	1.09	2.88	.52	-.35	.77	sand	mod. well sorted	v. coarse skewed	mesokurtic

*NOTE: Measurements are in "phi" units.

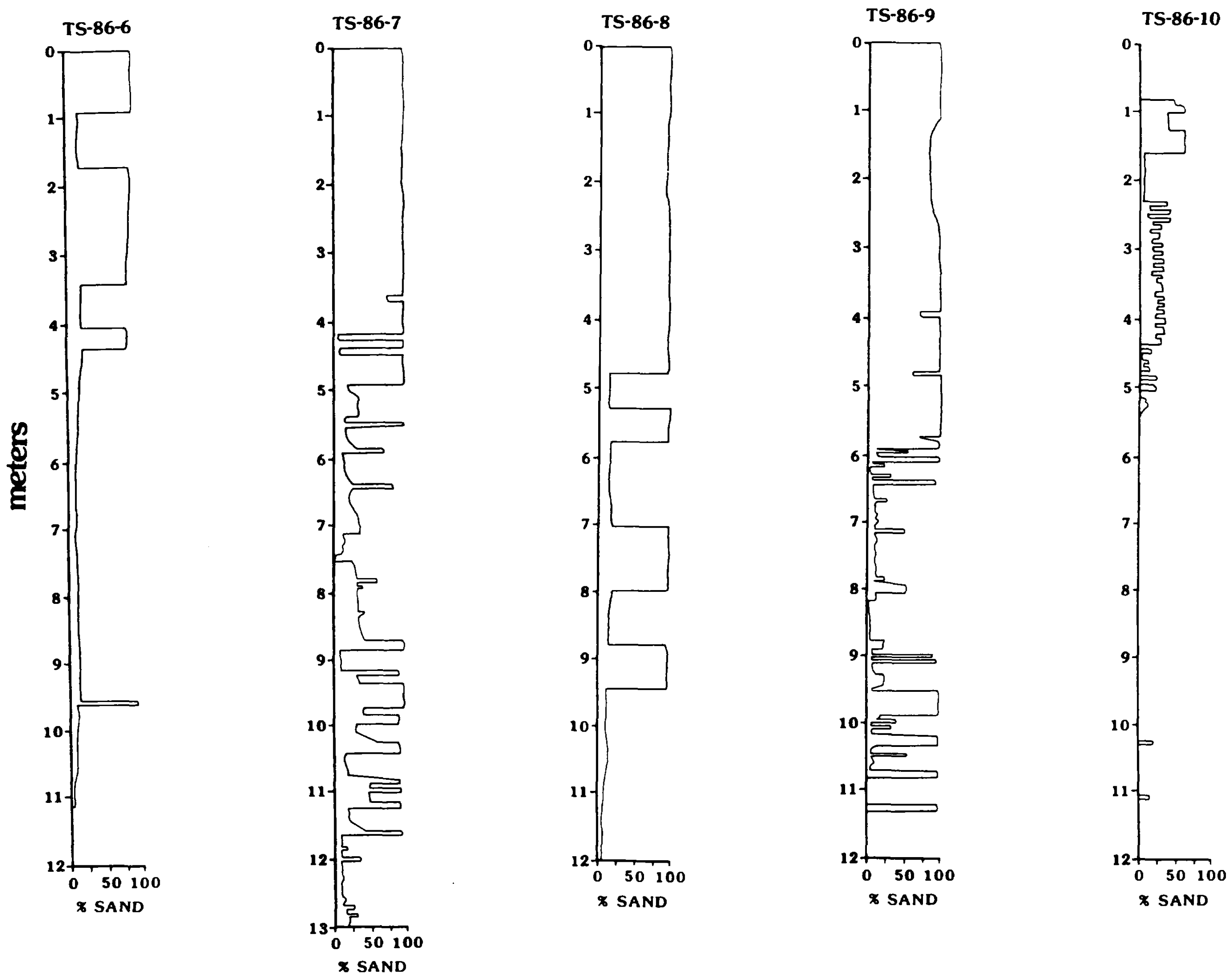

Figure 7. Sedimentary textural descriptions showing percent sand for Trinity Shoal vibracores TS 6 to TS 10.

or lenticular bedding, and a mean grain-size of 3.29 phi (Table 1). The percent sand is greater than 90% and is very well to well sorted. In contrast, the barrier environment is represented by recurved spit, tidal inlet, washover, and sand sheet environments of deposition. The typical barrier sequence coarsens-upward, representing the transgressive contact between the muddy lagoon deposits and the sandy flood-tidal delta and washover deposits. The facies of the barrier environment contain a variety of burrows throughout, sandy/shelly storm bedding, discrete shells, and lenticular, wavy, and small scale cross-beds. The mean grain-size of the barrier sub-environments is 3.19 phi, and is moderately to well sorted (Table 1). The lagoon environment is a coarsening-upward sequence of interbedded mud with silt and sand storm beds or washover deposits. Primary physical structures include small to large burrows, wavy and lenticular silt and sand beds, and shell fragments throughout. The sedimentary textural parameters in terms of percent sand for five of the Trinity Shoal vibracores analyzed for this study are illustrated in Figure 7. Sediment samples were obtained from the vibracores and used for analysis of grain size for transgressive and regressive facies associated with Trinity Shoal (Table 1).

Cross-Sections

Seismic profiles and vibracore logs (Fig. 2) were integrated to build five dip and five strike cross-sections (Fig. 8). Dip cross-sections depict the Trinity Shoal sand body rapidly thinning from the west to the east. Cross-section C - C' (Fig. 9) illustrate the interpreted depositional environments and facies associations. The combined thickness of the shoal and barrier environments exceed 8 m. The barrier sand body pinches out by cross-section E - E' (Fig. 8) and a 1 to 2 m thick shoal sand body blankets lagoonal mud farther to the east. The combined width of the shoal and barrier

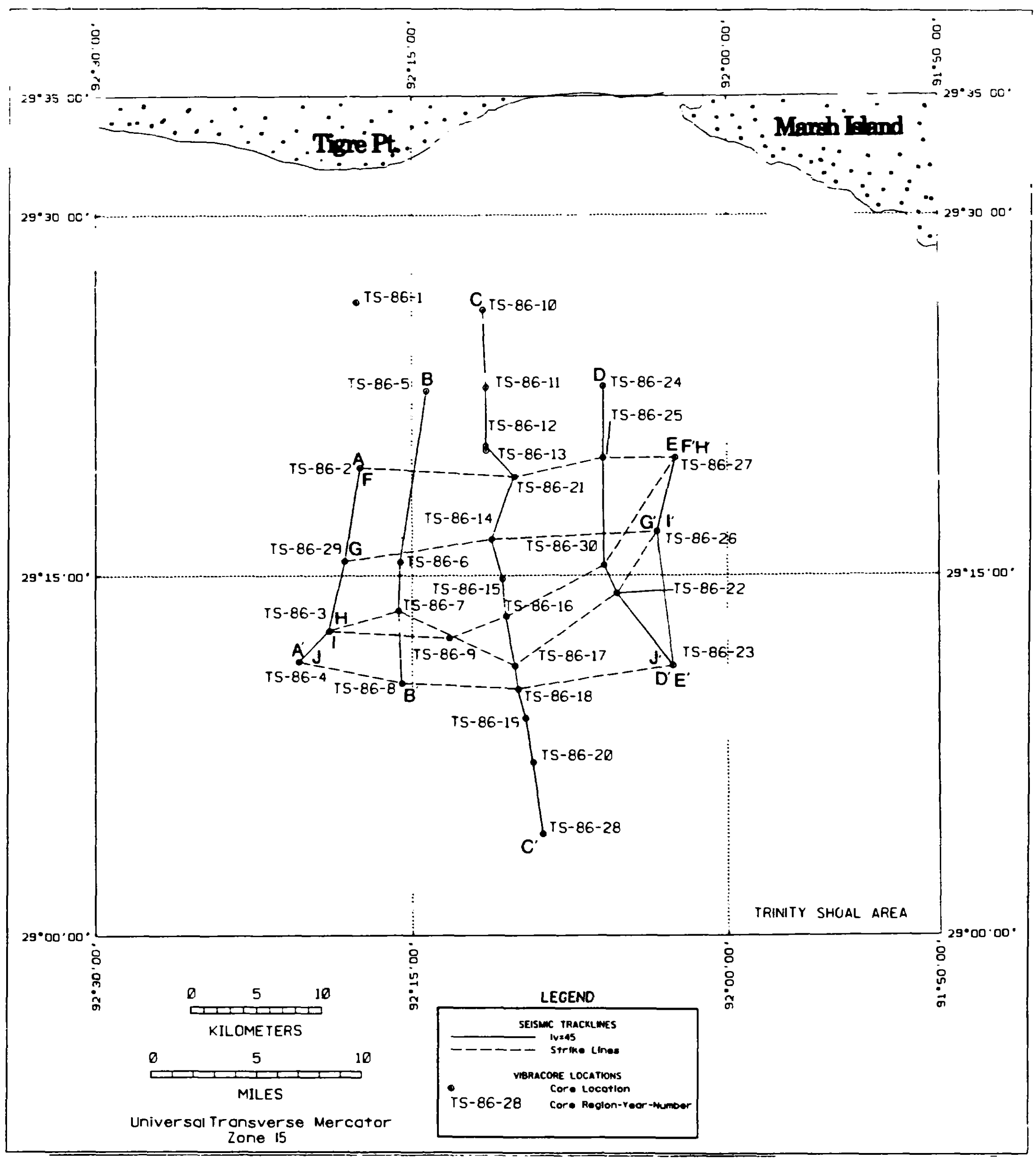

Figure 8. Vibracore locations and geologic cross-sections, Trinity Shoal.

environments of Trinity Shoal varies from 2 to 4 km.

Strike cross-sections also depict the Trinity Shoal sand body rapidly thinning to the east (Fig. 10 and 11). Cross-sections H - H' (Fig. 10) and J - J' (Fig. 11) illustrate the thickest portion of Trinity Shoal. Lagoonal mud form a persistent blanket throughout the area. The shoal sand body forms a thin 1 to 2 m layer overlying the core of the barrier deposits to the west and the lagoonal mud to the east.

Isopach Mapping

The Trinity Shoal isopach map of the combined shoal and barrier environments shows a westward-skewed sand body wrapping around the western margin of the Mississippi River's Late Holocene delta plain (Fig. 12). The thickness of the shoal and barrier deposits ranges from 0 to greater than 8 m. The thickest portion of the shoal and barrier deposit occurs on the southern or seaward flank of Trinity Shoal. This portion of the shoal also represents the highest quality and concentrated volume of sand within the entire area. Shoal and barrier sand thickness patterns trend in a general east-west direction across the study area.

The approximate total volume of sand contained within Trinity Shoal was determined by calculating the area between each 2 m contour from the isopach map using the following formula:

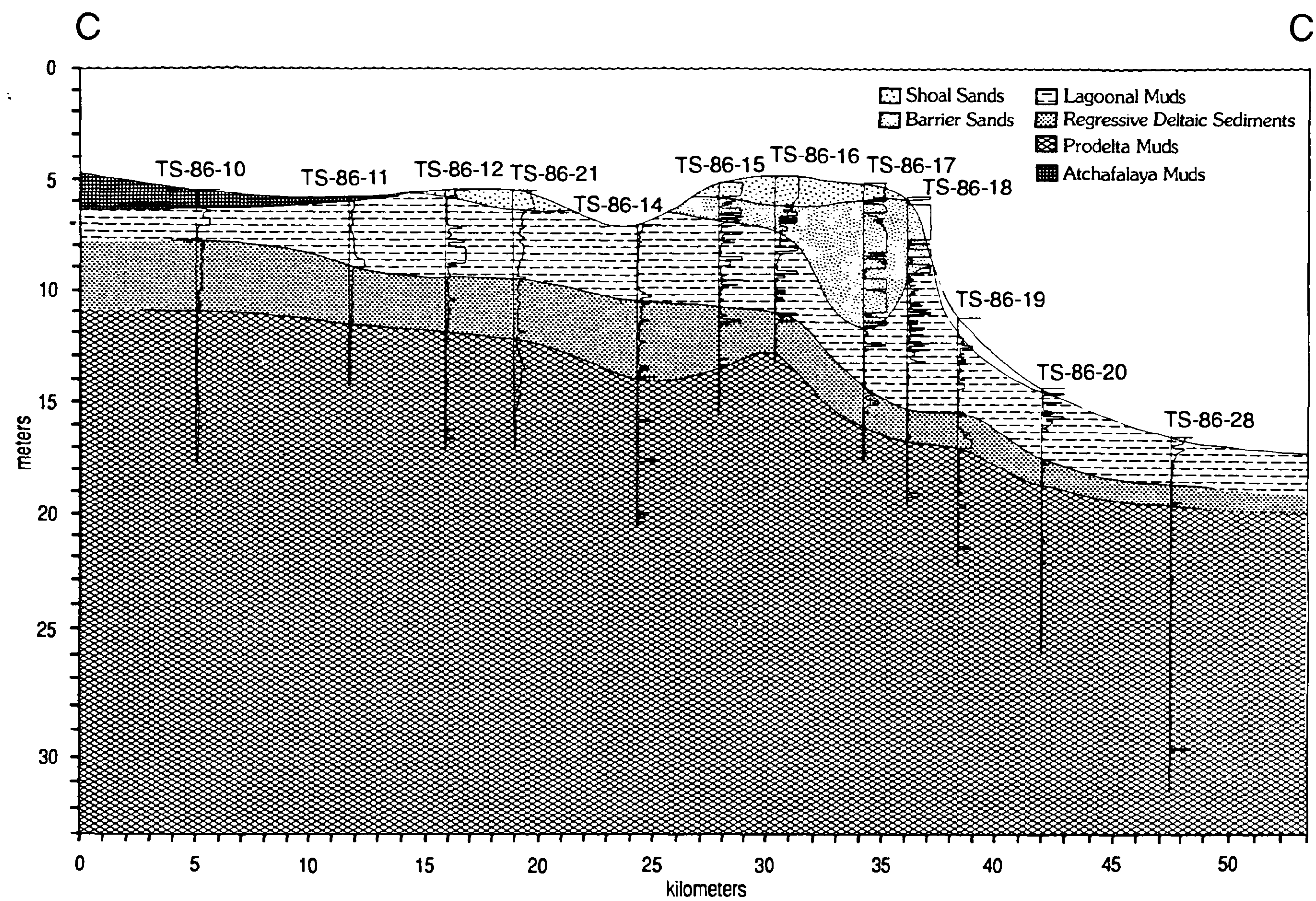

Figure 9. Stratigraphic dip cross-section C - C', Trinity Shoal.

$$\text{Volume} = \frac{\text{Area 1} - \text{Area 2}}{2} \times \text{Thickness}$$

The total volume of sand contained within the shoal and barrier environments was calculated at about 2 billion m^3. The volume of sand between contours is about 1.1 billion m^3 for the 0 to 2 m interval, 0.6 billion m^3 for the 2 to 4 m interval, 241 million m^3 for the 4 to 6 m interval, 65 million m^3 for the 6 to 8 m interval, and 3 million m^3 for the 8 to 10 m contour interval.

SUMMARY AND CONCLUSIONS

Louisiana is currently experiencing the highest rates of shoreline retreat and wetland loss in the United States. Barrier island restoration and beach replenishment projects require large amounts of construction aggregate for beach, dune, and back-barrier building. Trinity Shoal has tremendous potential as a source of aggregate for shoreline erosion control. The shoal's transgressive sand facies offer the best source of material for coastal erosion control projects in terms of volume and quality, with a calculated volume of 2 billion m^3 based on our analysis of the current data base. However, seismic grid and vibracore locations were chosen based on existing public nautical and bathymetric charts. Data interpretation and mapping has revealed Trinity Shoal extends farther to the west than shown on the published maps. Extending seismic and vibracore coverage to the west of the present grid will enable the true areal extent, thickness patterns, and total volume of quality sand in Trinity Shoal to be more accurately determined. Further study of the Holocene shoals on the Louisiana continental shelf will also provide greater insight into the processes that control coastal evolution and shelf sand development under the conditions of eustacy, subsidence, and other geologic processes.

Acknowledgments and Disclaimer

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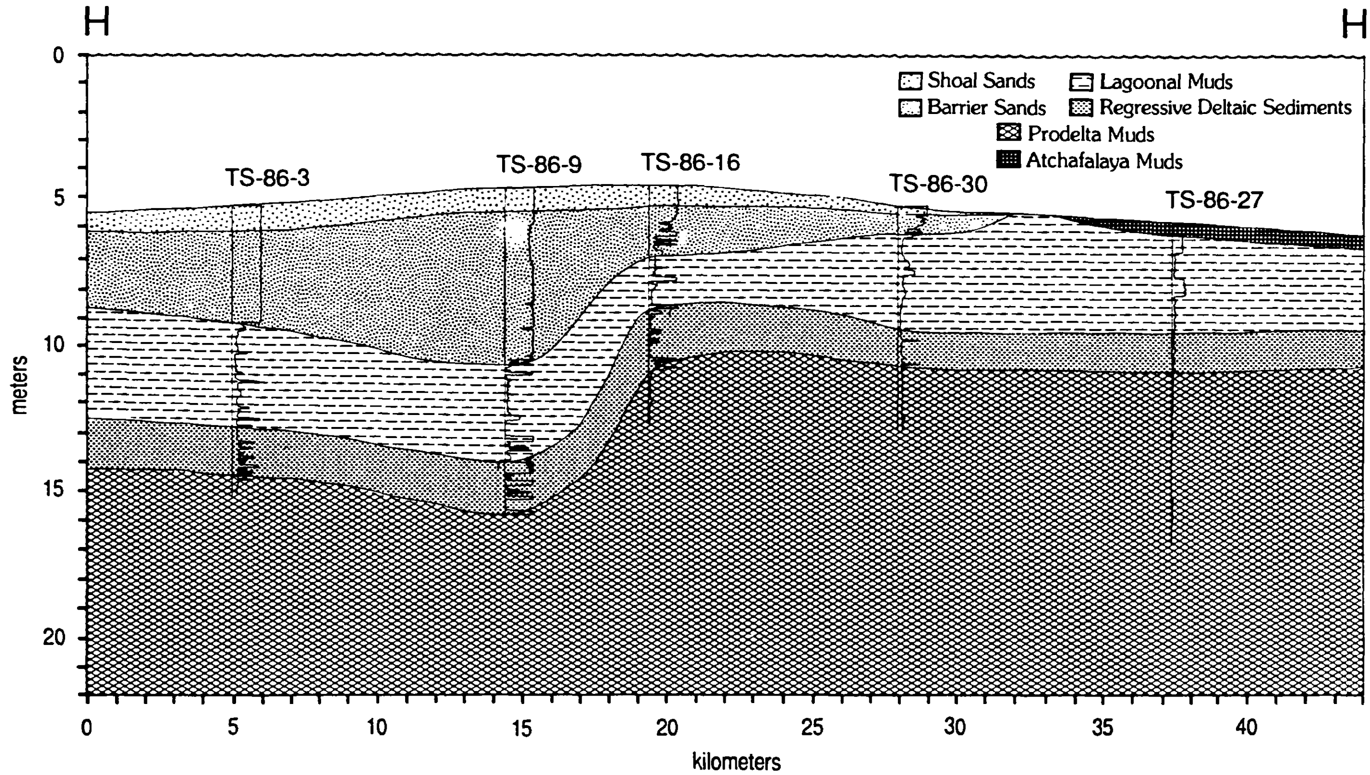

Figure 10. Stratigraphic strike cross-section H - H', Trinity Shoal.

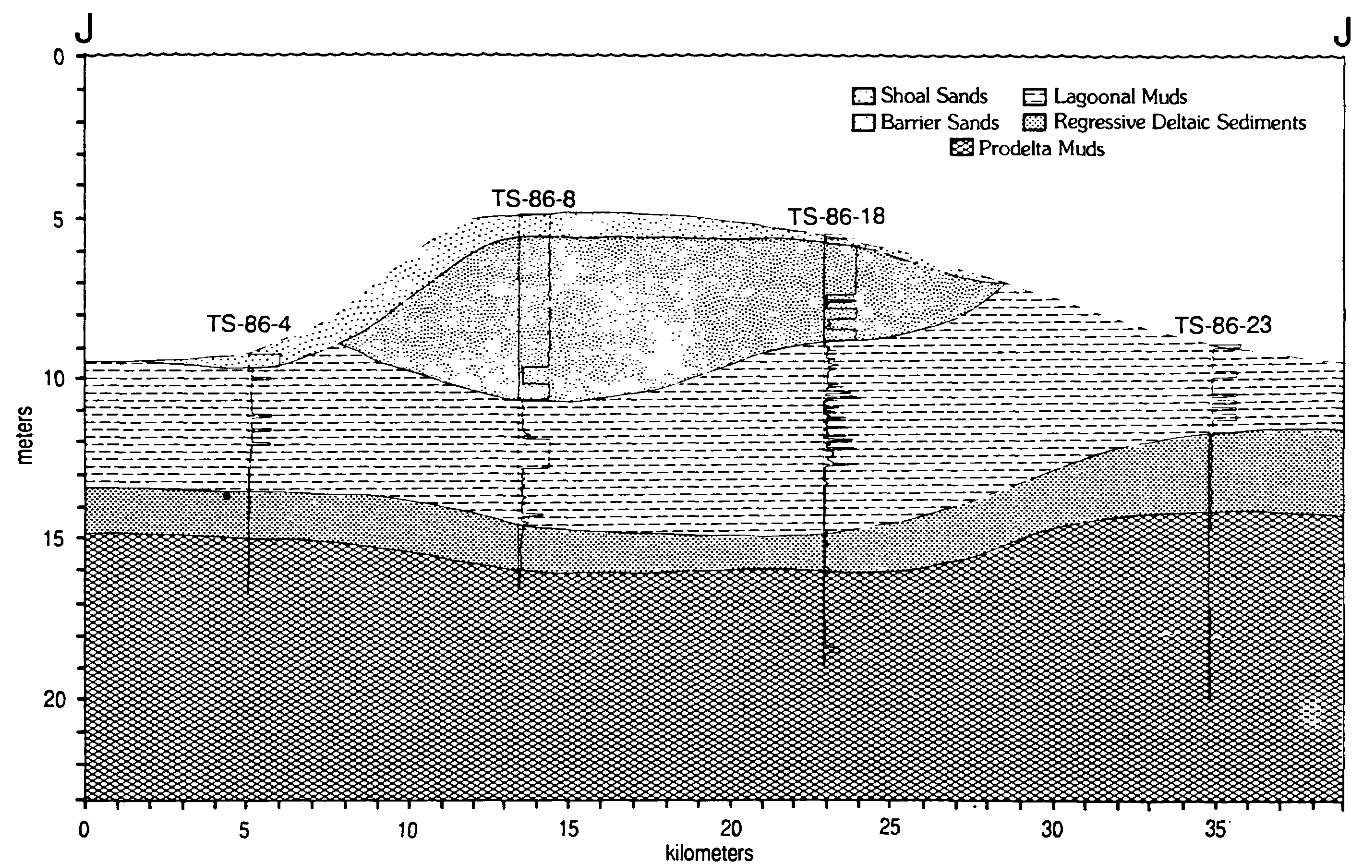

Figure 11. Stratigraphic strike cross-section J - J', Trinity Shoal.

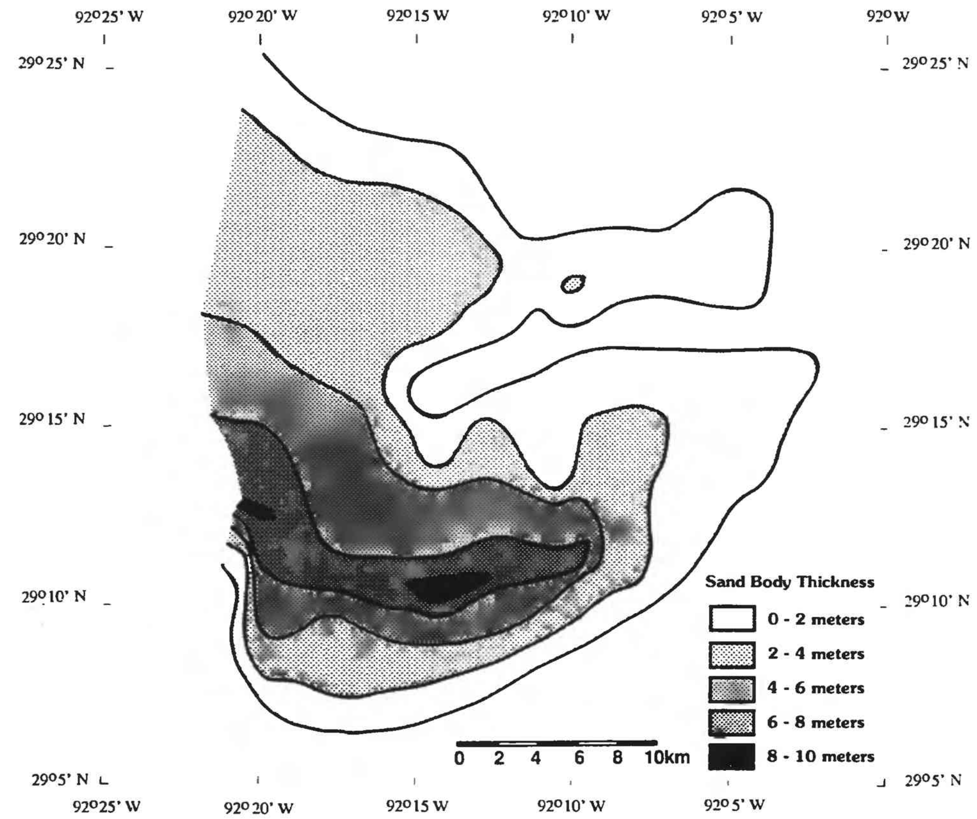

Figure 12. Isopach map of the transgressive shoal and barrier deposits, Trinity Shoal.

figures. Dr. D. Davis and Dr. M. Byrnes critically reviewed the paper. P. Connor performed the grain texture analyses, and S. Bollich and S. Sullivan typed the manuscript.

Disclaimer. Use of brand names in this report is for identification only and does not imply endorsement by the U.S.G.S. or by the Louisiana Geological Survey.

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(p. 481 follows)

RATES OF RELATIVE SEA LEVEL CHANGE IN THE NORTHERN GULF OF MEXICO

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ABSTRACT

Over the last 65 years, relative sea-level has averaged 0.23 cm/yr in the Gulf of Mexico, and as much as 1.5 cm/yr in the Mississippi River delta plain of Louisiana, ranking the second highest after Japan by global region. Under the conditions of rapid sea-level rise and subsidence, thousands of acres of productive coastal wetlands have been converted to open water each year. Between 1956 and 1978, Texas and Mississippi lost 11,400 ha and 2490 ha of wetlands respectively. Louisiana lost 18,755 ha of wetlands.

Relative sea-level rise (RSL), which is the combined effects of eustatic change and subsidence, ranges from 0.15 cm/yr to 0.23 cm/yr in Mississippi and Florida and 0.63 cm/yr to 1.5 cm/yr in Texas and Louisiana, respectively. The Environmental Protection Agency (EPA), National Resource Council (NRC), and the Intergovernmental Panel on Climate Change (IPCC) predict eustatic sea level to increase over the next century due to global climate change. With predicted change, areas currently influenced by subsidence will experience a dramatic increase in rates of land loss. Other areas in the northern Gulf of Mexico may begin to experience the coastal land loss conditions currently observed in Louisiana if the predictions are accurate.

INTRODUCTION

Thousands of acres of productive coastal wetlands in the northern Gulf of Mexico coast are converted to open water each year impacting valuable fur, fish, and waterfowl resources. Compactional subsidence and eustasy combine to form one of the most serious sea level rise threats to the coastal wetlands, beaches, and barrier islands. Barrier islands in Louisiana, which provide a natural buffer for the estuaries and wetlands from storms and hurricanes, have experienced increasing rates of shoreline erosion. In the late 1880s, total barrier island area in Louisiana was measured at 11,641 ha, and by 1988 the total area had decreased to 5,283 ha, a 55% decrease in area at a rate of 63 ha/yr (McBride *et al.*, 1991). Between 1933 and 1983, Louisiana lost 18,755 ha of wetlands (Britsch and Kemp, 1990). Texas and Mississippi lost 11,400 ha and 2490 ha of marsh respectively between 1956 and 1978 (Titus, 1988). RSL plays an important role in developing coastal management strategies in areas where coastal land loss is a growing concern (Penland *et al.*, 1990). The term relative sea level is used in the Gulf of Mexico, particularly in Texas and Louisiana, to describe the combined effects of eustatic sea-level and subsidence. Impacts of increased RSL rise include flooding and subsequent inundation of coastal bays and estuaries with saline waters from the Gulf of Mexico as well as increased vulnerability of the coastal population to storm impacts. This paper is intended to provide a synthesis of the rate, distribution and character of current trends in RSL in the Gulf of Mexico and the implications of shoreline conditions to predicted RSL rise trends.

DATABASE AND METHODS

Previous research has documented that the analysis of tide gauge records is a valid technique for measuring RSL rise (Gornitz *et al.*, 1982; Hicks *et al.*, 1983; Pirazzoli, 1986; Emery and Aubrey, 1990). It has been suggested that periods of data which do not exceed one lunar nodal tidal cycle yield anomalous results and are not representative rates of rise. A nodal tidal cycle is the 18.6-year period that it takes for the moon to complete its nodal cycle. Using tide gauge records of 20-year periods or more accounts for any water level variations resulting from this astronomical phenomenon as well as non-tidal effects such as wind, direct atmospheric pressure, river discharge, currents, water temperature, and salinity (Hicks, 1968).

Tidal records in the northern Gulf of Mexico were analyzed by two methods. The National Ocean Survey (NOS) maintains thirteen tide gauge stations providing summaries of daily mean, high and low water levels for each station throughout the Texas, Louisiana, and Florida coastal zones (Fig. 1). The NOS records water level readings every six minutes, 24 hours a day, at locations with direct tidal exchange with the Gulf of Mexico. This data set was used

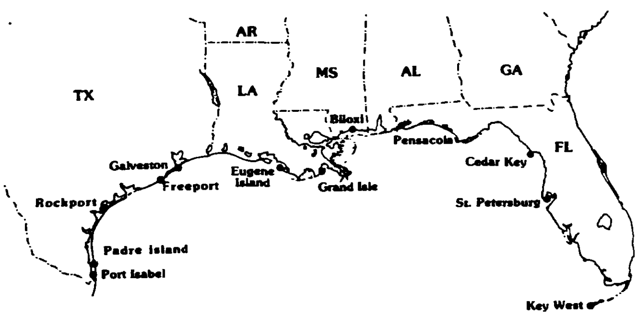

Figure 1. Location of tide gauge stations in the northern Gulf of Mexico.

to determine the character of RSL rise throughout the northern Gulf of Mexico (Lyles *et al.*, 1987). Statistical analysis on tidal records were performed in variant ways to determine the validity of different methods of analyses. The first statistical test was to determine any deviation between calculated yearly averages from monthly means *versus* yearly means calculated from daily records. The second statistical analysis compared yearly means over time to a 5-year running average. For each station, two time-series plots of the annual water level were constructed. The first plot was produced from the yearly means over period of record. The second plot was produced from a 5-year running average. The 5-year running average was intended to filter through anomalous data points. A linear regression was performed on each of these complete data sets in order to produce a best-fit straight line with a slope equal to the rate of RSL rise and compared to support data results. In each case, there was no significant difference in the relative rate of sea-level rise. Each station was then plotted in twenty-year epochs comparing RSL change through time. It was found that if the 20-year epoch occurred during a time of peak flooding, the data set appeared skewed. As a result, it was determined that the longest time period available for each station should be analyzed to obtain a more realistic picture of RSL at the station.

The last statistical analysis on the data set was to compare daily 8:00 am readings obtained from the U.S. Army Corps of Engineers (USACE) *versus* the daily means obtained from the NOS. The tidal station at Grand Isles was previously maintained by the USACE. In 1949, NOS acquired the responsibility of maintenance for the station and sent the 8:00 a.m. readings to the USACE. Analysis from the same time period of record enabled a simple comparative basis for the two data sets, and allowed for the data sets to be used interchangeably with no significant difference.

PREVIOUS SEA-LEVEL RISE STUDIES

The first RSL study in the United States was by Marmer in 1954. His work indicated that Louisiana had the highest rate of RSL in the northern Gulf of Mexico. Subsequent studies by Swanson and Thurlow (1973) indicated sea level rise in Texas and Louisiana ranged from 0.5 cm/yr at Port Isabel to 4.3 cm/yr at South Pass. However, this study was on a short period of record (1959-1970), and estimated higher rates of change. The first study focusing in Louisiana was by Boesch et. al. (1983), suggesting that local apparent sea-level changes in Louisiana are predominantly due to subsidence. A more recent study by Turner (1988), using a tide gauge database developed by the Louisiana Geological Survey (LGS), estimated RSL in the Louisiana coastal zone to range from 0.43 cm/yr to 0.89 cm/yr along Lake Pontchartrain to 2.12 cm/yr at Wax Lake Outlet at Calumet. Stations along the coast were recorded as 0.67 cm/yr at Grand Isle and 1.07 cm/yr at Eugene Island.

The Coastal Geology Section of LGS has maintained an ongoing RSL compilation program since 1983. LGS has compiled and analyzed data from the USACE and NOS records. These studies have indicated that sea-level rise varies according to the geomorphic region with rates from 0.50 cm/yr in the Chenier Plain and Pontchartrain Basin to 1.0 cm/yr in the delta plain (Ramsey and Moslow, 1987; Penland *et al.*, 1986; Ramsey and Penland, 1989; Penland and Ramsey, 1990 and Ramsey *et al.*, 1991). In comparison to surrounding states, Texas records a RSL rate of 0.63 cm/yr, Mississippi, 0.15 cm/yr, and Florida 0.23 cm/yr (Penland and Ramsey, 1990). This paper represents the latest update of water level change in Louisiana, Texas, Mississippi, and Florida.

RSL RISE

RSL refers to the long-term absolute vertical relationship between the land and water; eustasy coupled with subsidence are the driving forces behind the rapid rates of RSL in Louisiana. RSL is controlled by seven major factors (Fig. 2):

A) eustatic sea level,
B) geosyncline downwarping,
C) compaction of Tertiary and Pleistocene deposits,
D) compaction of Holocene deposits,
E) consolidation,
F) tectonic activity, and
G) subsurface fluid withdrawal.

Eustatic sea level (A) refers to global sea level which, by definition, excludes factors B, C, D, E, F, and G. Eustatic sea level is a function primarily of the changing volume of the planet's glaciers and ice caps, worldwide tectonic activity, and density-temperature relationships in the world's oceans. Global studies of tide gauge records are common in the literature and indicate that the Gulf of Mexico ranks second highest after Japan by region (Table 1). Several investigators have used water-level time-series data to determine rates of eustatic change in the U.S. (Komar and Enfield, 1987; Hicks, 1978; Marmer, 1954) Gornitz *et al.*,

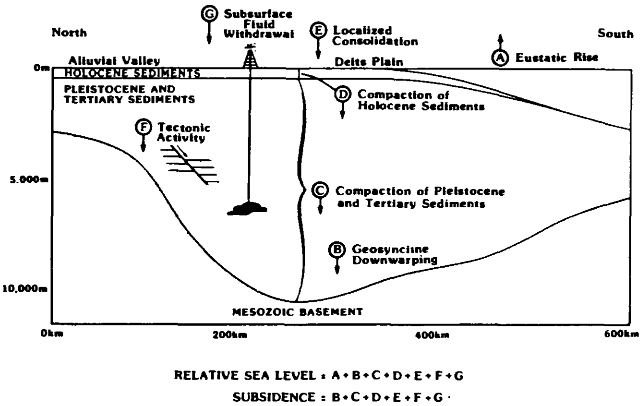

Figure 2. Factors in relative sea level (RSL) rise and subsidence (S) in the Mississippi River delta plain (Penland *et al.*, 1989).

1982, based on an analysis of more than 190 tide gauge records worldwide, concluded that mean eustatic rise rate sea level is rising at a rate of 0.12 cm/yr. For the Gulf of Mexico, Gornitz and Lebedeff (1987) calculated a mean sea-level rise rate of 0.24 cm/yr. In their report, effects of the lunar nodal cycle are removed, along with other long-term trends related to predominantly glacio-isostatic origin. Regionally, tidal stations along the northern Gulf of Mexico vary depending on the influence of subsidence and contamination of the data due to proximity of tidal stations to rivers, and the thickness of the Holocene sequences.

Table 1. Average sea-level changes by region (modified from Gornitz and Lebedeff, 1987).

	Long-Range Trends Removed			
	d_o = 250 km		d_o = 100 km	
Regional Mean	**Trend mm/yr**	**95% Confidenc interval**	**Trend mm/yr**	**95% Confidence interval**
1. Arctic	-0.1	0.8	0.6	1.2
2. Fennoscandia	1.5	0.3	1.8	0.3
3. Europe	0.6	0.1	0.5	0.1
4. Africa	1.9	1.0	2.0	1.0
5. Japan	2.5	0.6	2.4	0.6
6. Australia	1.5	0.3	1.5	0.3
7. Pacific Island	0.1	0.4	0.1	0.3
8. W.North America	0.0	0.2	-0.1	0.2
9. E.South America	1.2	1.2	1.3	1.5
10. Gulf of Mexico + Caribbean	2.4	0.4	2.5	0.4
11. E.North America	1.3	0.2	1.3	0.2
Global mean (all regions weighted equally)	1.0	0.1	1.0	0.1
Global mean (with weighting factors)	0.9	0.1	1.0	0.1

Texas

NOS maintains six stations along the Texas coast. These stations are Port Isabel, Padre Island, Rockport, Freeport, and Galveston. The longest period of record in Texas (1908 to present) occurs at the Galveston Pier 21 station, located at the east end of Galveston Island near the Houston Ship Channel. This station recorded a RSL rise rate of 0.63 cm/yr (Fig. 3). Stations around Freeport and Padre Island record a RSL rise rate of 0.50 cm/yr. On the southern end of Texas shoreline, the Port Isabel tide gauge station lies on the mainland shoreline of Laguna Madre at the south end of Padre Island. The data suggests that between 1944 and 1986, the rate of RSL rise was 0.31 cm/yr.

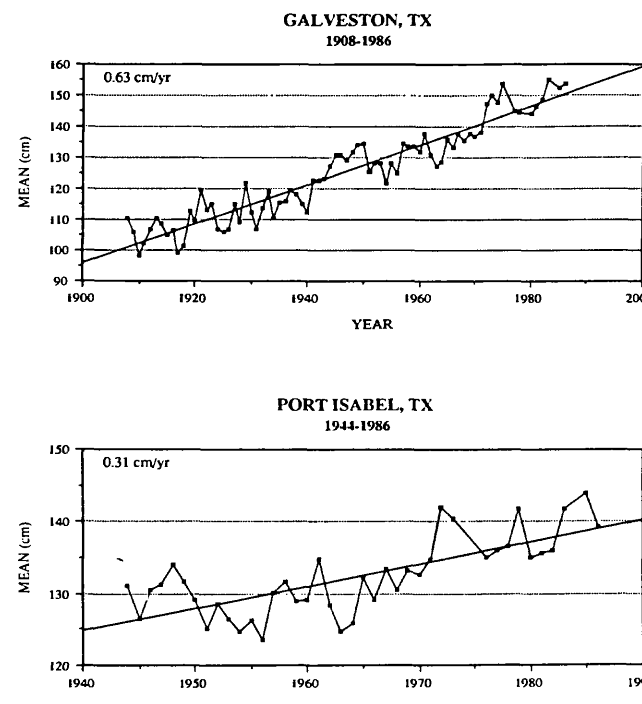

Figure 3. Water level time series for the Texas tide gauge stations (Penland and Ramsey, 1990).

Louisiana

The Eugene Island station lies on the Point au Fer shell reef system 8.0 km south of the prograding Atchafalaya River delta complex (Fig. 1). This station has a good maintenance record, but appears contaminated by Atchafalaya River flooding, notably the spring floods of 1972 and 1973 (Fig. 4). An analysis of the data record (1939-1971) indicates a RSL rise rate at Eugene Island of 1.19 cm/yr. Unfortunately, this station was discontinued in 1974, eliminating further investigations of the tidal record at this station. At

Grand Isle, the Bayou Rigaud station lies behind the barrier island on the Exxon Dock adjacent to Barataria Pass. After this station was destroyed in 1979, NOS established a new station at the U.S. Coast Guard station and renamed it East Point. The records show that, between 1947 and 1987, RSL rose steadily at a rate of 1.04 cm/yr. The water-level time series appears to have been relatively unaffected by Mississippi River flooding (Fig. 4).

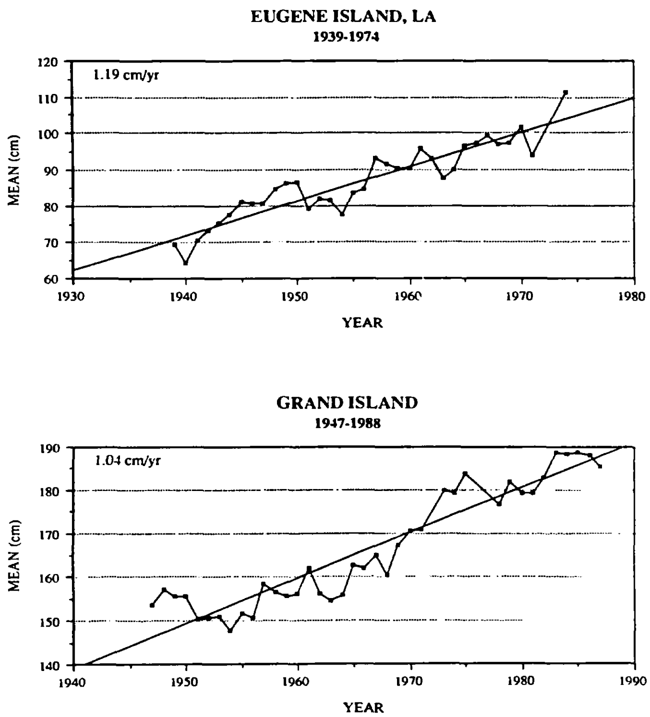

Figure 4. Water level time series for the Louisiana tide gauge stations (Penland and Ramsey, 1990).

Mississippi-Alabama

The Biloxi tide gauge station is on the mainland shoreline of Mississippi Sound, landward of Ship Island (Fig. 1). This tide gauge is connected to the Gulf of Mexico by Dog Keys Pass. A RSL rise rate of 0.15 cm/yr was calculated for the period of record, 1939 to 1983 (Fig. 5). In 1983 the maintenance on this station was transferred to the Mobile District of the Corps of Engineers.

Florida

The Pensacola tide gauge station lies on the mainland shoreline of Escambia Bay near the west end of Santa Rosa Island (Fig. 1). It is connected to the Gulf of Mexico by Perdido Pass. An analysis of the period of record, 1923 to 1986, reveals a rate of RSL rise of 0.23 cm/yr (Fig. 6). The Key West tide gauge station lies at the extreme western end of the Florida Keys in the southeastern Gulf of Mexico. The

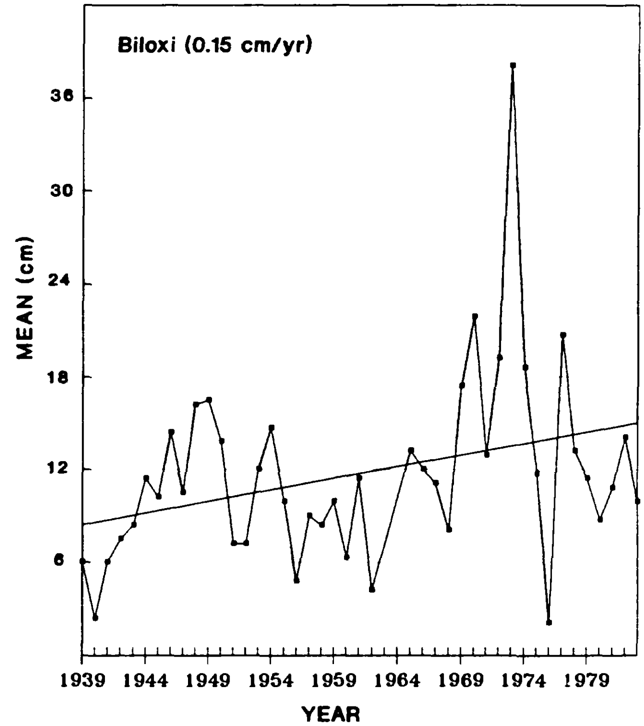

Figure 5. Water level time series for the Mississippi tide gauge stations.

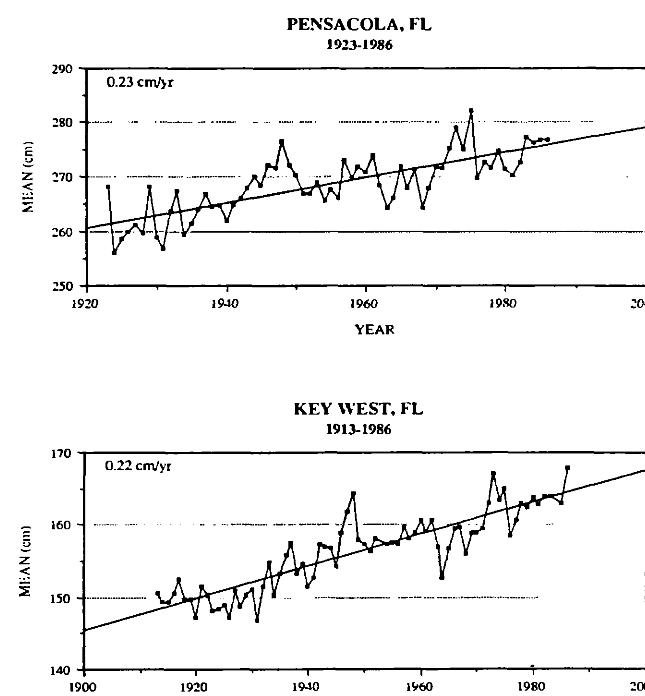

Figure 6. Water level time series for the Pensacola and Key West tide gauge stations (Penland and Ramsey, 1990).

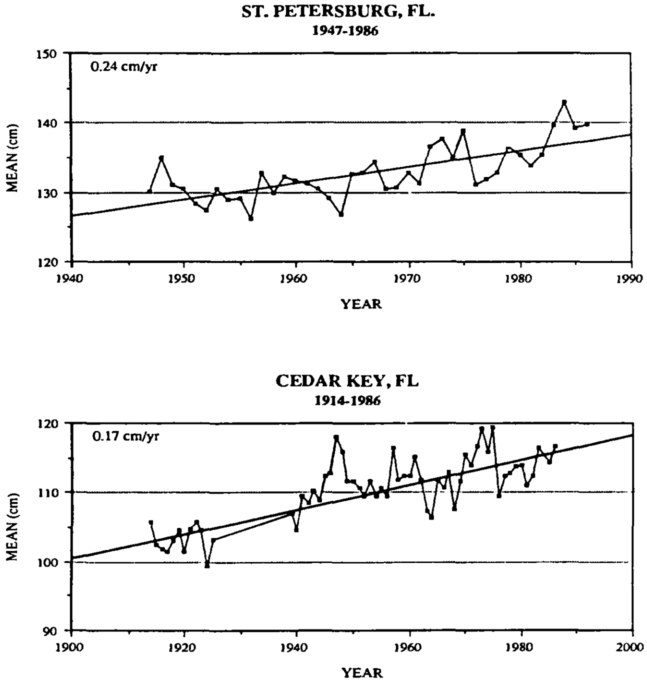

Figure 7. Water level time series for the Cedar Key and St. Petersburg tide gauge stations (Penland and Ramsey, 1990).

RSL rise rate for the period of record, 1913 to 1986, was calculated to be 0.22 cm/yr.

The Cedar Key tide gauge lies on an unnamed coastal island between Suwannee Sound and Waccasassa Bay in Florida's Big Bend region (Fig. 1), directly on the Gulf of Mexico. A RSL rise rate of 0.17 cm/yr was calculated for the period of record, 1914 to 1986 (Fig. 7). The St. Petersburg tide gauge station is located on the northern shore of Tampa Bay; connected to the Gulf of Mexico by a series of tidal inlets along the Tampa Bay barrier shoreline. Its period of record extends from 1947 to 1986 and yields a RSL rise rate of 0.24 cm/yr.

REGIONAL TRENDS

The trend of tidal stages in the Gulf of Mexico are parallel when plotted over time, in that, points indicating years of peak stage readings can be observed throughout the data set (Fig. 8). However, rates of use at each station in the northern Gulf of Mexico vary from state to state. Louisiana experiences a higher rate of RSL rise than any other state on the northern Gulf Coast due to the combined effects of eustatic sea level and subsidence, followed by Texas. The zones of highest RSL rise are associated with the Mississippi River delta plain, while the rates along the Chenier Plain to the west and the Pontchartrain Basin to the east decrease to levels comparable to those of adjacent coastal states.

In Texas, the rate of RSL rise range from 0.31 cm/yr in Port Isabel to 0.62 cm/yr at Galveston. The Galveston rate

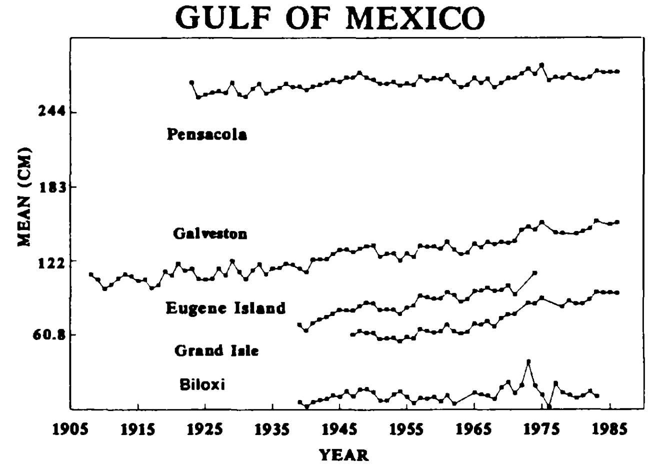

Figure 8. Water level time series for tidal stations in the northern Gulf of Mexico showing the parallel trend in the yearly means from station to station.

appears to be a continuation of the rates observed along Louisiana's Chenier plain. From north to south, the trend of decreasing RSL rise continues. Tidal stations located along rivers such as the Mississippi, Atchafalaya and Sabine appear to contaminate the data due to flood stages and control structures.

Moving eastward, the Mississippi, Alabama, and Florida tide gauges record the lowest rates of RSL rise. For Florida, the RSL rise rates average between 0.17 cm/yr at Cedar Key and 0.23 cm/yr at Pensacola. Biloxi recorded the lowest RSL rise rate with an average of 0.15 cm/yr for the period of record. All of these regions are not experiencing the high rates of subsidence that characterize Louisiana and Texas coasts and contribute directly to apparent accelerated sea level rise rates.

PREDICTED REGIONAL TRENDS

Future sea-level conditions in the Gulf of Mexico and estimates of eustatic sea level around the world have been a subject of recent debate with varying results (Table 2). Earlier studies in Louisiana suggested that future sea-level conditions could range from 69 cm to 75 cm from 1980 to the year 2020 and as high as 133 cm to 150 cm from 1980 to 2080, based upon readings from Eugene Island and Bayou Rigaud (Nummedal, 1983). The Environmental Protection Agency (EPA) predicted the rate of sea-level rise to increase over the next century. Rates of RSL for the Gulf of Mexico are expected to increase from 0.23-1.5 cm/yr to 0.6-3.7 cm/yr (Titus, 1988). A more conservative estimate by NRC shows eustatic sea-level to increase from 0.4 cm to 2.0 cm by the year 2100. The IPCC more recently have predicted future trends in sea level. It is their belief that an average rate of global mean temperature will increase 1°C above present mean temperatures by 2025 and 3°C before the end of the next century producing a sea level rise rate of about

Table 2. Estimated future global sea-level rise (modified from Emery and Aubrey, 1990).

Author(s)	Total Eustic sea-level rise (cm)	Time Period of Estimate	Estimated Future Global Sea-level Rise (cm/yr)
Gornitz *et al.* (1982)	40-60	1980-2050	.57-.86
Revelle (1983)	71	1980-2080	.71
Hoffman *et al.* (1983)	56-345	1980-2100	.47-2.88
Hoffman *et al.*(1986)	58-367	1980-2100	.23-3.06
NAS (1985)	10-160	1985-2100	.09-1.39
Robin (1986)	25-165	1985-2100	.22-1.43
Oerlemans (1989)	33	1985-2030	.73
Oerlemans (1989)	66	1985-2100	.57
Stewart (1989)	20-40	1985-2100	.17-.35
Meier (1989)	8-28	1985-2050	.52-.65
Raper et al (in press)	8-28	1985-2030	.18-.65

6 cm per decade over the next century (Houghton, J.T., *et al.*, 1990). Predicted rise of eustatic sea level is estimated about 0.5 cm/yr to 0.6 cm/yr by the end of the next century with significant variations between regions of the world. These rates fall into the EPA's low range. Louisiana is already experiencing EPA's mid forecasted range. If either predictions prove true, Louisiana can experience accelerated rates of land loss, and other areas of the U.S. can be expected to experience the Louisiana current trends with devastating effects on the coastal shorelines.

CONCLUSIONS

Analysis of National Ocean Survey and Army Corps of Engineers tide gauge records from stations along the U.S. Gulf Coast indicate that Louisiana is experiencing the highest rates of RSL rise in the Gulf of Mexico. Maximum rates in Louisiana ranged between 1.04 cm/yr to 1.19 cm/yr. Texas ranks second, with rates ranging between 0.31 cm/yr and 0.63 cm/yr, followed by Florida (0.17 cm/yr to 0.24 cm/yr), and Mississippi-Alabama (0.15 cm/yr). Increased rates in sea level rise over the next century will accelerate coastal erosion and subsidence processes which presently occur along the Louisiana shoreline.

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IMPLICATIONS OF ACCELERATED SEA-LEVEL RISE ON LOUISIANA COASTAL ENVIRONMENTS

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ABSTRACT: Natural and human-induced processes have combined to produce high rates of relative sea-level rise and coastal land loss in Louisiana. This paper presents historical trends in sea-level rise and the implication of predicted accelerated sea-level rise scenarios on Louisiana's coastal environments. Mean eustatic sea-level in the Gulf of Mexico is 0.23 cm/yr. In Louisiana, relative sea-level rise, which combines eustacy and subsidence, averages from 0.50 cm/yr in the chenier plain to 1.0 cm/yr in the delta plain. Subsidence due to the compaction of Holocene sediments is believed to be the major component influencing these high rates of rise. Subsidence contributes up to 80% of the observed relative sea-level rise in coastal Louisiana. The Environmental Protection Agency (EPA) predicts the rate of sea-level rise to increase over the next century due to global climate change. If these predictions are accurate, a dramatic increase in the coastal land loss conditions in Louisiana can be expected.

INTRODUCTION

Louisiana's coastal zone consists mainly of active deltas, fresh and salt marshes, natural levees, estuarine bay systems, and barrier shorelines. These environments are experiencing the worst coastal land loss problem in the United States. Between 1933 and 1983, Louisiana lost 18,755 ha of wetlands (Britsch and Kemp 1990). At these current rates, researchers predict barrier islands such as the Isles Dernieres will disappear by the year 2015, and Plaquemines and Terrebonne marshes can be expected to convert to open water between 2020 and 2080, respectively (Penland and Boyd 1981; Gagliano et al. 1981; McBride et al 1991). The high rate of wetland loss is of increasing concern to the fir, fish, and water fowl industries dependent on these fragile coastal ecosystems, and to the human infrastructure tied to this coastal region. A rise in relative sea level and a deficient supply of sediment are major components behind the coastal land loss problem facing the Louisiana coastal zone. This paper examines historical trends in sea-level rise and the implication of accelerated sea-level rise predictions on coastal land loss in Louisiana.

COASTAL LAND LOSS

Previous studies show that coastal land loss has persisted and accelerated since the 1900's (Britsch and Kemp, 1990; Dunbar et al. 1990). Coastal land loss refers to the set of processes that

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convert land to water. This process can be subdivided into two major types: coastal erosion and wetland loss. Coastal erosion describes the retreat of the shoreline along the exposed coasts of large lakes, bays, and the Gulf of Mexico. In contrast, wetland loss is used to describe the development of ponds and lakes within the interior wetlands and the expansion of large coastal bays behind the barrier islands and mainland shoreline.

Coastal Erosion

Louisiana is experiencing the highest coastal erosion rates in the United States (Morgan and Larimore 1957; Penland and Boyd 1981). Coastal erosion in Louisiana averages 4.2 m/yr and appears on the U.S. Geological Survey coastal erosion and accretion plates as the nation's erosion hot spot (figure 1). The average Gulf of Mexico shoreline change rate is -1.8 m/yr. By comparison, the Atlantic erodes at an average rate of -0.8 m/yr, while the Pacific coast is relative stable (Dolan, 1985). In Louisiana, the majority of the coastal erosion is concentrated in the barrier shorelines that front the Mississippi River delta plain. In addition to beach erosion, the total area of Louisiana's barrier shoreline is decreasing rapidly. In the late 1880's, total barrier island area in Louisiana was measured at 11,641 ha, and by 1988 the total area had decreased to 5,283 ha, a 55% decrease in area at a rate of 63 ha/yr (McBride et al. 1991).

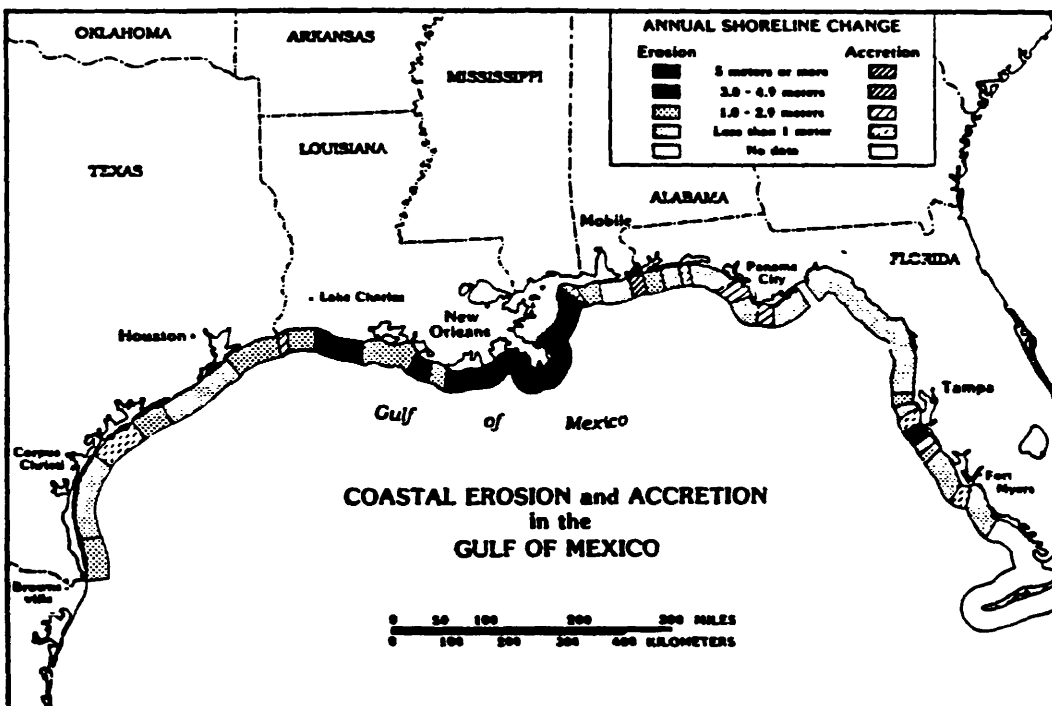


Figure 1. Coastal erosion and accretion in the Gulf of Mexico (modified from Dolan, 1985).

Wetland loss

Louisiana's wetland parishes contain the single largest concentration of coastal marshes in the contiguous United States. There are 7,256,000 ha of salt marsh, 2,858,000 ha of fresh marsh and 1,814,000 ha of swamp, a total of 11,928,000 ha (Alexander et al. 1986). Louisiana's wetlands account for 40% of the total wetlands in the U.S. However, 80% of the wetland loss occurs in the

Louisiana coastal zone. Of this total, 80% of the loss occurs in the delta plain and 20% in the chenier plain. Previous studies show that the rate of coastal land loss has accelerated over the last 75 years (Gagliano et al. 1981). Processes such as sediment deficiency, sea-level rise, subsidence, sediment compaction, storm events, and salt water intrusion have contributed to the overall deterioration of the wetlands. One of the most important processes which effect Louisiana's coastal zone is relative sea level rise.

SEA LEVEL HISTORY

Analysis of tide gauge data provides a measure of historical (0-50 yBP) relative sea-level rise and a view of the secular trends occurring in each of the Gulf coastal regions. Relative sea-level (RSL) reflects the combined effects of isostatic and eustatic factors. It refers to the long-term absolute vertical relationship between land and water, and is controlled by forces such as eustasy, crustal downwarping, compaction of Tertiary and Pleistocene deposits, compaction of Holocene deposits, consolidation, tectonic activity and subsurface fluid withdrawal. Eustacy refers to global sea level, and is a function primarily of the changing volume of the planet's glaciers and ice caps, worldwide tectonic activity, and density-temperature relationships in the world's oceans. The mean eustatic rise has been estimated to be 0.12 cm/yr. In the Gulf of Mexico, eustatic sea-level ranges from 0.23 to 0.24 cm/yr (Gornitz et al. 1982; Ramsey et al. 1989; Penland et al. 1989).

There are 78 tidal stations in the Louisiana coastal zone maintained by the U.S Army Corps of Engineers (USACE) and National Ocean Survey (NOS) (figure 2a). Data from these stations were analyzed and reviewed for anomalies occurring due to damage to the station or from re-positioning. Of these 78 stations, 20 gauges had data of sufficient length and quality for determining trends in relative sea level (figure 2b). Hicks (1968) found that using periods of record of 20 years or more balances the effects of any water level variations due to the moon's nodal cycle, as well as the effects of variations in nontidal factors such as wind, atmospheric pressure, river discharge, currents, water temperature, and salinity. Data was divided into three major geomorphic regions: chenier plain, delta plain and Pontchartrain basin. Monthly means and annual water levels were averaged for each of the stations. A time-series plot of the annual water levels with simple regression plots were performed to produce a best-fit regression line in which the slope represents the rate of relative sea-level rise. Polynomial regressions were performed on tidal records to indicate secular trends, and Holocene sediment thickness was compared with rates of sea level rise to determine correlations.

Chenier Plain

The Chenier plain is a series of ridges and mudflats located along the western Louisiana coast (Russell and Howe 1935; Howe et al. 1935). Holocene deposits of the chenier plain overlie the Pleistocene Prairie terrace, and reach a maximum thickness of about 10 m along the shoreline. There are eight tidal stations in the Chenier plain with 20 or more years of record. These stations, located along the Calcasieu River, Mermentau River, and the Intracoastal Waterway, are automatic recorders and staff gauges which have been in operation since 1942. Observed rates of relative sea-level rise as well as trends in monthly water-level stages in this area appear to be consistent. Relative sea-level rise averages 0.50 cm/yr (figure 3).

Delta Plain

The delta plain consists of the Teche, Terrebonne, Barataria, Balize, and St. Bernard geomorphic regions, associated with delta complexes built over the last 4,000 years. Holocene thickness in the delta plain ranges from 10 - 200 m.

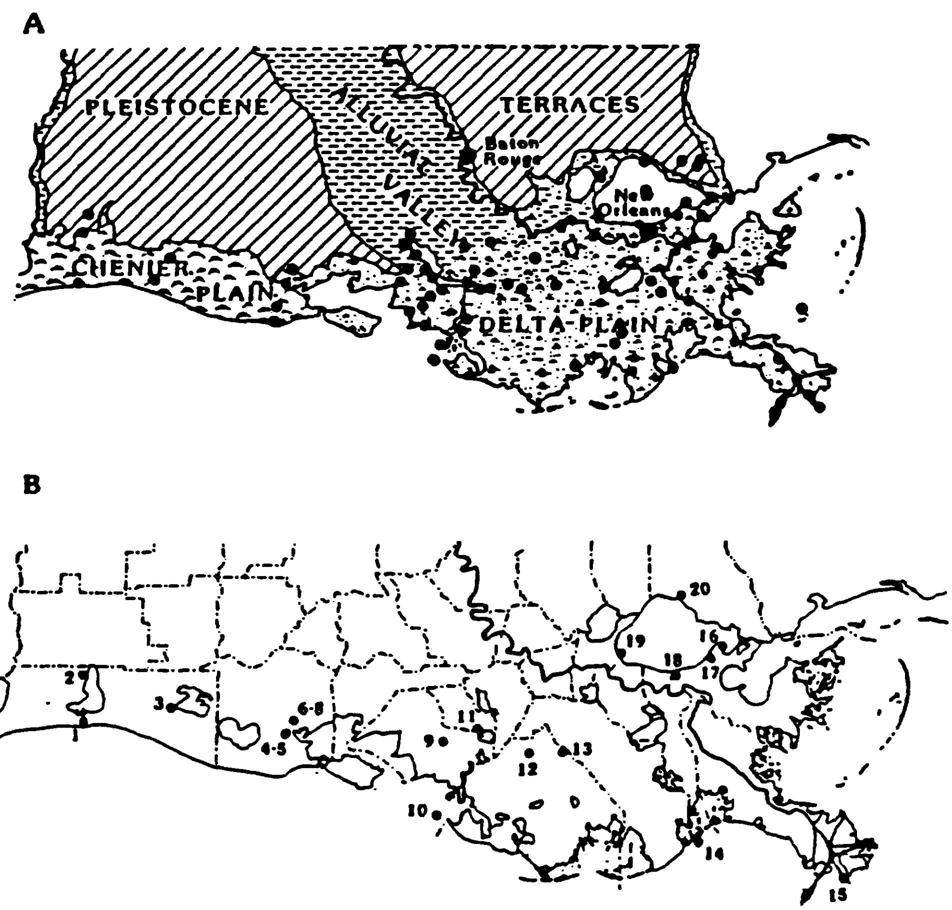


Figure 2. A) Location of tide gauge station in coastal Louisiana maintained by the Army Corps of Engineers and National Ocean Survey. B) Location of twenty tide gauge stations used in this study.

Teche. The thickness of the Holocene section in the Teche basin increases from west to east, because it overlies the western wall of the infilled Pleistocene valley of the Mississippi River (Kolb and Van Lopik 1958). Holocene sequences range from 10-15 m thick near Chenier au Tigre to more than 100 m near Morgan City. Vermilion Bay, West Cote Blanche Bay, East Cote Blanche Bay, and Atchafalaya Bay make up the Teche Basin. Water-level regimes in the Basin are complicated by the growth and expansion of the Atchafalaya River delta complex. In this region, increased seasonal flooding combined with high rates of sedimentation associated with delta growth, have amplified the effects of relative sea-level rise. The Teche Basin tide gauge station measured the combined effects of eustatic changes and compaction, with the added effect of rising Atchafalaya River stages. Therefore, readings from these stations are not truly representative of relative sea-level rise. The USACE maintains a total of 23 tide gauge stations throughout the Teche Basin. Relative sea-level rise, determined from stations with sufficient record, indicate rates ranging from 1.17 cm/yr at Eugene Island to 1.77 cm/yr at Calumet (figure 4).

Terrebonne. The thickness of the Holocene section in the Terrebonne delta plain ranges from 100 m to 200 m. The western margin is adjacent to the prograding Atchafalaya River delta and

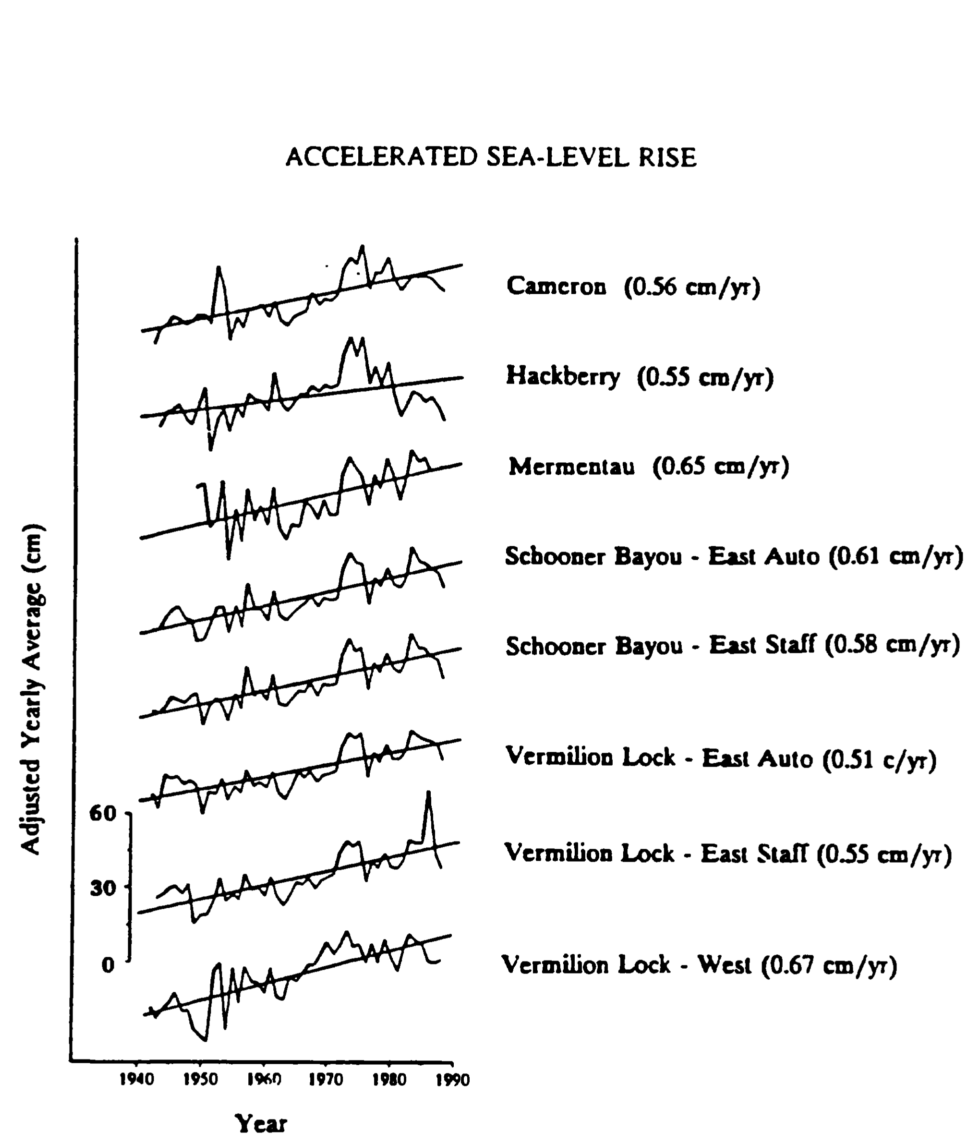


Figure 3. Water-level time series for stations in the chenier plain.

is, therefore, influenced by delta complex development. In contrast, the eastern section is not affected by the Atchafalaya River's discharge. The USACE maintains eight tide gauge stations in the Terrebonne delta plain. Average rates of relative sea-level rise in the Terrebonne delta plain are 1.0 cm/yr (figure 5). The Greenwood tide gauge station is located in Bayou Black in the western portion of the basin, and is influenced by the zone of flooding from the Atchafalaya River. The Houma station lies in the central portion of the Terrebonne delta plain 70 km inland on the Intracoastal Waterway in an area connected to the Gulf of Mexico.

Barataria Basin. The seaward margin of this deltaic estuary is formed by the Caminada-Moreau coast, Grand Isle, Grand Terre Islands, and Cheniere Ronquille. Caminada Bay and Barataria Bay are connected to the Gulf of Mexico by Caminada Pass, Barataria Pass, Pass Abel, Quatre Bayoux Pass, and Pass Ronquille (figure 6). The Barataria Basin lies over the eastern wall of the infilled Mississippi River alluvial valley. The thickness of the Holocene section in the Barataria basin increases from 10-15 m in the upper basin to more than 100 m at Grand Isle (Kolb and Van Lopik 1958). There are seven tidal stations, maintained by the USACE in the Barataria Basin. Three of these stations have records of 20 years or more. The longest record of tidal data in the Barataria basin occurs along the Gulf coast at the Grand Isle East Point station. Although this gauge was established in 1947, published records were not consistent until 1949. The rate of rise

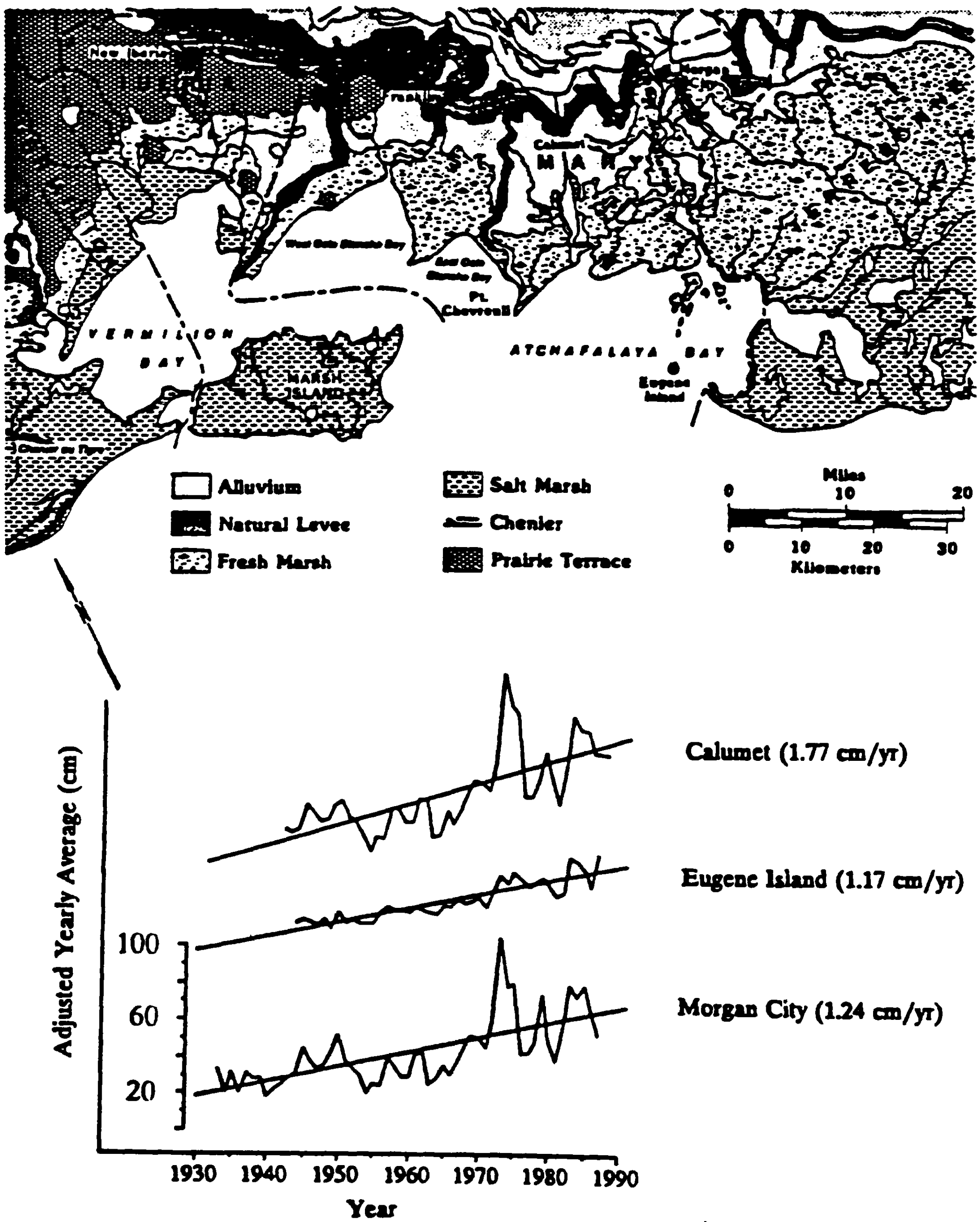


Figure 4. Water-level series for stations in the Teche Basin. Note the peak water level stages during the 1973 flood year in stations in the Atchafalaya floodway as oppose to peak flood year in Eugene Island further offshore.

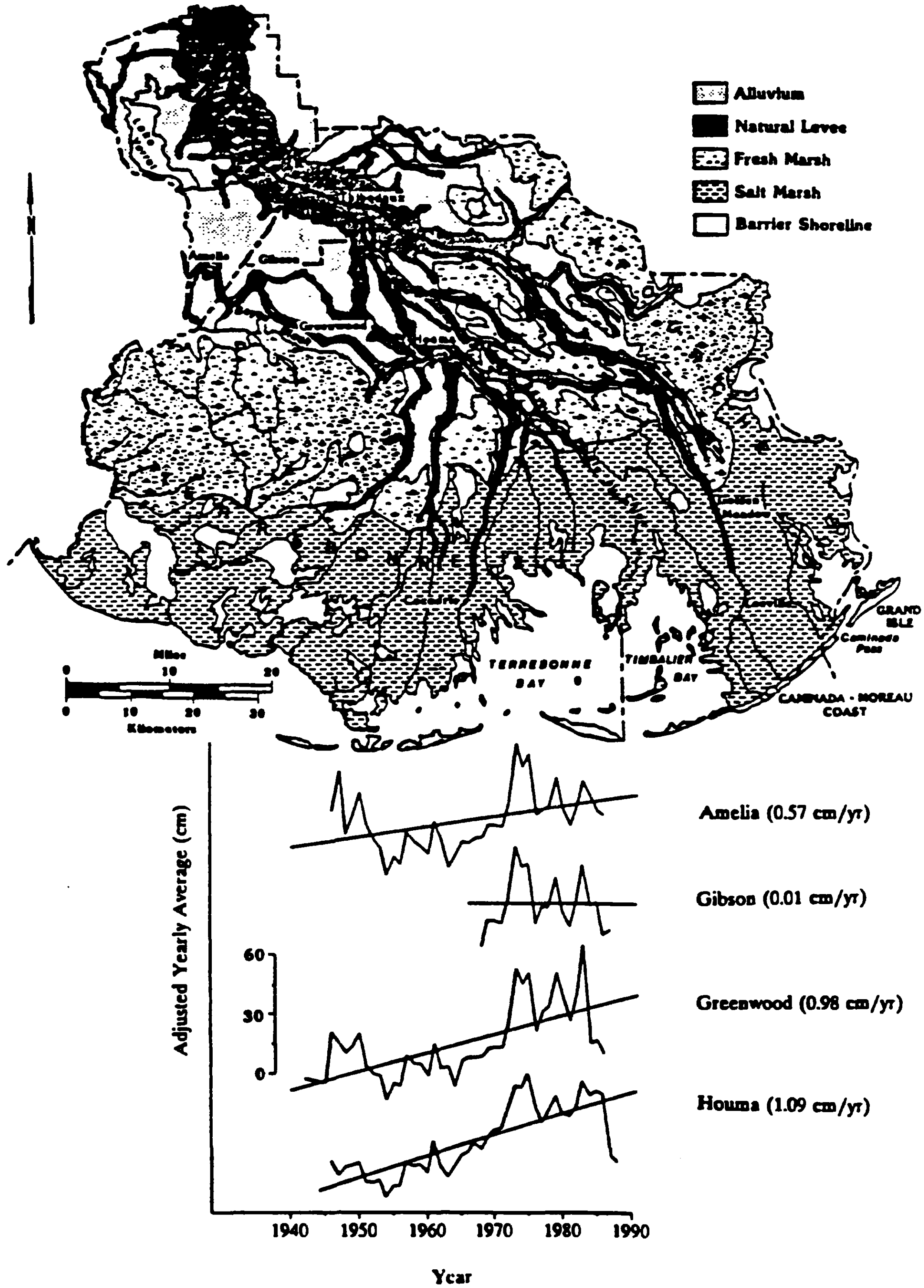


Figure 5. Water-level time series for Terrebonne Basin. Note that these stations are affected by flooding during 1973.

observed at the Grand Isle station was 1.11 cm/yr from 1949 to 1988 (figure 7).

Balize Delta Plain. In the Balize delta plain, the thickness of the Holocene section exceeds 30 m. The tidal regime in this coastal region is influenced considerably by the stages of the Mississippi River. The USACE maintains 10 tide gauge stations in the Balize delta plain and adjacent Mississippi River. Port Eads is representative of tide gauges in this area, and is located at South Pass about 4-5 km north of the Gulf of Mexico (figure 6). The period of record analyzed was between 1944 and 1988, and yielded a relative sea-level rise rate of 0.63 cm/yr (figure 7). As in the case with the Atchafalaya River, the erratic character of the tidal record reflects repeated flooding.

St. Bernard Delta Plain. The Holocene section in the St. Bernard delta plain increases in thickness from 15 - 20 m near Little Woods to more than 100 m near Breton Island (figure 8). The USACE maintains 10 tide gauge stations in the St. Bernard delta plain. South Shore and Little Woods, located on the south shore of Lake Pontchartrain, are representative of this region. The station located at Little Woods has been in operation since 1931. However, it was discontinued in 1977. The South Shore gauge has been in operation since May 3, 1949. Relative sea level rise in the St. Bernard region was recorded at 1.09 cm/yr and 0.99 cm/yr, respectively (figure 9).

Pontchartrain Basin

The Pontchartrain Basin is a marginal deltaic basin located between the Pleistocene terraces in the Florida Parishes and the St. Bernard delta complex. Progradation of the St. Bernard delta complex enclosed the Pontchartrain Basin. Here the Holocene sediments thin and pinch out against the pleistocene terraces to the north of the basin and reach a thickness from 10 - 15 m toward the south. The USACE maintains 11 tide gauge stations in this basin. Three stations along the Lake Pontchartrain shore have been in operation since 1931: West End, Frenier, and Mandeville (figure 8). Analysis of these stations yielded an RSL value of 0.45 - 0.50 cm/yr (figure 9).

DISCUSSION

There are three similarities found in the analysis of water-level data in coastal Louisiana. These similarities occur in tide gauge record character, the correlation of thickness of the Holocene to relative sea-level rise, and the secular trends from station to station. Peaks in water level records associated with flooding can be seen in stations located in the Mississippi and Atchafalaya Rivers, whereas tidal stations offshore (Eugene Island) and in protected waters such as the Intracoastal waterway and chenier plain indicate a much lower peak in water stages.

The second trend determined from the tidal record was the correlation between relative sea-level rise rates and the thickness of the Holocene sediment package. Relative sea-level averages 0.5 cm/yr in the chenier plain and 1.0 cm/yr in the delta plain (figure 10). Comparing the eustatic-corrected subsidence rates to relative sea level rise rates reveals that subsidence is a major contributor to relative sea-level rise in the Louisiana coastal zone. Subsidence accounts between 70% and 90% of the relative sea-level rise measured at the tidal stations in the delta plain and only 30% of the sea-level rise rates along the chenier plain and Pontchartrain Basin (figure 11).

The last similarity in tidal data occurs in secular trends. Hicks (1968) saw the significance of a secular trend in tidal data as well as yearly variation from station to station. This trend is the result of glacial-eustatic elastic and/or tectonic effects. Polynomial regressions on tidal records from each of the three regions show smaller cycles in water level stages. These regressions indicate that the secular trend was on an upward swing since the 1950's and peaked in the early 1980's.

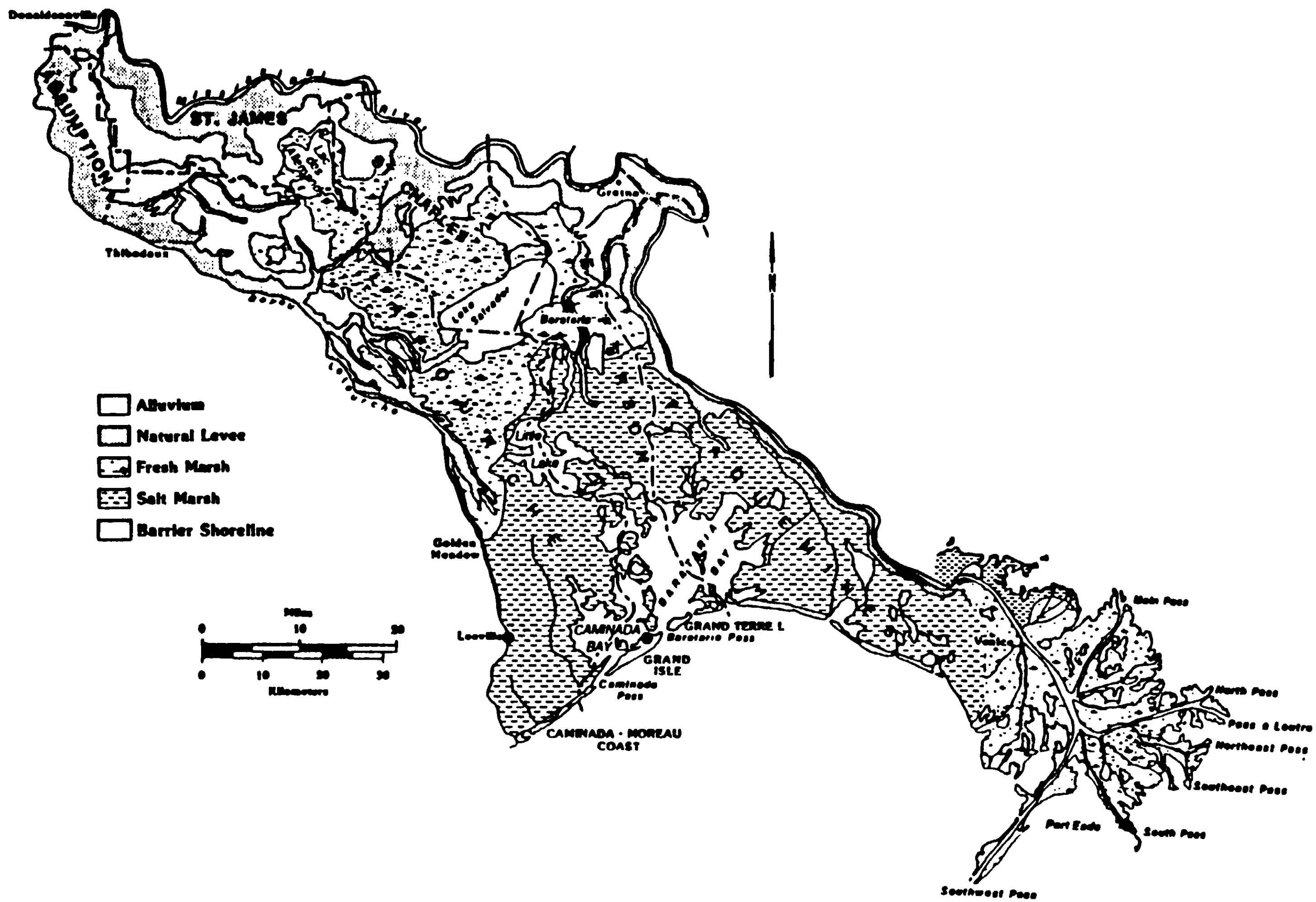
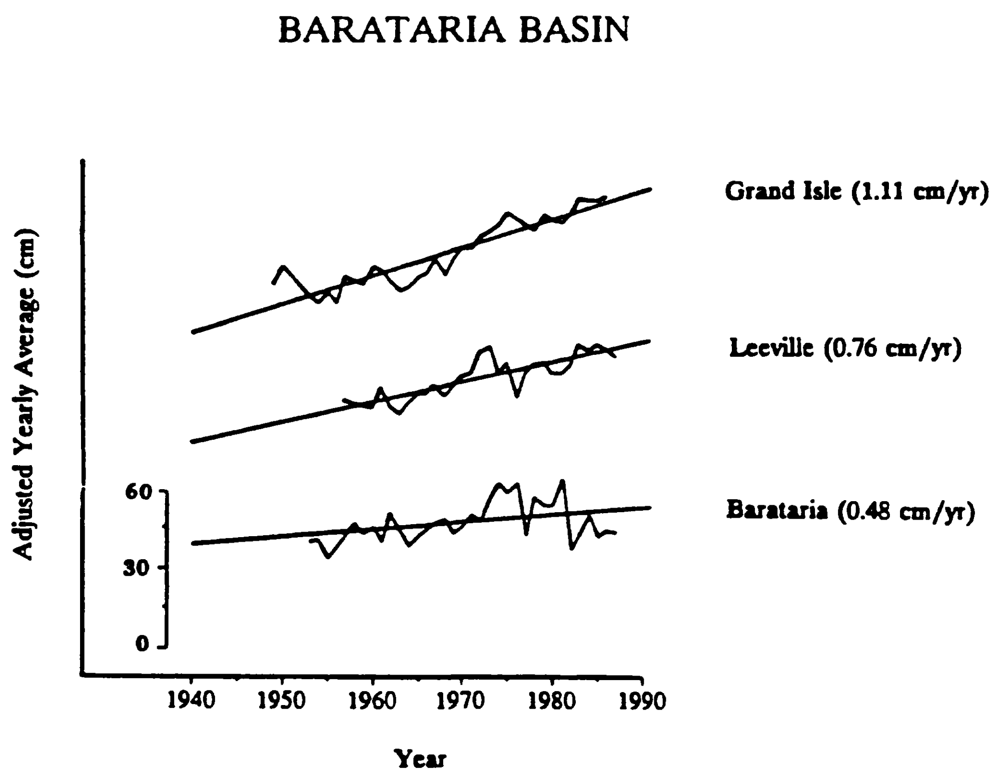


Figure 6. Location of tidal stations in the Barataria basin and Balize delta.



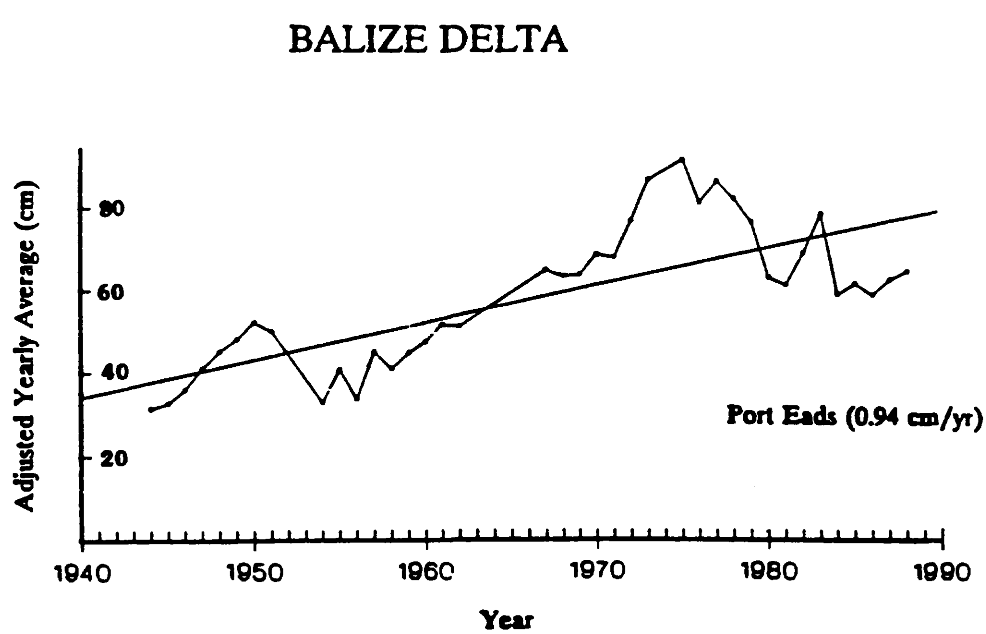


Figure 7. Water-level series for tidal stations in the Barataria basin and Balize delta.

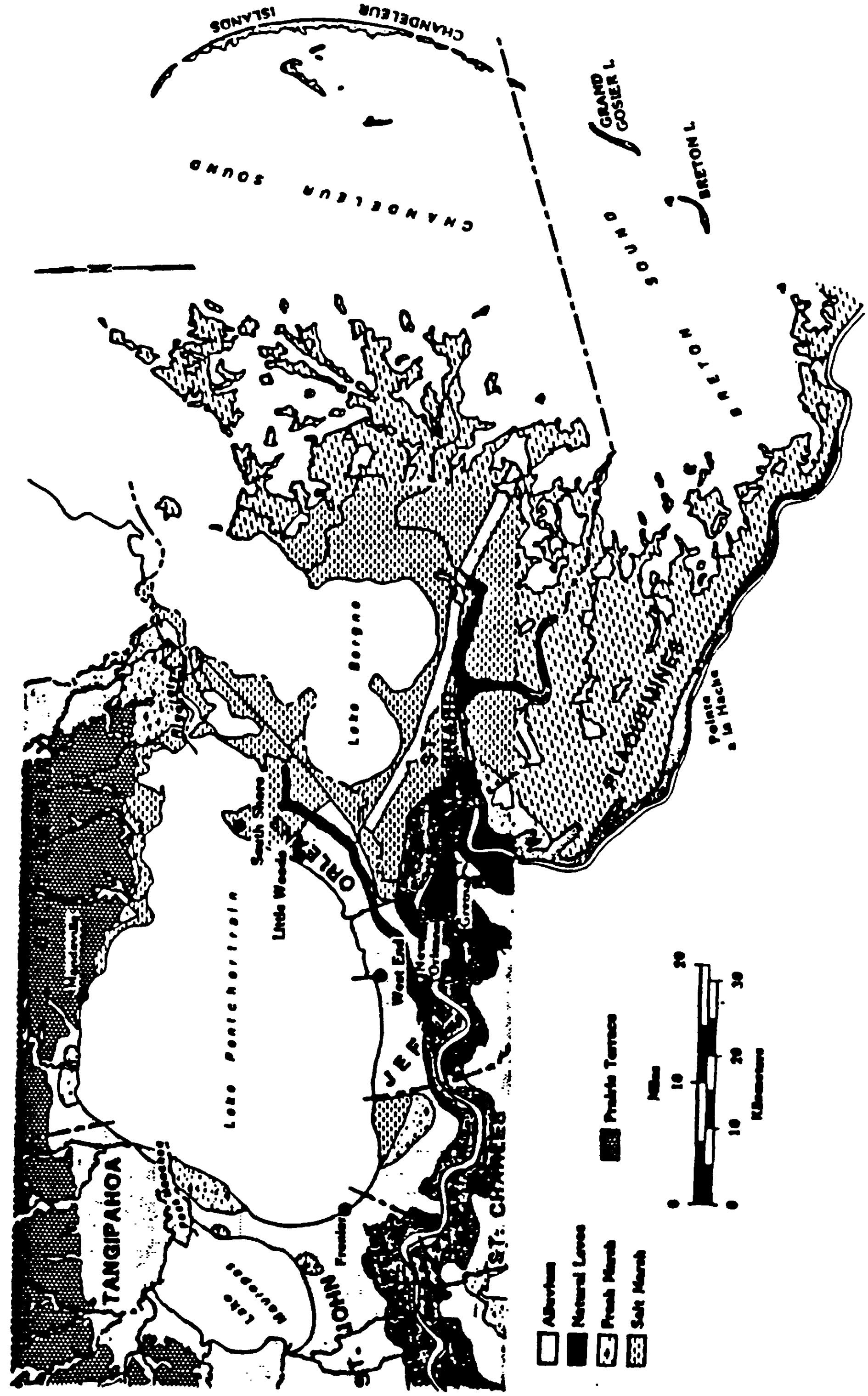


Figure 8. Location of the tidal stations in the St. Bernard and Pontchartrain regions.

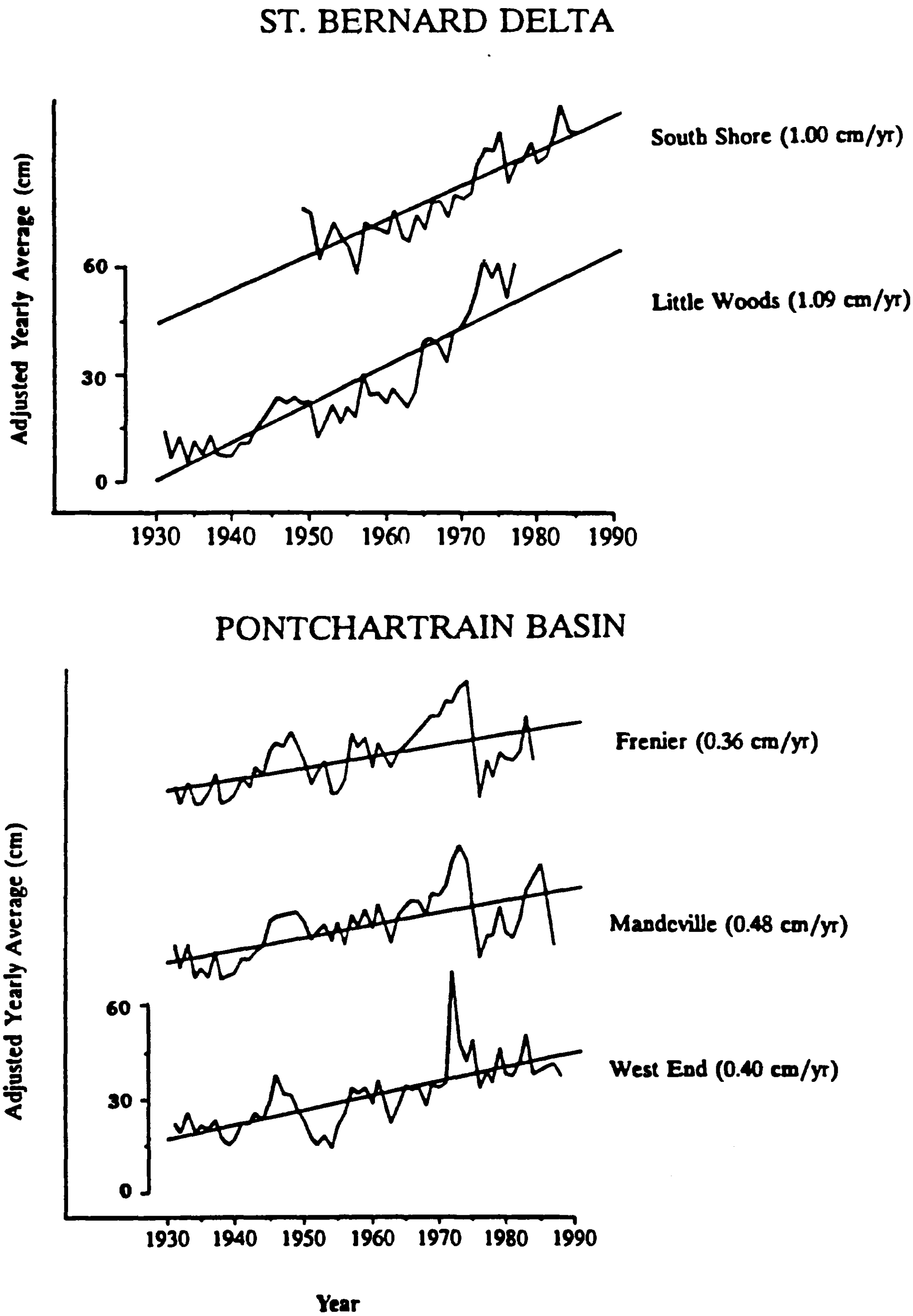


Figure 9. Water-level time series in the St. Bernard delta and Pontchartrain basin.

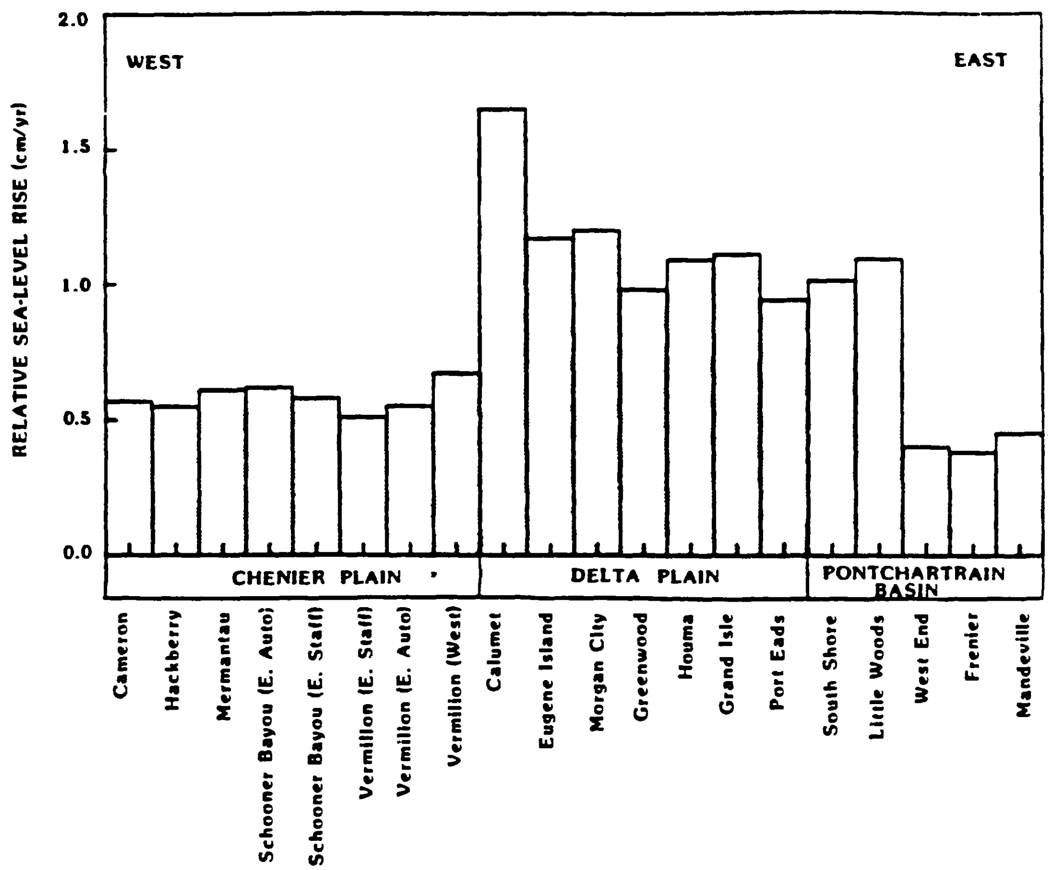


Figure 10. Relative-sea level rise in the chenier plain, delta plain and pontchartain basin.

Since that time the secular trend appears to be on a downward swing.

Future Conditions

The Environmental Protection Agency (EPA) and National Research Council (NRC) (1987) predict sea-level to rise significantly in coming years due to global warming. Acceleration in the rate of relative sea level rise stems from measurements showing increasing concentrations of carbon dioxide (CO_2), methane, chlorofluorocarbons, and other gases released by human activities. Several investigators have studied sea level rise due to the melting of the polar ice caps and glaciers by the year 2100 (figure 12). Thomas (1986) estimated sea level to rise 64 to 230 cm before the year 2100. A panel from the National Academy of Sciences Polar Research Board studied glacial contribution to sea level rise. This panel claims that Alpine and Greenland glaciers would contribute 10 to 30 cm by the year 2100. EPA estimates range from 15 to 45 cm above current sea level for the year 2025, and 60 to 210 cm by the year 2100 (Titus 1988). The EPA predicts the rate of sea-level rise to increase over the next century from the 0.23 cm/yr currently observed to 2.5 cm/yr from 1980 to 2100 as a low scenario to 3.2 cm/yr as a high scenario.

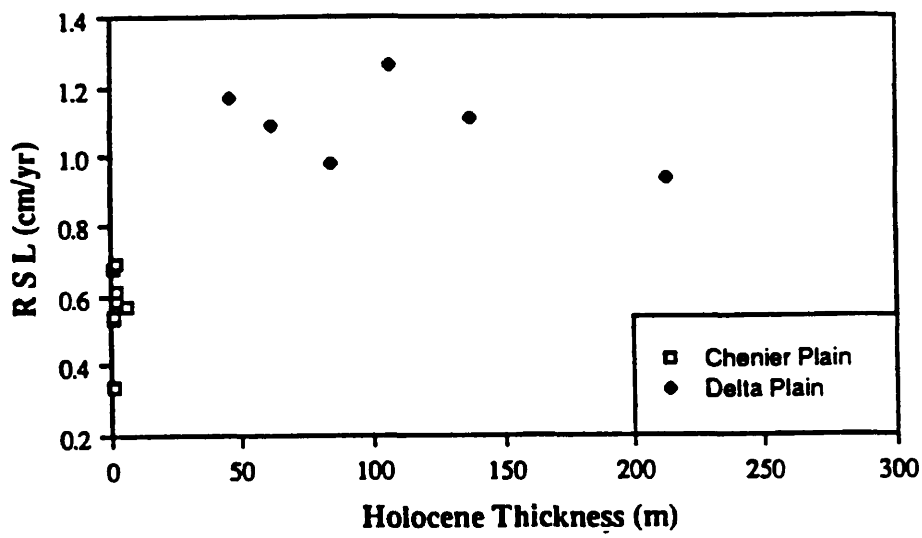


Figure 11. Relationship between thickness of the Holocene sediments and relative sea-level rise in the Mississippi River delta and chenier plains.

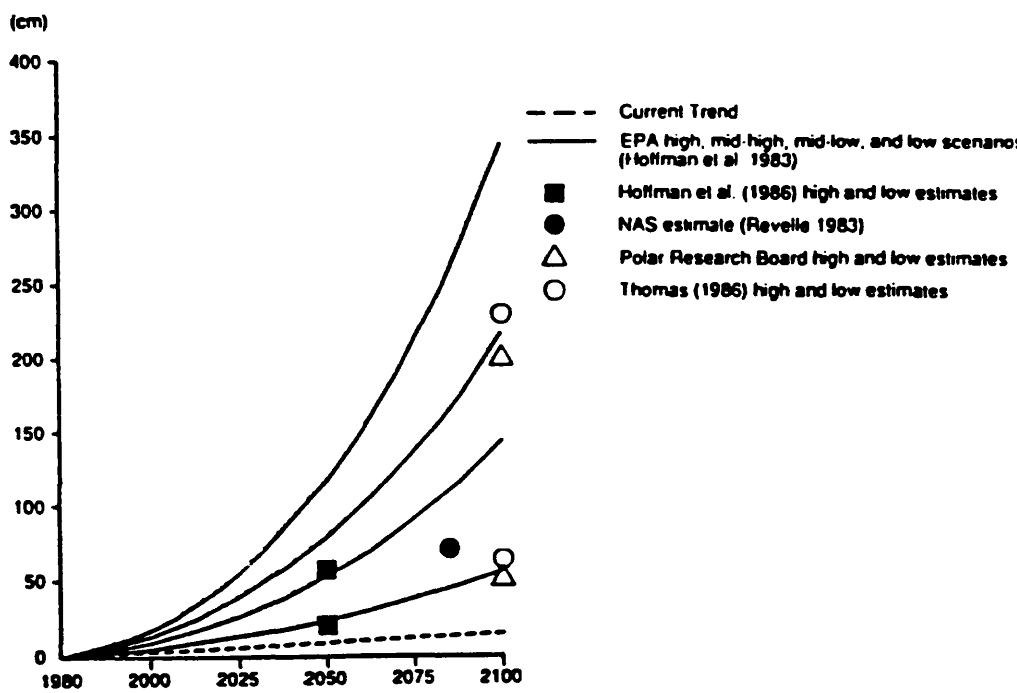


Figure 12. Global sea level rise scenarios from 1980 to the year 2100 (Titus 1988).

EPA created simulations for rising seas in the Mississippi Delta region. The result was that rising seas accelerate loss of seaward salt marshes. By the year 2100, expanded salt marsh habitats were flooded and converted to open water, and a complete loss of fresh and brackish marsh despite accretion rates of up to 10 mm/yr (Titus 1988).

Alternatives to the loss of our valuable wetlands will be found in the ability to manage the wetlands effectively. Wetlands must be able to keep pace with sea level rise. Fresh water diversion projects are methods for ensuring adequate sedimentation rates would contribute to marsh accretion and development. Maintaining protective barrier islands is another alternative. Lastly, tide gates can be used to protect both wetlands and developed areas that are vulnerable to sea level rise.

CONCLUSIONS

Tide gauge records give a good indication of trends in sea-level rise in the Louisiana coastal zone. RSL averages around 0.50 cm/yr in the chenier plain and Pontchartrain Basin and 1.0 cm/yr in the delta regions. This rate is five to ten times the average eustatic rate found in the Gulf of Mexico. Compaction of Holocene sediments is believed to be the major contributing factor for high rates of relative sea-level rise observed in the coastal zone. Secular trends in the data show that water level stages have been on a downward trend since the early 1980's. However, when comparing the entire record of each station through time, overall sea-level appears to be rising.

Controversy surrounds the issue of whether Louisiana's coastal wetlands can be sustained into the next century if the current levels of land loss continue. Of immediate threat to Louisiana, particularly Terrebonne and Lafourche parishes, is the forecasted loss of the Isles Dernieres by the turn of the century, which will dramatically impact the stability and quality of the Terrebonne Bay barrier-built estuary and the vegetated wetlands of lower Terrebonne basin.

How natural and human-induced causes of coastal erosion and wetland loss interact and impact each environment in the Louisiana coast are poorly understood. Each of these factors need to be carefully considered before management strategies can be adequately implemented. The Environmental Protection Agency (EPA) and National Research Council (NRC) predict sea-level to rise significantly in upcoming years due to global warming. If these predictions prove true, the delta plain could be reduced from 150.9×10^3 ha to 29.8×10^3 or to 4.9×10^3 ha if calculations are based on the highest rate of change.

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LATE QUATERNARY CHRONOSTRATIGRAPHIC FRAMEWORK, NORTHERN GULF OF MEXICO

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The stratigraphy of the late Quaternary of the northern Gulf of Mexico reflects the combined effects of glacio-eustatic fluctuations and deltaic processes. Sequence stratigraphy, the study of genetically related strata bounded by unconformities, provides a depositional history of relative sea level and sedimentary processes which can be used to construct a chronostratigraphic framework. Two main models of sequence stratigraphy exist, differing by defining their boundaries on either the maximum flooding surface, or the sequence boundary, created by subaerial erosion during sea level fall. Throughout much of the northern Gulf of Mexico, these two surfaces coincide. In accordance with the most common current practice, we will define our sequence boundaries on subaerial erosion surfaces.

The combination of sinusoidal glacio-eustatic fluctuations and subsidence results in a sea-level curve that can be divided into four components: falling, lowstand, transgressive, and highstand, each with a distinctive depositional style. In this paper, we will concentrate on the deposits of the Late Wisconsinan-Holocene (oxygen isotope stages 2 and 1) glacio-eustatic cycle. Extensive high resolution seismic data, industrial platform borings, vibracores, radiocarbon and oxygen isotope dates provide the database for this analysis.

During the last glacio-eustatic maximum, sea level fell close to, or beyond the margin of the continental shelf as continental glaciation removed water from the oceans. As the continental shelf emerged, coastal plain systems prograded and rivers extended. Rates of progradation on the low-gradient shelf were enhanced by absolute sea level fall. This regression was a rapid process and the resulting deltaic deposits tend to be fairly thin, reflecting the minimal *accommodation space*. Such deposits have been termed *shelf-phase* deltas. As eustatic fall continued, fluvial systems incised into the preexisting deltas, effectively cannibalizing their own deposits. Under these conditions, delta switching is a less important process, and delta lobes tend to "stack" progradationally. A typical thickness for these deposits is about 30 meters.

At eustatic lowstand, the positions of deltaic systems are fixed at the heads of the incised valleys, at or near the shelf margin. Submerged shoreline features indicate a fall to current depths of about -125m. The combination of greater subsidence, higher sea-floor gradient, and water depth, along with fixed locations, created a distinctly different deltaic style. These *shelf-margin* deltas are considerably thicker than their shelf-phase counterparts. Typical late Wisconsinan shelf-margin deltas are over 150m thick and have areal extents of about 5000 km^2. Additional differences from the shelf-phase systems are the increased importance of mass movement processes. Because the incised valleys control the location of the deltas, delta switching is relatively unimportant, and the deltaic lobes tend to stack vertically, or aggradationally. High sediment supply and rapid subsidence compete with the increased wave energy near the shelf margin to determine the morphology of the delta. Overall, most appear to have been lobate and fluvially-dominated.

During the low sea level phase in the Mississippi Delta area, the Mississippi Canyon was formed, and the Mississippi Fan deposited. Lowstand deltaic deposits here are confined to the Mississippi Canyon. The majority of deposition within the Canyon was complete by about 12000 BP. This timing may coincide with the maximum volume of meltwater coming down the Mississippi River as the glaciation waned. In association with the lowstand deltas of the smaller fluvial systems, submarine troughs fed sediment to slope fans in intraslope and interdiapiric basins.

Melting of continental glaciers began raising sea level about 18,000 years ago. Rising base level caused the flucial-deltaic systems to retrograde into the incised valleys, concentrating deposition within these laterally restricted containers. Deposition within the valleys was largely controlled by the rate of sediment supply. Extrabasinal systems tend to be choked with fluvial deposits. Those which received less sediment display a more complicated style of fill, reflecting the creation of estuarine conditions within the valleys. The huge sediment supply from the outwash plains of the Laurentide ice sheet caused the Mississippi River to fill its incised valley by about 9000 BP. A series of backstepping shelf-phase deltas was deposited during relative stillstands, onlapping the Type-1 unconformity as a transgressive systems tract. Similar relationships, though in much less extensive deposits, are seen in the Rio Grande and Brazos-Colorado systems of Texas, which have also filled their incised valleys. Throughout the remainder of the area, the transgressive systems tract is marked by reworked shoreline sands which developed in front of extensive lagoonal/estuarine systems.

Once sea level reached its current position, around 3,000 years ago, continuing deposition in the Mississippi Delta area has created the highstand systems tract, which has now reached the shelf-margin in the form of the Plaquemines-Balize delta complex. Off Southwest Louisiana, the highstand systems tract is represented by the Chenier Plain, which has prograded some 30 km in the last 3,000 years. Much of the coast of Texas consists of fluvial systems emptying into incompletely filled incised valleys, still remaining in the transgressive systems tract.

Although sequence stratigraphic concepts were developed for broad scale basin analysis, they also appear to describe the Late Wisconsinan-Holocene glacio-eustatic cycle. Closer examination calls for some modifications to basic model assumptions, such as constant sediment supply and subsidence, and simple gradient control of fluvial incision. Stratigraphic relationships indicate that systems tracts are not forming synchronously throughout the basin. Additionally, it appears that glacio-eustatic cycles are capable of forming deposits analogous to third-order sequences in time spans several order of magnitude less than thought necessary.

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AERIAL VIDEOTAPE MAPPING OF COASTAL GEOMORPHIC CHANGES

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Abstract

An aerial geomorphic mapping system was developed to examine the spatial and temporal variability in the coastal geomorphology of Louisiana. Between 1984 and 1990 eleven sequential annual and post-hurricane aerial videotape surveys were flown covering periods of prolonged fair weather, hurricane impacts and subsequent post-storm recoveries. A coastal geomorphic classification system was developed to map the spatial and temporal geomorphic changes between these surveys. The classification system is based on 10 years of shoreline monitoring, analysis of aerial photography for 1940 - 1989, and numerous field surveys. The classification system divides shorelines into two broad classes: natural and altered. Each class consists of several genetically linked categories of shorelines. Each category is further subdivided into morphologic types on the basis of landform relief, elevation, habitat type, vegetation density and type, and sediment characteristics.

The classification is used with imagery from the low-altitude, high-resolution aerial videotape surveys to describe and quantify the longshore and cross-shore geomorphic, sedimentologic, and vegetative character of Louisiana's shoreline systems. The mapping system makes it possible to delineate and map detailed geomorphic habitat changes at a resolution higher than that of conventional vertical aerial photography. Morphologic units are mapped parallel to the regional shoreline from the aerial videotape imagery onto the base maps at a scale of 1:24,000. The base maps were constructed from vertical aerial photography concurrent with the data of the video imagery. The linear nature of the mapping technique increases its analytical potential; the length of the units can be measured and are input into a physical shore-zone mapping program for quantitative analysis. Morphologic time series are developed to depict spatial and temporal geomorphic changes.

Introduction

Louisiana has the highest rates of coastal erosion in the Unites States (figure 1). Many of the processes contributing to barrier island erosion are poorly understood and are not quantifiable with any degree of confidence (Sallenger et al., 1987). It is essential to the successful management of our coastal resources that a better understanding of these erosional

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processes is obtained. Hurricanes, tropical storms, and cold fronts all contribute to the erosion of Louisiana's barrier islands (Dingler and Reiss, 1990; Ritchie and Penland, 1988). One of the goals of the five-year U.S. Geological Survey/Louisiana Geological Survey's Louisiana Cooperative Barrier Island erosion and Land Loss Study was to analyze the effects of these storms by investigating their qualitative and quantitative impact on the geomorphology of the shoreline (Sallenger and Williams, 1991; Williams and Sallenger, 1990).

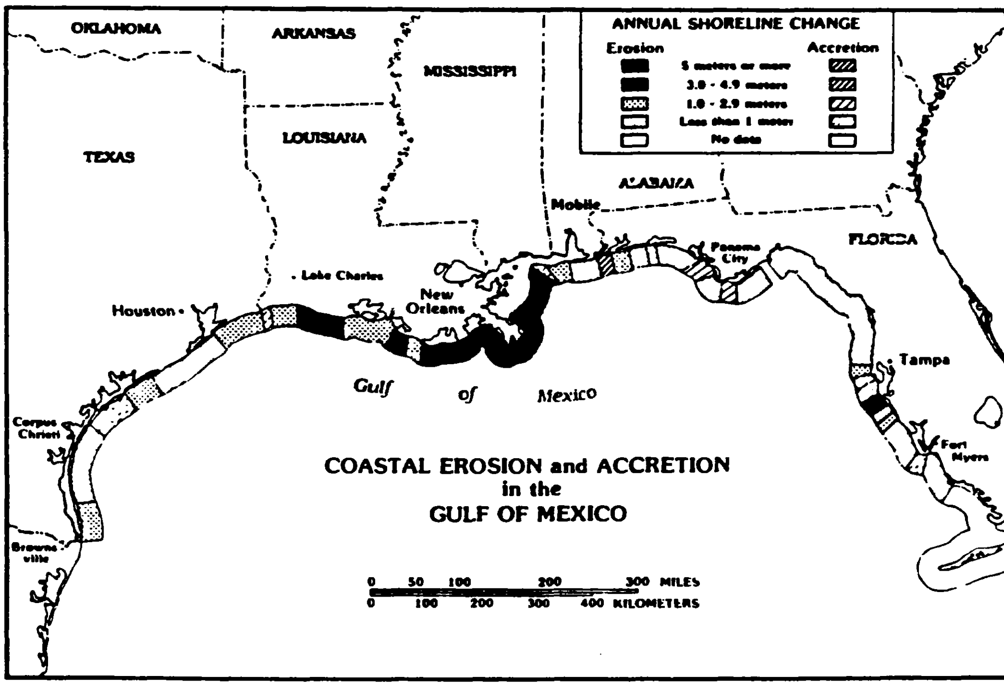

Figure 1. Annual shoreline change in Louisiana (after U.S. Geological Survey, 1988)

In order to assess the temporal and spatial variability of the shoreline morphology and barrier island erosion the Louisiana Geological Survey (LGS) developed an aerial videotape mapping system (Penland et al., 1989a). The coastal geomorphology is delineated using sequential annual and post-storm aerial videotape surveys and mapped on 1:24,000 base maps produced from concurrent vertical photography. A classification was developed to describe, quantify, and map the alongshore geomorphic character of the shoreline. Geomorphic maps consisting of a base map and morphologic descriptor bars were generated on an Intergraph computer mapping system (ICMS). The graphic representation of the shoreline morphology allows for quantitative analyses and assessment of geomorphic changes through space and time.

Data Bases

The videotape mapping technique requires geomorphologic data of the coastline and maps of current shorelines as a geographic reference for the morphology. Between 1984 and 1990 eleven sequential annual and post-hurricane aerial videotape surveys were flown covering a periods prolonged fair weather, hurricane impacts, and subsequent post-storm recoveries (McBride et al, in preparation, 1989a; Penland et al, 1989b, 1989c, 1988, 1987a, 1987b, 1987c, 1987d, 1986; Westphal et al., in preparation) (Table 1). LGS acquired color oblique aerial imagery from a Bell Jet Ranger model 206B, flying at an altitude of 100m and at a speed of 40-50 knots (kn) (figures 2 through 5). The data obtained from the aerial videotape surveys make it possible to delineate and map detailed geomorphic habitat changes at a resolution higher than that of conventional vertical aerial photography.

Figure 2. The aerial videotape imagery is taken from a Bell Jet Ranger 206B equipped with a video camera mount and a special window for shooting color photography.

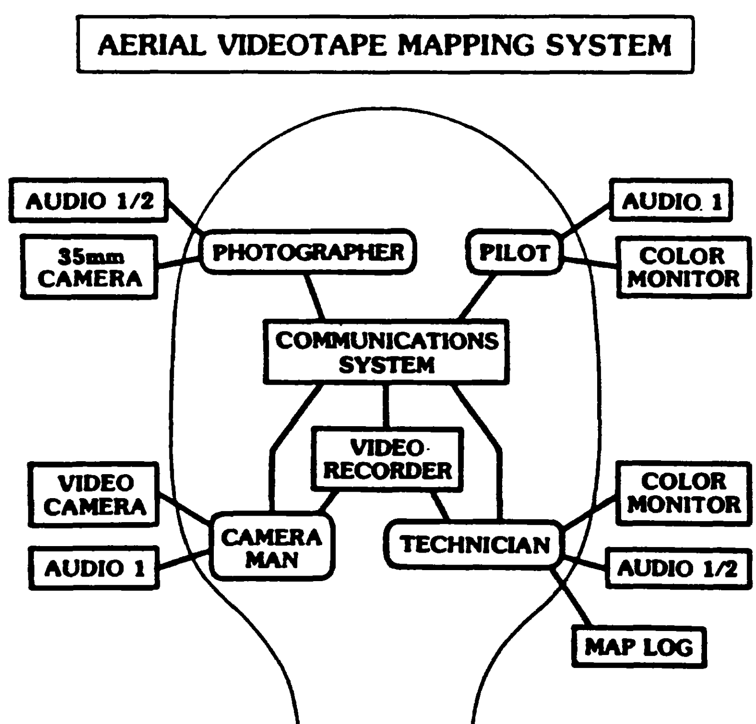

Figure 3. Diagram illustrates the equipment layout in the helicopter. All personnel are linked together by an inboard communication system.

Figure 4. The videotape camera is positioned on a mount in the helicopter. The camera mount reduces the effects of air turbulence and helicopter motion, producing a more stable videotape image.

Figure 5. The flight engineer sits on the back right-hand side of the helicopter and operates the communication system, video recorder, color monitor and flight log.

Table 1. Aerial videotape surveys of coastal Louisiana, Mississippi, Alabama, and Florida.

1. Aerial videotape survey of coastal Louisiana 1984: 187 p. and 45 tapes.
2. Aerial videotape survey of Louisiana's barrier shorelines 1985: 62 p. and 28 tapes.
3. Aerial videotape survey of Hurricane Danny impact zone in coastal Louisiana 1985: 87 p. and 19 tapes.
4. Aerial videotape survey of Hurricane Elena impact zone in coastal Louisiana, Mississippi, Alabama, and Florida: 29 p. and 25 tapes
5. Aerial videotape survey of Hurricane Juan impact zone in coastal Louisiana: 108 p. and 31 tapes.
6. Aerial videotape survey of coastal Louisiana 1986: 95 p. and 32 tapes.
7. Aerial videotape survey of coastal Louisiana 1987: 96 p. and 45 tapes.
8. Aerial videotape survey of coastal Louisiana 1988: 117 p. and 34 tapes.
9. Aerial videotape survey of the Hurricanes Florence and Gilbert impact zones 1988: 70 p. and 17 tapes.
10. Aerial videotape survey of coastal Louisiana, Mississippi, and Alabama 1989: in press.
11. Aerial videotape survey of coastal Louisiana 1990: in preparation.

In order to map the coastal geomorphologic data, base maps with shorelines concurrent with the video surveys are required as a geographic reference point. A Zoom Transfer Scope (ZTS), Baush Lomb model ZT-4, was used to produce the base maps from vertical aerial photography (1:15,000). The ZTS allows the photointerpreter to view the aerial photography and reference map; a 1:24,000 USGS topographic map, in superimposition by: (1) adjusting the scale of the photograph (1:15,000) to the scale of the reference map (1:24,000), and (2) correcting the photographic image for tilt and relief displacements by stretching, magnifying, and rotating it. In order to minimize cartographic errors in the production of the base maps, the base maps are drawn on mylar positioned over the topographic map. The shorelines thus produced additionally provide information about the amount and rate of coastal erosion and the extent of shoreline retreat (McBride et al, 1989b).

Coastal Geomorphic Classification

The LGS developed a coastal geomorphologic classification system for shorelines surrounding the Mississippi River delta and chenier plains based on 10 years of shoreline monitoring, analysis of aerial photography for 1940-1989, and numerous field surveys. The classification is used with imagery from low-altitude, high-resolution aerial videotape surveys to describe and quantify the longshore and cross-shore geomorphic, sedimentologic, and vegetative character of Louisiana's shoreline systems. The classification divides shorelines into two broad classes: natural and altered (Table 2). Each class consists of several genetically linked categories of shorelines. Each category is subdivided into morphologic types on the basis of landform relief, elevation, habitat type, vegetation density and type, and sediment characteristics. In addition, the classification allows for a description of the texture of the coastal geomorphologic features and the overall form of the longshore morphology.

Natural Shorelines

Natural shorelines, either bare or vegetated, have morphologies that reflect ongoing coastal processes rather than direct human impacts. The natural shoreline class is made up of five categories: (1) barrier, (2) tidal inlet, (3) storm, (4) erosional, and (5) marsh.

Table 2. Coastal geomorphic classification system.

Shoreline Class	Category		Morphologic Type
	Barrier		Intertidal flat Washover flat Washover terrace Dune terrace Continuous dune Fringing beach Perched beach Prograding dune ridge
Natural	Tidal inlet		Tidal inlet Flood-tidal delta Ebb-tidal delta
	Storm		Major washover channel Minor washover channel Interdune washover channel
	Erosional		Marsh platform Scarp
	Marsh		Salt marsh
	Protection	"soft"	Barrier restoration Beach nourishment Artificial dune Dune fencing
		"hard"	Seawall Groin Break water
Altered	Habitat disturbance		Spoil bank Pipeline landfall Dredge spoil Industrial structures Residential structures
	Transportation		Air strip Access canal (open) Access canal (closed) Distributary Piers Jetty Access road

The barrier types are a continuum of landform morphologies that represent the range from a high-erosion, sediment-deficient shoreline to a low-erosion, sediment-abundant shoreline; the trend is from intertidal flats through continuous dune fields. The barrier category includes intertidal flats, washover flats and terraces, dune terraces, continuous dunes, fringing beaches, perched beaches, and prograding dune ridges. Figure 6 illustrates the major washover and dune morphologies mapped in the barrier shorelines in Louisiana. Figures 7a-d are aerial photographs of these landforms; note the variations in relief, elevation, and habitat diversity. Tidal inlets represent channels that perpendicularly dissect the barrier shoreline connecting the backbarrier bay with the Gulf of Mexico. These tidal channels remain open, unlike the more ephemeral washover channels. A washover channel that breaches a barrier island will become a tidal inlet if the tidal prism is sufficient to maintain it. Two other morphologic types are incorporated in the tidal inlet category: flood-tidal deltas, which develop landward of the tidal inlets, and ebb-tidal deltas, which develop on the seaward side.

Three types of storm features can be identified: major, minor, and interdune washover channels. A major washover channel is a storm channel cut below sea level that is open during the normal tidal range (figure 8a). A minor washover channel is a well-defined storm channel cut through a barrier shoreline that is not open throughout the normal tidal range (figure 8b). An interdune washover channel is a small-scale washover channel that penetrates the foreshore terraces and dune types without dissecting the island. In the graphic presentation of the data, the direction of the arrow on the geomorphic maps indicates the predominant direction of storm flow.

Two types of erosional morphologic features can be identified. Marsh platforms are erosional outcrops of marsh root mat occurring on a beachface exposed by coastal retreat. An erosional scarp is produced when a retreating shoreline truncates a higher-relief backshore feature. Both of these features are common under normal circumstances; however, storm impacts do produce a greater exposure of marsh platform and erosional scarps per unit length of shoreline.

The marsh category comprises areas along the barrier shorelines where salt marsh or fresh marsh forms the shoreline. This category is common in sheltered areas where sandy beaches are nonexistent.

Altered Shorelines

The altered shoreline class includes sections of coast that are no longer natural because of the impact of human activities ranging from habitat disturbance to erection of seawalls and barrier island restoration projects (Mossa and Nakashima, 1989; Mossa et al., 1985; Penland and Suter, 1988). These are not natural shorelines, yet they form the land/water interface, so we have described their shoreline type as altered. The class is divided into three categories: (1) transportation, (2) protection, and (3) habitat disturbance (Table 2). The transportation types include jetty systems for maintenance of navigation channels and canals for access and transportation. Access roads to the shoreline, air strips, distributaries, and piers also fall into this category. Coastal protection types can be classified into hard and soft structures (Penland and Suter, 1988). Hard coastal structures include seawalls and groins built to stop coastal erosion and reduce sediment loss. Soft coastal structures include barrier restoration, beach nourishment, dune-building projects (artificial dunes), and dune fencing for coastal erosion control and habitat restoration. Morphologic types classified in the habitat disturbance category are dredge spoil, spoil bank, pipelines, and other industrial structures.

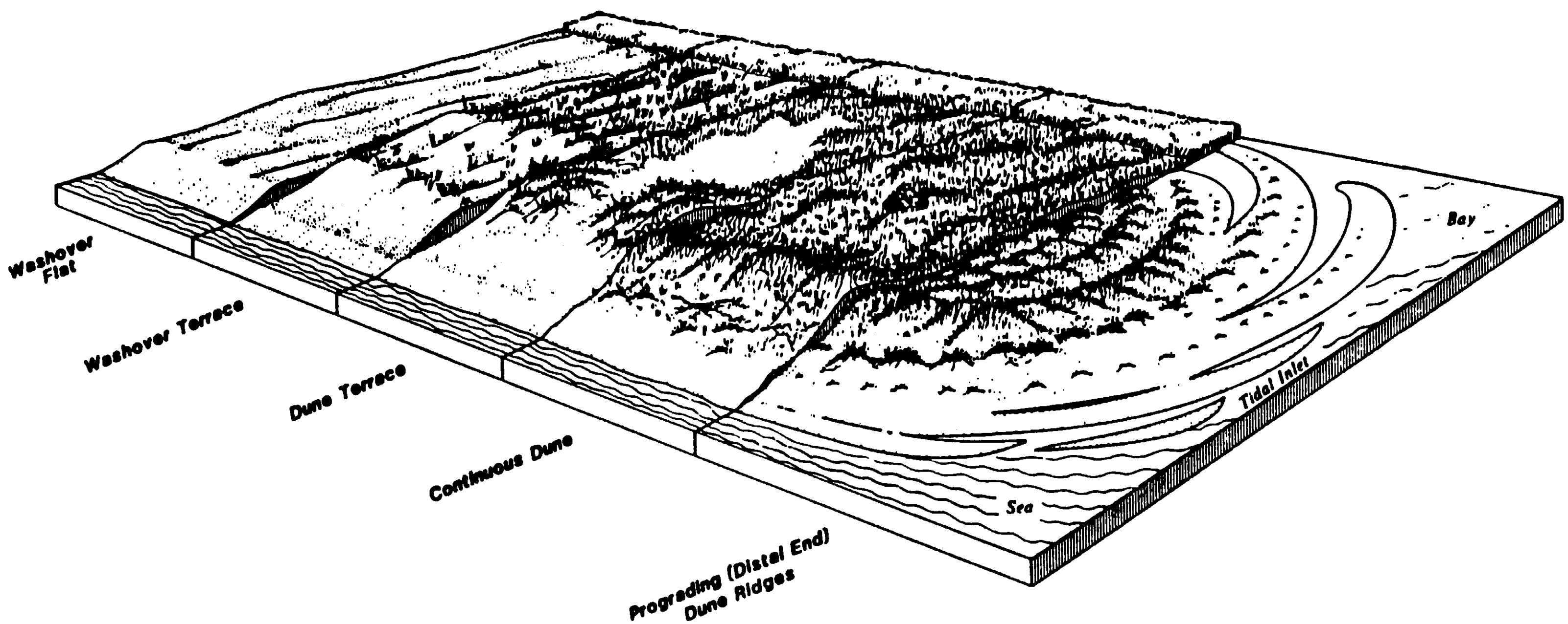

Figure 6. Primary washover and dune morphologic types in Louisiana (after Ritchie and Penland, 1990).

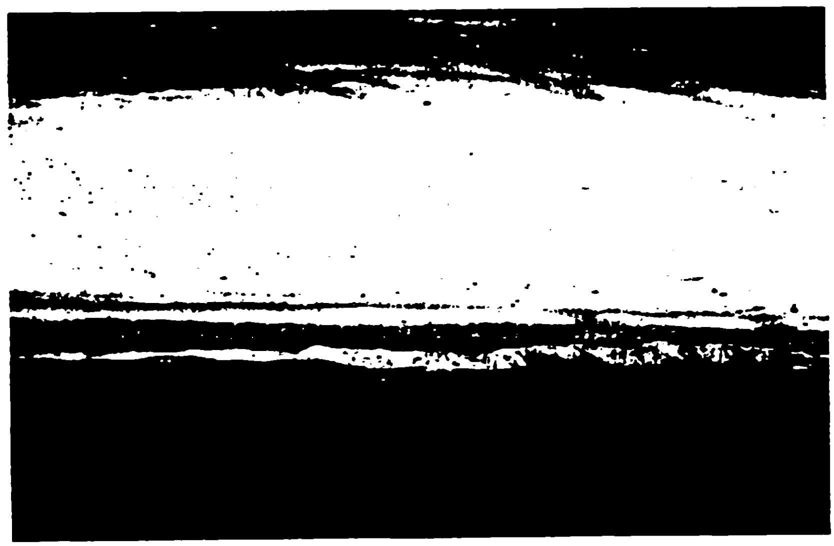

Figure 7a. Oblique aerial view of a washover flat.

Figure 7b. Oblique aerial view of a washover terrace.

Figure 7c. Oblique aerial view of a dune terrace.

Figure 7d. Oblique aerial view of a continuous dune.

Morphologic Types

Thirty-six coastal morphologic types can be identified in coastal Louisiana, based on landform relief, elevation, habitat type, vegetation density and type, and sediment characteristics. The category flats, for example, describes low-elevation, flat-relief landforms less than 1 m above mean tide level (MTL). Terrace describes partially and fully vegetated washover and dune surfaces typically 1-2 m above MTL. Washover flats are low-elevation, low relief washover surfaces devoid of significant vegetation, maintained or formed by frequent or recent washover events. Dune terraces are significantly vegetated washover surfaces where eolian processes have built hummocky and rim dune landforms. Washover terraces are washover surfaces with variable elevation, relief and vegetation, and constitute a transition between washover flats and eolian dominated dune terraces. Therefore, washover terraces can be considered either a low- or -high relief landform depending on and relative to the adjacent shoreline morphology. Continuous dunes are the highest-relief and highest-elevation landforms; they are well vegetated and diverse in habitats. Some of the morphologic types represent either areas whose morphologies and texture contain engineered coastal structures or areas directly impacted or disturbed by human activities.

Additional shoreline variables used to define the morphology include texture (sand, shell, concrete, detrital organics, rubble, etc.) and form (straight, undulating, serrate, etc.).

Figure 8a. Oblique aerial view of a major washover channel.

Figure 8b. Oblique aerial view of a minor washover channel.

Geomorphic Map Production

All morphologic types identified in the classification system can be used at any of three descriptive levels of the classification; this gives the classification scheme greater flexibility: (1) A primary morphology is the dominant longshore morphologic type per unit length of shoreline and is mappable on a 1:24,000 base map (is larger than 10m). (2) A modifier is a secondary longshore feature mappable at the same scale as the primary morphology. (3) A variant is an important feature that can be located and counted but is less than 10 m long.

Morphologic types, form, and structure are mapped as morphologic descriptor bars from the aerial videotape imagery onto the base maps parallel to the regional shoreline. A morphologic unit consists of a length of shoreline with a uniform morphologic type, texture and form. The shoreline length of the morphologic units is mapped from the aerial videotape imagery onto the base maps at a scale of 1:24,000, interpreted from the vertical aerial photography concurrent with the data of the video imagery. The morphologic units are mapped parallel to the regional shoreline. The resolution of the mapping technique consists of a 10m unit of shoreline length. Figure 9 illustrates the graphic mapping technique. The bottom modifier bar and variant describe features in the surf zone and/or foreshore; the upper modifier bar and possible variants describe the backshore features. A maximum of three modifiers and two variants, in addition to the primary morphology, can be allocated to each unit. Including form and texture of the shoreline, a total of eight variables can thus be allocated to each unit of shoreline length.

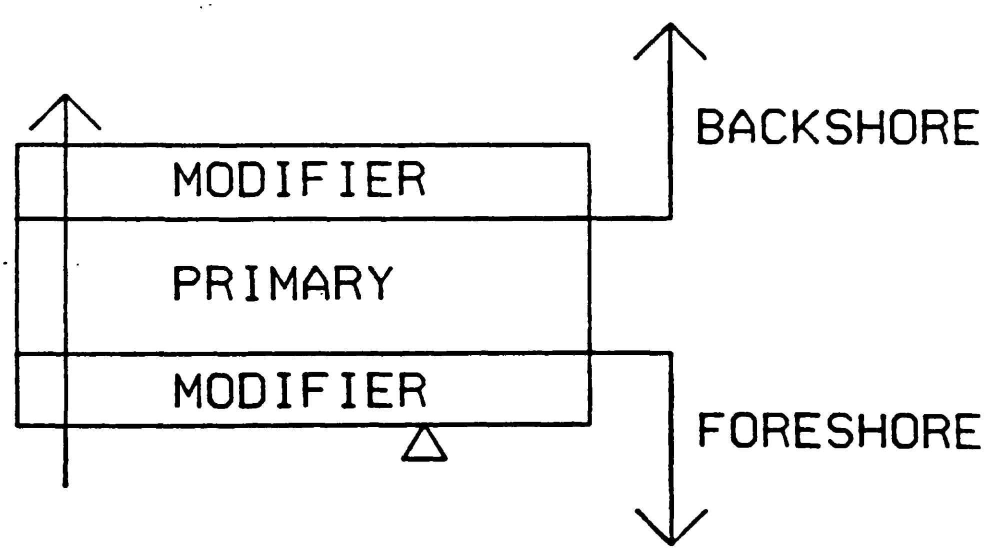

Figure 9. Framework for coastal geomorphic mapping technique. The primary bar describes the predominant longshore geomorphology. The modifier bars describe secondary characteristics of the longshore geomorphology along the backshore, or foreshore and surf zone. The arrow and triangle are examples of variant features and where they may occur in the graphic display to depict backshore, foreshore, or across-shore small-scale features.

Once the morphologic units are mapped the base maps and morphologic descriptor bars are digitized into the Intergraph Computer Mapping System (ICMS). The Louisiana Geological Survey developed patterns for each of the morphology types. The individual symbols of the patterns were created on the ICMS as "cells." The descriptor bars are filled through the ICMS' software with their respective patterns by multiplication of the cells. The ensuing maps create a morphologic time series of the spatial and temporal variability of the shoreline. Figures 10, and 11a-d represent an example of the ICMS generated patterns and geomorphic maps for the Isles Dernieres.

Quantitative Analysis

Once each unit is digitized into the ICMS, it can be measured. Measurements are made shore-normal to the descriptor bars and represent the per-unit length of exposed shoreline. The length, and morphologic and sedimentologic characteristic of each unit are input into a physical shore-zone mapping program for quantitative analysis (Reimer, 1988). The shore-zone mapping program allows for quantitative analysis of each of the descriptive levels of the coastal geomorphic classification and/or any combination of the eight possible variables that can be assigned to the morphologic units. Data output consists of the number of units, total unit length, and total unit percentage by variable for a specified shoreline length. Histograms depicting the spatial and temporal geomorphic changes of the shoreline are subsequently generated by the ICMS. Figures 12 and 13 demonstrate the analytical potential of this videotape mapping technique. The data presented reflect both the temporal and spatial variability of the coastal morphological changes in the Isles Dernieres. Dramatic alteration of the coastal morphology occurred as a result of hurricane impacts and subsequent post-storm recoveries.

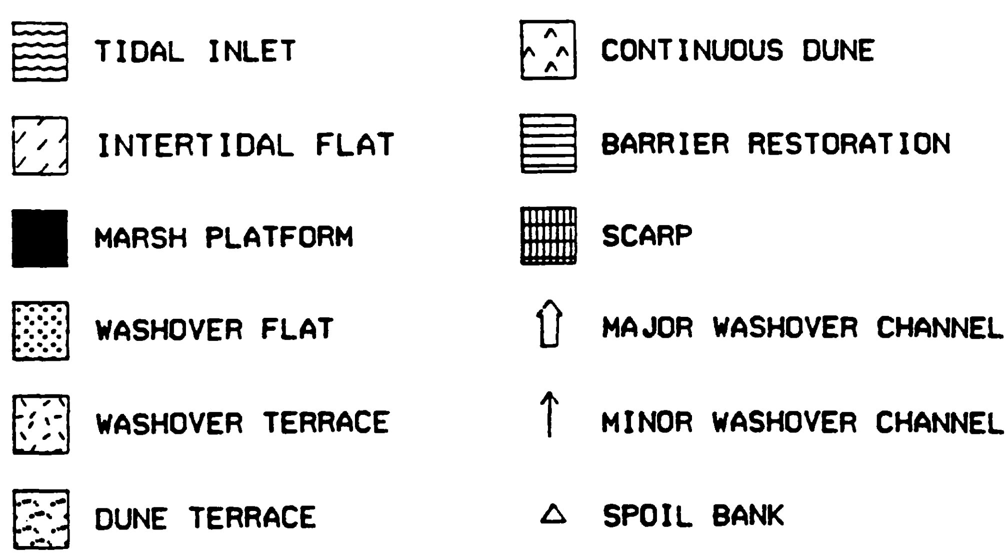

Figure 10. Patterns for morphologic types. This figure functions as a legend for figures 11a-d.

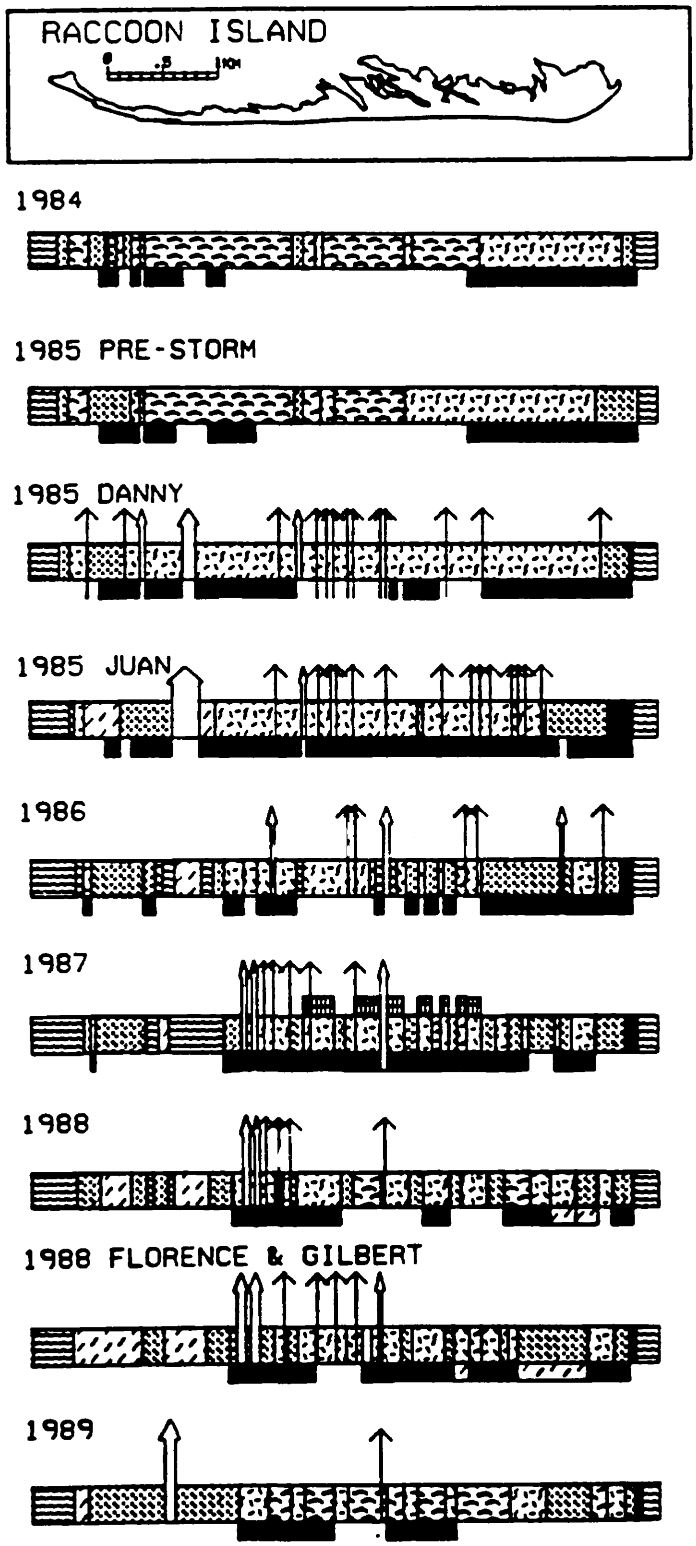

Figure 11a. Raccoon Island geomorphic changes, 1984-1989.

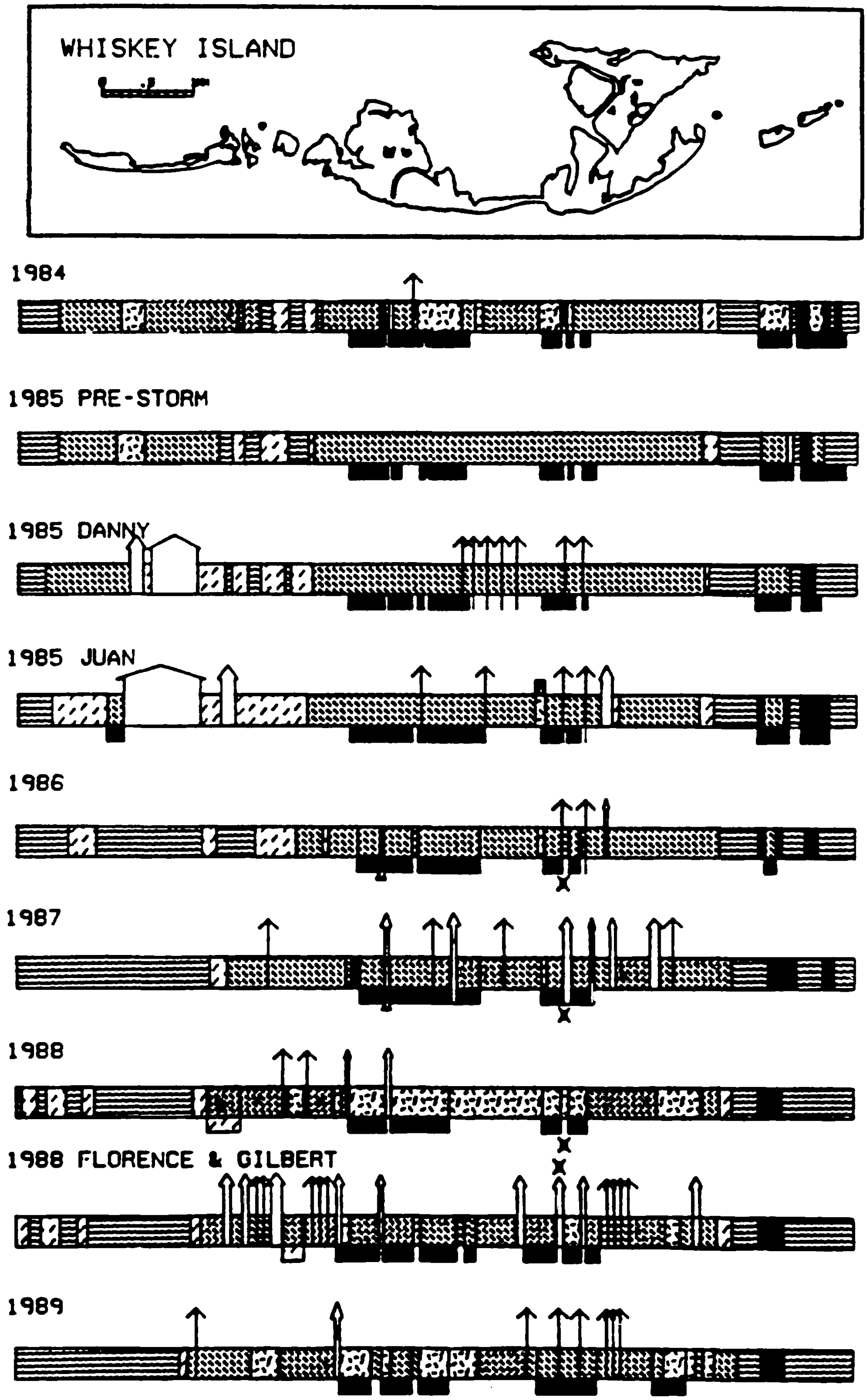

Figure 11b. Whiskey Island geomorphic changes, 1984-1989.

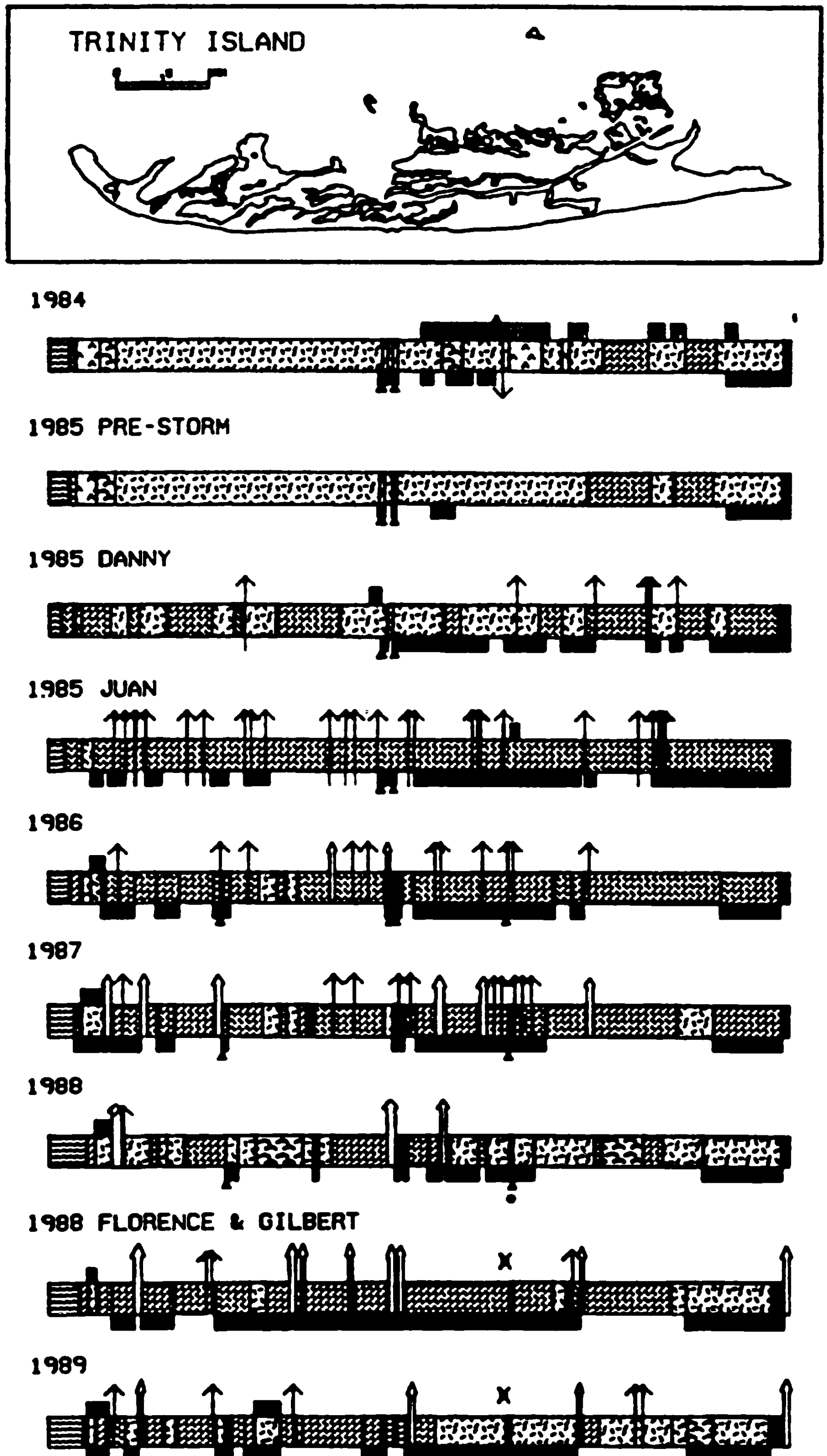

Figure 11c. Trinity Island geomorphic changes, 1984-1989.

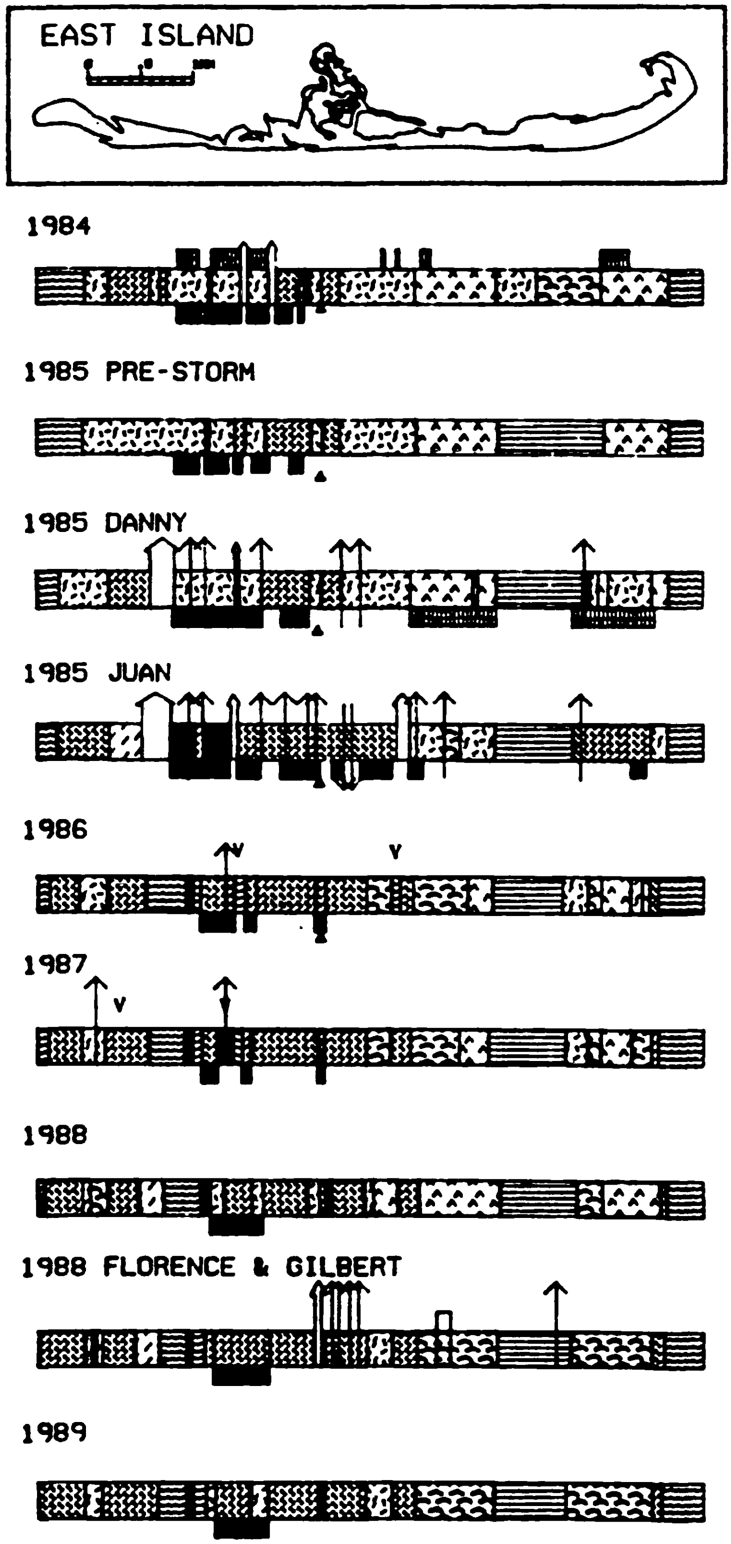

Figure 11d. East Island geomorphic changes, 1984-1989.

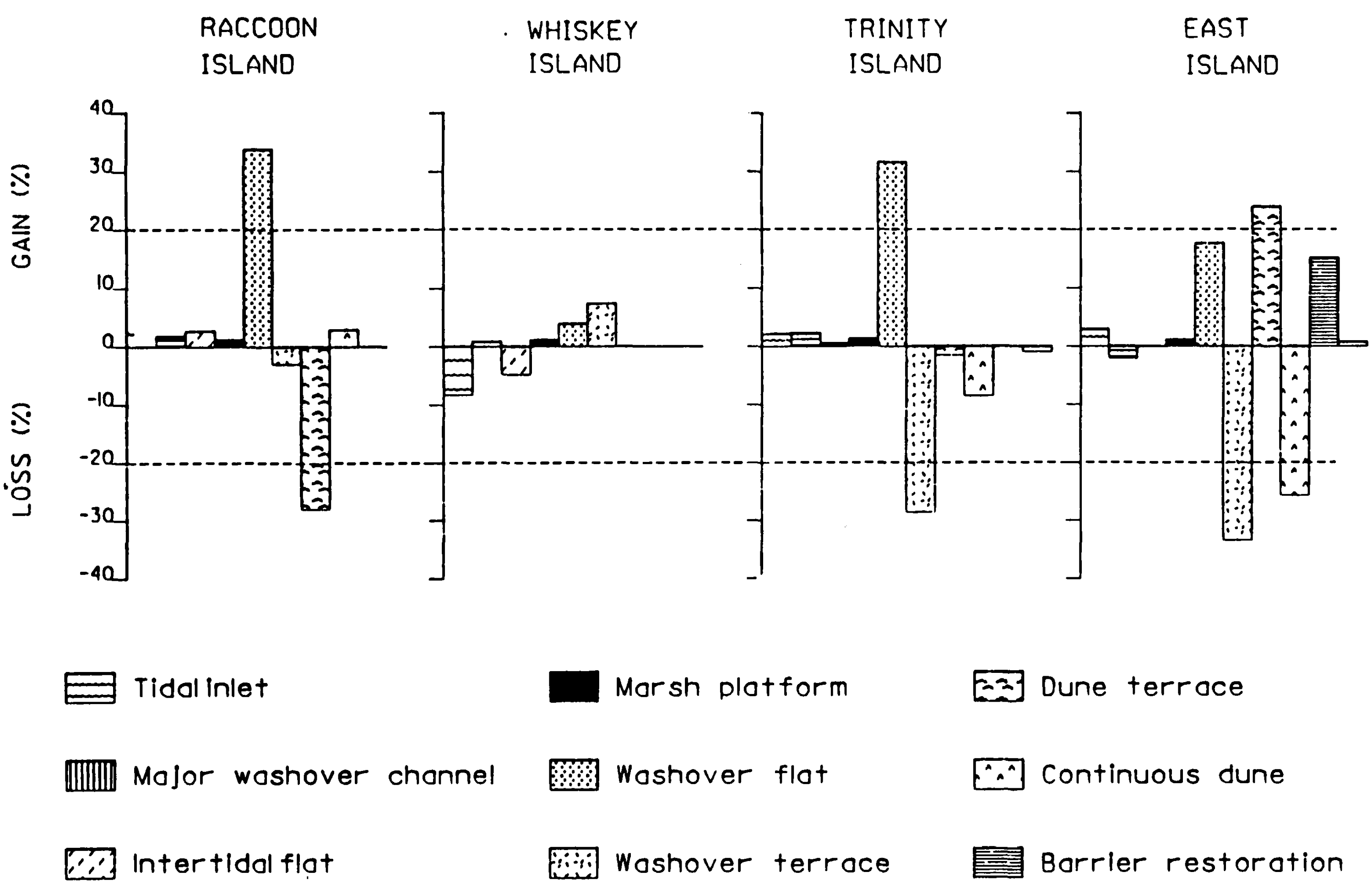

Figure 12. Percentage change in the primary morphology of the Isles Dernieres between 1984 and 1989.

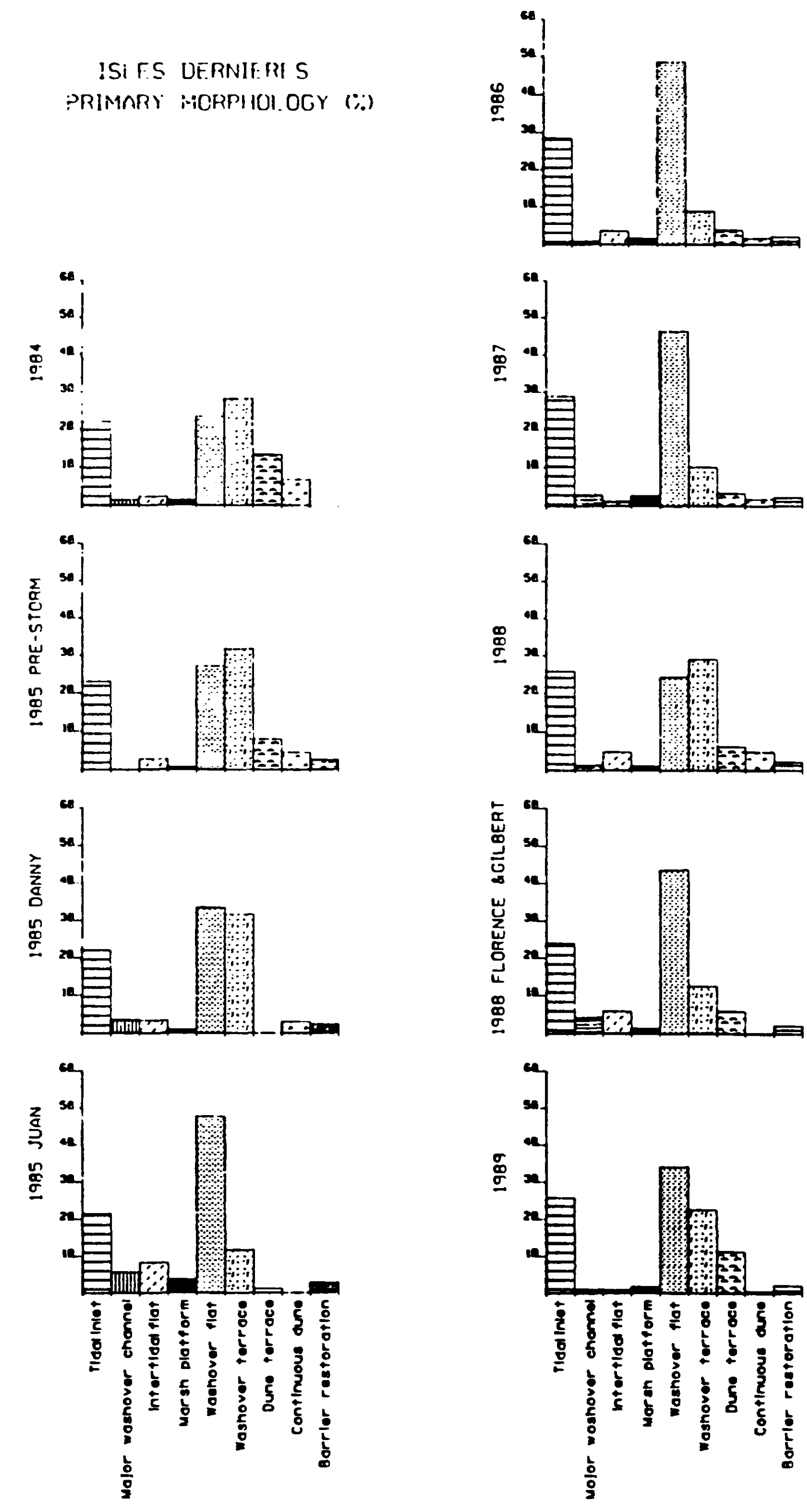

Figure 13. Primary morphology (%) per unit length of the Isles Dernieres shoreline: sequential annual and post-hurricane surveys between 1984 and 1989.

Conclusions

A coastal geomorphic mapping system was developed to examine spatial and temporal variability of shoreline geomorphology and barrier island erosion in Louisiana. The mapping technique uses sequential aerial videotape surveys and a coastal geomorphic classification to delineate and map the longshore and cross-shore geomorphic, sedimentologic and vegetative character of Louisiana's shoreline system. The geomorphic character of the shoreline can be delineated at a resolution higher than that of conventional vertical aerial photography. The linear nature of this videotape mapping technique allows for the assessment and quantification of geomorphic changes through space and time. The aerial geomorphic mapping system has proven to be cost- and time-efficient, and beneficial to management, protection, restoration, and preservation plans and operations in the coastal zone.

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ACCURACY STANDARDS AND DEVELOPMENT OF A NATIONAL SHORELINE CHANGE DATA BASE

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ABSTRACT: Data associated with mapping shoreline position provides baseline information used by scientists, managers, and planners for quantitative assessment of historical trends and prediction of future conditions. Unfortunately, many decisions based on application of this information rely on the assumption that all data and techniques are error-free. This paper provides an overall perspective of shoreline change assessment in light of potential errors associated with shoreline mapping. Proposed measurement and accuracy standards are presented within the framework of an automated process for organizing and integrating geographic information. A shoreline change GIS strategy is discussed, and application of this procedure for Harrison County, Mississippi is presented. This integrated design provides an accurate and comprehensive method for collecting, storing, retrieving, transforming, and displaying spatial data. Development of a national shoreline change data base for science and coastal zone management applications should proceed using this technology.

INTRODUCTION

Quantitative knowledge of shoreline change is essential for planning and designing many coastal projects. Scientists, engineers, and planners have long recognized the usefulness of mapping shoreline position to estimate erosion and accretion. These data are also important in developing sediment budgets, monitoring engineering modifications to a beach, examining geomorphic variations in the coastal zone, studying the role of natural processes in altering shoreline position, establishing setback lines, and predicting future shoreline change through numerical modeling. At present, a consistent digital data base of historical shoreline position, comparative rates of change, and natural and human-induced factors affecting those changes does not exist on a national or regional scale at a level of accuracy sufficient for scientific or management application.

In response to enactment of the Upton/Jones Amendment (Section 544 of the Housing and Community Development Act of 1988) to the National Flood Insurance Act, the National Flood Insurance Program (NFIP) now allows for payment of flood insurance claims for undamaged structures threatened by erosion and subject to "imminent collapse" (National Research Council,

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1990). The Federal Emergency Management Agency's (FEMA) Federal Insurance Administration asked the National Research Council to provide advice on appropriate erosion management strategies to be administered through the National Flood Insurance Program. A primary recommendation of that study was to use historical shoreline data to immediately begin mapping erosion hazard zones. Erosion rate data do exist for certain coastlines; however, the rate of shoreline change is not documented to an adequate level of detail or consistency along much of the U.S. coast. Reliable and up-to-date measurements of spatial and temporal shoreline movements will be required to develop a legally defensible erosion rate data base. This paper proposes measurement and accuracy standards for compilation of shoreline position data and presents a prototype shoreline change geographic information system (GIS) for direct input, storage, retrieval, analysis, and output of information.

Significant effort has been expended over the past two decades to collect, measure, and analyze rates of shoreline movement along coastlines of the United States. Many of the studies have been regional in scope (e.g., Langfelder et al., 1970; Dolan et al., 1979; Morton, 1979; Penland and Boyd, 1981; Everts et al., 1983; Rice and Leatherman, 1983; Shabica et al., 1984; Anders et al., 1990; McBride et al., this volume) while others have been site specific (e.g., Leatherman, 1984; Byrnes et al., 1989; McBride, 1989). However, not since the U.S. Army Corps of Engineers National Shoreline Study in 1973 has there been a unified effort to assess variations in rates of shoreline movement on a national scale. An examination of that study by the U.S. General Accounting Office indicated that inconsistencies in methodology and evaluation criteria prevented the study from satisfying any but the broadest requirements (U.S. General Accounting Office, 1975). Although significant amounts of data have been compiled for much of the U.S. coastline as part of the U.S. Geological Survey National Atlas (May et al., 1983), inconsistent methodologies again limit the usefulness of the information for providing accurate assessments of shoreline change.

Since then, significant advances in computer hardware and software have made it possible to capture and analyze information with a high degree of accuracy and at much reduced cost. Consequently, a re-analysis of historical shoreline information should be performed to meet scientific and legal standards for applicability to coastal projects. In addition, it is likely that future coastal zone management decisions will evolve in response to the development of this data base. To this end, three primary considerations must be confronted when collecting, analyzing, and applying shoreline change data. They are:

1) What type of information is available and how accurately does it represent historical shoreline position?

2) Which analysis techniques provide the most accurate assessment of shoreline change?

3) What are the benefits of using an automated process to organize and integrate geographic information?

The following discussion will use a three-step approach to provide background on the evolution of shoreline change assessment, specifics of accurate shoreline mapping procedures in light of inherent and operational errors, and recent developments in GIS technology as it applies to analysis of shoreline position change. As an example, the design of a shoreline change GIS for Harrison County, Mississippi will be used to illustrate the applicability of a proposed standard strategy for development of a national shoreline change data base.

HISTORICAL PERSPECTIVE

A number of manual and automated techniques have been developed to compile information on historical shoreline position. The use of maps and aerial photography to analyze the rate and direction of shoreline movement requires two general procedures: 1) compilation of shoreline position data in analog or digital form, and 2) a comparative analysis of these data to determine specific rates of change. A variety of methods have been used for creating composite shoreline change maps. Originally, temporal comparisons of shoreline movement were synthesized using standard cartographic techniques for producing map overlays (Morgan and Larimore, 1957). These detailed and time-consuming procedures resulted in accurate representations that accounted for changes in map projection, horizontal datum, scale, and coordinate system. More rapid but less accurate approximations of these procedures can be performed by enlarging or reducing maps to a common scale. Using this approach, composite map overlays can be assembled using instruments such as a Map-O-Graph, Zoom Transfer Scope, or projecting light tables (Dolan et al., 1978; Ellis, 1978). Once overlays are created, changes in shoreline position can be measured directly.

Determining shoreline change from aerial photography is significantly more involved than using maps. Although vertical aerial photographs are sometimes thought of as pictorial maps, they rarely are orthogonal. Stafford (1971) and Stafford and Langfelder (1971) introduced the point measurement technique for determining shoreline change rates from aerial photographs. This approach provides accurate estimates of shoreline position change at control locations; however, a continuous representation of the coastline cannot be obtained. To generate maps from near-vertical photographs, tilt and scale distortions can be eliminated using optical and analytical techniques. Stereoscopic plotters eliminate photographic distortion by placing the air photo back into its tilted position and projecting the image at a selected scale. The projected image has all tilt and scale variations removed, and a rectified photograph is produced that can be treated as a map. Smaller instruments, such as the Vertical Sketchmaster and Zoom Transfer Scope, work on the same basic principle to remove tilt, but are not as accurate. Aligning carefully selected control points and working in small areas near stable control points on the air photo produce the most reliable results. Projecting instruments, such as light tables and the Map-O-Graph, can remove scale variations between air photos but cannot correct for tilt distortion.

Several computer software packages are now available that allow a small mapping laboratory to generate composite shoreline maps from original maps and near-vertical aerial photographs (Leatherman, 1983; McBride, 1989). These techniques use various algorithms, including a least-squares adjustment, to rectify aerial photographs to a scaled, non-tilted condition. This procedure involves digitizing control points on an air photo and comparing the location of each point to its known location in a geographic coordinate system. The least-squares procedure uses a calculated correction factor to adjust a group of control points to their "proper" position. Therefore, the correction is not specific to tilt or scale variations, but simply corrects for all inherent errors simultaneously. The resulting correction is a "best fit" position for all control points on an air photo.

A detailed qualitative assessment of shoreline position change can be extracted from accurate map overlays; however, quantitative summaries provide a level of documentation necessary for most current applications. Once shoreline position is recorded accurately, temporal comparisons can be determined manually from composite maps or calculated directly from digital data.

For the past decade, a computerized data bank of shoreline change rates has been compiled and updated for coastlines of the United States, including Chesapeake Bay, the Great Lakes, and Alaska (May et al., 1983). Known as the Coastal Erosion Information System (CEIS), it contains data acquired by a variety of methods ranging from precise engineering surveys to general appraisals of old photographs. Although this shoreline change data base was created from the most comprehensive information available, analysis techniques varied considerably, as did the level of accuracy and quality assurance. As a consequence of map scale and data quality, shoreline change classification maps created from this data base (Dolan et al., 1985) provide generalized regional trends at best. At the time, this was the best approach for generating shoreline change information; however, advances in computer cartography and GIS technology now provide a foundation for designing a complete strategy for accurately compiling historical shoreline position data and associated natural and cultural attributes that impact spatial and temporal response of coastal systems.

SHORELINE MAPPING

Shoreline position is a function of five primary factors: 1) coastal processes, 2) relative sea level, 3) sediment budget, 4) climate, and 5) human activities (Figure 1). Creating an accurate map is always a complex surveying and cartographic task, but the interaction of these five factors

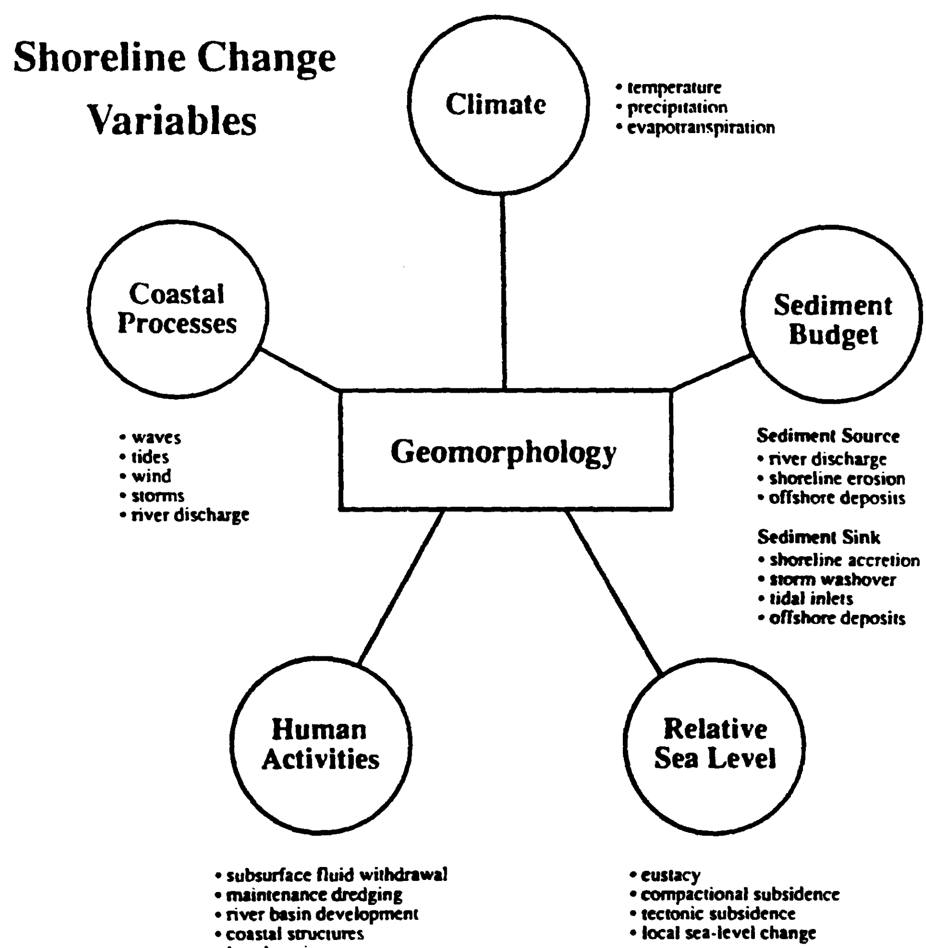

Figure 1. Interaction of processes affecting shoreline change (modified from Morton, 1977)

make shoreline mapping especially difficult. Historically, shoreline field surveys were so time consuming that long periods resulted between successive maps. Such infrequent data collection can make trends in historical shoreline change difficult to interpret. More recently, air photos, which have the benefit of a relatively synoptic view and potentially frequent collection and analysis, have been used to update historical maps.

Comparing shoreline positions generated from successive maps and air photos must be accompanied by potential error estimates to gage their impact on measured changes. All source information and data capture techniques used for shoreline mapping contain inherent and operational errors. Inherent error results from inaccuracies present in source documents; operational error is produced during data capture and manipulation (Walsh et al., 1987). Table 1 lists potential errors associated with shoreline mapping. Although map errors are inherent, compiled shoreline information should be corrected to reflect a common horizontal datum and brought to a common scale, projection, and coordinate system before data from successive maps are compared (Snyder, 1987; McBride, 1989). In addition, if air photos are to be treated as maps, images must be rectified to eliminate or minimize the effect of distortions in the photographic process.

Data Sources

A number of data sources exist for assessing spatial and temporal changes in shoreline position. These include U.S. Geological Survey (USGS) topographic quadrangles, National Ocean Service (NOS) topographic sheets, local engineering surveys, and near-vertical aerial photography. Each data source addresses a specific need that is dependent upon project objectives.

Maps. Maps and charts are classified as either metric or non-metric based on quality of construction. A metric quality map generally contains a graticule of meridians and parallels (Ellis, 1978), and represents all map features in precise relation to one another and to the grid. The most common maps used for documenting changes along the coast are USGS topographic quadrangle maps. These maps are created at scales from 1:24,000 to 1:250,000 (Ellis, 1978). The primary purpose of these maps is to portray the shape and elevation of the terrain above a given datum, usually the high water line (HWL). Accurate delineation of the shoreline is not a primary concern on these land-oriented maps. However, shoreline position routinely is revised on 1:24,000 topographic maps using aerial photographic surveys. Many shoreline mapping studies have used these data for quantifying changes in position, but more accurate and appropriate sources generally are available.

Table 1. Potential Errors Associated with Shoreline Mapping (from Anders and Byrnes, 1991)

ACCURACY		PRECISION
Maps and Charts	Aerial Photographs	
scale	interpretation of HWL	annotation of HWL
horizontal datum changes	location of control points	digitizing equipment
shrink/stretch	quality of control points	temporal data consistency
surveying standards	aircraft tilt and pitch	media consistency
publication standards	altitude changes (scale)	operator consistency
photogrammetric standards	topographic relief	
projection	negatives vs. contact prints	

The preferred cartographic data source for mapping shoreline position is topographic maps produced by the National Ocean Service (formerly U.S. Coast and Geodetic Survey). Because this agency specifically is charged with surveying and mapping topographic information along the coast, NOS topographic maps (T-sheets) have been used in the study of coastal erosion and protection, and frequently in courts in investigations of land ownership (Shalowitz, 1964). Most of these maps are planimetric in that only horizontal position of selected features is recorded; the primary mapped feature is the high-water shoreline. From 1835 to 1927, almost all topographic surveys were made by planetable; post-1927 maps are produced using aerial photographs (Shalowitz, 1964). Mapped shoreline survey data often are used on USGS topographic quadrangles, suggesting that T-sheets are the primary source for accurate shoreline surveys. Scales of NOS topographic survey maps are generally 1:10,000 or 1:20,000, although others exist. These large-scale products provide the most accurate representation of shoreline position besides direct field measurements using engineering methods and large-scale photomaps created using a stereoplotter.

Aerial Photography. Since the 1920s, aerial photography has been used to record shoreline characteristics in many coastal regions. However, these data cannot be used directly to produce a metric map. Aircraft tilt and relief (scale variation) may cause serious distortions that must be removed by rectification. A number of graphical methods and computational routines exist for removing distortions inherent in photography (Leatherman, 1983; Anders and Byrnes, 1991). Orthophotoquads and orthophotomosaics are photomaps made by applying differential rectification techniques (stereoplotters) to remove photographic distortion. Ease of data collection and the synoptic nature of this data source provide a significant advantage over standard surveying techniques.

Data Capture and Analysis

Once data sources are identified, a variety of factors affecting accurate data capture must be considered. Photographic parameters include photo quality, the number and quality of control points, and shoreline annotation procedures; cartographic parameters include map scale, projection, horizontal datum, and ellipsoid characteristics. The accuracy of topographic surveys depends on the date and purpose of the survey, the topographer, the methods used, and the amount of triangulation control available in the area. The most critical limitation is that associated with restricted horizontal control. The most accurate way to register mapped features to a grid is to use triangulation station positions (Crowell et al., in press). If these data exist, they are the most accurate points on the map (Shalowitz, 1964). Newer maps contain many control points but older maps typically contain few. Often, the graticule on a map represents the only level of primary control. In addition, media distortion and incomplete map information present varying degrees of difficulty. Map paper distortion, or shrink and stretch, is recognized as being non-linear and can represent a 1% change in scale with a 60% increase in humidity (Snyder, 1987). Media destruction, such as folds and tears, can cause more serious problems.

Although a variety of distortions intrinsic to air photos must be eliminated or minimized to reduce measurement errors to an acceptable level, delineation of the high-water shoreline is the most important and most subjective part of shoreline change analysis. The interpreted shoreline is delineated as the wet/dry boundary on a beach, and is usually recognized by an abrupt or subtle change in contrast on aerial photography, or the outer limits of emergent marsh vegetation, as seen in lagoons and estuaries. Along mud, marsh platform, and light sand beach coastlines, or with overexposed or grainy photography, this can be extremely difficult unless the interpreter is familiar with the area or has access to pertinent geomorphic information. Shell deposits, debris along the beach, and vegetation can obscure actual shoreline position. It is best to have a single interpreter who is familiar with the coastline so that all interpretations remain relatively consistent.

Although computational techniques exist for removing most inherent photographic distortions (Leatherman, 1983), many mapping laboratories use an optical/graphical strategy for compiling photo-derived shorelines. A least-squares fitting procedure can produce reasonable results; however, an equivalent, if not more accurate, representation of shoreline position can be attained through careful rectification of aerial photographs to high-quality maps (Byrnes et al., 1991). Using a Zoom Transfer Scope, each photograph is registered to a large-scale map base (T-sheet) and adjusted for best fit. Coastal features are annotated on a clear, stable acetate base. After the initial acetate photomap is produced, it can be used to help rectify other shorelines for the same area by overlaying them on the map base. New control points (structures built after T-sheet publication) on photographs are mapped relative to original control on the map base. These points are referenced with subsequent photos, building horizontal control point by point and thereby minimizing error. This better reflects changes between actual shorelines than two separately generated maps. Two important components of this procedure are: 1) data interpretation procedures can be quality checked at any stage of annotation, and 2) a metric-quality photomap on stable acetate base is the end product (Figure 2). The photomap is particularly important in terms of data cataloging for quality control checks and future examination.

<u>Computer Mapping.</u> In recent years, development and improvement of hardware and software for computer cartography have greatly reduced the time and effort required to produce accurate maps. Digitizing maps is faster than manually drafting them, and the time needed for reproduction, coordinate system conversion, modification, and change of scale is reduced tremendously. When maps are electronically digitized, they are traced into the computer using a high-precision digitizing table and cursor. The computer converts the points on the table to real-world units (meters, feet, latitude-longitude, etc.) in a graphics file using a transformation routine unique to each map. After capturing all cartographic data at original scale, maps are stored at a 1:1 scale and actual ground distances and areas can be determined directly. McBride et al. (this volume) present a detailed mapping strategy for compiling historical shoreline data, quantifying rates of change, and assessing the magnitude of inherent and operational error associated with mapping shoreline position.

<u>Shoreline Position Change.</u> Once shoreline position has been recorded accurately, temporal comparisons can be determined manually from composite maps or calculated directly from digitized data. The manual process involves establishing transects perpendicular to the composite shoreline trend at the desired along-the-coast interval and measuring distances between shorelines along each transect. The measured distance is divided by the time interval between shorelines to determine rate of change. For projects covering large areas that require a high density of calculated shoreline position changes, automated techniques can save significant amounts of time. The basic procedure is similar to the manual technique. Transects are established perpendicular to an arbitrary baseline that is parallel to the average trend of digitized shorelines, and the intersection of these transects with each shoreline represents a data point. Baseline length depends on general shoreline orientation and natural breaks in shoreline continuity. Anders et al. (1990) used a cartesian coordinate system for each baseline with the x-axis directed alongshore and the y-axis directed offshore. Digitized data were used to generate shoreline changes at approximately 50 m intervals along the coast. Byrnes et al. (1989) used a similar technique; however, high-water shoreline position was digitized as latitude-longitude pairs. Digital data were converted to state plane coordinates and referenced to a baseline parallel to the shoreline trend. Cubic spline interpolation was used to compare temporal data at exact alongshore positions.

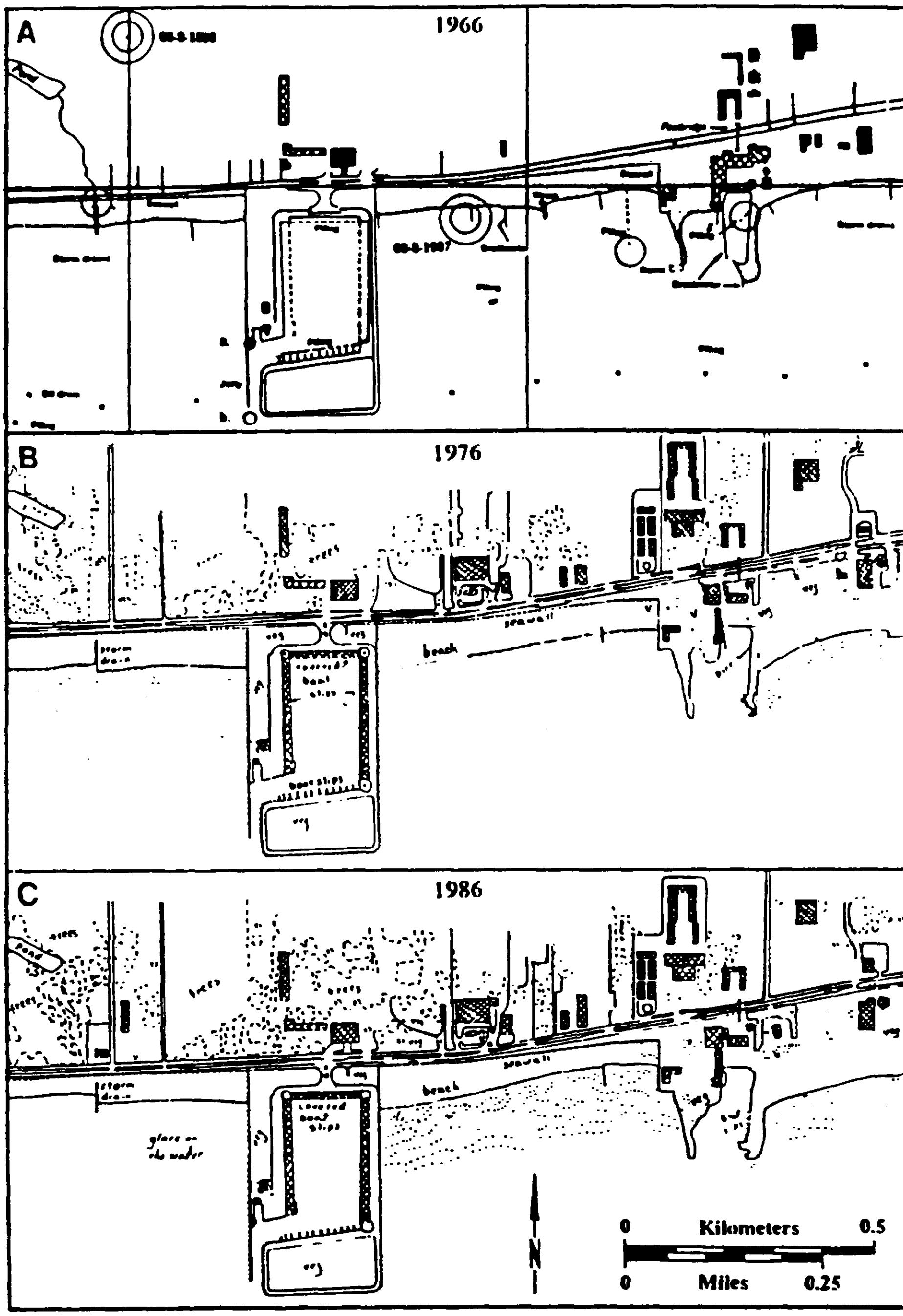

Figure 2. Comparison of a base map with metric-quality photomaps for the Biloxi, MS area. A) T-sheet 11804 (January 1966); B) photo-interpreted shoreline for October 21, 1976; C) photo-interpreted shoreline for October 17, 1986. On the photomaps, solid lines indicate shoreline and roadways, solid lines with perpendicular tick-marks indicate seawalls and bulkheads, cross-hatched areas are structures, dashed lines on land are tree canopy margins, and dotted lines in water indicate shoals.

An improvement to these techniques, which addresses the dynamic nature of inlet shorelines, is being developed. Based on changes in shoreline orientation, a best-fit line is created through a series of digitized shoreline points for all time periods. Depending on orientation, each segment could be described by 2 to N points, where N is the total number of coordinate pairs. Straight line segments are averaged for each shoreline to create a mean shoreline orientation. Transects are created perpendicular to the mean shoreline at an along-the-coast interval specified by the user. Temporal comparisons of digitized data are made for each transect, producing rates of shoreline change.

Proposed Measurement and Accuracy Standards

It is implicit in geographical resource information evaluation that collection and processing of environmental data lead to improvements in resource management. In the case of shoreline change evaluation, these data are used as baseline measurements for quantitative assessment of historical trends and prediction of future conditions. Management decisions regarding coastal development and appropriate setback criteria often are based on the assumption that all data and techniques used are error-free; this is not a realistic assessment. Because many procedures and data sources exist for evaluating historical shoreline change, it is important to develop guidelines for application of a strategy that employs the most accurate data. The following standards are proposed to attain a reliable representation of historical shoreline position.

1) Low-altitude aerial photography (scale ≥ 1:24,000) and large-scale NOS topographic sheets (scale ≥ 1:20,000) should be the primary data sources.

2) Low-altitude aerial photography must be of cartographic quality with good contrast for interpreting high-water shoreline position along the beach. Pen line width used for interpreting and plotting shoreline position should be ≤ 0.25 mm.

3) Aerial photography should be rectified to remove inherent distortions before comparisons are made.

4) A high-precision (±0.1 mm or less) electronic digitizer and cursor should be used to capture shoreline position data. The seaward edge of the annotated high-water shoreline should be digitized.

5) Computer cartography and CADD software should be used to accurately capture and transform map data for comparison at a common scale, projection, ellipsoid, and horizontal datum (see McBride et al., this volume).

6) Primary control for digitizer setup should be triangulation station coordinates obtained from the National Geodetic Survey (see Crowell et al., in press). A detailed procedure using this information is presented in Byrnes et al. (1991).

7) All shoreline data should be compiled using the 1983 North American Datum (NAD) or converted from NAD27 to NAD83 after data capture (see Wade, 1986; Morgan, 1987).

8) Data quality assurance tests should be adopted, including map overlays for temporal comparison of primary and secondary controls and repeatability tests.

9) A detailed analysis of inherent and operational errors must be performed to gage the significance of measured change (see Anders and Byrnes, 1991; McBride et al., this volume; Crowell et al., in press). Total root-mean-square error for individual maps should not exceed ±15 m.

10) Personnel working on a shoreline change project should be familiar with natural and cultural factors affecting historical evolution of the coast (e.g., hurricane impacts, beach replenishment).

These guidelines are proposed as a template for accurate analysis of shoreline change; however, it is recognized that every project has specific needs and limitations. Most of the proposed standards will not be affected by project specifics, but if other cartographic source material has to be used, mylar or bromide bases are recommended.

SHORELINE CHANGE GEOGRAPHIC INFORMATION SYSTEM

A geographic information system is an automated approach used to capture, store, retrieve, transform, analyze, and display georeferenced spatial data. Geographical data describe objects in terms of their position with respect to a known coordinate system, their attributes that are unrelated to position (e.g., geomorphic characteristics), and their spatial relationship with each other (topological information describing spatial units and their boundaries). The capability of a GIS to perform spatial analyses is a primary factor in distinguishing it from computer-aided design and drafting (CADD), computer cartography, and computer graphics display software. Internally referenced geographic features identify a true GIS (Logan and Bryant, 1987). These systems should be viewed as much more than a means of coding, storing, and retrieving data; instead, they should be thought of as a model of the real world (Berry, 1987). In this sense, it is possible for scientists and planners to examine a range of possible relationships for evaluating the impact of natural and human-induced change on landscape evolution.

Prior to application of computer technology to mapping, all procedures had one aspect in common; the spatial data base was a drawing on a piece of paper or film (Burrough, 1986). Georeferenced information was represented by points, lines, and areas that were displayed using symbols, color, or text, with the meaning explained in a legend. Occasionally, more information was available than could be printed on the map, and a memoir was provided. Because the map base, and its accompanying memoir, are the data base, several important consequences result. First, original data are limited by map constraints, and many local details are lost; second, areas that are large relative to map scale can only be represented by a series of maps that must be edge-matched for accurate representation; and third, the printed map is a qualitative document, and it is very difficult to readily extract accurate quantitative information for spatial analyses (Burrough, 1986). Years ago, it was not important that initial mapping costs were large because mapped information was considered relevant for 20 years or more. This is not the case today where the need for up-to-date information about how the earth's surface is changing is critical to planning and management strategies. Computer mapping and GIS methodologies are providing new approaches to natural resource evaluation and management, thus expanding our understanding of complex process-response relationships.

In addition to potential analysis benefits, a number of practical considerations are addressed by a GIS. First, map data are more secure and better organized; second, redundant map information is eliminated; third, map revisions can be completed much faster and more accurately; and fourth, map data are easier to search, analyze, and present (Korte, 1991). Most important, a GIS provides a standardized framework for consistent data capture and analysis. The following sections describe a general strategy for application of GIS technology to the analysis of shoreline position change, and its adoption for a shoreline change study along the Mississippi Sound coast in Harrison County, Mississippi.

Proposed Development Strategy. The proposed GIS strategy consists of six basic components: 1) source data, 2) data input, 3) interactive application modules, 4) geographic data base, 5) spatial analysis, and 6) data output (Figure 3). This framework provides an automated approach for examining spatial relationships between natural and cultural influences.

The initial step in the strategy is compilation and evaluation of available source data. It is imperative that all inherent errors be evaluated thoroughly to gage the significance of measured change, and whether this level of error will affect study objectives. Data input includes all aspects of data capture in the form of maps, field observations, electronic sensors, textual attributes, and information stored on magnetic media. Traditionally, digitizing points and lines (vector method) has been most common for representing spatial phenomena. However, since the advent of computers, the application of raster data structures (digital image processing) has provided an added level of knowledge for analyzing coastal change (Maffini, 1987). Each approach has merit for specific applications; vector data may be more appropriate when real world spatial conditions can be defined as points and lines, whereas raster data is more applicable for information containing gradational boundaries (thematic data). Because the analysis of shoreline position change is based (at least theoretically) on a distinctive boundary, vector data structures continue to dominate accurate analyses of shoreline movement. With increased resolution for capturing coastal information directly from electronic sensors and raster scanners, a certain level of electronic digitizing and photogrammetric processing may be replaced by these techniques in the future.

A component of data capture procedures involves application-specific software modules for the type of geographic information being processed. For example, map data have certain cartographic parameters that must be retained during data capture. CADD systems are designed for digitizing but computerized cartographic procedures also are needed for accurate representation of map data within a GIS. As such, data transformation is an integral part of these applications. This involves transformations needed to remove cartographic inconsistencies among data sources and minimize or eliminate errors. Standard transformation procedures found in most GIS software include map scale, projection, and horizontal datum adjustments. Geographic queries include logical retrieval of data, whereas geographic processing involves calculation of areas and perimeters for quantifying change. Other related application software modules accept engineering surveys and global positioning system (GPS) data for horizontal control.

The geographic data base component in figure 3 describes the structure and organization of digital data with regard to position, spatial relationships (topology), and attributes of geographical elements. Prior to GIS application for shoreline change evaluation, database management was performed manually by the user. The probability of misplacing captured data was much greater compared with automated database management systems. However, the goal is the same; examine cause and effect relationships to develop models for describing the response of a coastal system to existing and expected changes. The capability of a computer system to evaluate these spatial relationships defines a GIS. Given this potential, the user of a GIS will want to pose a number of questions that may be answered by combinations of data retrieval and analysis options. Specific examples regarding shoreline change include: 1) What is the average magnitude of change for a given section of beach?, 2) What is the average change rate for shorelines within 1000 m of jetties?, 3) What upland characteristics are present in areas where change rates are >5 m/yr?, and 4) Using measured rates of change for a section of beach, where will the shoreline be in 100 years? Although these and many other questions could be answered

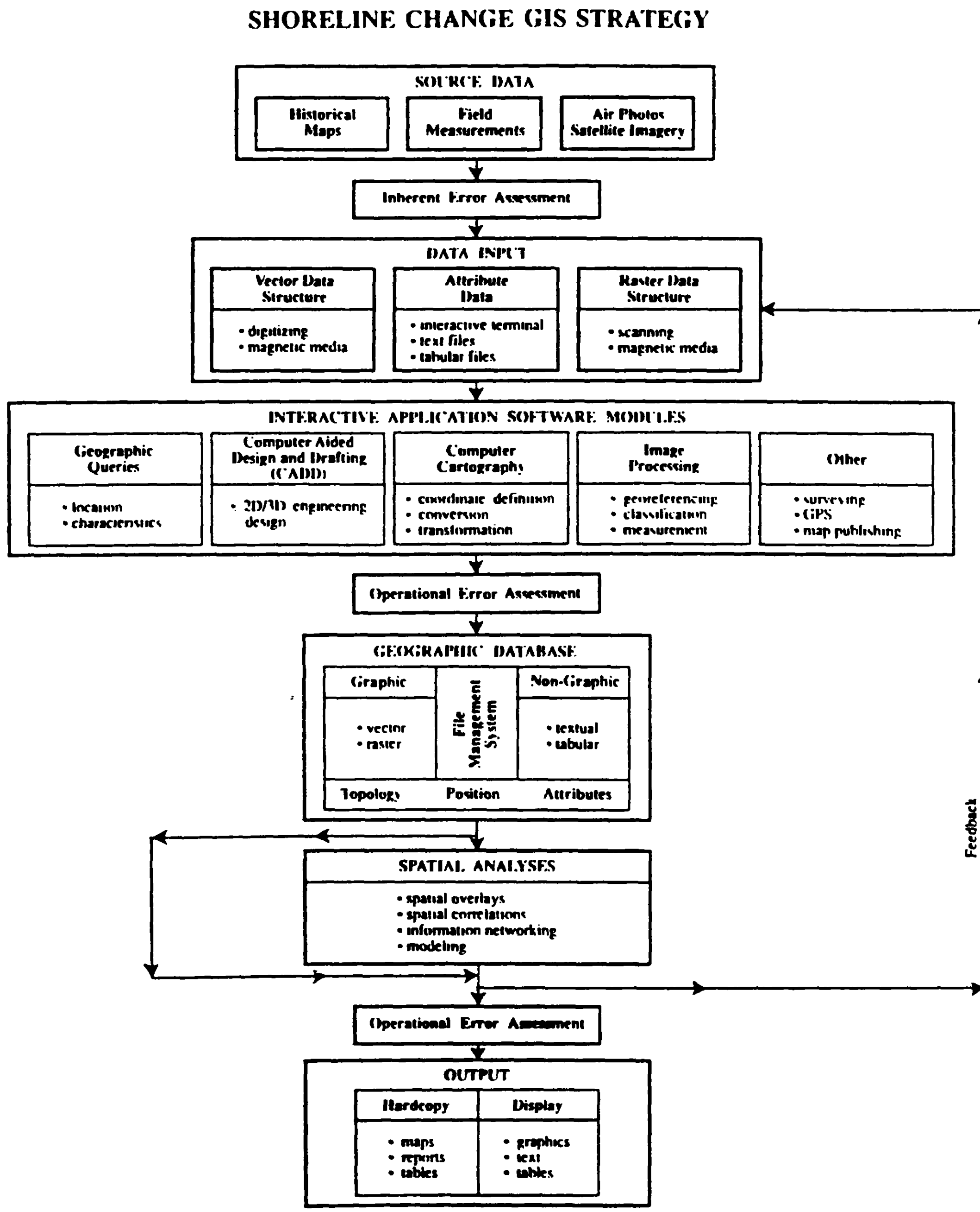

Figure 3. Proposed strategy for development of a shoreline change GIS.

using time consuming conventional methods, an integrated and automated approach is more efficient and generally more accurate.

Finally, data output is related to the way in which information is displayed and results are reported to a user. Data may be displayed as maps, tables, reports, and text on a computer terminal or as a hardcopy. Map publishing capabilities should meet or exceed national map accuracy standards.

Application of Procedure. As part of a shoreline change study for Harrison County, Mississippi, the GIS strategy described here was used to compile and analyze changes in historical shoreline position. Intergraph's Modular GIS Environment (MGE), with MicroStation 32 (CADD), Projection Manager (computer cartography), Modular GIS Analyst (spatial analysis), and the relational data base Oracle, comprise the software system used for data compilation and analysis. The hardware platform is a Unix-based workstation with 16 megabytes of primary memory and a large-format digitizer with plotter attached as peripherals. The study site was considered ideal for examining spatial relationships because it presents a wide variety of natural and human-induced factors that affect shoreline change. The Gulf coastlines of Cat and Ship Islands respond to coastal processes without substantial influence from cultural activities (Figure 4). In contrast, the mainland shoreline of Mississippi Sound has been engineered since the 1920s, and responds to an interaction between natural processes and human influences. The Sound shoreline is backed by a seawall, has numerous storm drainage pipes intersecting the beach and disrupting longshore sand transport, and is periodically replenished with sand.

Historical shoreline position data were compiled for the area between St. Louis Bay and Biloxi Bay for temporal and spatial comparison. Data sources were NOS T-sheets (scale ≥1:20,000) and color or color-infrared aerial photography (1:24,000). CADD and computer cartography software were used to accurately digitize and transform data from maps and rectified

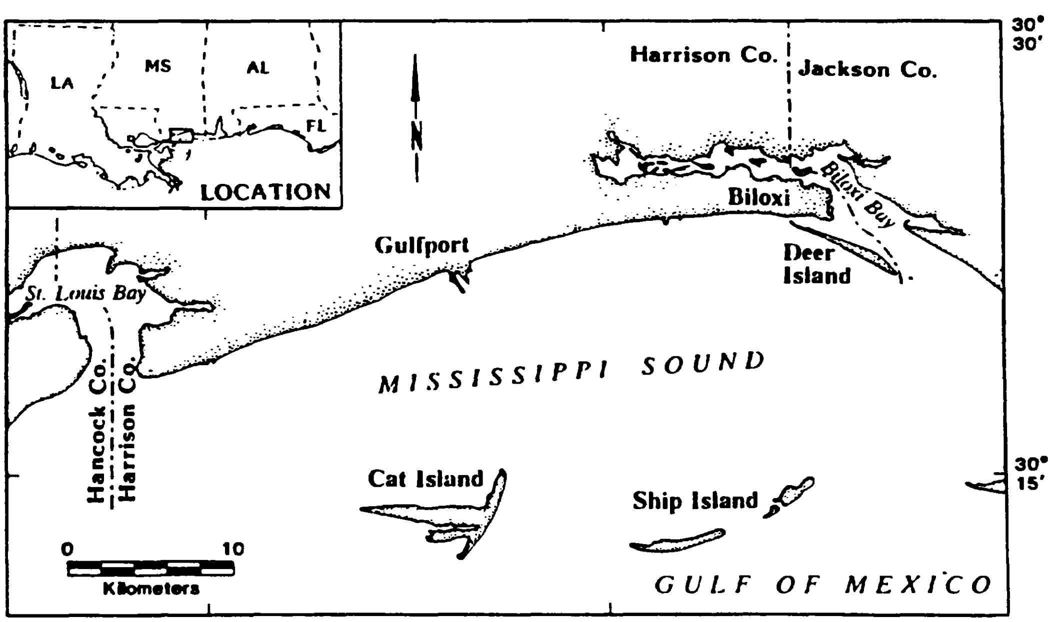

Figure 4. Location map of the study area.

photomaps. Evaluation of inherent and operational errors for individual time periods indicated that the root-mean-square error did not exceed ±10 m. From 1851 to 1986, the average rate of shoreline change was 0.2 m/yr (±0.14 m/yr). This rate reflects long-term natural processes and the influence of two major beach replenishment projects, the construction of numerous drainage pipes that intersect the beach near the water line, and other engineering modifications. Consequently, engineering structures and non-graphical attributes were referenced with shoreline position in the GIS to examine associations. In this sense, spatial relationships throughout the system can be examined to isolate cause and effect scenarios related to specific impacts. A few of the questions regarding the Harrison County project are: 1) Does an increase in the number of drainage pipes per unit length of shore impact rates of change?, 2) What influence does recreational activity have on shoreline change (ie., as recreational activity increases, does shoreline change increase)?, and 3) What areas have the highest rates of change, and is there a common factor linking these areas? Many other scientific and management-related associations can be tested using GIS technology once compiled geographic information is available. This level of integration provides a comprehensive and accurate assessment of change relative to cultural and natural factors.

SUMMARY

Considerable effort has been spent over the past few years collecting and compiling information on historical shoreline position. Much of this data has provided valuable baseline information to scientists, managers, and planners. However, it is often easy to overlook the level of detail needed to accurately record these data. Court cases regarding property rights in the coastal zone and damage claims to FEMA through the National Flood Insurance Program rely on this information. At present, an adequate digital data base of historical shoreline position, relative rates of change, and factors affecting change does not exist on a national scale at a level of accuracy sufficient for scientific or management applications.

Recently, significant advances in computer technology have made it possible to compile and analyze shoreline position information with a high degree of accuracy and at much reduced cost. Therefore, it is likely that a great deal of historical shoreline position data will have to be re-evaluated to meet basic requirements for applicability to coastal-related projects. Important data collection and analysis considerations include source data reliability, appropriate analysis techniques, and efficient database management strategies. This paper addresses each of these topics and proposes measurement and accuracy standards for development of a consistent national shoreline change data base. Recognizing that the quantity of information to be assembled on a national scale is immense, a shoreline change GIS strategy is presented that integrates interactive mapping applications, such as CADD and computer cartography, with database management functions for establishing spatial relationships. Application of this procedure is presented for a shoreline change study in Harrison County, Mississippi. This strategy should replace existing approaches (e.g. May et al., 1983) for compiling shoreline change information for a number of reasons, including: 1) an integrated approach for data capture and analysis is emphasized; 2) error assessment procedures are included as a means of quality assurance, 3) interactive software applications (e.g. computer cartography) stress accuracy and precision, 4) textual data is referenced with graphics elements for spatial analysis, and 5) a consistent data base is created.

ACKNOWLEDGEMENTS

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REGIONAL COASTAL EROSION RESEARCH AND BEACH PRESERVATION

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Abstract

Understanding the relative contributions of processes causing coastal erosion is important to mitigation of beach erosion. These processes are complex and may be difficult to determine from local studies. Large scale (tens of kilometers) regional studies provide a larger context within which to interpret results of local studies and can reveal processes that may not be found in smaller scale studies. For example, using historical bathymetric comparisons and other methods, we define the rates and pathways of net sediment transport and sediment budgets for the littoral cells along the 150 km of the central Louisiana coast. We find that, in places, the net alongshore transport on the inner shelf exceeds 1 million cubic meters/year, much greater than is occurring by wave forced currents in the nearshore. The transport observed on the inner shelf effectively bypasses a wide tidal inlet, resulting in net transport between adjacent littoral cells. Within rather broad error limits, the volume of sand eroded over the past 100 years in the littoral cells has been accounted for by the volume of sand deposited. Most of the net sand transport is longshore, suggesting that gradients in longshore transport are of prime importance in forcing the observed erosion, even though sea-level rise relative to the land is rapid. Without a regional scale investigation, understanding the processes causing erosion of Louisiana's barrier islands would have been very difficult.

Introduction

The processes responsible for coastal erosion are complex and difficult to determine. Understanding the relative contributions of the different processes is important to mitigation of erosion and preservation of beaches. For example, knowing the relative contributions of sea-level rise, gradients in longshore transport, and net cross-shore transport to forcing erosion is important to the economic analysis and engineering design of beach nourishment projects. In many cases, knowledge of the important processes over large temporal (several decades) and spatial (tens of kilometers) scales is required to understand the system and how adjacent systems interact with one another. Large scale regional studies are expensive and time consuming and hence are beyond the scope of design studies for many small scale site specific engineering projects. However, as will be shown below, there kinds of studies help reveal processes responsible for shoreline and shoreface erosion that would not have been easily determined from small scale local studies.

In cooperation with state agencies and universities, the U.S. Geological Survey (USGS), through the National Coastal Geology Program, conducts research on a variety of coastal issues, including erosion. The objective of the erosion research is to improve our capability to predict erosion caused by natural processes and activities of man. At present, our understanding of the processes leading to coastal erosion is rudimentary, at best. Without understanding the processes, accurate prediction is difficult, if not impossible. One of our approaches is to increase understanding of sediment budgets, the rates and pathways of sediment movement within coastal systems. Improved methodologies for determining sediment budgets can be applied to different coastal systems around the country. Knowledge of the sediment budget is basic information required to predict erosion and to determine whether mitigation is cost effective and warranted.

In this paper, we use the results of the recently completed Louisiana Barrier Island Erosion Study to demonstrate the usefulness of large scale regional studies in determining the processes of shoreline erosion. Louisiana's barrier islands are eroding at rates exceeding, in places, 30 m/year. The processes causing these extraordinary rates of erosion have been basically unknown. The Louisiana Barrier Island Erosion Study investigated the geologic framework and evolution of Louisiana's barrier islands and the quantitative processes responsible for their maintenance and change (for an overview of the study, see Sallenger and others, 1987, and Sallenger and others, 1991). In this paper, we focus on one aspect of that study: results derived from comparisons of historical bathymetry that are relevant to computing the sediment budget. After first discussing methodology, we use the results of sediment budget analyses to assess some of the important processes contributing to erosion of the barrier islands that may not have been discernible from small scale local investigations.

Methodology

Comparisons of historical and recent bathymetric surveys were used to reveal patterns and volumes of erosion and accretion. The patterns and volumes were used subsequently to infer net transport directions and rates and to calculate the local budget of sediments within littoral cells.

Bathymetric data covering the area shown in Figure 1 were obtained from different sources for three periods. Sounding data totaling 63,909 observations were digitized from U.S. Coast and Geodetic Survey (USCGS) hydrographic smooth sheets from 1878 to 1906. These surveys are referred to as the 1880's bathymetry. Sounding data in digital form totaling 315,856 observations were obtained from the National Geophysical Data Center for the years 1933 to 1936. These surveys, also conducted by the USCGS (now the National Ocean Survey), are referred to as the 1930's bathymetry. Finally, the USGS collected, through contract surveys, digital sounding data totaling 232,289 observations for the period 1986 to 1989 (Williams and others, 1989). These surveys are referred to as the 1980's bathymetry. An evaluation of data quality and maps showing data density can be found in Jaffe and others (1988) and List and others (1992).

These data sets were processed with standard commercial surface modeling software to yield grids of surface elevation (Hopkins and others, 1991). After correcting for relative sea-level rise during the study period (Jaffe and others, 1991), grids were numerically subtracted to yield the patterns and volumes of erosion and accretion. Changes between 0.5 m of accretion and 0.5 m of erosion were considered within the error level inherent in this type of analysis and were omitted from further consideration (List and others, 1992).

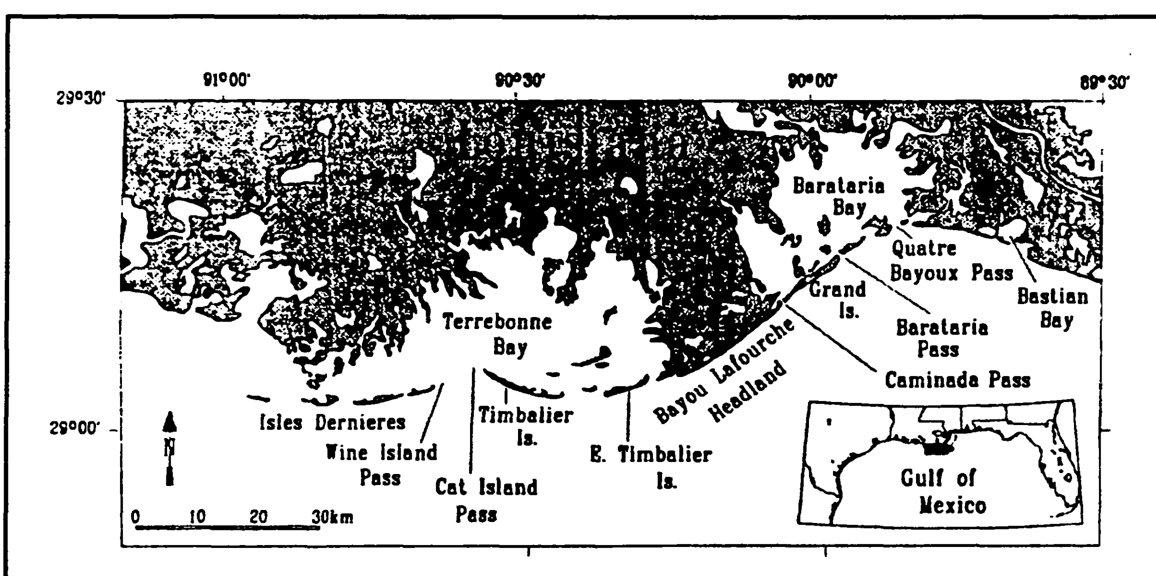

Figure 1. *Study area.*

As an example of bathymetry for the study area, we show the 1980's bathymetry in Figure 2A. A comparison of bathymetry from the 1930's to 1980's for the entire study area is shown in Figure 2B. All bathymetric and change maps from the Louisiana Barrier Island Erosion Study are presented in a large format, color atlas (List and others, in press).

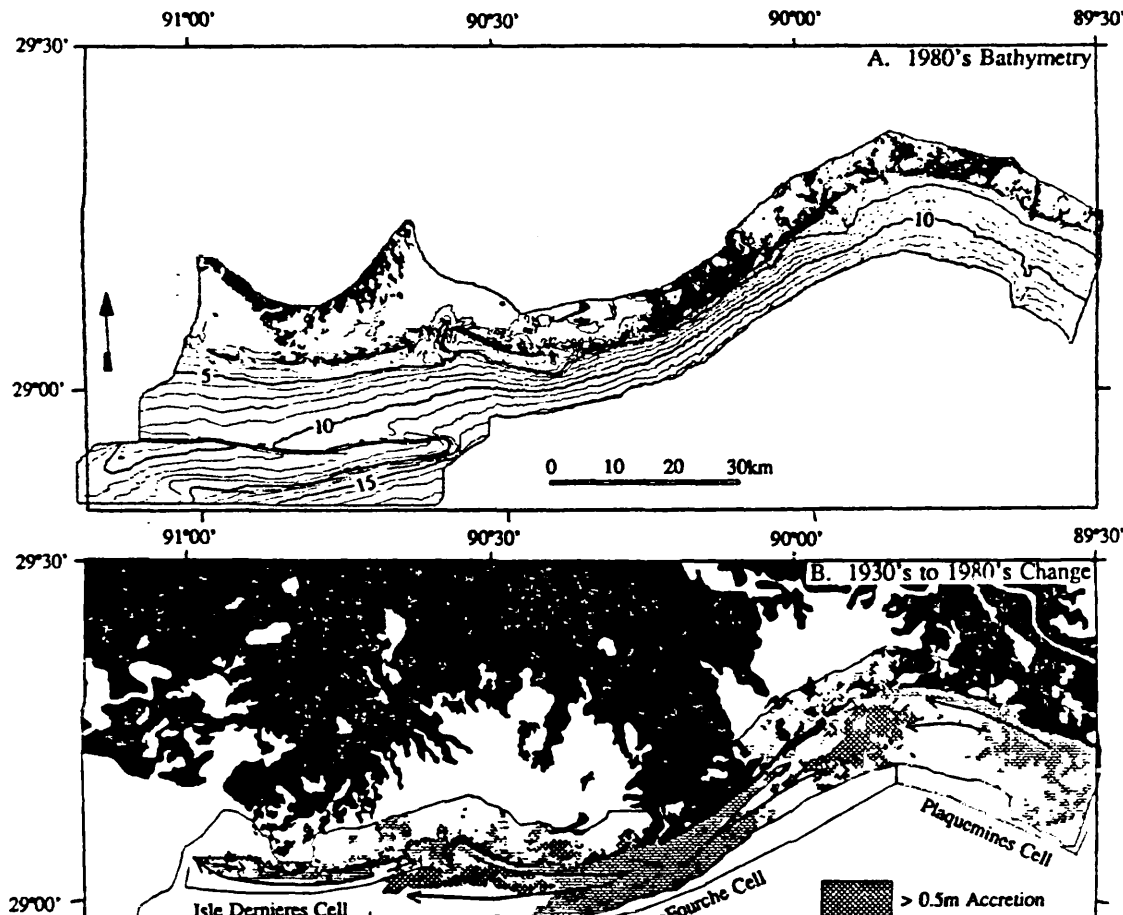

Figure 2. A. *Bathymetry acquired by the USGS within the study area in 1980's. Other bathymetric data used in the study were obtained by other sources in the 1880's and 1930's.* **B.** *For the entire study area, bathymetric change between 1930's and 1980's. Also shown are the generalized transport directions and locations of specific littoral cells.*

Transport Pathways and Sediment Budget

Littoral Cells

A convenient framework within which to interpret pathways of sediment transport is to define littoral cells, reaches of coast containing complete cycles of erosion and accretion. The general pattern of erosion and accretion in the study area is for erosion of the subtle coastal headlands (middle to late Holocene-age delta lobes of the Mississippi River) and deposition in embayments that lie between the headlands (Figure 2B; Penland and others, 1988). Generalized directions of net transport are then based on a variety of directional bathymetric changes, including spit progradation, inlet migration, and the progressive development of inner shelf sand bodies.

Based on these patterns of erosion and accretion and interpretations of transport, the study area has been divided into three littoral cells. The study area is dominated by two large accretional regions, offshore of Cat Island Pass and offshore Barataria Pass, and by three large erosional regions, from west to east: Isles Dernieres, Bayou LaFourche Headland, and in Plaquemines Parish offshore Bastian Bay (Figure 1). We interpret each of the accretional areas to be convergence zones for sediment transported from the headlands. These depositional regions define the limits for three littoral cells: Isles Dernieres Cell, Bayou LaFourche Cell, and Plaquemines Cell (Figure 2B).

Shoreline and Shoreface Erosion

In each of the three littoral cells, the barrier islands and associated headland areas have extensively eroded. For example, in the 1880's, the Isles Dernieres were nearly a continuous barrier island; by the late 1980's, these islands were eroded both on the landward and seaward sides (Figure 3A) and segmented by new and wider inlets (Figures 4A and B). The average rate of erosion on the Gulf side of the islands was 11.1 m/yr, whereas the bay side eroded at 0.5 m/yr (McBride and others, in press). Between 1896 and 1988, average barrier width changed from 1171 m to 375 m, a decrease of 68 percent. The Bayou LaFourche headland is experiencing even more rapid erosion than Isles Dernieres; over the past 100 years, the shoreline has retreated as much as 28.5 m/yr (Figure 3B; McBride and others, in press). A comprehensive discussion of shoreline erosion in the study area is given in the large format color atlas (Williams and others, in press).

In each cell, large volumes of sediment have been eroded from the headlands (Figure 5). For example, during each time period, roughly 35 $m^3/m/yr$ were removed from the eroding area of Isles Dernieres Cell. In contrast, for the Bayou LaFourche Cell, the quantity eroded was a factor of 6 more, or about 200 $m^3/m/yr$. Note that the rate of Gulf-side shoreline erosion in the Bayou LaFourche Cell was only a factor of 2 more than Isles Dernieres. The volume differences largely result from different shoreface scales; the Isles Dernieres shoreface extends several kilometers offshore to a depth of 3-6 m whereas the Bayou LaFourche Cell extends offshore more than 10 km to depths greater than 12 m (Figure 3).

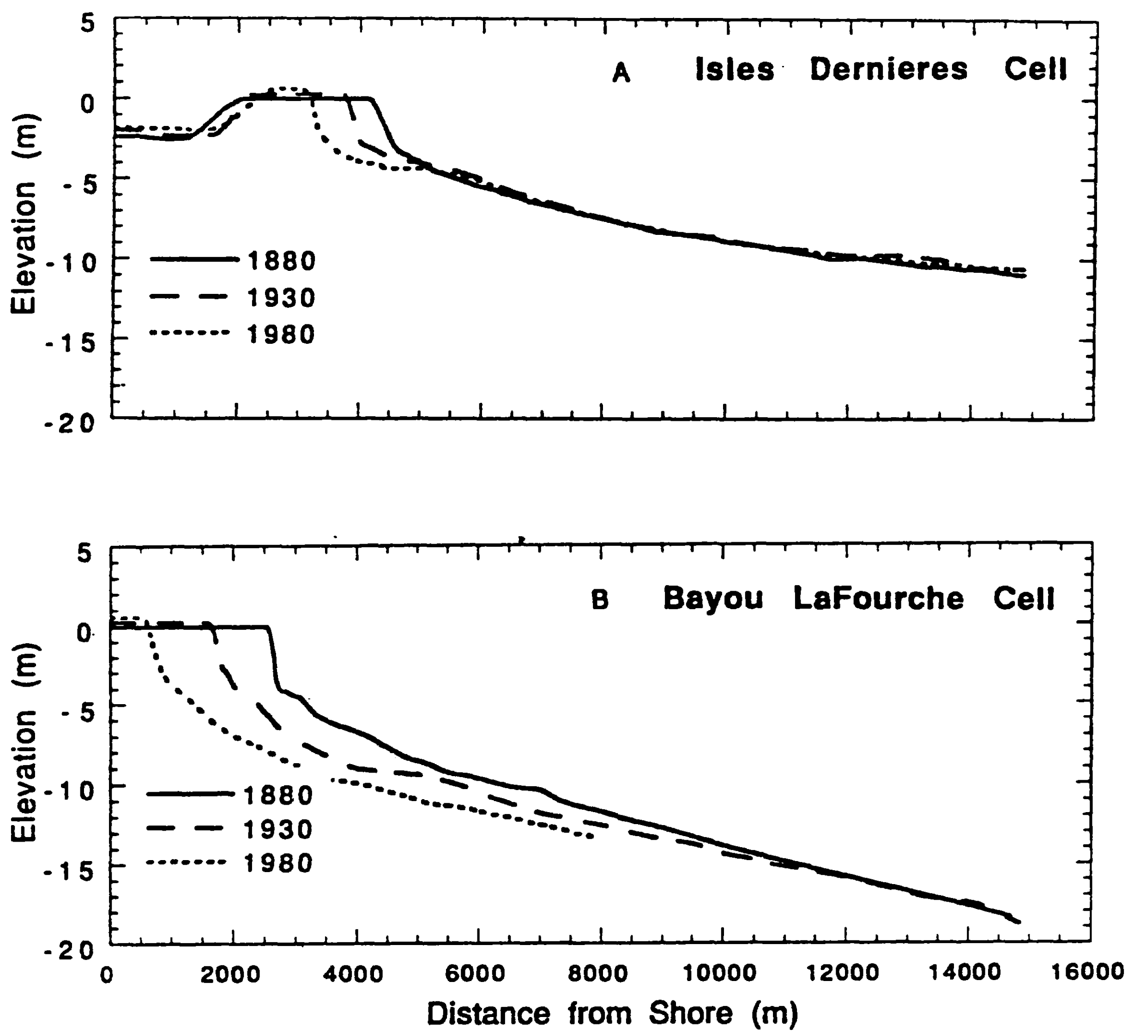

Figure 3. A. *Example shoreface profiles from the 1880's and 1980's of the Isles Dernieres Cell.* **B.** *Example shoreface profiles from the 1880's and 1980's from the Bayou LaFourche Cell.*

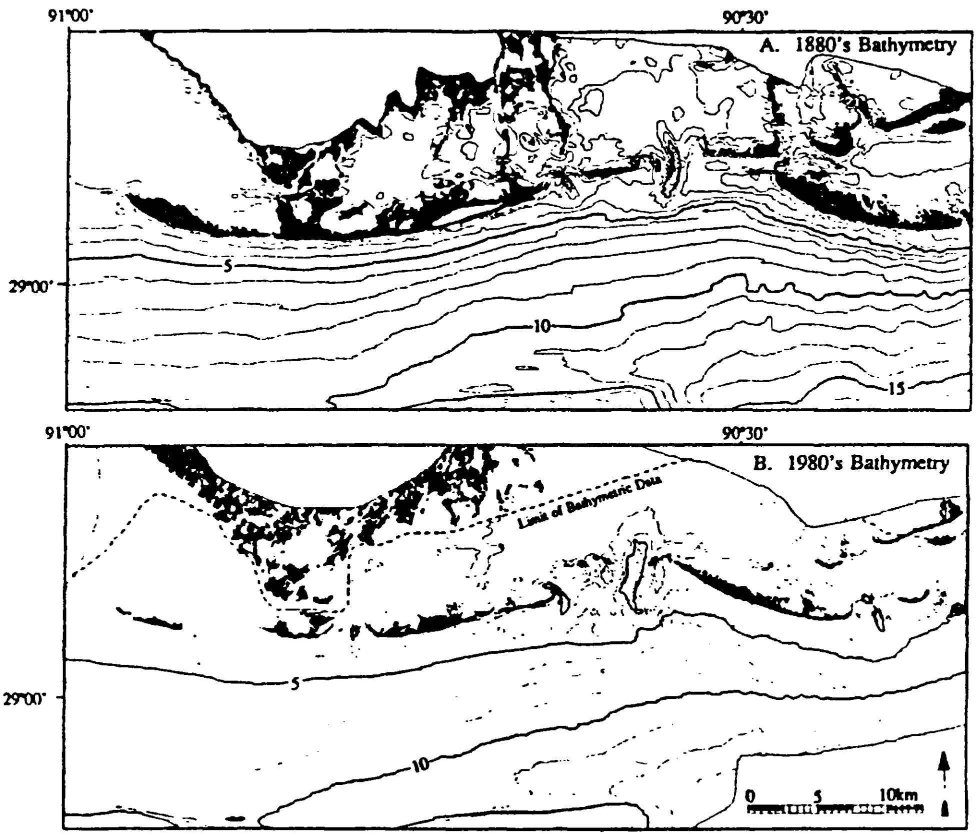

Figure 4. *Bathymetry and shorelines for the Isles Dernieres Cell and western part of Bayou LaFourche Cell:* **A.** *1880's;* **B.** *1980's.*

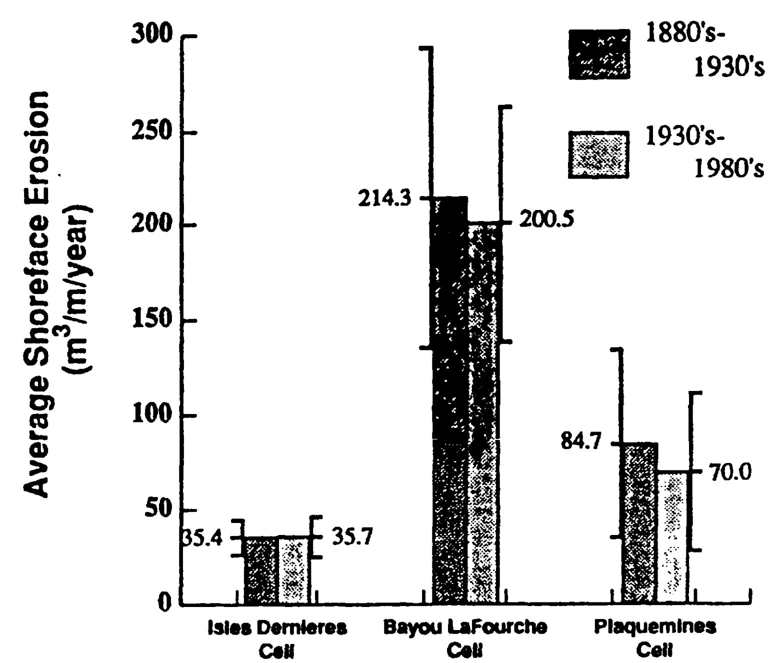

Figure 5. *Rates of shoreface erosion per unit meter of shoreline length for the erosional part of each cell. Estimates of the range of errors are shown.*

Transport Pathways and Rates

As noted above, the generalized net sediment transport directions indicate transport from the headlands to the embayments (Figure 2B). The net transport is not only occurring in the nearshore where breaking waves are forcing longshore transport, but also in deeper water on the shoreface seaward of where we normally expect breaking waves. The distinction between nearshore and shoreface deposits can be better seen in Figure 6, showing bathymetric comparisons for the western part of the study area. Note the nearshore deposits developing in the vicinity of Cat Island Pass that are results of east-to-west transport. These deposits were created, for both time periods, by westward spit progradation of Timbalier Island and filling of the inlet throat, forcing westward inlet migration. These deposits could have readily been formed by gradients in transport forced by breaking waves. In contract, two sand bodies developed offshore Timbalier Island during the 1880's and 1930's. The sand bodies extended 6 to 8 km to the west, obliquely from shore (Figure 6A). During the 1930's to 1980's, these sand bodies coalesced and prograded westward 18 km across the mouth of Cat Island Pass (Figure 6B). The development of these sand bodies may be in part a function of wave forced nearshore processes in the surf zone; however, they extend into water depths of 8 m, significantly seaward of where we normally expect transport induced by breaking waves. Note that during the period 1930's to 1980's, the shoreface sand body prograded westward at greater than 1 million m^3/yr, nearly twice the transport rate observed in the nearshore (Jaffe and others, 1989).

By the 1980's, the lobe of sediment had effectively bypassed Cat Island Pass and approached the Isles Dernieres (Jaffe and others, 1989). As is apparent in Figure 6A, during the 1880's to 1930's, the band of shoreface erosion was relatively uniform along the length of Isles Dernieres. However, during the 1930's to 1980's, there was a decrease in the width of eroding shoreface on the east end of the islands. The shoreline erosion rate at the east end decreased from 11 m/yr during the 1880's to 1930's to 4.9 m/yr during the 1930's to 1980's (Jaffe and others, 1989). Natural nourishment from the lobe may have contributed to this decrease in shoreline erosion.

Balance of Sand Eroded to that Deposited

To determine whether sand was conserved within a particular cell, the volumes of sand eroded were compared to the volumes of sand accreted (Figure 7.) Based on cores through similar sedimentary environments in the study area, the sand content of eroded sediments was estimated to be 31 percent of the total volume, with the balance composed of mud (List and others, 1991). As is evident from Figure 2B, erosion far exceeded deposition. We have assumed that the observed depositional environments are composed of sand. The eroded mud, which is more likely to stay in suspension in turbulent nearshore and shoreface waters, is assumed dispersed widely into deeper water. However, in places, cores in shallow water deposits show the presence of surprising amounts of mud. Limited evidence suggests there is considerable variability in the percent sand of deposits through the study area, with the greatest mud content in the large deposit offshore Barataria Pass. This unquantified percent sand adds uncertainty to the sand budget analysis, particularly in the eastern part of the study area.

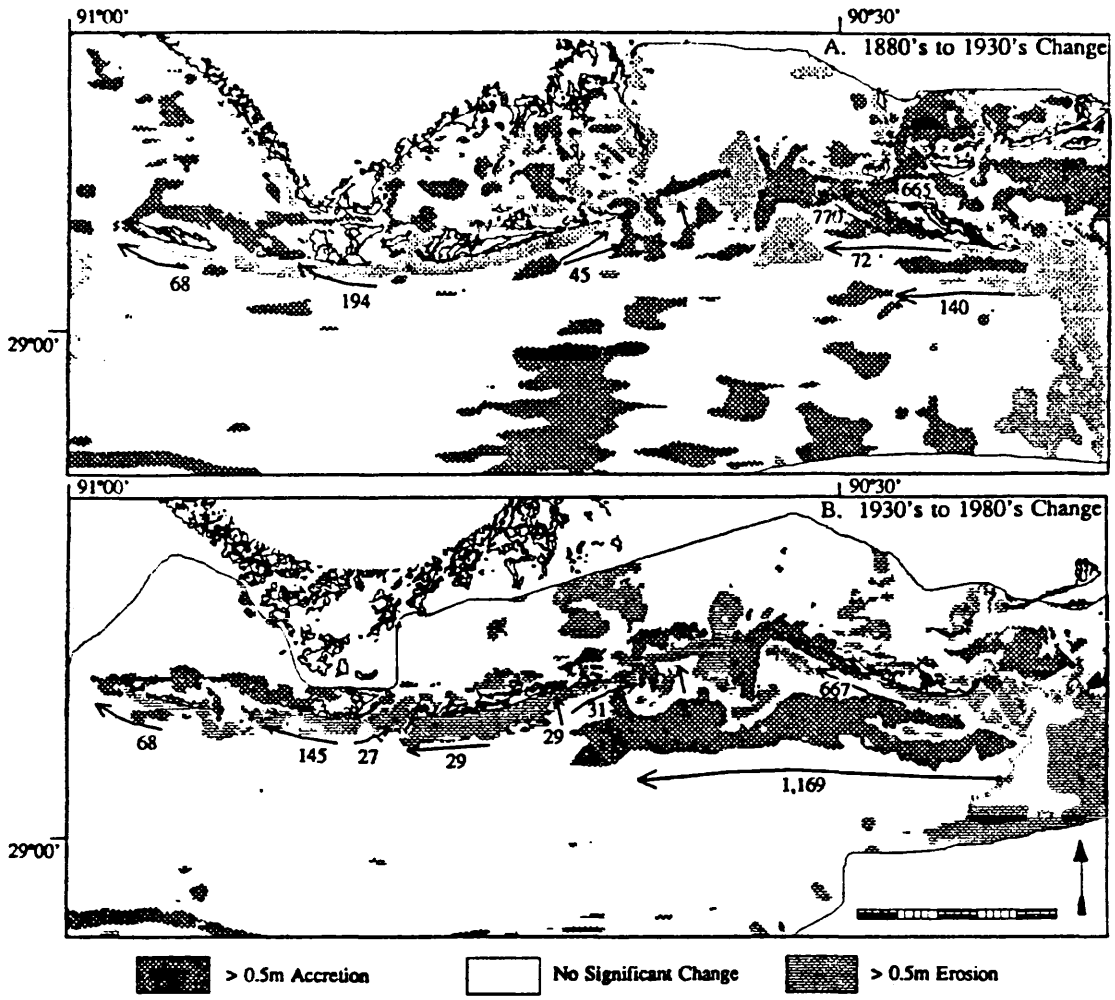

Figure 6. *Comparisons of bathymetry for the Isles Dernieres Cell and western part of the Bayou LaFourche Cell:* **A.** *1880's to 1930's;* **B.** *1930's to 1980's. Also shown are directions and inferred rates of net transport. The rates are x 1,000* m^3/yr.

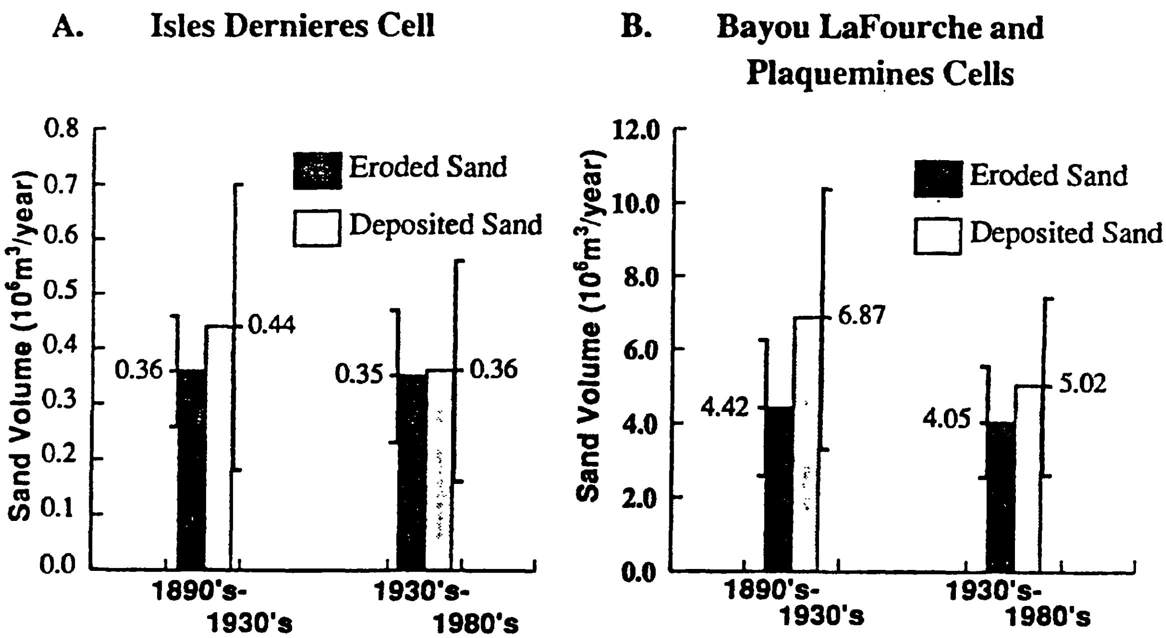

Figure 7. *Accounting of eroded and accreted sands for each cell:* **A.** *Isles Dernieres Cell. Estimates of the range of errors are shown.* **B.** *Bayou LaFourche and Plaquemines Cells combined.*

We combined the Bayou LaFourche and Plaquemines Cells since they share a common depositional area, their individual contributions being indistinguishable (Figure 2B). Within each cell, or combined cells, the rates of erosion and deposition are surprisingly consistent between the different periods of comparison (Figure 7). For example, in the Isles Dernieres Cell, annual eroded sand for the 1880's to 1930's was 360,000 m^3/yr, while for the 1930's to 1980's, it was 350,000 m^3/yr. However, it should be noted that these estimates have rather large error bars (Figure 7). Estimates of deposited sand for these two periods were more variable, the estimates being within 18 percent.

Within the error limits of the comparisons, the sand eroded within a cell, or group of cells, could be roughly accounted for by deposited sand. Note for the combined LaFourche/Plaquemines Cells that, even though the eroded and deposited sediment volumes are within imposed error limits, the deposited sand volume is larger than the eroded. If the deposit had significant amounts of mud, as suggested above, sand volumes within deposits would have been over-estimated. Hence, the deposited volumes would decrease, approaching the quantity of eroded sand.

Since most of the eroded sand can be roughly accounted for in local deposits, we can assess the relative importance of different modes of transport. Each of the deposits in the study area was interpreted as to whether it originated primarily by gradients in wave-forced longshore transport in the nearshore, gradients in longshore transport driven by inner shelf processes on the shoreface, or massive onshore transport infilling gaps between deteriorating barrier islands (e.g., east end of Figure 6). Spit deposits and inlet fill causing inlet migration were classified as being formed by longshore transport in the nearshore, whereas deposits prograding along the shoreface sub-parallel to the shoreline were classified as longshore transport on the shoreface. If there was evidence that the sediment first moved longshore prior to onshore, the deposit was classified as originating from longshore processes. All deposits could be classified as one of the three types of deposits.

In the Isles Dernieres Cell, most of the deposited sand was transported from its source by longshore transport in the nearshore (Figure 8). In contrast, in the combined Bayou LaFourche and Plaquemines Cells, most of the material was transported from its source by longshore transport on the shoreface (Figure 8). However, for all cells, the total contribution of gradients of longshore transport, both nearshore and shoreface, to forming the observed deposits was greater than 80 percent. Based on this finding, gradients in longshore transport can account for most of the observed erosion in the study area. This is a surprising result since sea-level rise relative to the land is high, about 1 cm/yr of which about 90 percent is due to subsidence (Penland and Ramsey, 1990). The result is consistent with a recent model study which found sea-level rise to be of secondary importance in forcing coastal erosion of Louisiana's barrier islands over the last 100 years (List and others, 1991).

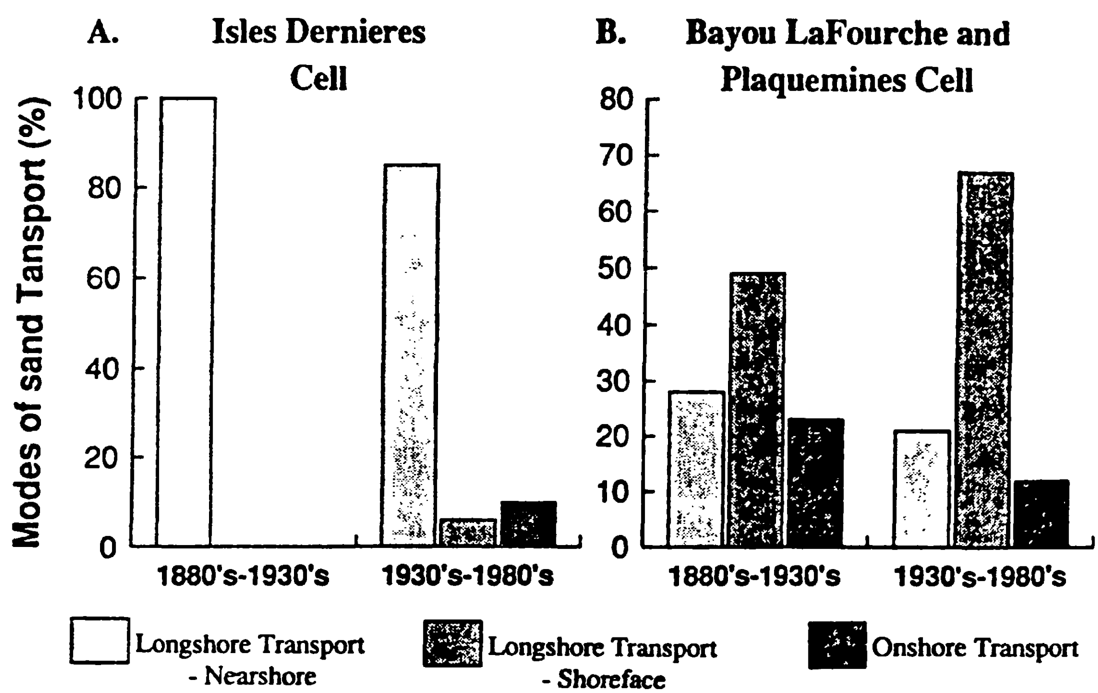

Figure 8. *Classification of each sedimentary deposit in regard to whether it originated primarily by nearshore processes, shoreface processes, or onshore transport.*

Conclusions

Large scale regional studies of the processes causing coastal erosion are useful in managing and preserving beaches because they provide a large context within which to interpret results of smaller scale studies on site specific problems and can reveal processes that operate on larger spatial scales and over longer periods. For example, in a study on the erosion of Louisiana's barrier islands, we have found a number of results that may not have been found without conducting a large scale study. These include:

- In places, the transport alongshore on the inner shelf exceeds 1 million cubic meters/year, much greater than is occurring by wave forced currents in the nearshore.
- The transport observed on the inner shelf effectively bypasses a wide tidal inlet, resulting in net transport between adjacent littoral cells.
- Within rather broad error limits, the volumes of sand eroded in the littoral cells is accounted for by the volumes of sand deposited.
- Even though relative sea-level rise is rapid, about 1 cm/yr., most of the net sand transport is longshore, suggesting that gradients in longshore transport are of prime importance in forcing the observed erosion.

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