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Framework and Evolution of a Transgressed Delta Lobe: The St. Bernard Shoals, Gulf of Mexico

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Dedication

I dedicate this master's thesis to the late Dr. Shea Penland for his tireless efforts focused on Louisiana coastal issues, geologic education, and his personal assistance on this project as well as his teachings.

Acknowledgments

First and foremost I thank my advisor, Dr. Mark Kulp, without whom this project could never have happened, for helping to develop a project in my area of interest, and for his continual encouragement and advice. I would also like to express thanks to Dr. Dawn Lavoie and Dr. Mike Miner both of whom provided much needed guidance. I would also like to extend my gratitude to Jeff Motti, Dane Fischer and the crew of the R/V Acadiana. I also thank all my friends and fellow geologists at UNO. Of course, I am thankful for the help and support of my family and especially my wife, Tiffany.

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Abstract

Four modern shoals on the Louisiana continental shelf are proposed to have formed through transgression, marine reworking, and submergence of Mississippi River deltaic lobes. However, one of these shoals, the St. Bernard Shoals, is dissimilar to the other shoals in morphology and stratigraphy. Understanding the processes that lead to these differences resulted in the development of a wholly new model for subaqueous shoal evolution.

The results of this study suggest that the St. Bernard Shoals are transgressive remnants of a near shelf-edge delta lobe that was transgressed and truncated by marine processes after fluvial abandonment. Subsequent to truncation, the shoals formed through subaqueous excavation and reworking of coarse grained sediment contained within underlying distributary channels by hurricane related marine currents. As a result the shoals are bound at their base by a ravinement surface and lie directly upon progradational facies associated with previously unrecognized southern progradation of the La Loutre distributary network.

Keywords: shoal, transgression, deltaic evolution, Mississippi River delta, St. Bernard Shoals, shelf currents, transgressive history, tropical cyclones, secondary reworking

Introduction

Sandy marine shoals have been identified across a range of modern continental shelves and are widely recognized within a suite of ancient shelf intervals. Interest in ancient shoals exists because they can provide important hydrocarbon reservoirs, whereas modern shoals provide an analogue model for reservoir exploration and are potential marine aggregate resources; collectively both provide information on rates and styles of shelf evolution and transgression (e.g. Field, 1980; Penland et al., 1988; Snedden and Dalrymple, 1999; McBride et al., 1999; Catteneo and Steel, 2003). Herein is presented an analysis of a modern, mid to outer shelf shoal system in the northern Gulf of Mexico that provides strong support for an intrinsic link between modern shelf morphology, antecedent geology, and seafloor processes associated with large magnitude storms.

The Northern Gulf of Mexico continental shelf is a microtidal, wave dominated environment with numerous fluvial systems depositing sediment onto the shelf. The shelf morphology, shallow stratigraphy, surficial sediments, and delta plain are the product of Quaternary glacio-eustatic sea-level fluctuations coupled with the deposition of fluvial sediments (Beard et al., 1982). The recent ~120 m rise in sea-level began approximately 18,000 years ago (Fairbanks, 1989). Coinciding with the end of rapid Holocene transgression ~7,000 yrs BP, the Mississippi River began building a substantial delta plain (Frazier, 1967). Mississippi River sediments have contributed to the large deltaic plain through phases of fluvial-driven progradation followed by marine transgression of deltaic packages. As a result of the Holocene transgression and subsidence-driven, localized transgressions of abandoned Mississippi River delta lobes, several shore-

parallel subaqueous sand bodies have developed on the continental shelf (Fisk, 1944; Kolb and Van Lopik, 1958; Ludwick, 1964; Frazier, 1967).

The four subaqueous sand bodies offshore from the Mississippi River delta plain of southern Louisiana are Outer Shoal, Trinity Shoal, Ship Shoal, and St. Bernard Shoals (Fig. 1; Fisk, 1944; Kolb and Van Lopik, 1958; Ludwick, 1964; Frazier, 1967). These shelf sand bodies are located beyond the edge of the modern subaerial Mississippi River delta marshes and barrier islands. Three of the four shoals are single, elongate, shore-parallel deposits as much as 6-m thick, consisting of as much as 100% fine to medium-grained sand. In contrast, the St. Bernard Shoals consist of 61 individual sand bodies with varying orientations, elevations, and directions of apparent migration (Fig.2). The St. Bernard Shoals are also located at some of the deepest water depths (15 - 20 m) relative to other late Holocene shelf shoals associated with the Mississippi River delta.

Many regional studies on stratigraphic relationships, deltaic evolution, and Louisiana continental shelf geology have contributed toward the development of a generalized evolutionary model for Louisiana shelf shoals (e.g. Fisk, 1955; Frazier, 1967; Frazier, 1974, Penland et al., 1988). These models ascribe shoal formation to marine reworking and transgressive submergence of abandoned deltaic headlands. Subsequent to deltaic abandonment, marine processes rework and transform a former deltaic depocenter into a transgressive barrier island system. As relative sea-level rise continues, sandy sediment is no longer available to replenish sediment that was removed from the system; the barrier island system undergoes transgressive submergence and conversion to an inner-shelf shoal (Fig. 3) (Penland et al., 1988). This model of transgressive

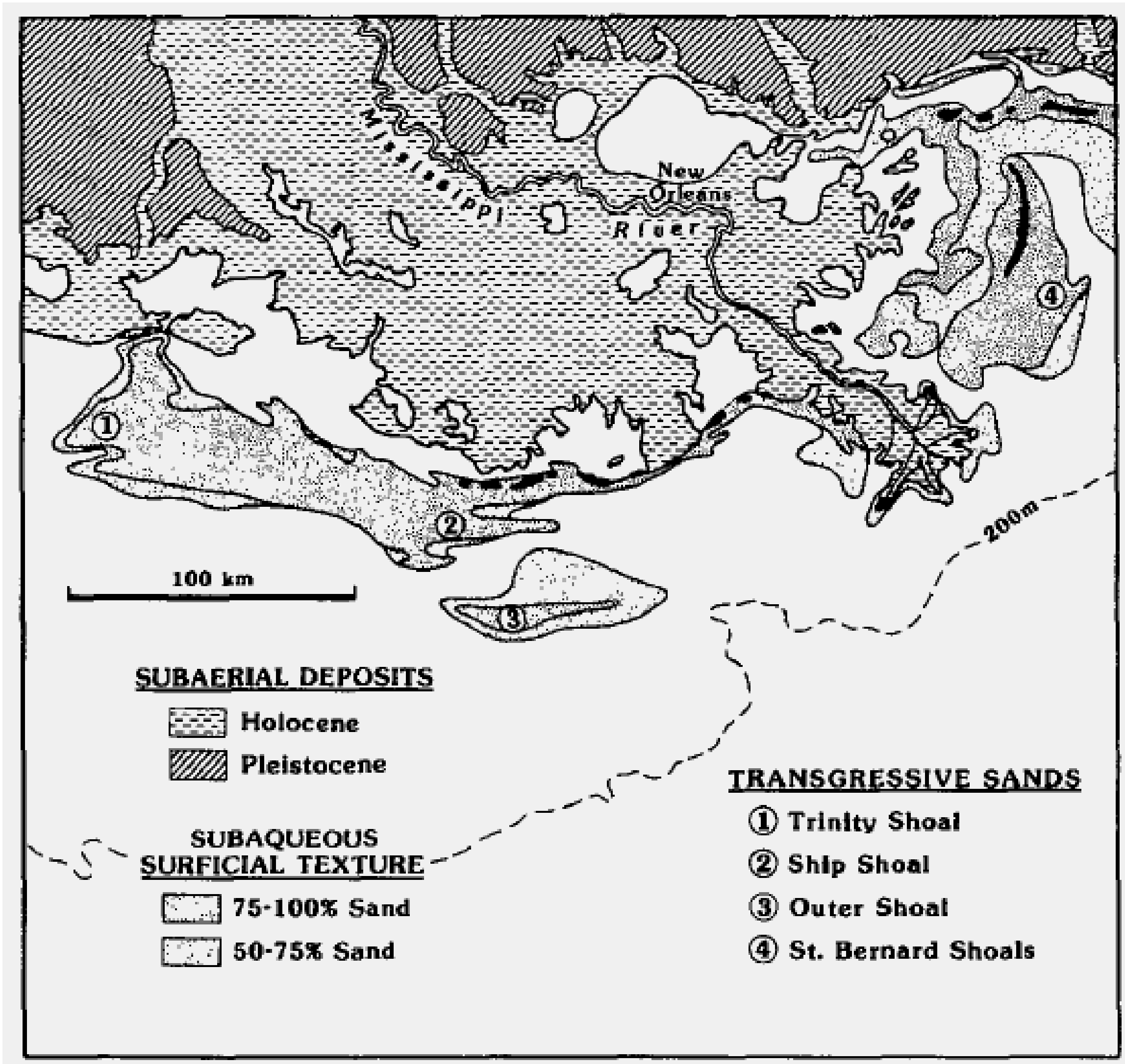


Figure 1. Distribution of the four Holocene age sand shoals on the Louisiana continental shelf (modified from Frazier, 1974). Note the shore parallel strike of the shoal bodies.

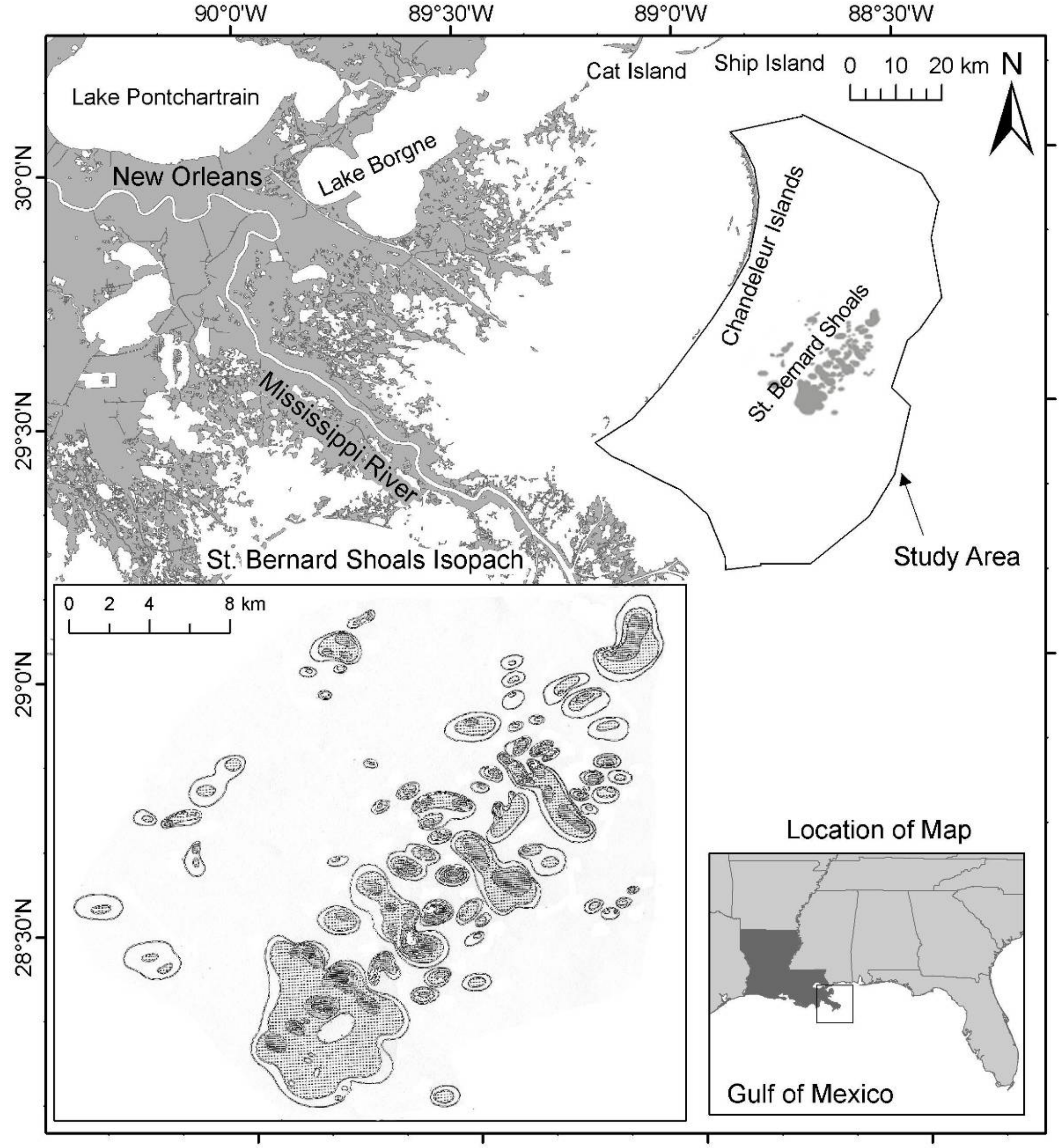


Figure 2. Regional map of southeast Louisiana showing the study area and location of the St. Bernard Shoals. The shoals are located southeast of the Southern Chandeleur Islands across a bathymetric high between the 16 m and 20 m isobaths. Contour map of the St. Bernard Shoals in the lower left is from Pope et al. (1993).

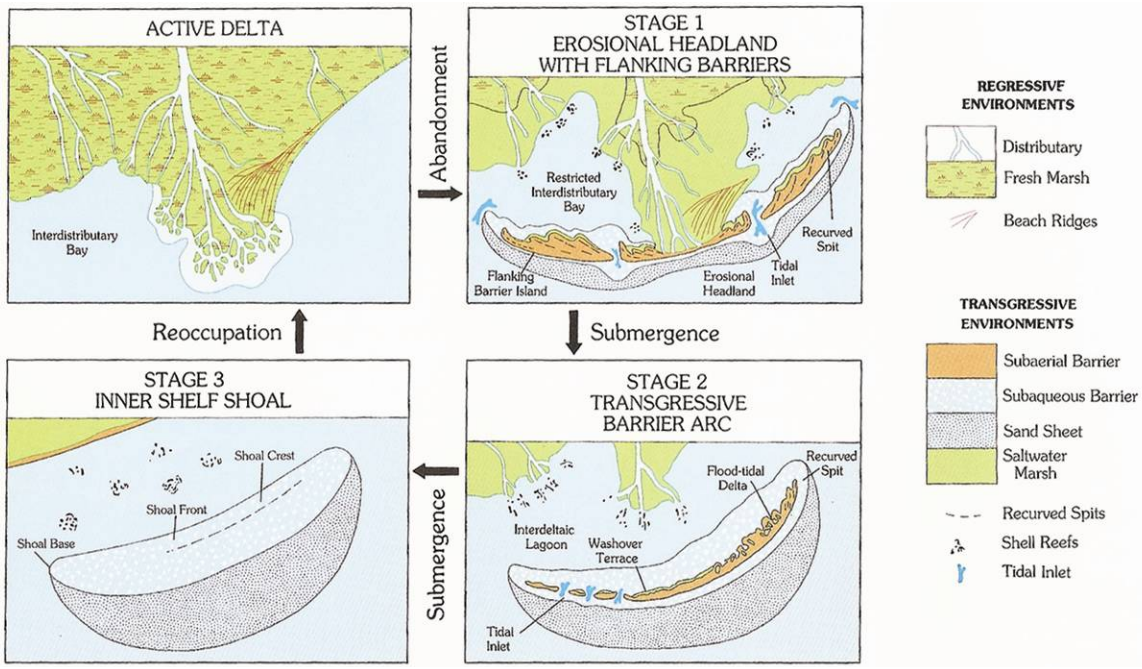


Figure 3. The qualitative concept of deltaic barrier island evolution ending with transgressive submergence as described by Penland et al. (1989). The figure demonstrates the geomorphic evolution for transgressive systems evolving from a delta as a result of abandonment and relative sea-level rise.

submergence recognizes that deltaic depocenters were formerly located in the general vicinity of the modern shoals, and analogs for various stages of this style of barrier island evolution exist today within the Mississippi River delta plain. The Caminada-Moreau Headland is an example of the first stage of transgressive submergence, and the Chandeleur Islands are proposed as an example for stage two. The three-stage model of Mississippi River deltaic barrier island evolution presented by Penland et al. (1988) describes the transformation of shallow water, shelf-phase deltaic headlands into submerged shoals, but does not fully address the transformation of relatively deeper water, outer shelf deltas (similar to the modern Belize complex; *sensu* Fisk et al., 1954) into their transgressive counterparts.

Rationale

The intent of this study is to develop a conceptual model that describes the evolution of the modern St. Bernard Shoals from their deltaic counterpart and more comprehensively characterize the late Holocene evolution of the eastern Louisiana continental shelf. This model is developed by reevaluating existing vibracore and seismic reflection data and analyzing recently acquired high-resolution seismic profiles, side-scan imagery, and sediment grab samples. The specific goals were to: 1) document the general stratigraphy of the St. Bernard Shoals, 2) define the relative chronology of fluvial and marine events that led to their formation and unique geometry, and 3) establish whether the shoals have undergone any major modifications during a 20-year lapse of investigations in this area.

Study Area

The boundaries of this study are the Chandeleur Islands to the northwest, the edge

of the St. Bernard Delta to the southeast, the edge of the Balize Delta to the south and the boundary of Frazier's (1967) delta lobe 8 of the St. Bernard Delta to the north. The St. Bernard Shoals are located in the center of the study area, ~25 km southeast of the southern end of the Chandeleur Islands and cover an area >350 km^2 area (fig. 2). Water depth above the St. Bernard Shoals ranges from 15 - 20 m, whereas the depth of the study area ranges from 0 m at the Chandeleur Islands shoreline to more than 45 m at the edge of St. Bernard prodelta deposits. The timeframe of investigation for this project begins at the initial deposit of the St. Bernard Delta and contains the entire evolution of the St. Bernard delta up to present day.

Regional Geologic Setting

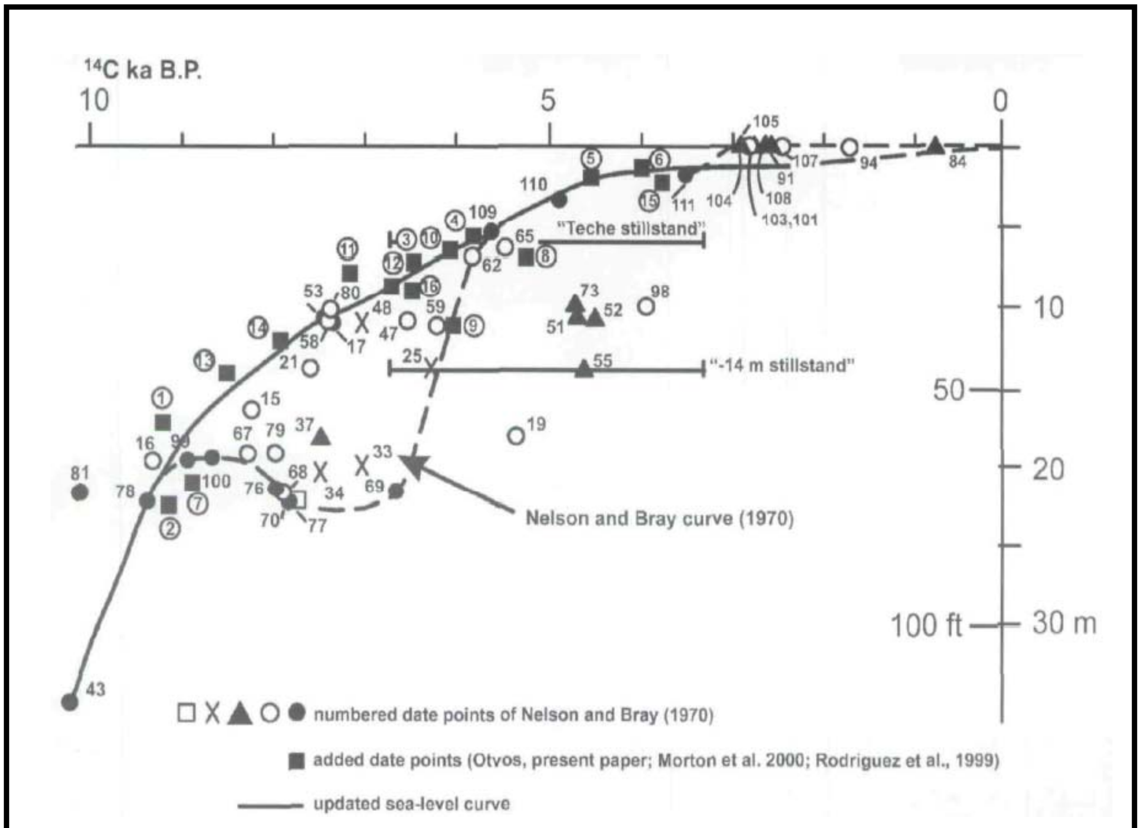
During the last sea-level lowstand ~18,000 yrs BP, fluvial systems bypassed the subaerially exposed northeastern Gulf of Mexico shelf through incised valleys and deposited sediment on the continental slope, building shelf-edge deltas (Fairbanks, 1989; McBride et al., 2004). An ensuing 120 m rise in sea-level produced a regional unconformity overlain by a broad transgressive sand sheet (Fairbanks, 1989). East of the study area this feature has been called the Mississippi Alabama Florida (MAFLA) sand sheet (McBride et al. 2004). Below the Mississippi River delta, it is recognized as an unnamed transgressive sand sheet. Much of the MAFLA sand sheet sediment is derived from the reworking of large packages of coarse sediment deposited in incised valleys during the Pleistocene sea-level lowstand (McBride et al. 2004). The sediment of these incisions derived from the southern Appalachian Mountains and Coastal Plain (Hsu, 1960; Frazier, 1975; Mazzullo and Bates, 1985; Ludwick, 1964). The Appalachian sediment consists of igneous and metamorphic minerals from the Blue Ridge and

Piedmont, and Paleozoic clastic and carbonate strata of the Appalachian Fold and Thrust Belt (Hsu, 1960). The coastal plain sediment is fine to medium grained, feldspar-poor, and derived from Mesozoic and Cenozoic clastics (Hsu, 1960; Frazier, 1975; Mazzullo and Bates, 1985; Ludwick, 1964). Little to no sediment is deposited across the Mississippi-Alabama shelf from present day rivers (McBride et al. 2004). All of the current fluvial networks have created bayhead deltas that do not contribute to the sedimentology of the middle continental shelf (McBride et al., 2004).

Quaternary Sea-Level for the Northern Gulf of Mexico

Otvos (2004) developed the most recent compilation of eustatic sea-level curves for the northern Gulf of Mexico (Fig. 4) from three previous studies (Nelson and Bray, 1970; Morton et al., 2000; and Rodriguez et al., 1999) and contributed new radiocarbon and optically stimulated luminescence (OSL) dates from numerous rotary drill cores across the Gulf of Mexico. Törnqvist (2006) established the most recent curve for the Mississippi River delta plain area using radiocarbon dated subsurface basal peat layers from widely separated areas of southern Louisiana (Fig. 4). On the basis of all available data (e.g. Otvos, 2004 and Törnqvist 2006), when the St. Bernard delta lobe 9 was abandoned ~2,000 years ago (Kolb and van Lopik, 1959; Curray and Moore, 1962; Frazier, 1967), sea-level was 1 to 1.25 m lower than the present day sea-level elevation (Otvos, 2004, Törnqvist, 2006) (Fig. 4).

McBride et al. (2004) used data from 225 cores to reconstruct the geologic history of the northeastern Gulf of Mexico since the sea-level lowstand 18,000 yrs BP. McBride et al. (2004) propose that overlying the erosional unconformity produced during the Holocene transgression is an estuarine/lagoonal deposit, above which is a shoreface



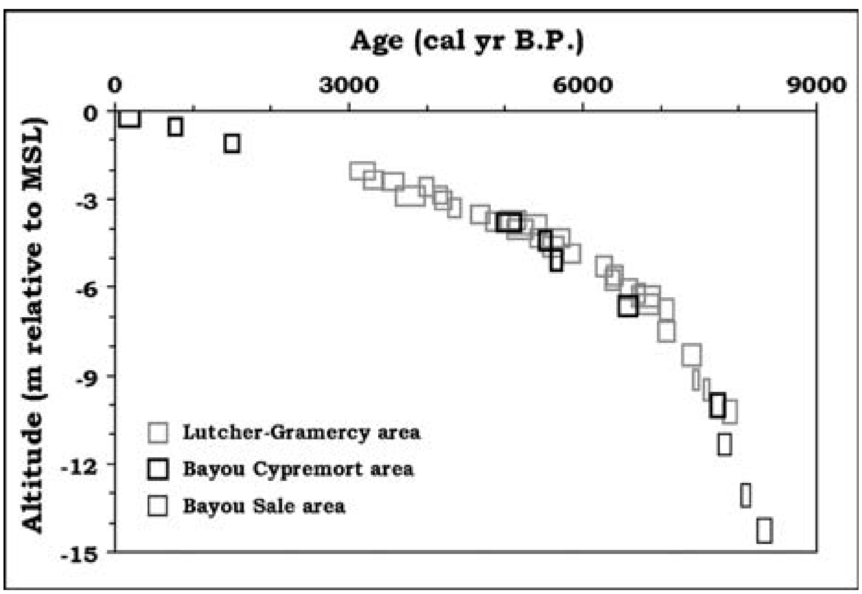


Figure 4. (Top) Sea-level curve for the Gulf of Mexico showing the last 10,000 years of the Holocene transgression (from Otvos 2004). (Bottom) Sea-level curve from Törnqvist (2006) for southern Louisiana closely mimics the smooth rise of sea-level depicted at top.

ravinement surface and sand sheet. On the eastern Louisiana continental shelf, deposits associated with progradation of the St. Bernard delta complex stratigraphically overlie these early to middle Holocene transgressive deposits. Above the progradational deposit of the St. Bernard delta is a locally significant ravinement surface. This ravinement extends from the modern Chandeleur Island shoreface seaward where it is overlain by the St. Bernard Shoals (McBride et al., 2004).

Holocene Evolution of the Eastern Louisiana Shelf

Kulp et al. (2002) used lithostratigraphic data collected from boreholes and sediment cores in conjunction with seismic reflection data to characterize the distribution of the Holocene sedimentary package across the central Gulf of Mexico continental shelf. These data were used to develop two maps. The first was a structural contour map of the base of the topstratum, and the second map was an isopach map of sediments stratigraphically above the late Wisconsian unconformity produced during Holocene marine flooding. From these maps a slope of 1:1,700 (0.03^{o}) dipping south-southwest was calculated for the surface underlying the St. Bernard delta complex in the area of the St. Bernard Shoals (Fig. 5).

Once relative sea-level rise slowed 7000 yrs BP, the Mississippi River began to prograde the delta plain across the continental shelf (Frazier, 1967). The modern delta plain has been recognized as a 1^{st}-order element of the total Holocene succession by Roberts (1997), who established the hierarchy of stratigraphic units within the Holocene delta plain. This unit was deposited stratigraphically above the MAFLA sand sheet along the Louisiana coast (Frazier 1967; Sydow and Roberts, 1996; McBride et al., 2004; Otvos, 2004). The delta plain is in turn constructed of multiple, spatially and temporally

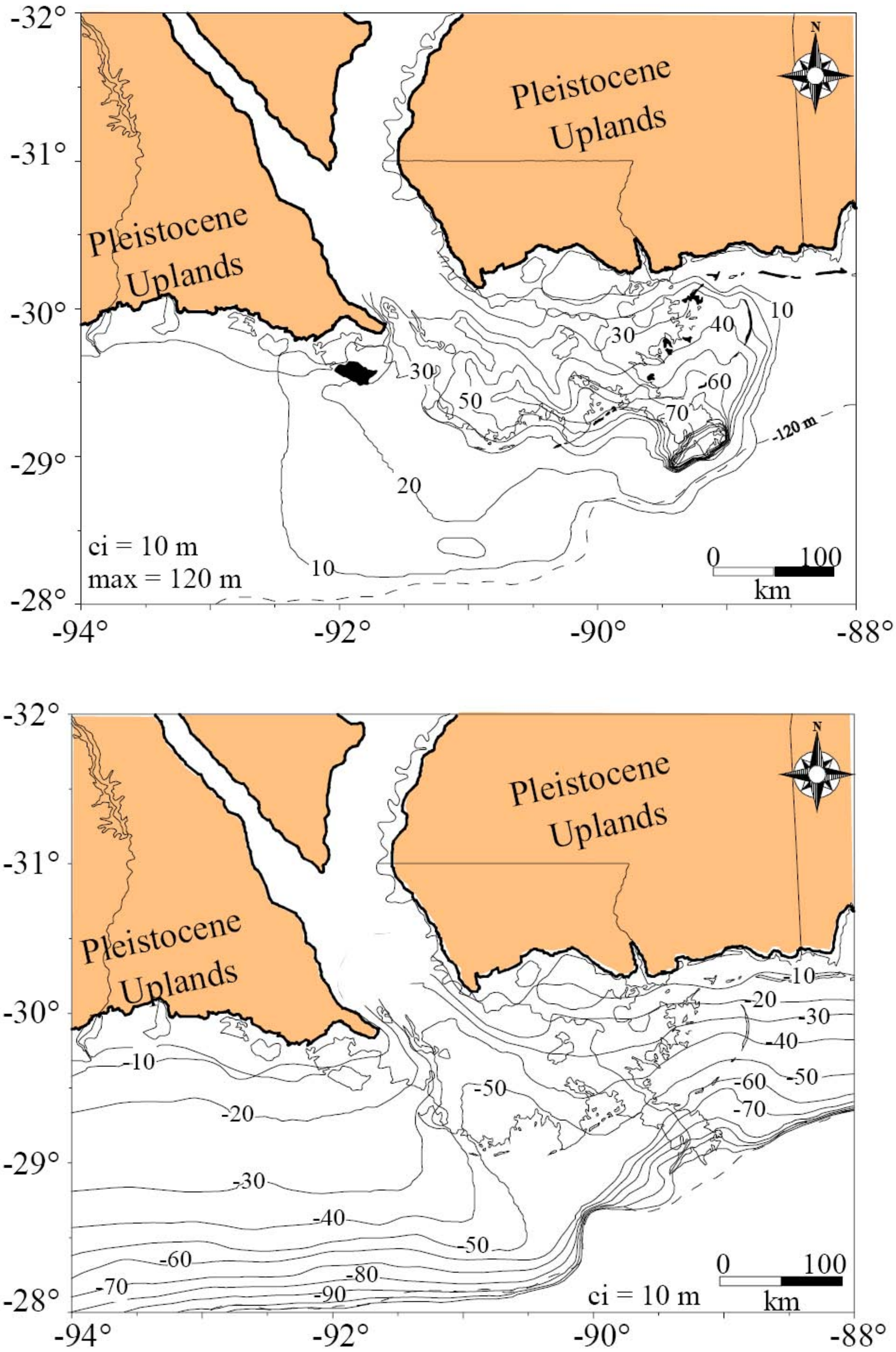


Figure 5. (Top) Isopach map of the topstratum lithosome showing the total thickness of the deposit constructed by the Mississippi River during the Holocene. Structural contour map of the base of the Holocene lithosome. Contours are drawn on the Holocene-Pleistocene contact (Bottom). From Kulp et al. (2002).

offset delta complexes, which are 2nd-order stratigraphic elements formed during 1,000 to 2,000 year time spans (Roberts, 1997). In the early stages of delta building, delta complexes were restricted to the western and central Louisiana continental shelf (Frazier 1967). The Mississippi River did not begin depositing sediment onto the eastern Louisiana continental shelf until ~4,000 years ago (Figs. 6 and 7); Fisk, 1955; Kolb and van Lopik, 1958; Curray and Moore, 1962, Frazier, 1967; Otvos and Giardino 2004, Törnqvist, 1996). This phase of deposition within the broader Holocene chronology of Mississippi River delta deposition has become known as the St. Bernard deltaic phase (Frazier, 1967).

Chronology of the St. Bernard Delta Complex

Fisk (1955) suggested that the eastern Louisiana shelf was the site of active deltaic deposition and development of the St. Bernard Delta Complex between 2,800 yrs BP and 1,800 yrs BP. Delta complexes are constructed from overlapping delta lobes, 3rd-order units linked to a trunk distributary (Fig. 8; Roberts, 1997). It is common practice to name delta lobes based upon the trunk distributary (Roberts, 1997). Kolb and Van Lopik (1958) subdivided the St. Bernard delta complex into a northern Metairie lobe and a more southern La Loutre lobe, with active deposition within each lobe between 2,800 and 2,200 yrs BP and 2,500 and 1,700 yrs BP, respectively. Curray and Moore (1962) also divided the St. Bernard delta complex into northern and southern lobes, however they suggested the southern delta lobe, Terre aux Boeuf, was initiated first, with primary activity between 2,800 and 2,200 yrs BP (Fig. 9). The northern delta lobe of Curray and Moore (1962) was suggested to be younger and active between 2,500 and 1,700 yrs BP. Frazier (1967) described six separate delta lobes; those lobes important to this study

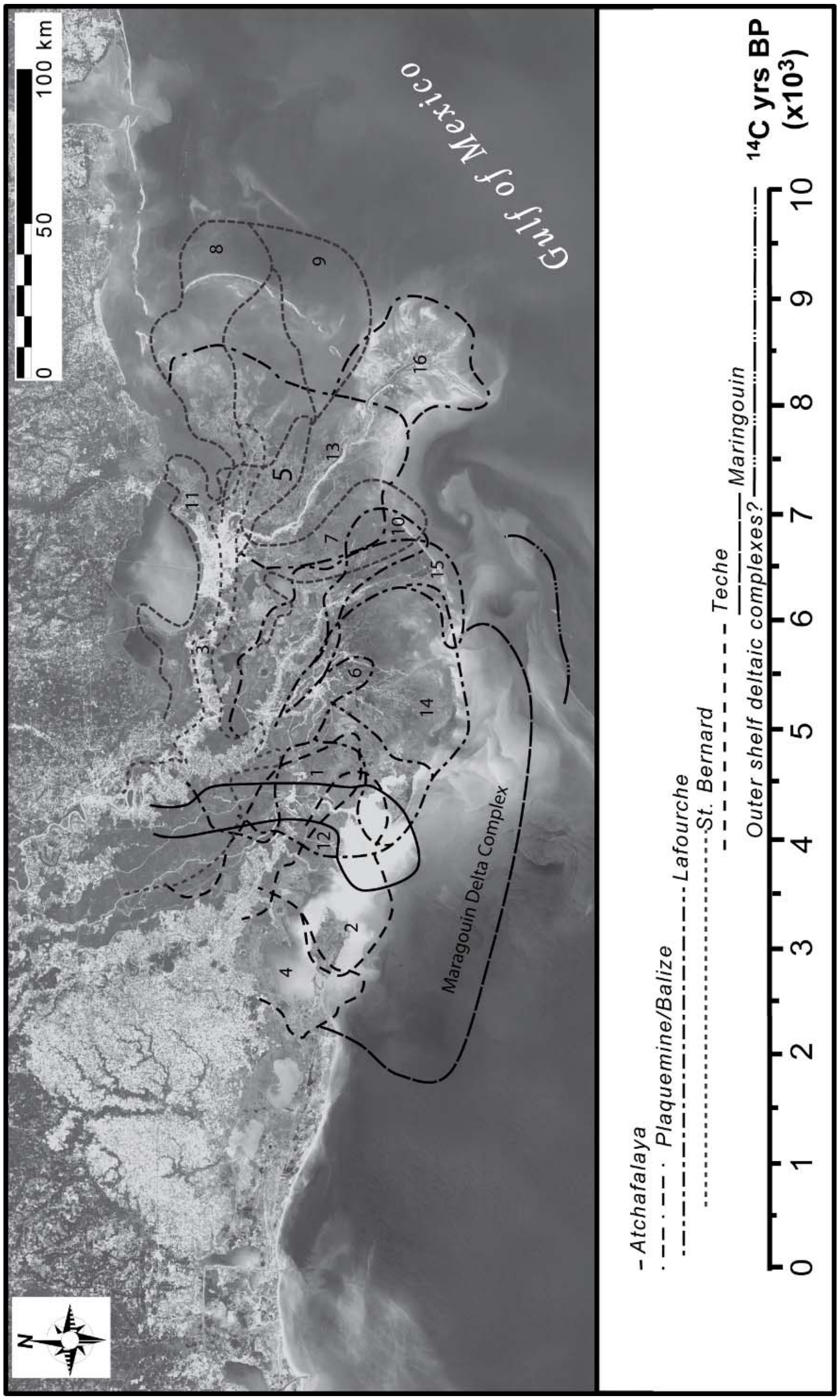


Figure 6. Map showing the 15 delta lobes of the Mississippi River delta based on Frazier's (1967) chronology. According to this model the St. Bernard Shoals are associated with delta lobe 9 of the St. Bernard Delta Complex. Delta lobe ages and chronology are contained in figure 8 (modified from Kulp et al., 2005).

Figure 7. Holocene chronology of the Mississippi River delta development. Numbers refer to delta lobes in figure 7. Modified from Frazier (1967).

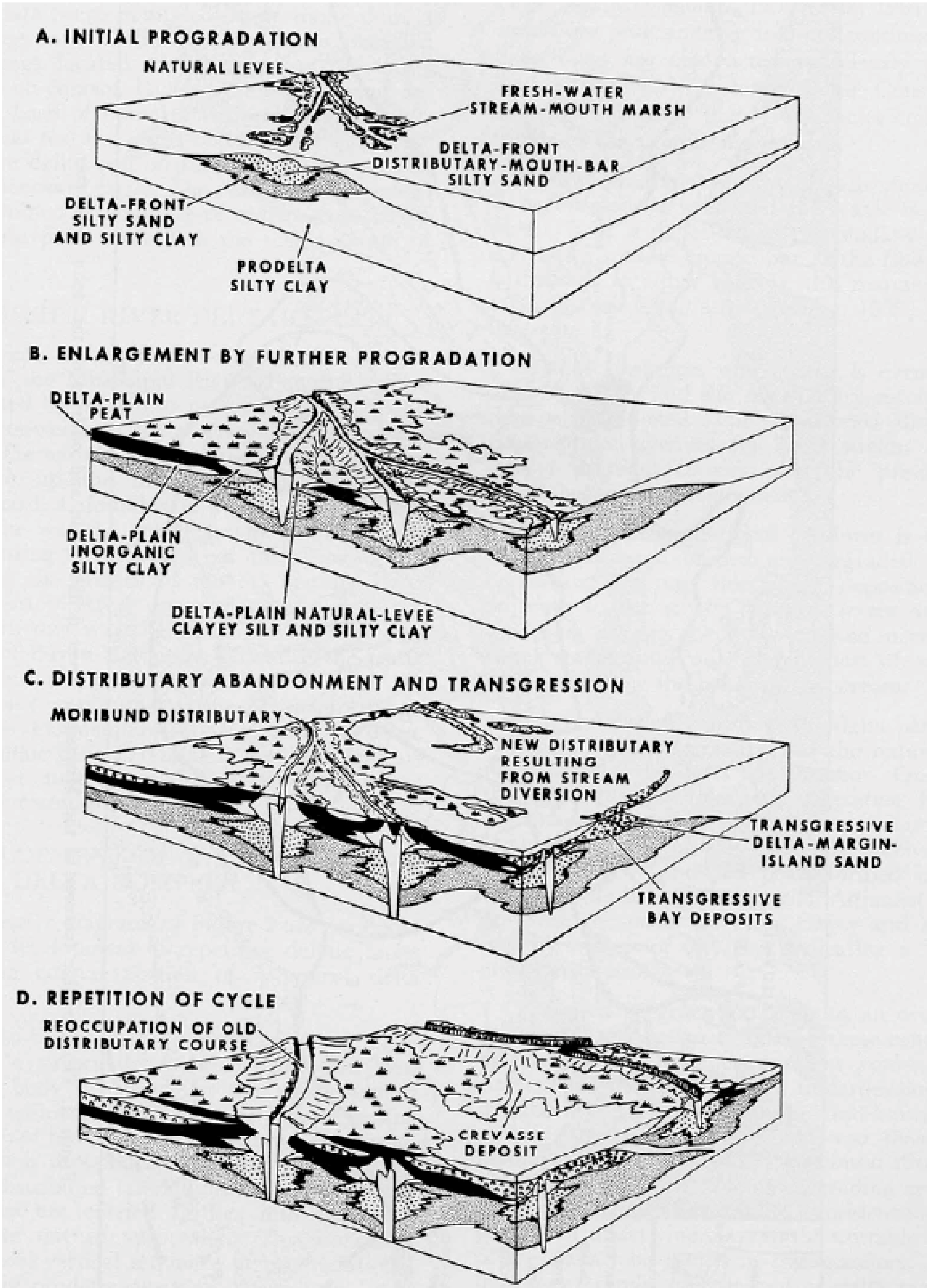


Figure 8. Deltaic progradational facies model developed by Frazier (1967) showing the development of a delta lobe and the spatial arrangement of various facies.

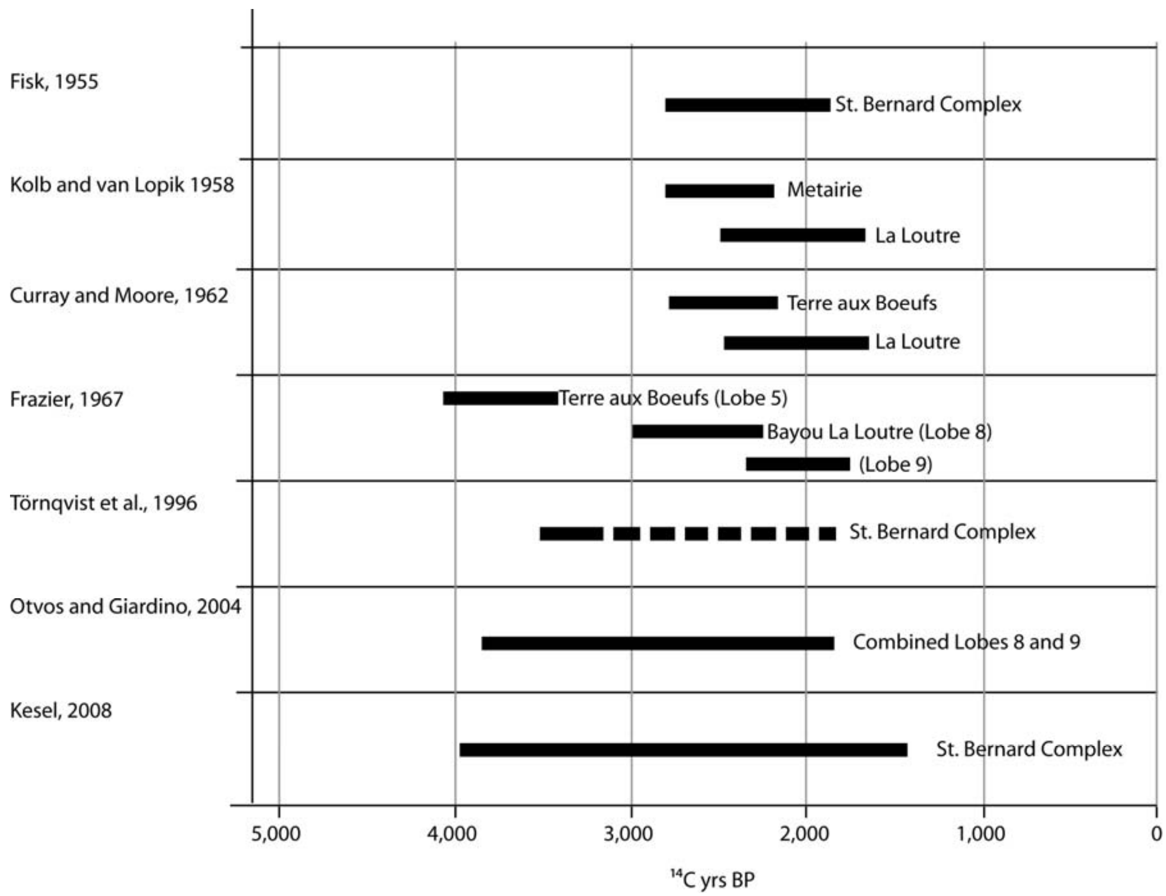


Figure 9. Graph depicting the various proposed chronologies for the St. Bernard delta complex and associated delta lobes.

are the Terre aux Beouf lobe (lobe 5), 4,100 – 3,400 yrs BP, the La Loutre lobe (lobe 8), 3,000 – 2,200 yrs BP, and lobe 9, 2,300 – 1,800 yrs BP. Frazier (1967) did not associate lobe 9 with any distributary network. Otvos and Giardino (2004) combined Frazier's La Loutre lobe and lobe 9 and proposed an initiation date of 3,800 yrs BP and an abandonment date of 1,800 yrs BP for the combined lobe. Törnqvist (1996) suggested the St. Bernard delta complex was initiated 3,500 yrs BP and abandoned by 1,800 yrs BP but provided no insight to the timing of individual delta lobe chronologies within the complex. Kessel (2008) suggested 4,000 yrs BP as the date of initiation for the St. Bernard delta complex and 1,500 yrs BP as the date of final abandonment.

St. Bernard Shoals

The first known recorded recognition of the St. Bernard Shoals is from a British Naval Survey map of coastal Louisiana and Mississippi published in 1778 (Fig. 10). In the area of the shoals the map contains bathymetric measurements across the shoals and a notation of "sand" for the composition of the seafloor at this location. It was not until the middle of the 20th century however, that the shoals became a topic of scientific inquiry.

Previous Studies of the Eastern Louisiana Shelf and the St. Bernard Shoals

Kindinger et al. (1982) used boomer subbottom profiles and surficial sediment samples collected on the eastern Louisiana continental shelf to establish the geologic history of the area since the middle Pleistocene. Kindinger et al. (1982) state that the shoals statigraphically overlie a delta fringe facies of the St. Bernard delta complex which has locally been incised by channels. In the model proposed by Kindinger et al. (1982) the incised distributary channel supplied the sediment for the shoals. The investigators further stated that the St. Bernard Delta complex overlies an estuary deposit that was

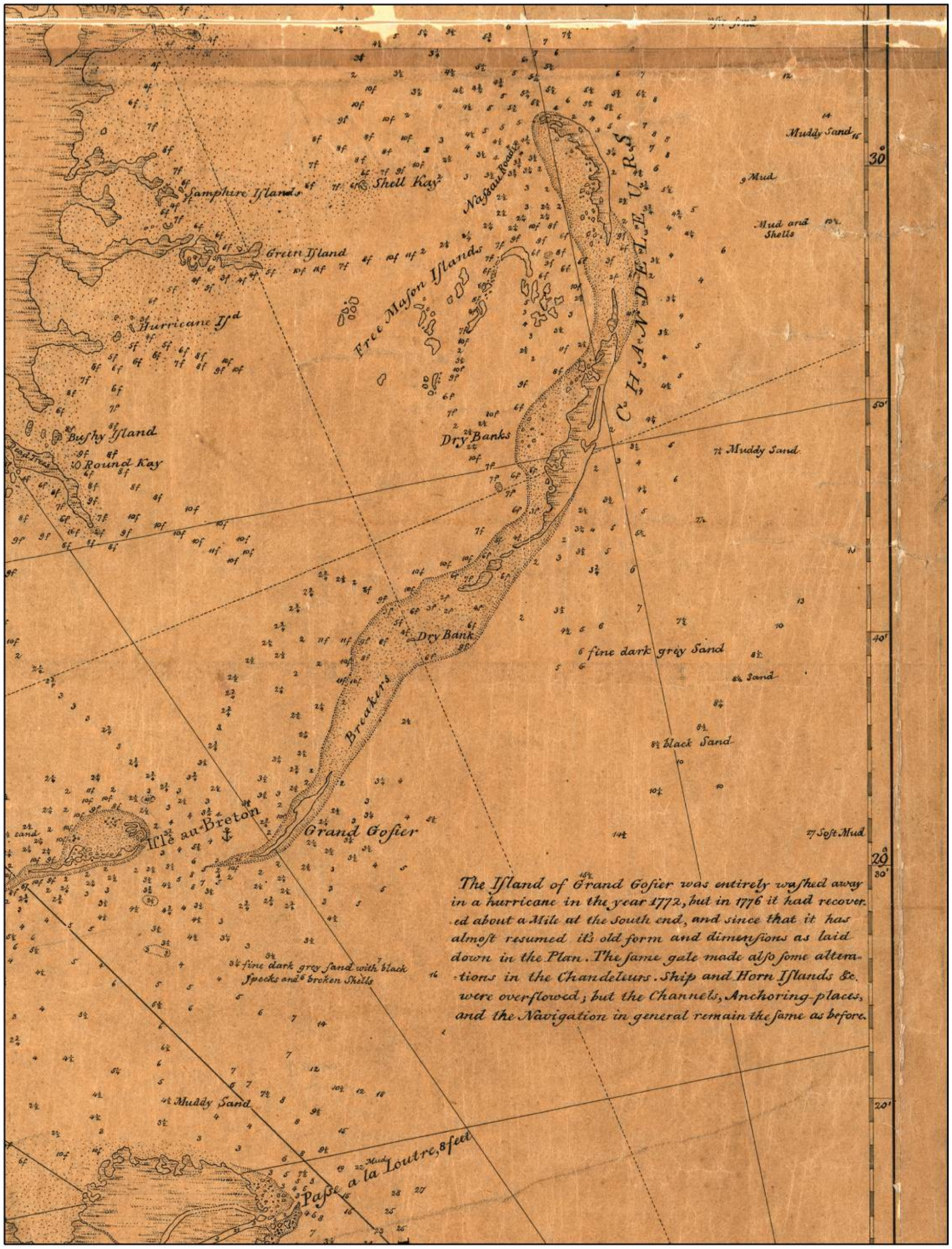


Figure 10. Section of 1778 British Naval Survey Map of the Louisiana coast with depth measurements in fathoms (1 fathom = 1.8 m). This portion of the map shows the Chandeleur Island, Grand Gossier, Biloxi Marsh, and the St. Bernard Shoals. The shoals are acknowledged by the soundings and the labels ‘Sand’ and ‘Black Sand’ southeast of the Chandeleur Islands.

deposited during the end of the Holocene transgression.

Brooks et al. (1995) also used the 1987 seismic data and vibracores to characterize the eastern Louisiana continental shelf. The authors identified prodelta, delta front, distributary, lagoon, sand sheet, and shoal facies. Brooks et al. (1994), state that underlying the St. Bernard Shoals are well developed backbarrier lagoonal deposits, deposited after abandonment of the underlying deltaic package. The interpretation presented by Brooks et al. (1995) conflicts with the models proposed by Pope et al. (1993) and this study.

Pope et al. (1993) provided a more detailed study of the shoals using the seismic data and vibracores collected in 1987 and produced an isopach map of the shoal platform (Fig. 11). The authors did not, however, utilize the data to investigate the St. Bernard Shoals beyond their characterization of the shoal sand resources. Pope et al. (1993) performed sediment analysis on only the top 1.0 m of strata penetrated by the cores. The work by Pope et al. (1993) suggests that the St. Bernard Shoals lie stratigraphically above distributary channels of the St. Bernard delta complex and that sediment comprising the shoals is derived from the reworking of these channels during a local transgression.

St. Bernard Shoals Morphology

The morphology of the St. Bernard Shoals is quite different than that of the three other shoal systems of the Louisiana continental shelf (Fig. 1). The St. Bernard Shoals are a group of 61 discrete sand bodies located on a bathymetric platform in 15 to 20 m of water (Figs. 11 and 12). This bathymetric platform is herein referred to as the St. Bernard Bathymetric High, and is located approximately 25 km southeast of the Chandeleur Islands. This platform covers an area of 530 km^2 and is characterized by an internal

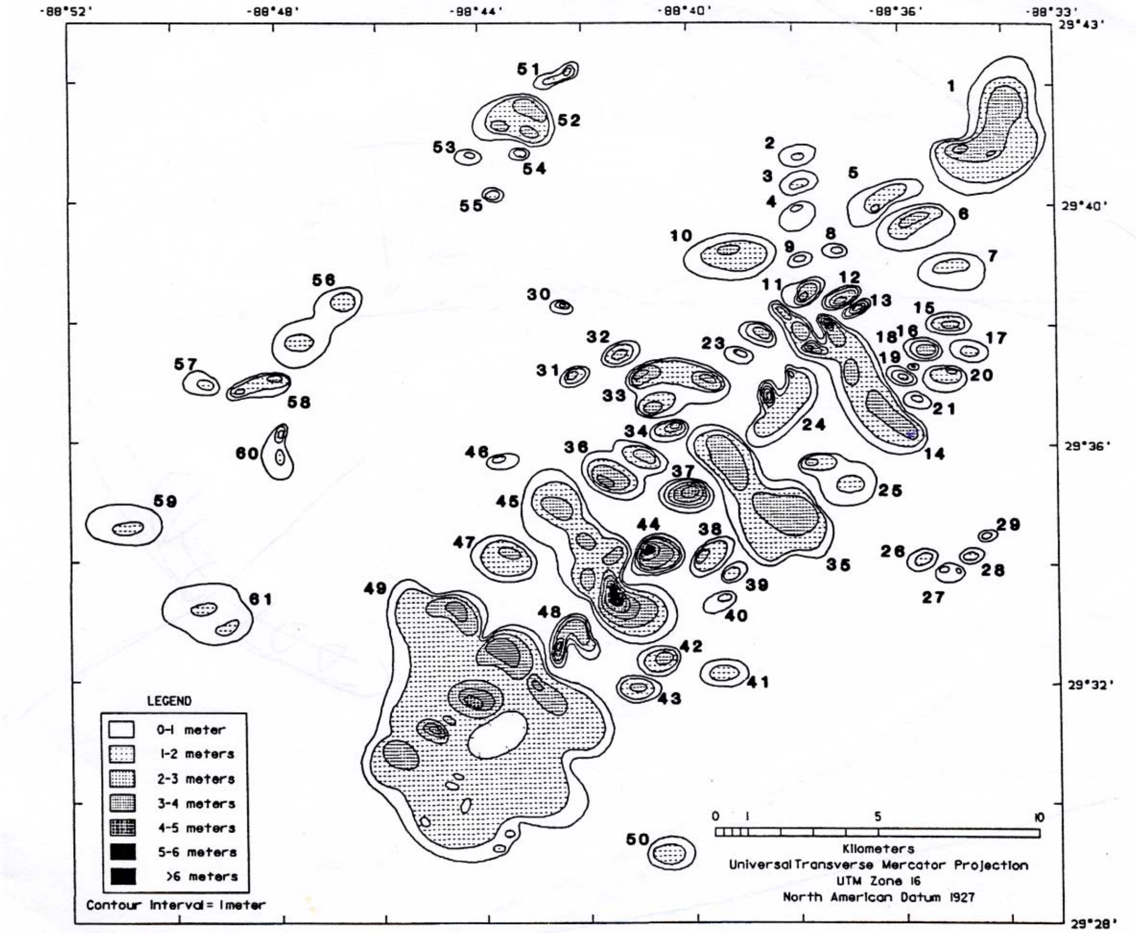


Figure 11. Isopach map of the St. Bernard Shoals from Pope et al. (1993). Many of the larger shoals are oriented oblique to the Chandeleur shoreline and have steeper northeast side. The smaller shoals have more varied morphologies. Contour interval is 1 m.

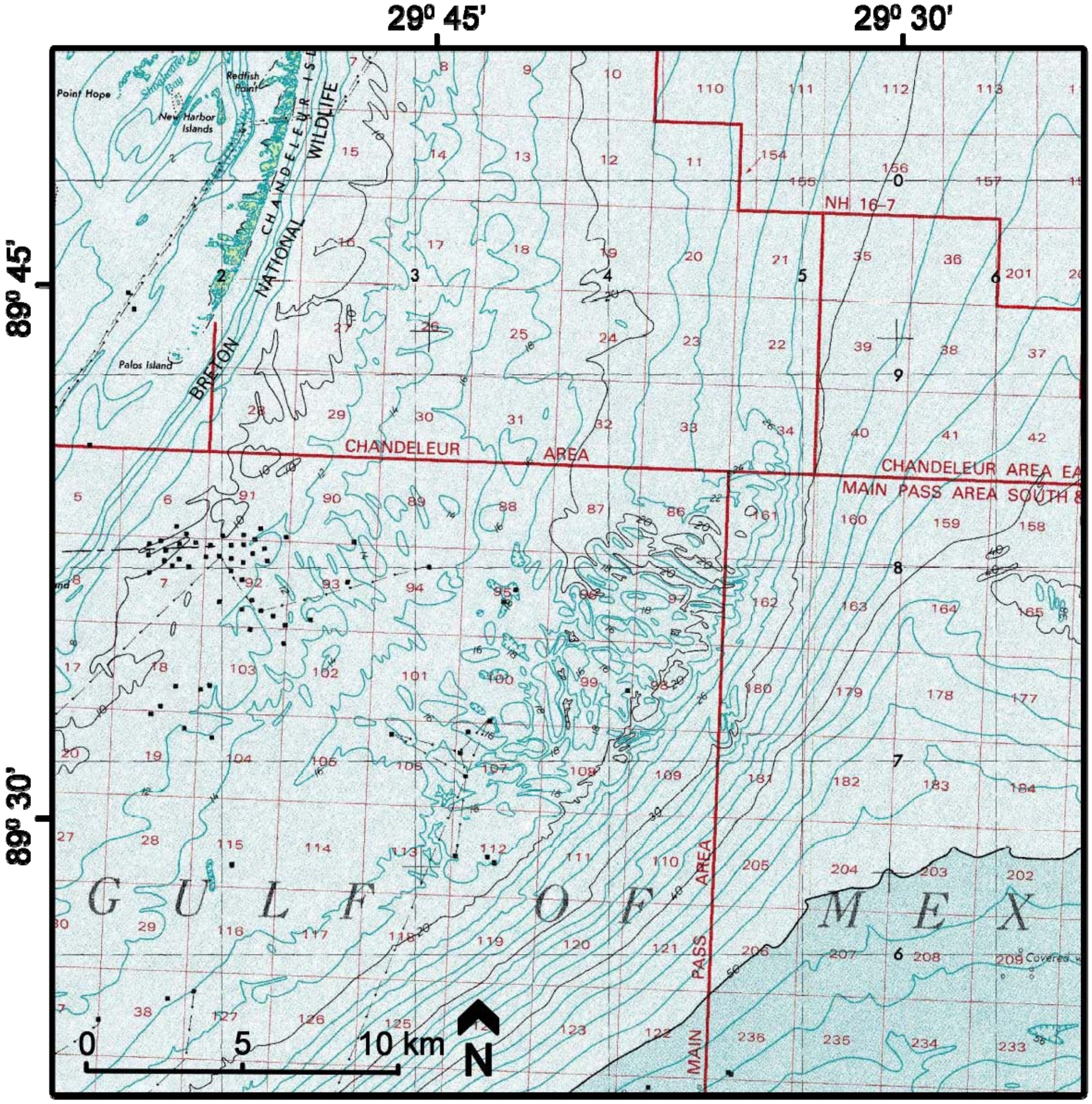


Figure 12. Section of USGS 1:250,000 scale Breton Sound map showing the irregular bathymetry created by the St. Bernard Shoals. Contour interval is 2 m.

irregular bathymetry reflecting the morphology of the shoals. Individual shoals within the St. Bernard Bathymetric High range in aerial extent from 0.05 km^2 to 44 km^2 and have widely varying morphologies on the basis of orientation, trends of their longitudinal axes, wavelength, and height above the adjacent seafloor.

The St. Bernard Shoals can be separated into two morphologic groups. The first group consists of the 8 largest shoals. The strike of these shoals is northwest, approximately perpendicular to the Chandeleur Islands shoreline. The strike of the entire shoal platform is parallel (northeast) to the Chandeleur Island System (Fig. 13). The larger shoals also have north to northeast dipping slip faces with calculated slope angles of 0.6^o to 2^o, and lower gradient stoss side slopes of 0.5^o to 0.065^o. These values were calculated from seismic data collected in 1987. The larger shoals are bounded on either side by along-strike bathymetric lows referred to as swales. The areal extent of each of these larger shoals varies between 44 km^2 to 3 km^2 with an average length of 6 km and average width of 2 km (Pope 1993). The smaller shoals have a much wider range of strike and dip directions, and many do not have clearly identifiable stoss and lee sides. However, on average this smaller suite of shoals trend in the same directions with similar slopes. The individual shoals can also be separated into two different fields. The larger shoal field lies in 16 - 20 m of water and is approximately 30 km long. The smaller one lies 5 km northwest of the larger field in 15 km of water (Pope 1993).

The three other shelf shoals associated with the Mississippi River delta are composed of a single, shore-parallel, 75% to 100% fine-grained sand deposit (Frazier, 1974). All four shoal deposits, including the St. Bernard Shoals, are recognized as the product of local transgressions reworking abandoned delta lobes deposited during the

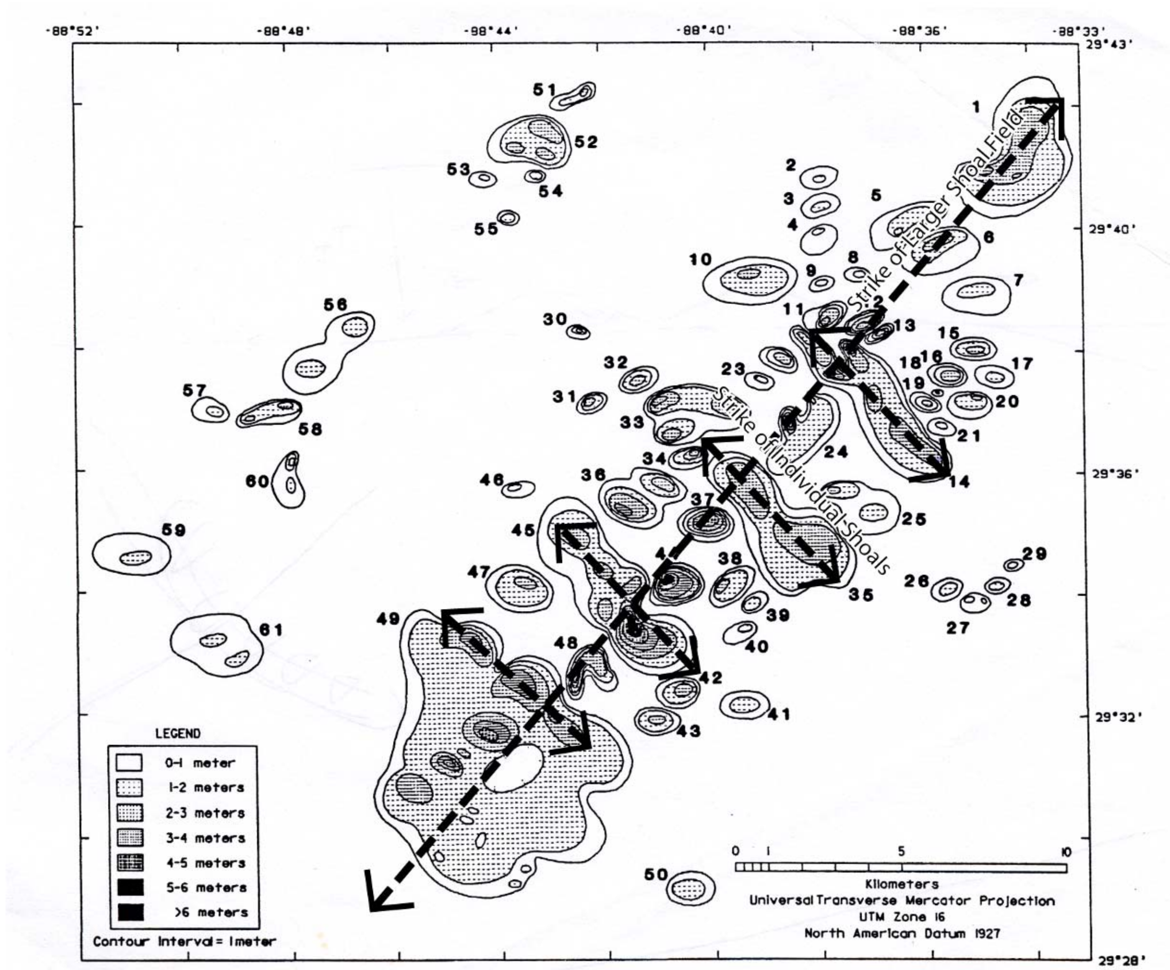


Figure 13. Isopach map of the St. Bernard Shoal Platform from Pope et al. (1993) modified to show the northeast strike of the larger shoal field and the northwest strike of individual shoals.

Holocene evolution of the Mississippi River delta (Penland et al., 1988). Each shoal system is therefore thought to represent the approximate position of a former shoreline. Ship Shoal has been shown to be the remnants of a former barrier shoreline through the presence of beachrock and a backbarrier faunal assemblage by Penalnd et al. (1986). Ship and Trinity Shoals are located in 10 m of water; where as Outer Shoal is in 20 m of water. Trinity Shoal and Ship Shoal were built by the transgressive submergence of Bayou Cypremont-Sale delta lobes (4,800 to 3,900 years ago) and the Maringouin delta complex (7,300 to 6,000 years ago), respectively (Frazier, 1967). Outer Shoal lies in 20 m of water and has been associated with the elevation of sea-level 9,000 years ago (Penland et al., 1989b). The St. Bernard Shoals occupy the same isobath as Outer Shoal (-15 to -20 m) and overlie Frazier's (1967) delta lobe 9 of the St. Bernard delta (3,000 – 2,000 years ago) (Figs. 7 and 8). Stratigraphic relationships within vibracores taken through the St. Bernard Shoals suggest that they formed during the transgression of Frazier's (1967) delta lobe 9.

Methods

Two data sets were the primary sources of information for this study. The first set consists of seismic profiles and vibracores collected in 1987 by Louisiana Geological Survey (LGS) as part of a cooperative effort with the United States Geological Survey (USGS) to inventory sand resources on the Louisiana continental shelf. Seismic profiles were collected using the *R/V Acadiana*, and vibracores were collected using the *R/V Blue Streak*. Seismic data was collected during the 1987 effort, and a preliminary analysis of this data provided the basis for selecting locations for vibracoring. The 1987 data collection methodology described below is referenced from Pope et al. (1993). In this thesis these data will be referred to as the CI-87 data set.

The second, less extensive collection of data, consisting of CHIRP sub-bottom seismic profiles, side scan imagery, and eight surficial sediment grab samples, was collected in 2008 by the University of New Orleans aboard the *R/V Acadiana*. This data set was collected specifically for the purposes of this study and is concentrated in the area of the St. Bernard Shoals. These data will be referred here in as the SBS-08 data set.

Approach of this Study

Previous works on the shoals were examined and placed into a framework understanding of facies associations and regional stratigraphy. Next, vibracores were analyzed based upon these observations and depositional facies were identified. Vibracores were then integrated with seismic profiles to lithostratigraphically classify identified seismic facies. Common units and observations were grouped, and facies were identified. These facies were then traced regionally to delineate their vertical and lateral distribution. With this approach major features and facies, such as sand shoals and

distributary channels, were identified. From these data depositional processes were inferred and substantiated by the regional distribution of each facies. Seismic profiles were also used to identify the regional channel network, delta morphology, and distal extent of the St. Bernard delta complex.

Two regional stratigraphic cross sections were constructed using the vibracore interpretations. Figure 14 is a map of the cores used in developing the cross sections. Seismic profiles and vibracores were analyzed to develop a map of regional channels. An isopach map of the basinward edge of the St. Bernard Delta was developed using seismic profiles. The St. Bernard Shoal isopach map developed by Pope et al. (1993) was modified on the basis of reinterpretations of seismic profiles and vibracores presented in this study.

CI-87 Seismic Lines

A total of 400 line-km of seismic profiles from the CI-87 data set were analyzed for this study (Fig. 15). The profiles were collected using a 5 kHz transducer and an ORE Geopulse boomer system with a 300 to 800 Hz frequency filter and a 50-cm resolution. Return signals were split-traced on an EPC 3200 recorder with sweep rates of 0.125 seconds for each channel resulting in a 0.25 second effective display for the entire record. A signal velocity of 1,500 ms^{-1} was assumed for all depth calculations. All data were recorded on an HP 4300 reel-to-reel recorder for playback. Navigation was accomplished using a Northstar 600 Loran-C receiver and a Morrow XYP-200 real-time Loran plotter. Navigation data were recorded on magnetic tape using a Texas Instruments Silent 700 and processed into trackline charts by the USGS. Navigation shot points were marked on the seismic records every 5 minutes in real time. The original digital data for the survey is

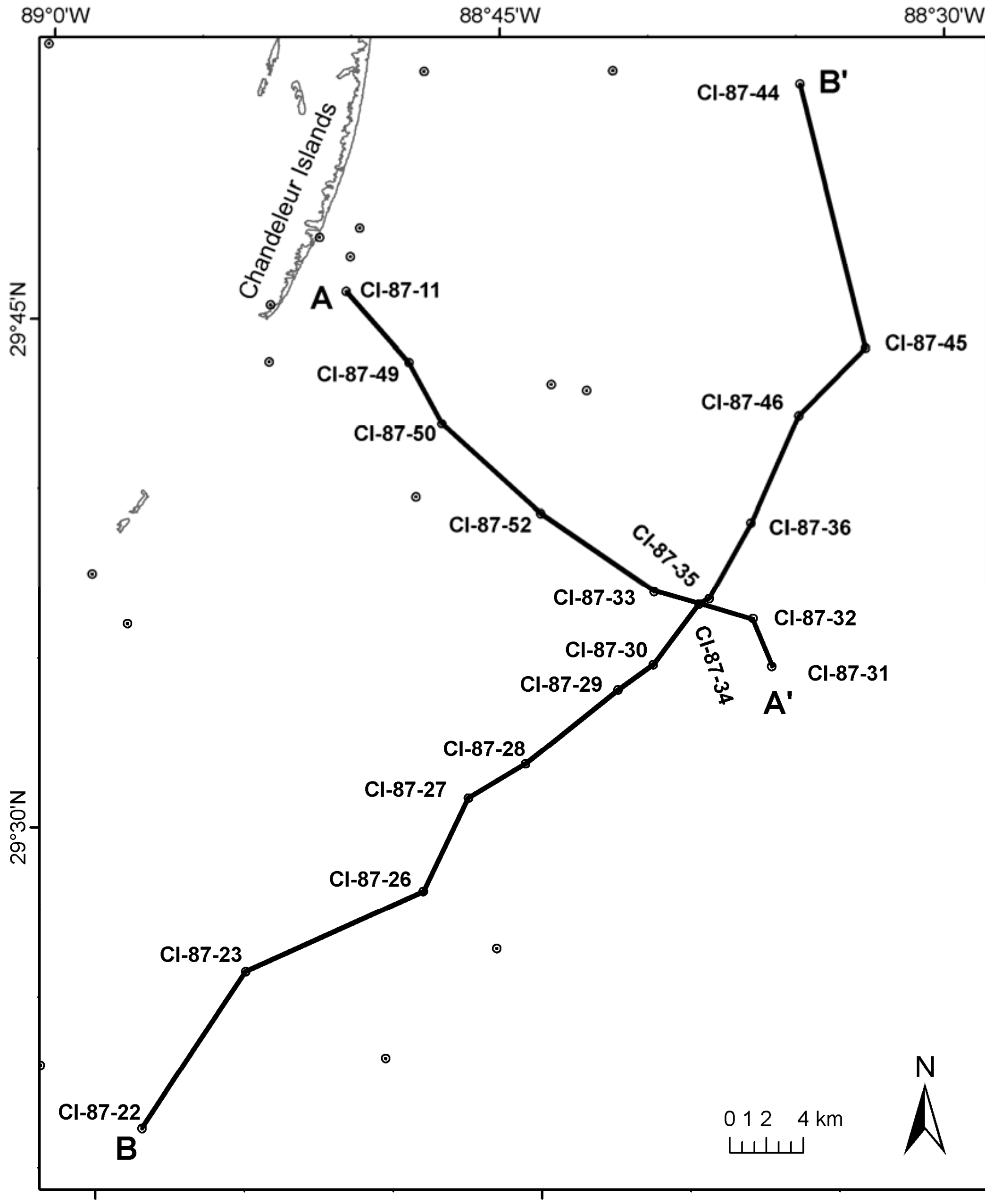


Figure 14. Location of geological cross-sections A-A' and B-B' and included vibracores. A Total of 11 facies were identified in the cores and correlated across the study area to define the regional distribution of stratigraphic relationships.

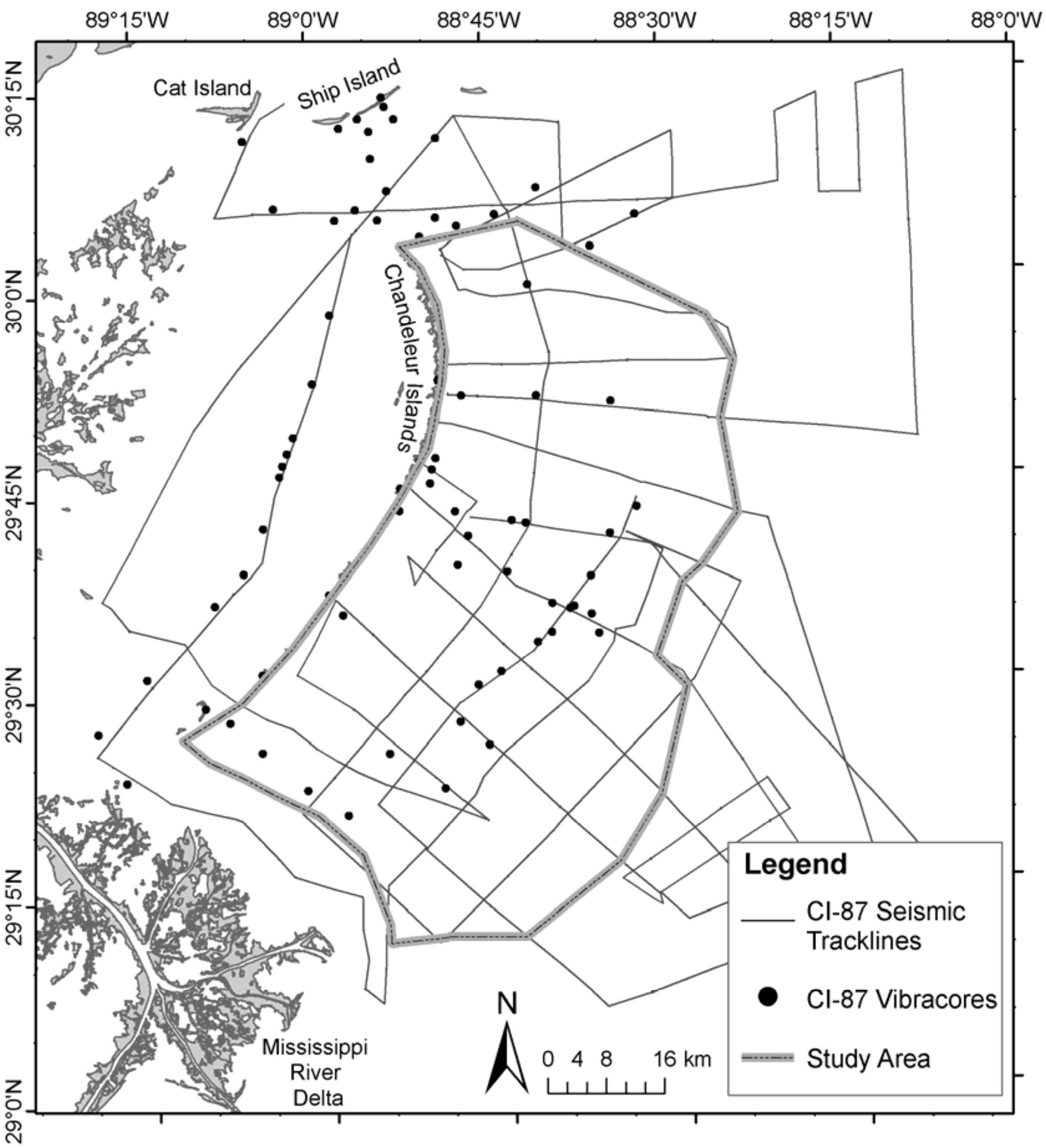


Figure 15. Map showing the seismic tracklines and vibracores locations from the CI-87 data set.

no longer available; however, analog copies of the entire data set are archived within the University of New Orleans Coastal Research Laboratory. Digital trackline data are available and provided the opportunity to locate imaged features geospatially by comparing analog seismic records to the available digital trackline and positioning data.

CI-87 Vibracores

A total of 47 Vibracores from the CI-87 data set were analyzed for this study (Table 1) (Figs. 16 - 20). Vibracore locations were chosen based upon primary interpretation of the seismic profiles collected during the 1987 R/V Acadiana cruise. The vibracoring process employed a pneumatic vibrating core barrel to penetrate sea-floor sediments. The barrels used to collect the cores had an outside diameter of 10.3 cm, a length of 9.3 m, and were made of fiberglass. Each vibracore was acquired through two separate coring attempts. First a core barrel was vibrated to maximum penetration then extracted. Next a second barrel was driven to within 1m of the bottom of the first run using a high-pressure water drive system to remove sediments above that depth. The second core was then vibrated to maximum penetration. Using this approach the total length for the vibracores ranged between 6 and 12 m. Sediment consolidation was the most significant in the top 0.50 m to 1.25 m of the core. Vibracores were then capped, labeled, and transported back to the lab for analysis. The original vibracores and core photos were not available for this study. The results from 19 sediment samples obtained from the cores in order to perform sediment analysis were published by Pope et al. (1993) and the USGS usSEABED data release (2006) (Table 2). These sediment samples were all taken from within the top 1 m of the vibracores because the focus of Pope et al. (1993) was to characterize the St. Bernard Shoals sedimentary texture and assess the shoal

Corename	Latitude	Longitude
CI-87-10	29.775328	-88.838615
CI-87-11	29.758106	-88.841675
CI-87-12	29.785328	-88.855560
CI-87-13	29.752829	-88.884453
CI-87-20	29.431175	-89.091118
CI-87-21	29.383121	-89.028618
CI-87-22	29.350622	-88.972786
CI-87-23	29.425619	-88.911674
CI-87-24	29.380621	-88.835007
CI-87-25	29.432564	-88.770561
CI-87-26	29.462008	-88.810562
CI-87-27	29.507004	-88.783340
CI-87-28	29.522837	-88.750565
CI-87-29	29.557558	-88.697227
CI-87-3	30.086149	-88.821121
CI-87-30	29.569223	-88.676949
CI-87-31	29.566170	-88.610565
CI-87-32	29.590057	-88.620010
CI-87-33	29.605057	-88.675011
CI-87-34	29.598112	-88.650009
CI-87-35	29.600613	-88.644173
CI-87-36	29.637278	-88.619171
CI-87-37	30.075317	-88.791397
CI-87-38	30.087818	-88.737228
CI-87-39	30.119205	-88.676949
CI-87-4	30.063374	-88.844452
CI-87-40	30.081984	-88.538338
CI-87-41	30.044764	-88.603340
CI-87-42	30.000042	-88.693893
CI-87-43	29.861992	-88.687225
CI-87-44	29.725052	-88.886398
CI-87-44	29.851992	-88.582230
CI-87-45	29.720886	-88.551117
CI-87-46	29.688942	-88.590004
CI-87-47	29.705332	-88.708618
CI-87-48	29.708942	-88.728340
CI-87-49	29.722275	-88.807785
CI-87-5	30.048653	-88.866951
CI-87-50	29.691442	-88.790565
CI-87-51	29.655888	-88.806671
CI-87-52	29.645611	-88.736954
CI-87-6	29.941711	-88.817505
CI-87-7	29.885324	-88.825562
CI-87-8	29.865047	-88.793343
CI-87-9	29.789217	-88.832787

Table 1. CI-87 vibracore names and location. The water depth and penetration for each vibracore are in the logs (Figs. 16 to 19). (Projection: UTM NAD 83 Zone 16N).

Figure 16. Symbols used in CI-87 vibracore logs.

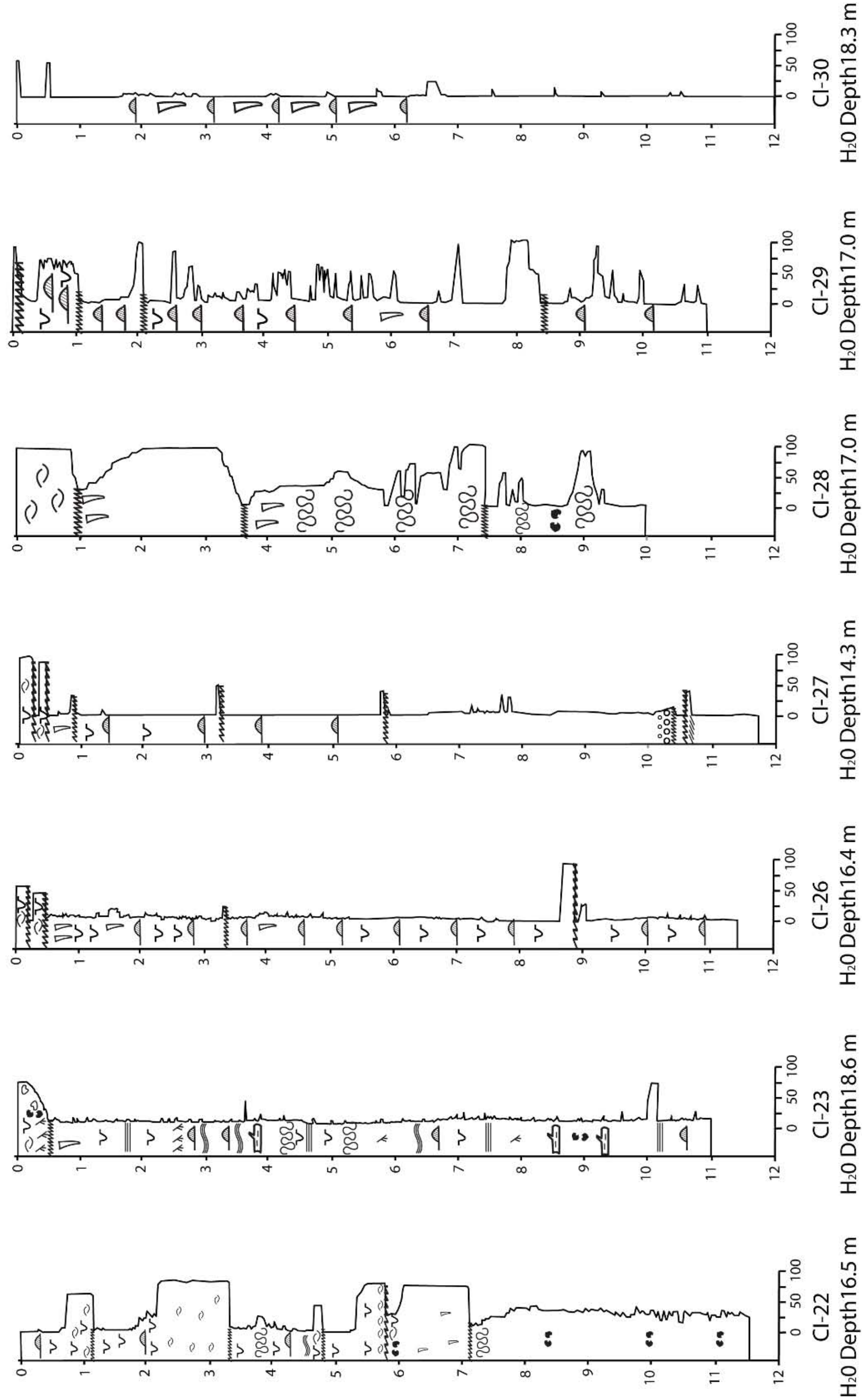


Figure 17. Vibracore logs for CI-87 cores CI-22 to CI-30.

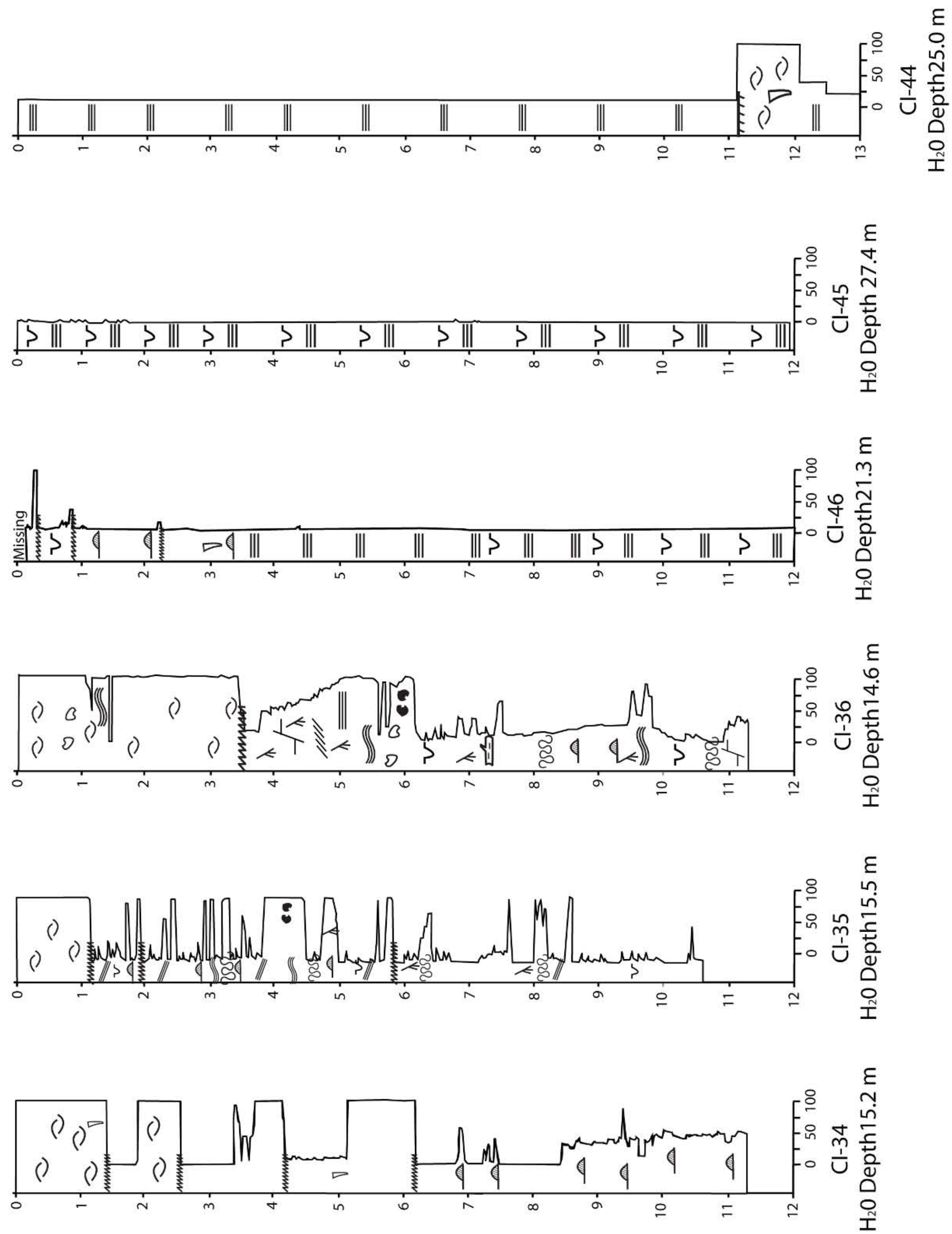


Figure 18. Vibracore logs for CI-87 cores CI-34 to CI-46.

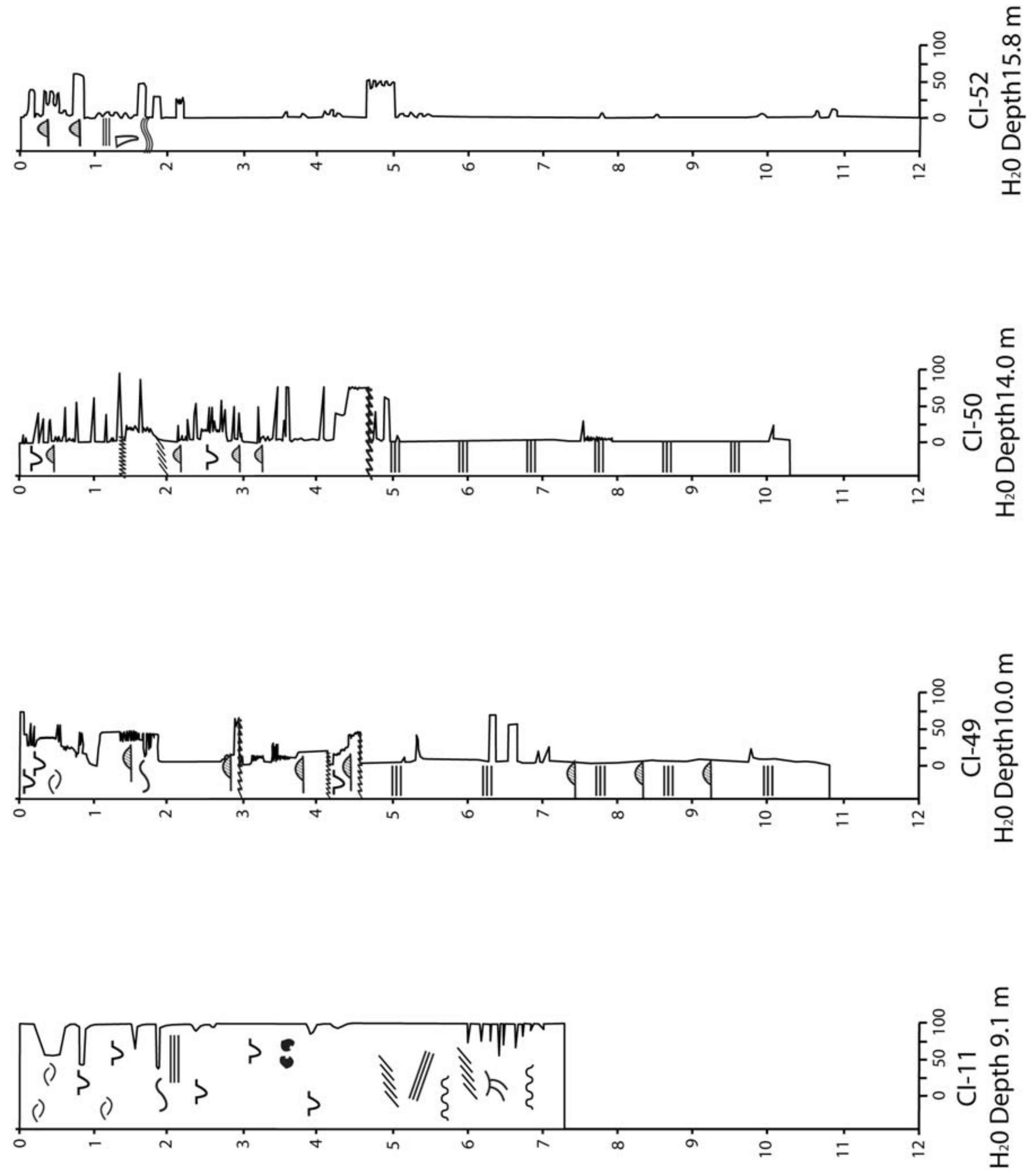


Figure 19. Vibracore logs for CI-87 cores CI-11 to CI-52.

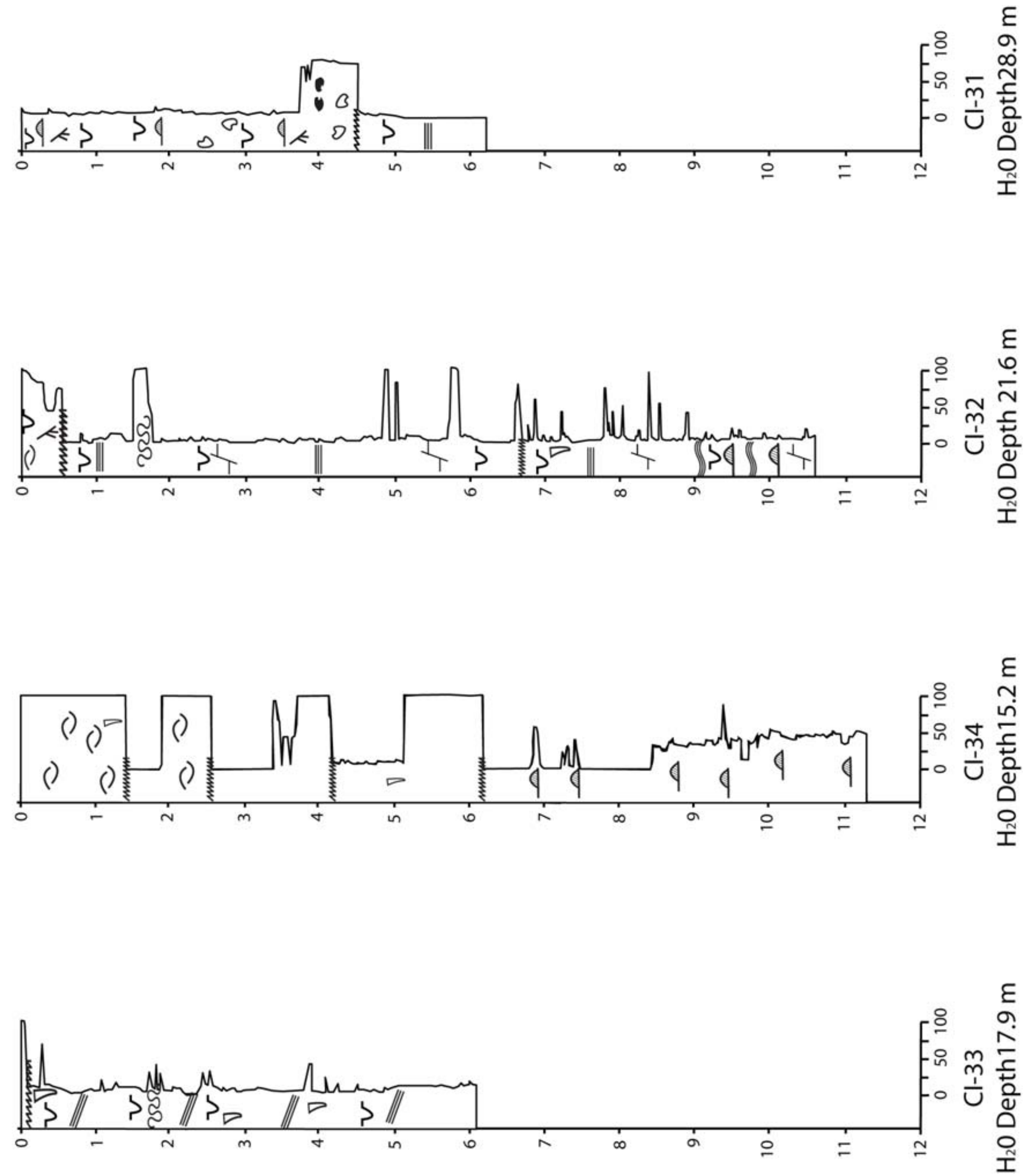


Figure 20. Vibracore logs for CI-87 cores CI-34 to CI-31.

CORE NUMBER	SAMPLE DEPTH	CALCULATION OF MOMENT MEASRURE STATISTICS				CALCULATION OF FOLK STATISTICS				CALCULATION OF INMAN STATISTICS				TEXTURAL STATISTICS			
		MEAN SIZE	SORT-ING	SKEW-NESS	KUR-TOSIS	MEAN SIZE	SORT-ING	SKEW-NESS	KUR-TOSIS	MEAN SIZE	SORT-ING	SKEW-NESS	KUR-TOSIS				
CI-87-22	.10M	3.70	0.45	-0.46	-0.23	3.71	0.47	-0.03	0.83	3.71	0.51	-0.03	0.39	MUDDY SAND	WELL SORTED	NEAR SYMMETRICAL	PLATYKURTIC
CI-87-23	.05M	3.22	0.34	0.22	2.31	3.21	0.33	-0.04	1.53	3.20	0.27	-0.09	1.48	SAND	VERY WELL SORTED	NEAR SYMMETRICAL	VERY LEPTOKURTIC
CI-87-24	.25M	3.31	0.33	0.68	2.15	3.30	0.33	0.13	1.47	3.32	0.27	0.13	1.03	SAND	VERY WELL SORTED	FINE SKEWED	LEPTOKURTIC
CI-87-25	.10M	3.52	0.93	-0.27	-0.77	3.56	0.99	-0.03	0.91	3.50	1.04	0.06	0.49	MUDDY SAND	MOD. SORTED	NEAR SYMMETRICAL	MESOKURTIC
CI-87-26	.40M	3.26	0.47	-0.13	1.32	3.26	0.46	0.07	1.61	3.27	0.42	0.04	1.02	SAND	WELL SORTED	NEAR SYMMETRICAL	VERY LEPTOKURTIC
CI-87-27	.10M	3.07	0.37	0.58	1.08	3.05	0.38	0.03	0.93	3.04	0.38	-0.08	0.65	SAND	WELL SORTED	NEAR SYMMETRICAL	MESOKURTIC
CI-87-28	.10M	2.93	0.36	-0.27	0.99	2.94	0.36	0.07	0.88	2.96	0.38	0.14	0.55	SAND	WELL SORTED	NEAR SYMMETRICAL	PLATYKURTIC
CI-87-29	.10M	4.19	0.90	-1.21	0.26	4.17	0.88	-0.71	0.98	3.95	0.95	-0.69	0.39	SANDY MUD	MOD. SORTED	V. COARSE SKEWED	MESOKURTIC
CI-87-30	.05M	4.38	0.81	-2.07	3.47	4.50	0.65	-0.69	2.03	4.40	0.51	-0.58	1.58	SANDY MUD	MOD. WELL SORTED	V. COARSE SKEWED	VERY LEPTOKURTIC
CI-87-31	.10M	3.41	1.14	-0.08	-1.36	3.41	1.18	0.03	0.62	3.45	1.36	0.09	0.22	SANDY MUD	POORLY SORTED	NEAR SYMMETRICAL	VERY PLATYKURTIC
CI-87-32	.05M	2.85	0.49	0.60	1.14	2.84	0.50	0.14	1.28	2.87	0.46	0.12	0.94	SAND	WELL SORTED	FINE SKEWED	LEPTOKURTIC
CI-87-33	.05M	3.01	0.61	1.40	2.71	2.29	0.54	0.24	1.88	2.92	0.38	0.02	2.05	SAND	MOD. WELL SORTED	FINE SKEWED	VERY LEPTOKURTIC
CI-87-34	.10M	2.42	0.69	0.78	0.71	2.40	0.68	0.15	0.99	2.44	0.66	0.15	0.74	SAND	MOD. WELL SORTED	FINE SKEWED	MESOKURTIC
CI-87-35	.05M	2.75	0.37	-0.04	0.63	2.75	0.40	-0.01	1.24	2.75	0.39	-0.01	0.70	SAND	WELL SORTED	NEAR SYMMETRICAL	LEPTOKURTIC
CI-87-36	.05M	2.74	0.40	-0.29	0.27	2.74	0.42	-0.04	1.24	2.74	0.42	-0.03	0.65	SAND	WELL SORTED	NEAR SYMMETRICAL	LEPTOKURTIC
CI-87-46	.20M	3.10	0.56	0.32	-0.12	3.10	0.59	0.17	1.12	3.14	0.56	0.18	0.80	SAND	MOD. WELL SORTED	FINE SKEWED	LEPTOKURTIC
CI-87-47	1.0M	2.87	0.40	0.20	2.16	2.87	0.36	-0.03	1.05	2.86	0.35	-0.05	0.77	SAND	WELL SORTED	NEAR SYMMETRICAL	MESOKURTIC
CI-87-48	.01M	3.93	1.02	-0.80	-0.71	3.96	1.02	-0.55	0.72	3.77	1.11	-0.51	0.37	SANDY MUD	POORLY SORTED	V.COARSE SKEWED	PLATYKURTIC
CI-87-52	.05M	3.56	0.85	-0.83	-0.77	3.61	0.86	-0.66	0.76	3.41	0.94	-0.66	0.36	SANDY MUD	MOD. SORTED	V. COARSE SKEWED	PLATYKURTIC

Table 2. Sediment grainsize analysis from Pope et al. (1993) for 19 samples taken within the top 1.0 m of several cores.

sediments viability as a shoreline nourishment borrow source. Because the vibracores and photos were not available, this study relies upon the descriptions that were completed in 1989 and archived at UNO.

SBS-08 Seismic Data

An additional 384 line-km of seismic profiles was collected during a June 2008 UNO survey aboard the *R/V Acadiana* as part of the SBS-08 data set (Fig 21). The profiles were collected using an Edgetech SB-216S CHIRP system with a 2 to 16 kHz frequency range and 6-cm resolution. This provided a higher resolution seismic dataset than the CI-87 data. Velocity of the signal was assumed to be 1500 ms^{-1}. Return signals were recorded using Edgetech 3200 Discover Subbottom software and were backed-up to external hard drives.

SBS-08 Side Scan Data

384 line-km of side scan imagery was collected as part of the SBS-08 data set using a Klein 3000 Sonar System with dual frequency ranges of 100 kHz 500 kHz (Fig. 21). A 200 m horizontal swath of sea-floor was imaged. Data was recorded using *Klein Sonar Pro* and .sdf and .xtf files were backed-up on external hard drives.

SBS-08 Sediment Samples

Eight sediment grab samples were collected along a transect of the axis of Shoal 14 (Fig. 10) using a Ponar grab-sampler. Sites for sediment sampling were selected by real-time analysis of the side-scan profile and seismic reflection data (Fig. 22). Samples were bagged and numbered and returned to UNO for sediment analysis. Sediment samples were analyzed using a MicroMetrics LS200 particle size analyzer.

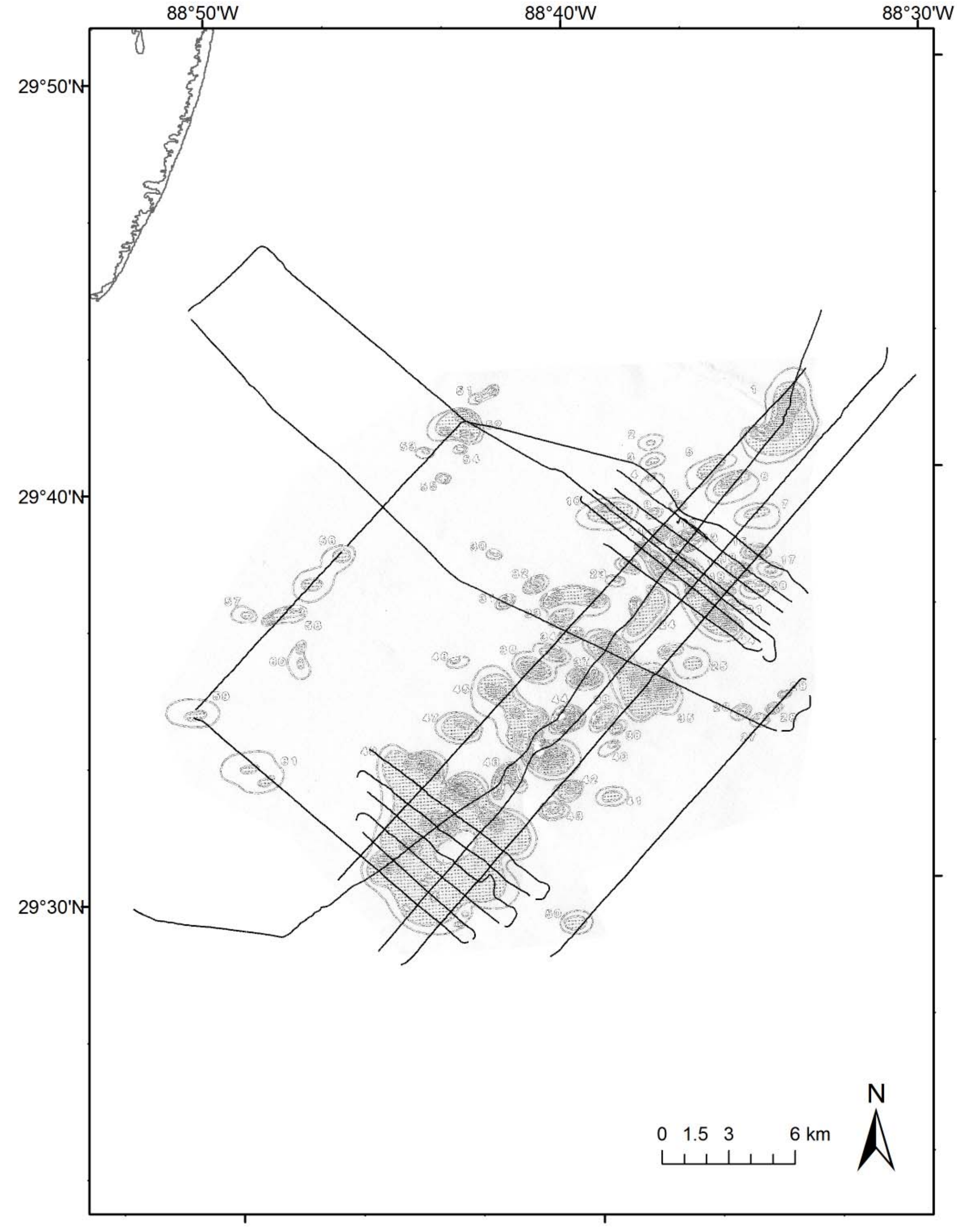


Figure 21. Trackline map from the SBS-08 *R/V Acadiana* cruise.

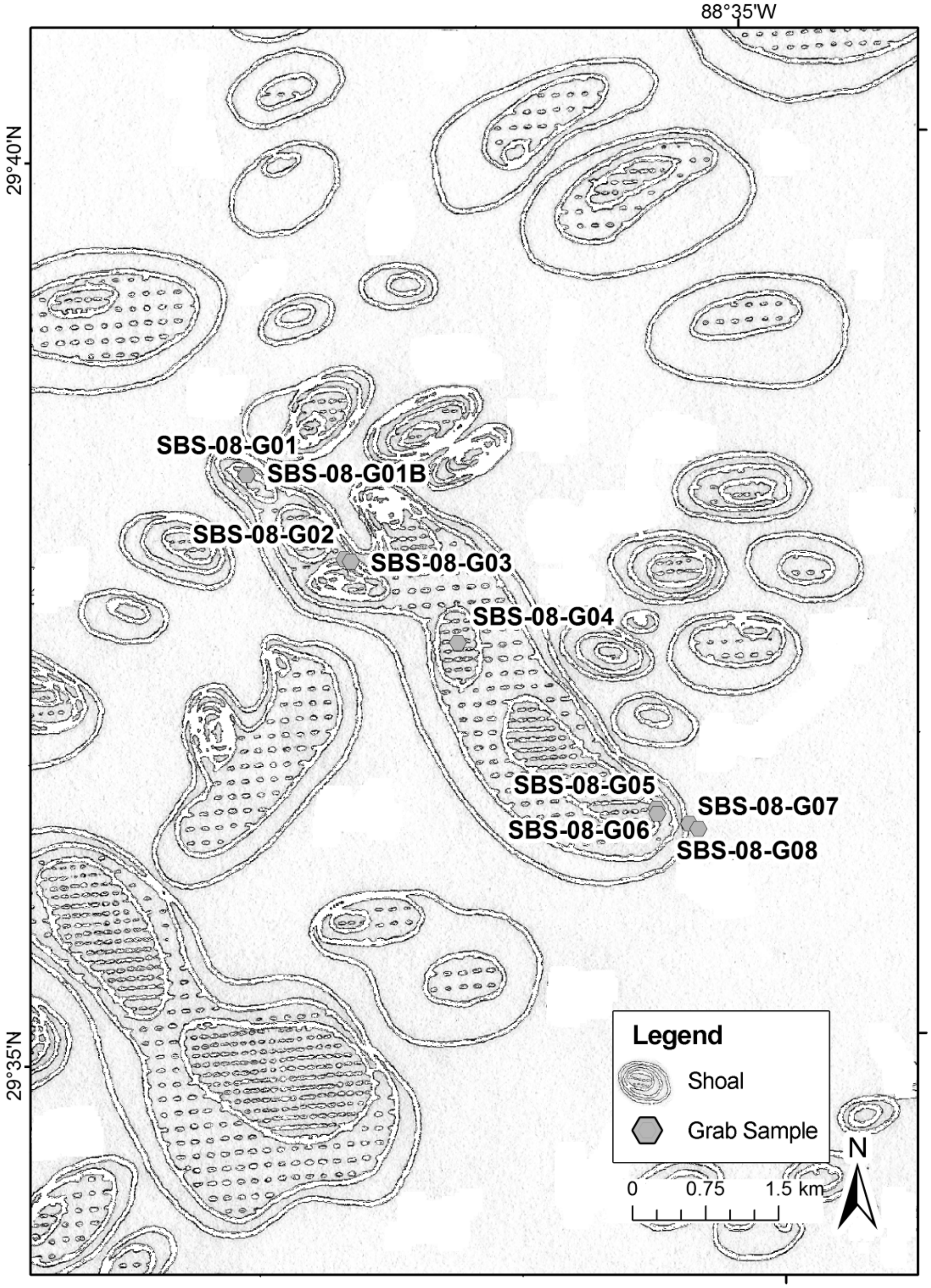


Figure 22. Location of surficial sediment grab samples acquired during the SBS-08 *R/V Acadiana* cruise. (Shoal #14 on figure 11).

Grain-size and sorting coefficients were determined and graphed using Grainsize Time Saver (Kulp, 2001). Statistical ouput by this method uses the Inman (1952) approach to determining mean and sorting. All classes were defined using the Wentworth grain size scales (table 3).

Navigation

Differential GPS positioning was acquired using a Thales dual-frequency Z-Max GPS receiver with a 1.00 s update rate. *Hypack* software was used to record navigation and to serve the GPS signal to the CHIRP and Side Scan systems. CHIRP and Side Scan software systems recorded the positioning data which was then imbedded into the data files.

SBS-08 Dataset Methodology

Select lines from the SBS-08 dataset were investigated in order to compare the SBS-08 data with results from the CI-87 data analysis. CI-87 vibracores were integrated with the SBS-08 sub-bottom profiles to classify seismic facies. The sand shoal seismic facies was then identified, and depositional and erosional processes were inferred on the basis of regional stratigraphic relationships. SBS-08 seismic profiles were also used to map the regional distributary channel network and identify some aspects of the Holocene deltaic morphology underlying the St. Bernard Shoal System.

St. Bernard Shoals 2008 Grab Samples

Grainsize Data Table

Core ID

Sample I.D.	Units	5% sample finer than	10% sample finer than	16% sample finer than	25% sample finer than	50% sample finer than	75% sample finer than	84% sample finer than	90% sample finer than	95% sample finer than	Sample mean grain size	Standard Deviation	%Sand	%Silt	%Clay
SBS_Grab-01	mm	0.004	0.099	0.125	0.145	0.179	0.210	0.222	0.230	0.241	0.174		91.7	4.0	4.4
	phi	7.8	3.3	3.0	2.8	2.5	2.3	2.2	2.1	2.1	2.6	0.4			
SBS_Grab-01b	mm	0.088	0.116	0.132	0.148	0.181	0.218	0.235	0.249	0.266	0.183		96.5	2.2	1.2
	phi	3.5	3.1	2.9	2.8	2.5	2.2	2.1	2.0	1.9	2.5	0.4			
SBS_Grab-02	mm	0.013	0.077	0.095	0.111	0.142	0.178	0.194	0.206	0.221	0.144		92.3	5.4	2.2
	phi	6.3	3.7	3.4	3.2	2.8	2.5	2.4	2.3	2.2	2.9	0.5			
SBS_Grab-03	mm	0.076	0.087	0.097	0.108	0.135	0.166	0.181	0.192	0.205	0.139		98.7	1.3	0.0
	phi	3.7	3.5	3.4	3.2	2.9	2.6	2.5	2.4	2.3	2.9	0.5			
SBS_Grab-04	mm	0.005	0.020	0.088	0.114	0.149	0.180	0.191	0.200	0.210	0.140		87.1	8.6	4.3
	phi	7.7	5.6	3.5	3.1	2.7	2.5	2.4	2.3	2.3	2.9	0.6			
SBS_Grab-05	mm	0.001	0.001	0.002	0.003	0.007	0.026	0.039	0.055	0.074	0.020		7.7	58.2	34.2
	phi	10.8	10.2	9.2	8.6	7.1	5.3	4.7	4.2	3.8	6.9	2.3			
SBS_Grab-06	mm	0.001	0.001	0.001	0.002	0.005	0.014	0.027	0.041	0.058	0.014		4.1	53.9	41.9
	phi	10.7	10.1	9.4	8.9	7.6	6.1	5.2	4.6	4.1	7.3	2.1			
SBS_Grab-07	mm	0.001	0.002	0.002	0.003	0.010	0.049	0.073	0.090	0.105	0.038		20.1	52.4	27.5
	phi	10.5	9.4	8.9	8.3	6.6	4.3	3.8	3.5	3.3	6.3	2.6			
SBS_Grab-08	mm	0.001	0.003	0.005	0.012	0.089	0.147	0.161	0.169	0.177	0.083		59.8	26.6	13.6
	phi	9.4	8.6	7.7	6.4	3.5	2.8	2.6	2.6	2.5	5.2	2.6			

Table 3. SBS-08 sea-floor sediment grab sample analysis. Analysis shows the shoals to contain 90% to 100% fine to very fine-grained sand.

Results

Using all available data and additional analysis, stratigraphic and morphologic features of the progradational deltaic complex and the overlying transgressive deposits were mapped. The approach was to identify facies, a distributaries network, and modes of deposition in order to develop a paleogeomorphic framework that contributed toward the modern morphology and stratigraphy of the study area. Using individual facies descriptions from 21 vibracores, two regional cross sections showing the distribution of 8 lithofacies were created. Several seismic cross section were also developed for this study, and their locations are depicted in figure 23 along with side scan images and vibracores discussed in this section

Interpretations and Major Stratal Boundaries

Eight separate lithofacies were interpreted from the available core descriptions. Features such as grain size, color, organic debris, shell content, physical structures, and stratigraphic contacts were used to differentiate the suite of facies discussed herein. Previous progradational lithostratigraphic facies described by Coleman and Prior (1980) and Coleman (1981), and transgressive lithofacies described by Penland et al. (1988) and Brooks et al. (1995) formed the existing framework for facies recognition.

Six seismic facies were identified by the relationships between reflectors and between groups of reflectors. Previous seismic interpretations by Mitchum (1977), Kindinger (1982), Penland et al. (1989), Suter et al. (1989), Pope et al. (1993), and Brooks et al. (1995) were evaluated and used as the basis for the seismic facies definitions. Seismic profiles were then integrated with the CI-87 vibracores.

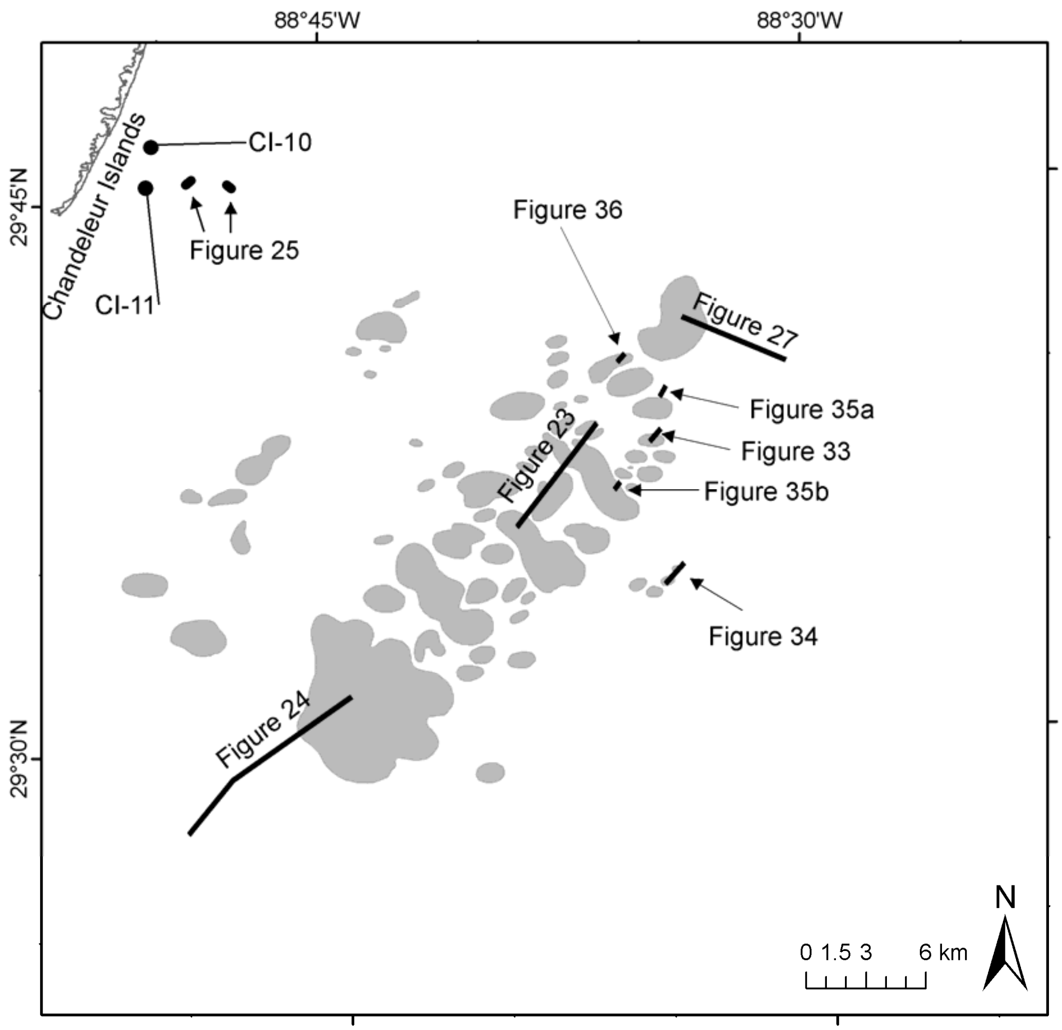


Figure 23. Map showing the location of side scan imagery, seismic profiles, and vibracores from the CI-87 and SBS-08 data sets that are discussed and shown throughout the text.

Progradational Facies

Five progradational lithofacies were identified from the vibracores: prodelta, delta front, distributary channel, bay fill, and beach ridge. However, only four progradational seismic facies were identified due to the inability to distinguish between delta front and prodelta in the seismic profiles.

Prodelta: The top 11 m of vibracore CI-44, located 32 km offshore the Chandeleur Islands contains dark grey, horizontally laminated clay interbedded with silt (Fig 17). The prodelta facies does not contain any coarse-grained material or organic detritus, and burrowing and shell material are rare. These characteristics match prodelta lithofacies described by Coleman and Prior (1980), which consists of fine-grained, dark grey, laminated clay and silty-clay beds.

Delta Front: The top 3 m of vibracores CI-46 and the bottom 2 m of vibracore CI-36 contain laminated to irregular beds of sandy fine-grained muds and silts with occasional burrowing (Fig 17). As described by Coleman and Prior (1980), the delta front lithofacies consists of burrowed to lenticular to wavy-bedded fine sandy to silty clay. Coarse-grained sediment is periodically brought into this environment by storms and floods creating coarser grained lenticular to wavy beds. The delta front lithofacies locally contains evidence for burrowing. In several cores (CI-26, CI-30, CI-45, and CI-46) the contact between the delta front and prodelta facies is distinguishable only by a slight coarsening in grain size.

Prodelta/Delta Front Seismic Facies: The prodelta and delta front seismic facies consist of basinward-dipping or flat-lying reflectors and cannot be separately defined in the seismic record.

Distributary Channel: The interval between 3.8 and 4.5 m in CI-31 contains fine-grained sand (2.0 – 2.5 phi) with clay clasts. The base of this sand deposit is interpreted as an erosional surface (Fig 19). As described by Coleman and Prior (1980) the distributary channel lithofacies directly overly an erosional surface. This unconformable relationship is interpreted to reflect the basal scour surfaces of past distributary channels. In some vibracores (CI-28, CI-36, CI- 49 and CI-50) the scour surface is overlain by an overall fining upward sequence from which two sub-units can be identified. The lower lithofacies is composed of abundant light-grey to grey to tan fine sand that fines upward into the upper deposit of fine-grained, interbedded, lenticular to wavy fine sand. Organic detritus is common in the upper unit along with sand-filled burrows but contains little bioclastic sediment. Here these strata are interpreted to represent a lower channel-fill sequence and an upper channel-fill deposit. The whole distributary lithofacies also locally contains deformed bedding that has been interpreted to reflect load-driven deformation during times of rapid sedimentation or channel slumping. In seismic data the distributary channels are identifiable by a channel-like geometry that truncates adjacent reflectors (Fig. 24). Within the channelform, sets of reflectors exhibit local acoustic transparency, show chaotic returns, or sub-horizontal hummocky orientations (Mitchum et al., 1977).

Bay Fill: Vibracore CI-35 contains repetitive fine-grained sands bounded by an erosional surface. Overlying this deposit are laminated mud and silt (Fig. 17). The bay fill deposit consists of repetitive, 1 – 2-m thick, sandy deposits capped by clay interbedded with silty to sandy lenticular beds. The fine-grained beds typically contain organic debris, shell fragments, and burrows. These characteristics are some of the identifying features of

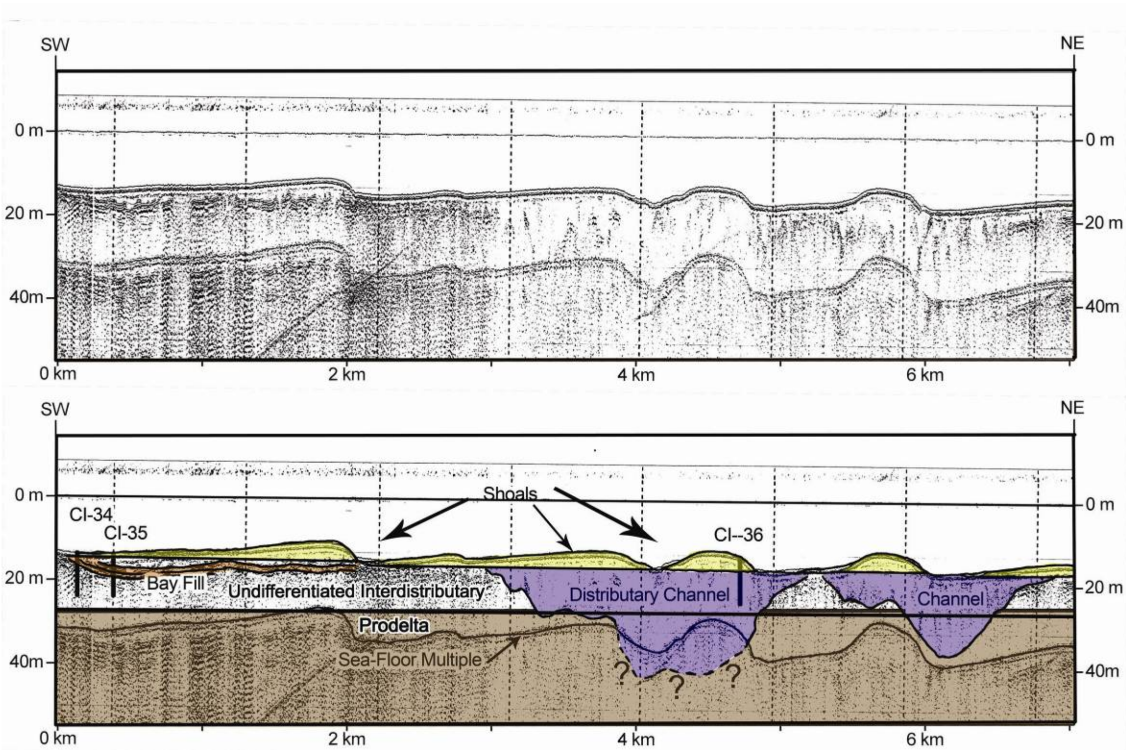


Figure 24. CI-87 seismic profile (top), and CI-87 seismic profile with seismic facies interpretation and accompanying vibracores showing spatial relationships between various progradational and transgressive facies (below). The areas that are acoustically transparent are interpreted to be distributary channels and contain a high percentage of sand. The transgressive shoal facies directly overlie regressive facies. Note that the intrashoal areas of the seafloor lie below the adjacent shoal bases and are therefore cutting across deeper strata than the shoal base ravinement. Location of the seismic profile is shown in figure 23.

the bay-fill facies described by Coleman and Prior (1980). This sequence of fine-grained sand with an erosional basal contact overlying fined-grained laminae typically is repeated 2 to 3 times in the core each sequence is truncated by an overlying erosional contact. In the seismic record the bay-fill facies is identified by sigmoidal reflectors downlapping underlying horizontal reflectors. The reflectors typically have a maximum 0.5 degree dip away from the adjacent channels. The oblique to sigmoidal reflectors dip away from adjacent channels and continue for as much as 2 km. The bay-fill seismic facies can also contain several repeating sets of oblique to sigmoidal reflectors representing several phases of progradation. (Figs. 24 and 25).

Progradational Shoreface: The top 5 - 6 m of vibracores CI-10 and CI-11 contain fine to medium-grey sand (1.5 to 2.75 phi) with cross beds, ripple cross stratification and intervals of massive bedding (Fig. 26). The cores also contain shell fragments and burrows at the top of the core, and discontinuous lags of woody debris and detrital organics a basal sandy interval. Cores CI-10 and CI-11 are unique from the remaining cores in the that the lower ~2 m of each core contains fine-grained grey sand with steeply dipping laminae, extensive trough cross beds, ripples and clay drapes. Both cores are markedly similar in textural composition and substantially different from units observed in the other CI-87 core descriptions. The preponderance of cross bedding and ripples suggest an environment of active sandy sediment transport.

In seismic profile this lithofacies appears as a set of steeply seaward dipping, high-amplitude reflectors (Fig. 27). Spacing of these reflectors is ~ 2 - 8 m with an average seaward dip of 5˚ to 11˚. These closely parallel the geometry of lower shoreface

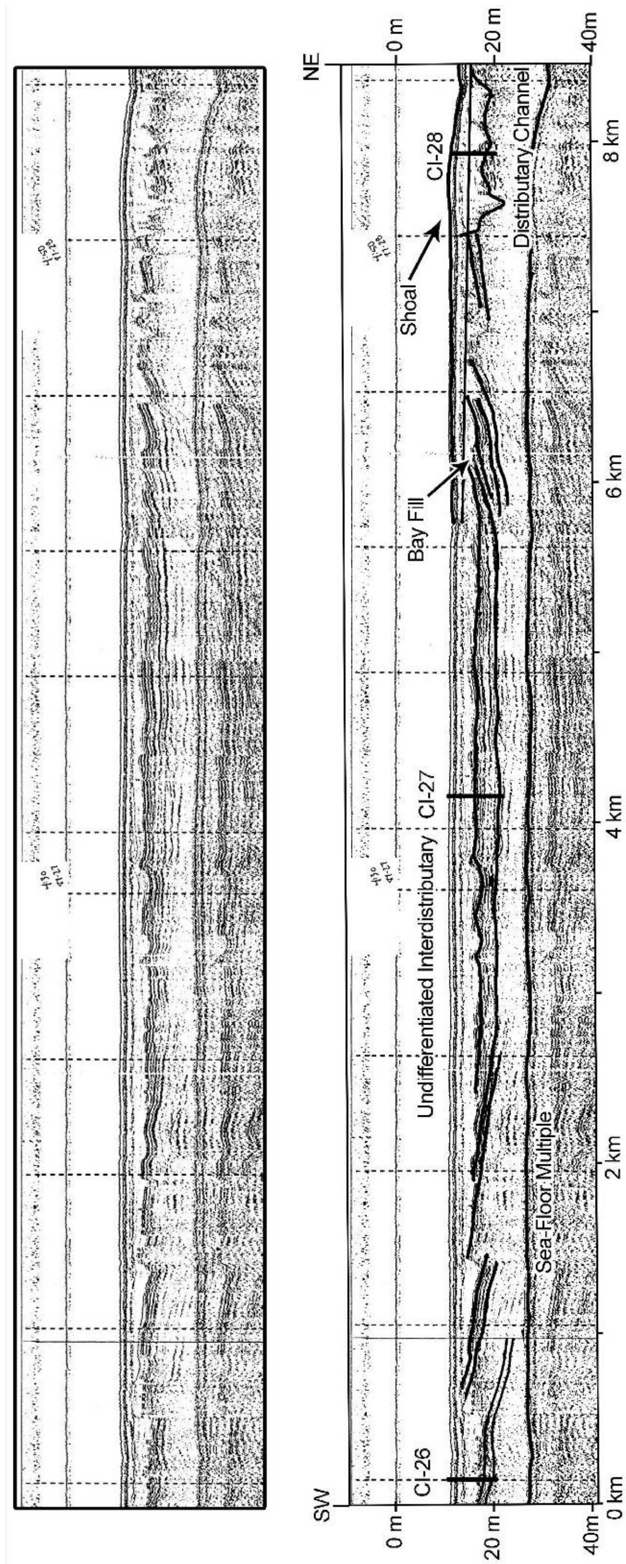


Figure 25. CI-87 seismic profile (top) and CI-87 seismic profile with seismic facies interpretation and accompanying vibracores showing spatial relationships between a distributary channel and adjacent bay fill facies (bottom). The adjacent bay fill facies on laps onto the undifferentiated interdistributary in the center of the seismic profile. Location is shown in figure 23.

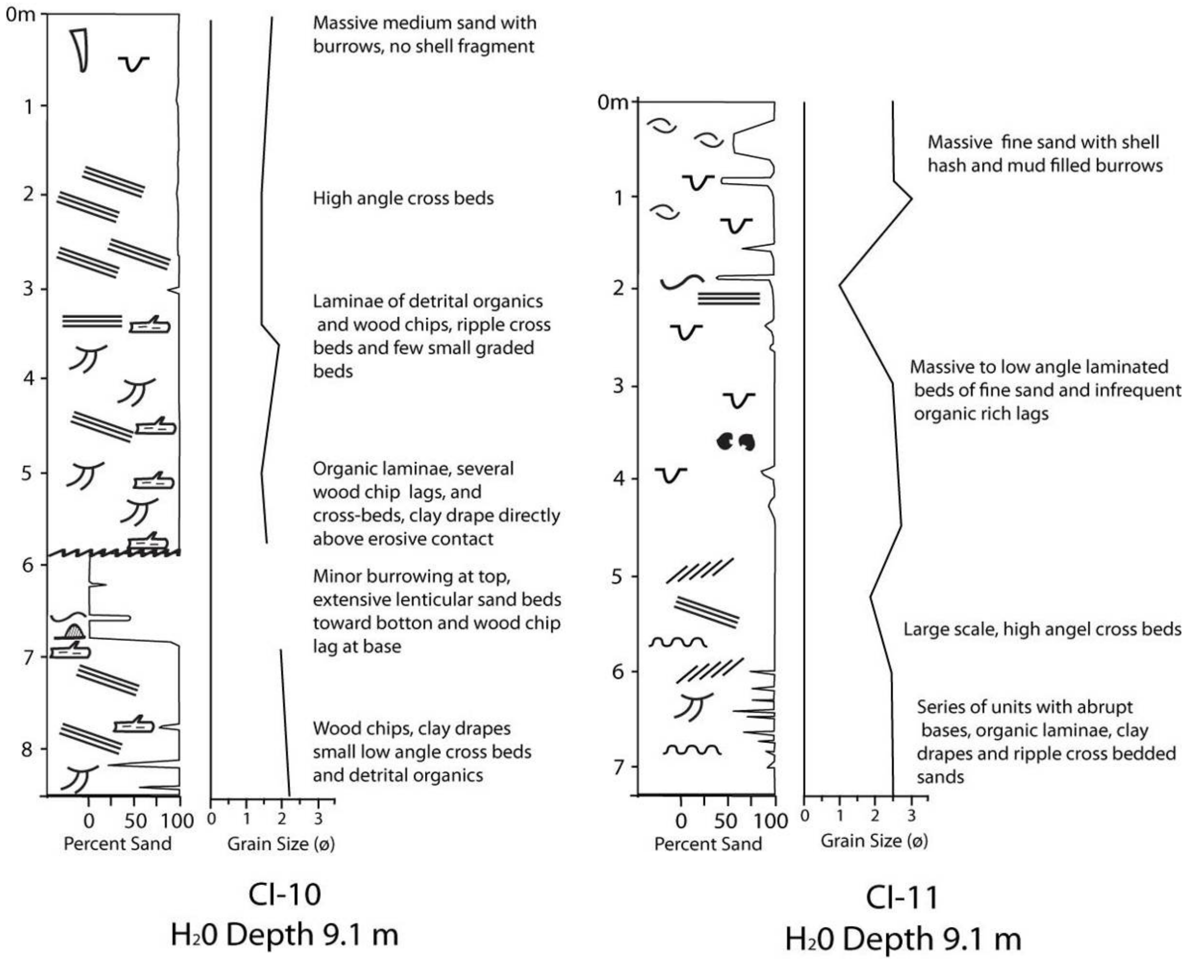


Figure 26. Description logs of vibracores CI-10 and CI-11 logs taken through the progradational shoreface lithofacies. The sand content and high-angle cross beds suggest deposition within a high-energy setting, such as the lower shoreface. Accumulations of detrital organics and fines likely took place within swales across a large area of lower shoreface migrating sediments. Vibracore locations are shown in figure 23.

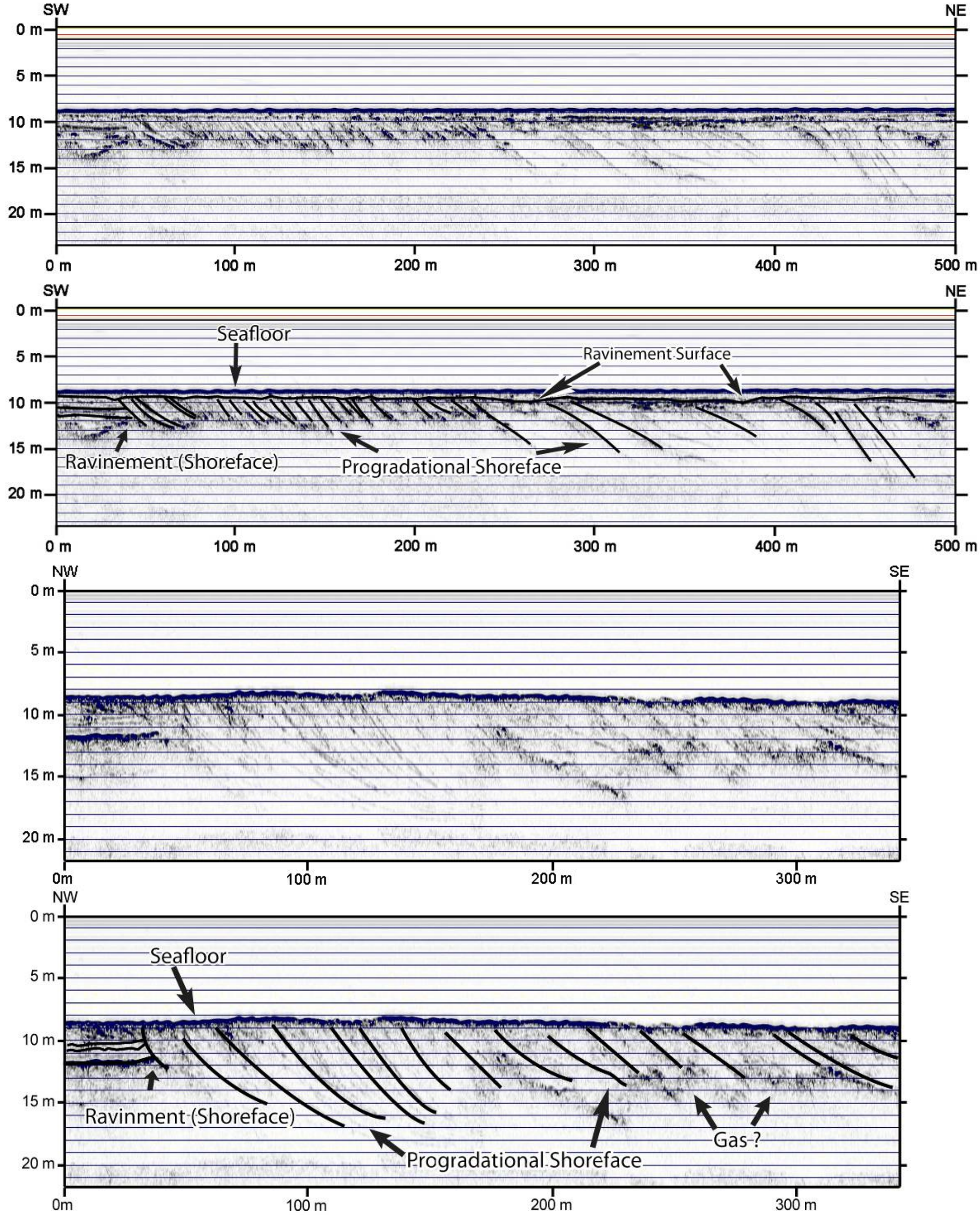


Figure 27. SBS-08 seismic reflection profile showing the characteristics of the progradational shoreface seismic facies. The steep angle of the reflectors suggest deposition in a high energy environment The truncation of reflectors top suggest erosion during transgression. The dip direction of the steep reflectors indicates the approximate seaward direction. Location is shown in figure 23.

environments within beach ridge plains identified elsewhere on the modern delta plain (e.g. Gerdes, 1982). Studies of modern beach ridge systems similarly consist of multiple, low angle reflectors dipping seaward (Jol et al., 1996; Van Heteren et al., 1998; Smith et al., 1999; Moore et al., 2004; Rodriguez and Mayer, 2006; Hampson et al., 2008).

Herein this unit is interpreted to represent a progradational shoreface that fronted and underlay a beach ridge plain similar to beach ridges abutted against distributary systems elsewhere on the modern delta plain (e.g. Gerdes 1985; Kulp et al., 2005). Suter et al. (1988) similarly suggested the presence of a beach ridge plain at this location on the basis of seismic and core data. The importance of prograded beach ridge plains as part of asymmetrical, wave-dominated deltas in the Mississippi River delta has not been extensively considered. A necessity to forming such composite deltaic headlands (prograded beach ridges against prograded deltaic sediment) is the presence of a nearby headland undergoing erosion and supplying sediment downdrift against an advancing fluvial network. This juxtaposition provides insight to the relative timing and location of delta-lobe scale erosive and depositional centers within a larger deltaic complex.

Transgressive Facies

The undifferentiated interdistributary, shoal, and sand sheet facies were the only transgressive lithofacies described in CI-87 vibracores taken around and through the St. Bernard Shoals. A ravinement seismic surface is described from the CI-87 seismic profiles that extend basinward of the shoals. This surface is the same basal ravinement underlying the shoals and sand sheet.

Undifferentiated interdistributary: The interdistributary bay lithofacies consists of a burrowed, silty clay to clayey silt with lenticular beds of fine sand. Shell fragments and

sand-filled burrows are common. The top 5.5 m of vibracore CI-26 is the best example of the interdistributary bay facies as described by Coleman and Prior (1980) (Fig 16). This interval contains fine-grained horizontal to wavy laminated silt and mud beds interbedded with fine-grained sand layers and burrows. Because of the fine-grained nature of the interdistributary bay facies, the basal contact with the underlying delta front and prodelta deposits is gradual and difficult to identify in the vibracores and seismic profiles. The transition to interdistributary bay is often identified by an upward increase in burrowing and shell material. In seismic profiles, underlying and adjacent to many bay-fill reflectors are continuous flat to concave-up reflectors interpreted to represent the interdistributary bay facies (Fig. 25).

Shoal: The top 3.5 m of vibracores CI-36 contains 90 - 100% fine-grained (2 - 2.5 phi), well sorted, moderate yellowish brown sands with horizontal to wavy laminations. This interval also contains shell fragments and clay clasts (Fig. 17). The base of this interval is described as an erosional contact. These attributes match those of a shoal facies described by Penland at al. (1989), and Brookes et al. (1995). For this study the shoal lithofacies is described as a massive, very well-sorted to well-sorted, fine-grained (0.17 - 0.25 mm, 2.0 - 2.5 phi), moderate yellowish brown sand that is rounded to sub-rounded. As is typical of Mississippi River sediment, the sand of the St. Bernard Shoals is feldspathic or arkosic (25%), (oligoclase dominate) and are garnet rich with very little staurolite/kyanite. (Hsu, 1960). The deposits are typically between 1 and 4-m thick. The sand deposit may have subtle, shallow dipping to horizontal laminae, shell fragments, root fragments, and organic debris. At the base of the shoal facies is an erosional surface interpreted to be a shoal ravinement surface. The shoal seismic facies can be described as

a unit elevated above the sea-floor with few to no internal reflectors and an irregular to chaotic basal reflector. This basal reflector is identified as the shoal ravinement that the shoals stratigraphically overlay. In some intrashoal areas the seafloor lies below the adjacent shoal base ravinement (Fig. 24).

Sand Sheet Facies: The top 0.5 m of vibracores CI-27 contains fine-grained, dark grey sand with burrows and shell fragments and an erosional contact at the base (Fig. 16). This deposit is lithologically similar to the sand sheet facies described by Brooks et al. (1995) for the eastern Louisiana continental shelf. For this study the sand sheet lithofacies is described as fine-grained grey to dark grey sand. The facies also contains silt and clay clasts, burrows, and shell fragments in some intervals. The deposit is thin, ranging between 10 and 50 cm in thickness. At the base of the sand sheet deposit is a ravinement surface. This facies can not identified in the seismic data due to the thinness of the deposit.

Ravinement surface: Seismic reflection geometries suggests a ravinement surface, is identified in seismic profiles continuing basinward of the shoals. This ravinement surface is indicated by a relatively steep sea floor that truncates underlying reflectors, suggesting post-depositional truncation. The ravinement surface extends as much as 30 m below sea-level. The ravinement surface is identified in CI-87 seismic line 23 (Fig. 28) as a moderately steep surface with internal shallow reflectors terminating against it.

Regional Stratigraphic Relationships

Two regional geologic cross sections were constructed in order to show the stratigraphic relationships of the facies recognized in this study. Cross section A-A’ is a depositional dip-parallel, northwest trending transect extending from the Chandeleur Islands

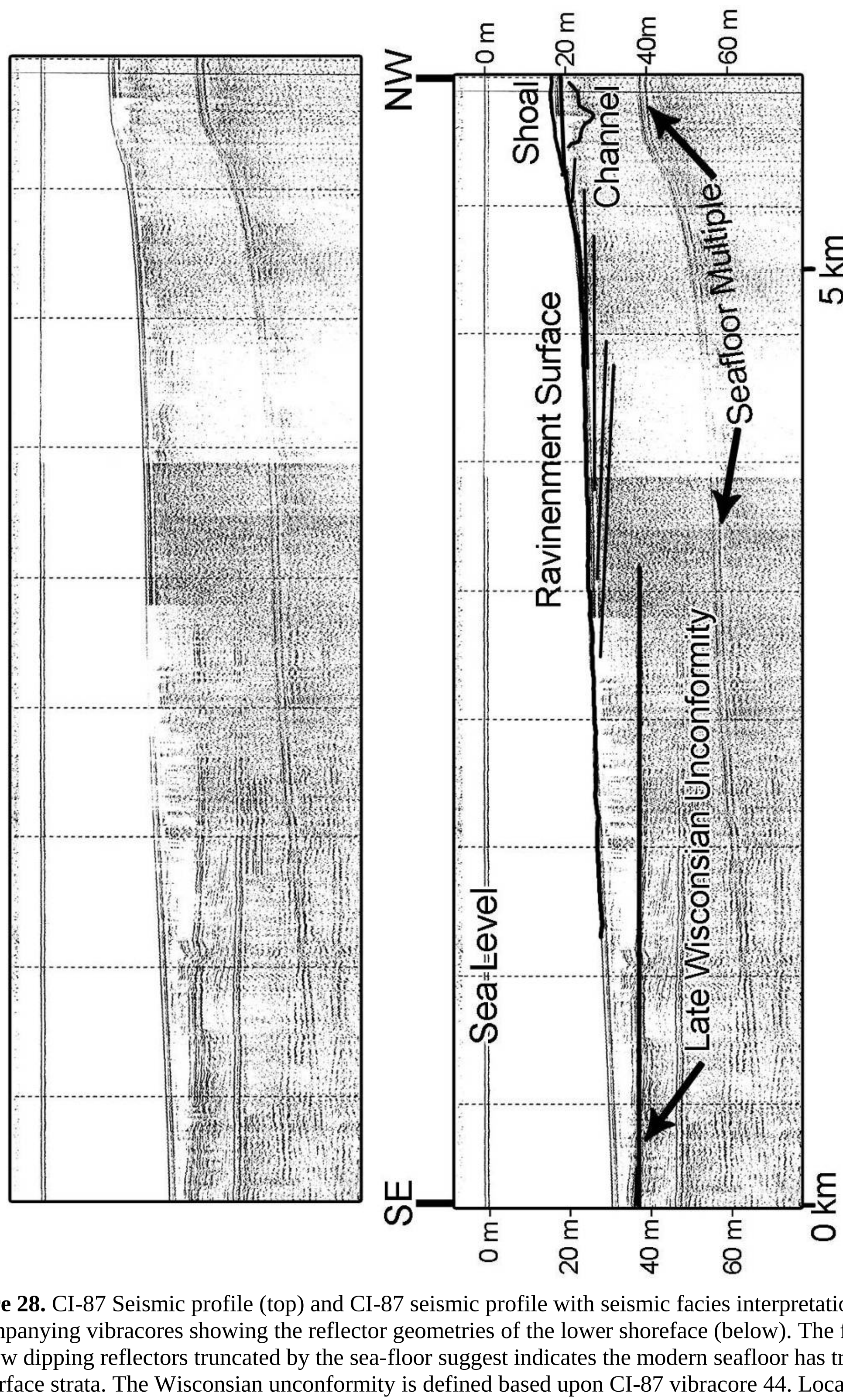


Figure 28. CI-87 Seismic profile (top) and CI-87 seismic profile with seismic facies interpretation and accompanying vibracores showing the reflector geometries of the lower shoreface (below). The flat to shallow dipping reflectors truncated by the sea-floor suggest indicates the modern seafloor has truncated subsurface strata. The Wisconsian unconformity is defined based upon CI-87 vibracore 44. Location of seismic cross profile is shown in figure 23.

to the basinward edge of the St. Bernard Shoals (Figs. 17 and 29). The cross section was constructed using vibracores CI-11, CI-49, CI-50, CI-52, CI-33, CI-34, CI 32, and CI-31. Vibracore CI-11 is located 2 km south of the Chandeleur Islands. The top 4 m of CI-11 contain a sand-rich interval identified as the progradation shoreface facies. CI-49 was taken through an abandoned distributary channel incised into the delta front of the St. Bernard Delta. Many of the remaining cores in this cross-section penetrated regional progradational facies (prodelta and delta front facies at the bottom with distributary channel, bay fill) in the bottom and transgressive facies at the top (undifferentiated interdistributary, shoal and sand sheet facies). Vibracores CI-31, CI-32, CI-50, and CI-49 contain the only distributary channel facies in this cross section on the basis of the qualifying characteristics previously discussed. However, several other channels are apparent in the CI-87 seismic line 9 which intersects this stratigraphic cross section in several places. At the southeastern end of the cross-section in 28 m of water is core CI-31, which contains a distributary channel facies incised into the underlying prodelta deposit. No transgressive sand sheet facies is present in the top of the vibracore. The tops of vibracores CI-50 and CI-52 also do not contain the transgressive sand sheet facies. The tops of cores CI-49, CI-33, CI-34, and CI-32 do however contain transgressive shoal/sand sheet deposits.

Cross Section B-B' trends southeast to northwest along the strike of the shoals (Figs 17 and 30). The transect contains vibracores CI-22, CI-23, CI-26, CI-27, CI-28, CI-29, CI-30, CI-34, CI-35, CI-36, CI-46, CI45, and CI-44. Vibracore CI-22 is interpreted to contain deposits from two separate progradational units, separated by a transgressive sand deposit. The lower deltaic deposit in this vibracore is the western edge of the St. Bernard

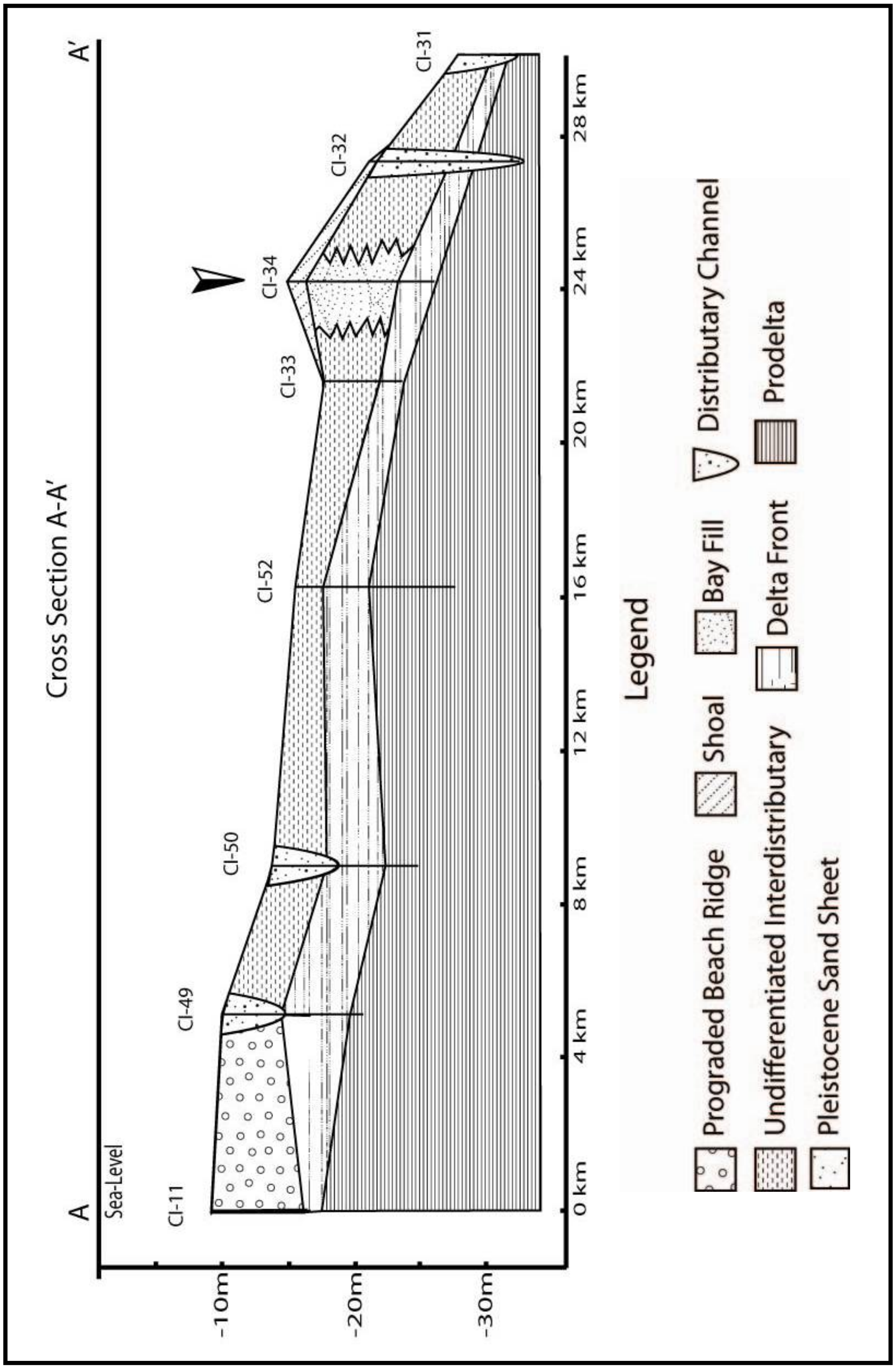


Figure 29. Stratigraphic cross section A-A’ located along the depositional dip direction of the St. Bernard delta complex. The vertical transition from prodelta to upper deltaic facies indicate a regressive interval and progradation. Note that the transgressive shoals facies sit directly atop the progradational deltaic facies. Vertical exaggeration is 300x.

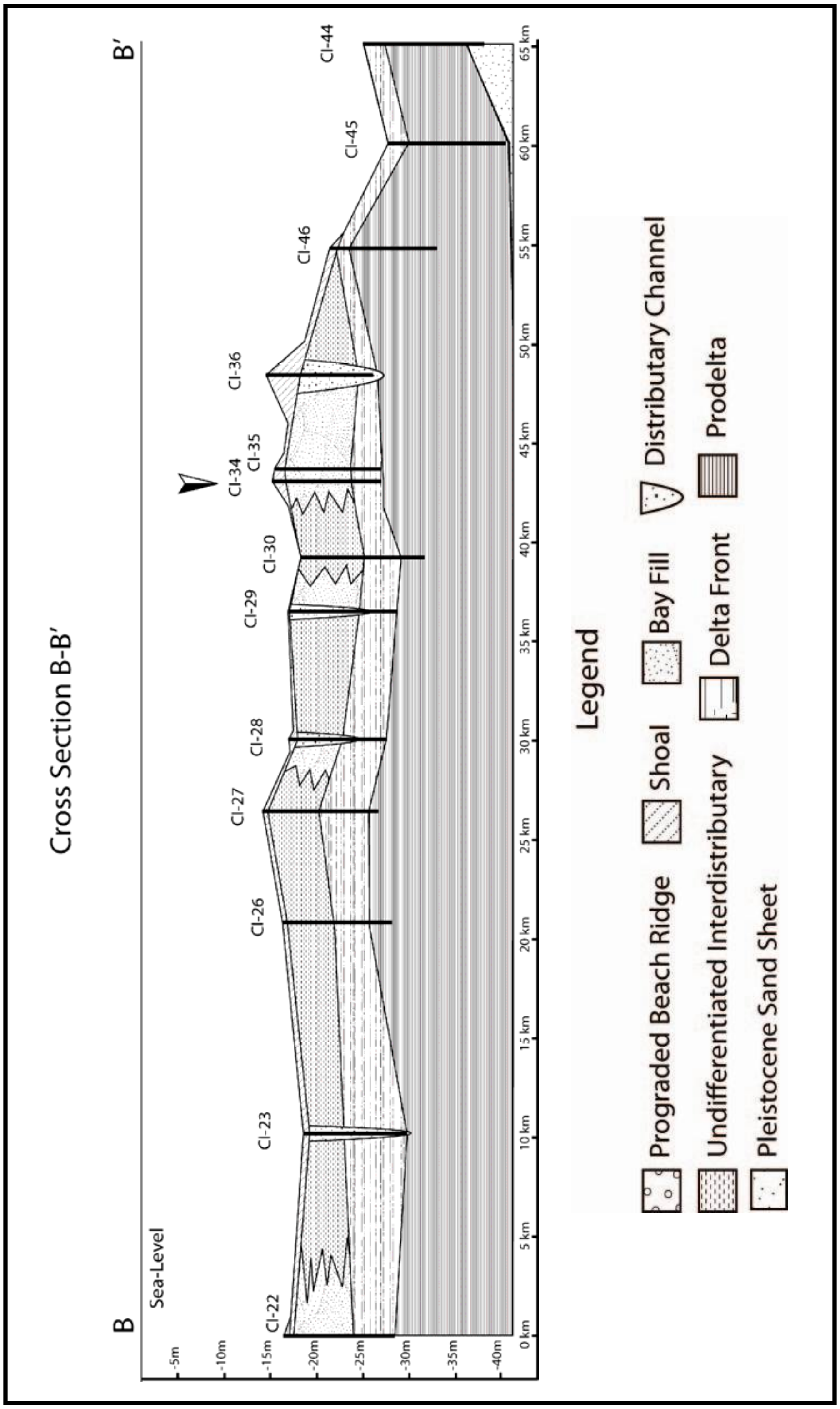


Figure 30. Stratigraphic cross section B-B' located along depositional strike of the St. Bernard bathymetric high. The vertical transition from prodelta to upper deltaic facies indicate a regressive interval and progradation. Note that the transgressive facies extends across almost the entire cross section. In the southwestern end it is covered by the Plaquemines delta, and on the northeastrern end of the section there is no sand sheet. Verticale exaggeration is 4,700x.

delta and contains a laterally continuous prodelta and delta front lithofacies at the base of the core and a bay-fill deposit above. The St. Bernard Delta progradational deposits are capped by a transgressive sand sheet. Above the sand sheet is the prodelta of the Plaquemines delta. Between vibracores CI-23 and CI-45 the entire deposit is interpreted to consist of sediment from the St. Bernard delta progradation and transgression.

Vibracore CI-44 contains a transgressive sand sheet deposit at its base which is interpreted to be the early Holocene transgressive sand sheet (Kulp et al., 2002). The top 11m of the vibracore contain St. Bernard prodelta clays. The lower-most units of the other cores along this transect consist of laterally continuous prodelta and delta front facies overlain by undifferentiated interdistributary, bay-fill or distributary channel deposits. At the top of most of these cores is a sand rich transgressive unit that extends nearly uniformly across the cross section. This transgressive unit is present as either a shelf sand sheet facies, or in the case of cores CI-28, CI-34, CI-35, and CI-36 as the St. Bernard Shoal facies. The exception is vibracores CI-30, CI-45 and CI-44. Vibracores CI-45 and CI-44 are north east of the St. Bernard Shoals and only contain the prodelta facies. CI-30 is located within the St. Bernard Shoal field but contains no transgressive facies at the top of this core. This results from subsequent erosion of the transgressive sand sheet after deposition. Scour features present in the side scan imagery near this location suggest this to be the most likely explanation. The large interdistributary deposit between vibracores CI-23 and CI-28 (Fig. 30) marks the southwestern edge of the St. Bernard Shoals.

St. Bernard Delta Maps

The distribution of distributary channels were mapped using the 1987 seismic

lines and CI-87 vibracores (Fig. 31). Previous authors have identified or mapped distributaries in the eastern Louisiana continental shelf including Frazier (1967), Kindinger (1982), Penland and Suter (1983), Penland et al. (1988), Suter et al. (1988), Pope et al. (1992), and Brooks et al. (1995). However no investigator has developed a distributary network map east of the Chandeleur Islands. The trends of the northwestern-most intervals of the channels in this study were constructed based upon the channel maps of Suter et al. (1988). Despite the wide spacing of the seismic lines in the study area it is possible to map the trends of the primary channel network. The limitations of the data coverage however prevented detailed mapping.

The distributaries mapped suggest a well developed paleodistributary network extending from the Mainland Biloxi Marshes to southeast beyond the St. Bernard bathymetric high. In the area of the outermost shoal field the channel network bifurcates in numerous directions creating a digitate framework of channels. This area is interpreted to be the approximate landward edge of the deltaic headland. All but one channel terminates before the trend of small shoals southeast of the major shoal field. Seismic data collected in 2008 shows only one large channel extending past this line. It should also be noted that all distributary channels within the shoal platform lie stratigraphically below one or more of the large shoals.

The thickness and distal edge of the St. Bernard Delta were mapped using the CI-87 seismic data (Fig. 32). The edge of the delta is mapped as the location where the last traceable reflector from the St. Bernard Delta downlaps onto the underlying early Holocene transgressive surface (Fig. 5). The base of core CI-44 contains the Pleistocene sand sheet and was used to identify the seismic reflection signature representative of the

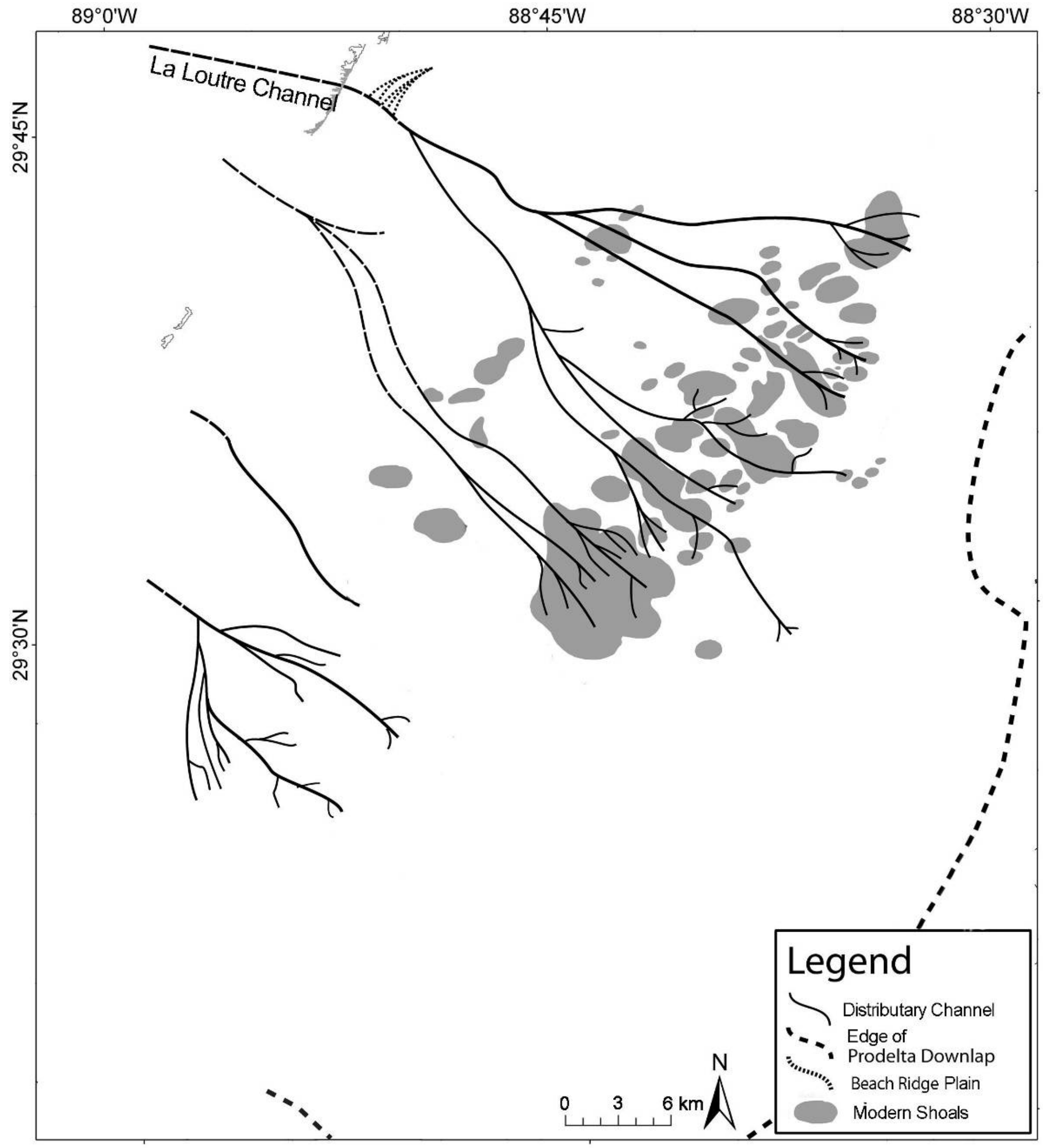


Figure 31. Map showing the regional distribution and extent of distributary channels, the location and interpreted geometry of the previously described beach ridge plain, and the edge of the prodelta offlap. All of the larger shoals lie above or are closely associated with one or more distributary channels.

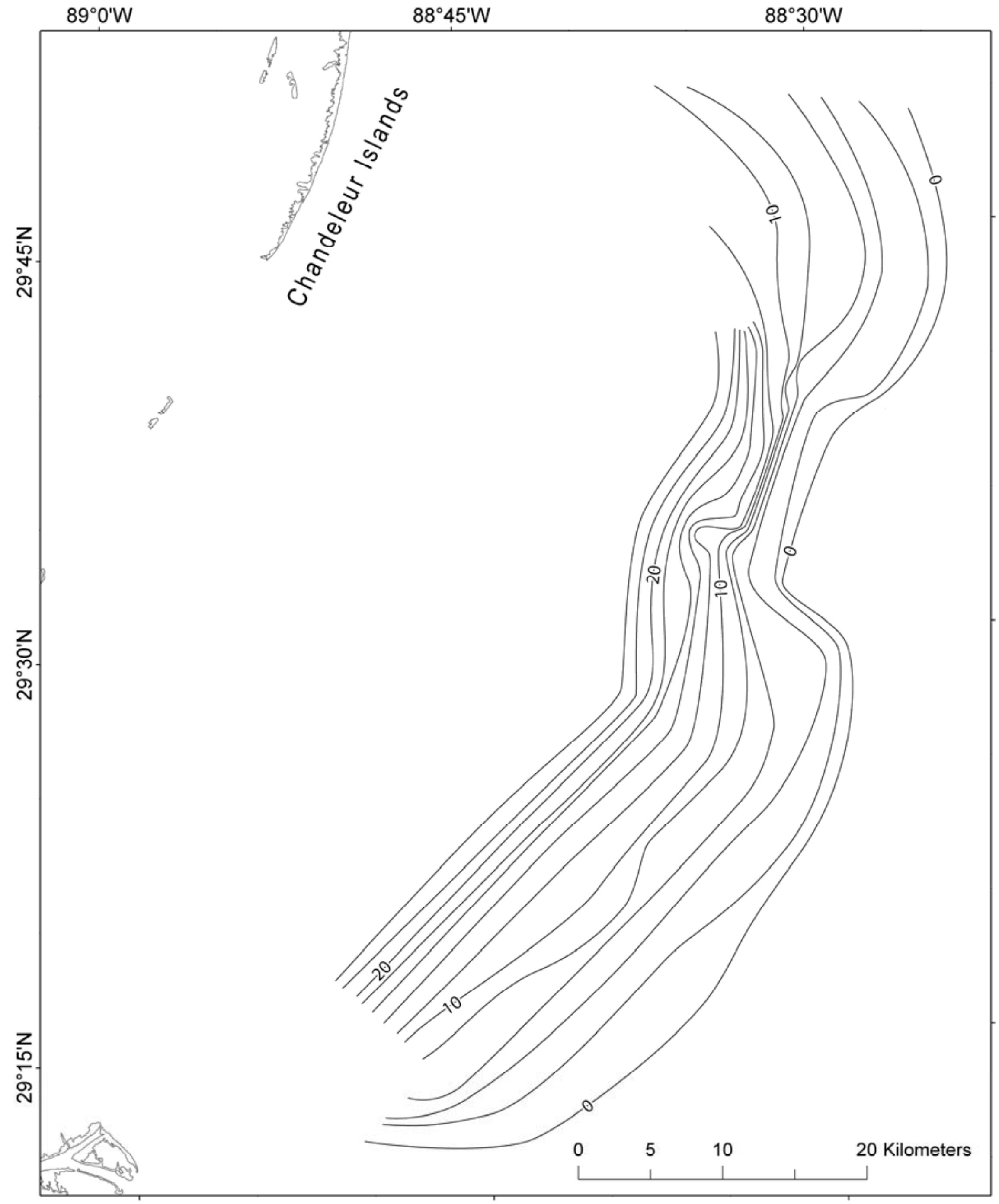


Figure 32. Isopach map of the distal edge of the St. Bernard Delta complex. Notice the bunching of contours towards the northern edge along the northeastern end of the St. Bernard Bathymetric high. The landward section of the delta is not mapped because the contact between the St. Bernard Delta and the underlying Wisconsian Unconformity is obscured in the seismic record by the overlying sediment. Contour interval is 2 meters.

unconformable surface and sand sheet. The reflector interpreted to represent the early Holocene transgressive sand sheet was also used to measure the thickness of the delta deposit. The reflector representing the top of the Pleistocene surface is not distinguishable through the entire seismic record because it is masked by thicker fluvial, deltaic and shelf deposits across much of the study area. For this reason only the distal edge of the deltaic deposit is mapped.

2008 Side Scan Imagery

The 2008 seismic data shows that in many inter-shoal swales the sea-floor lies at a lower elevation than the adjacent ravinement surface stratigraphically beneath the shoals. Figure 33 is a cross section for the SBS-08 seismic profiles and shows a shoal with a basal ravinement surface adjacent to a lower-lying inter-shoal swale. As previously suggested, the side-scan imagery from the inter-shoal areas show a very chaotic sea-floor morphology. Sandwaves, scarps, and areas of intense scour have all been identified in these areas (Fig. 34). Another interesting morphologic feature present in the inter-shoal swales has been termed pedestals. Pedestals are small, 1 – 2-m high features with steep sides (15˚ - 60˚) (Fig 35). No pedestals have been directly sampled through sea-floor grab samples or vibracores. However, in seismic reflection data the pedestal are acoustically transparent, and have high reflectivity in side scan imagery, suggesting they consist mostly of sand. The general direction of sediment transport interpreted from the orientation of sand waves imaged on the top of several shoals and the orientation of shoal slip faces is east/northeast (Fig. 36).

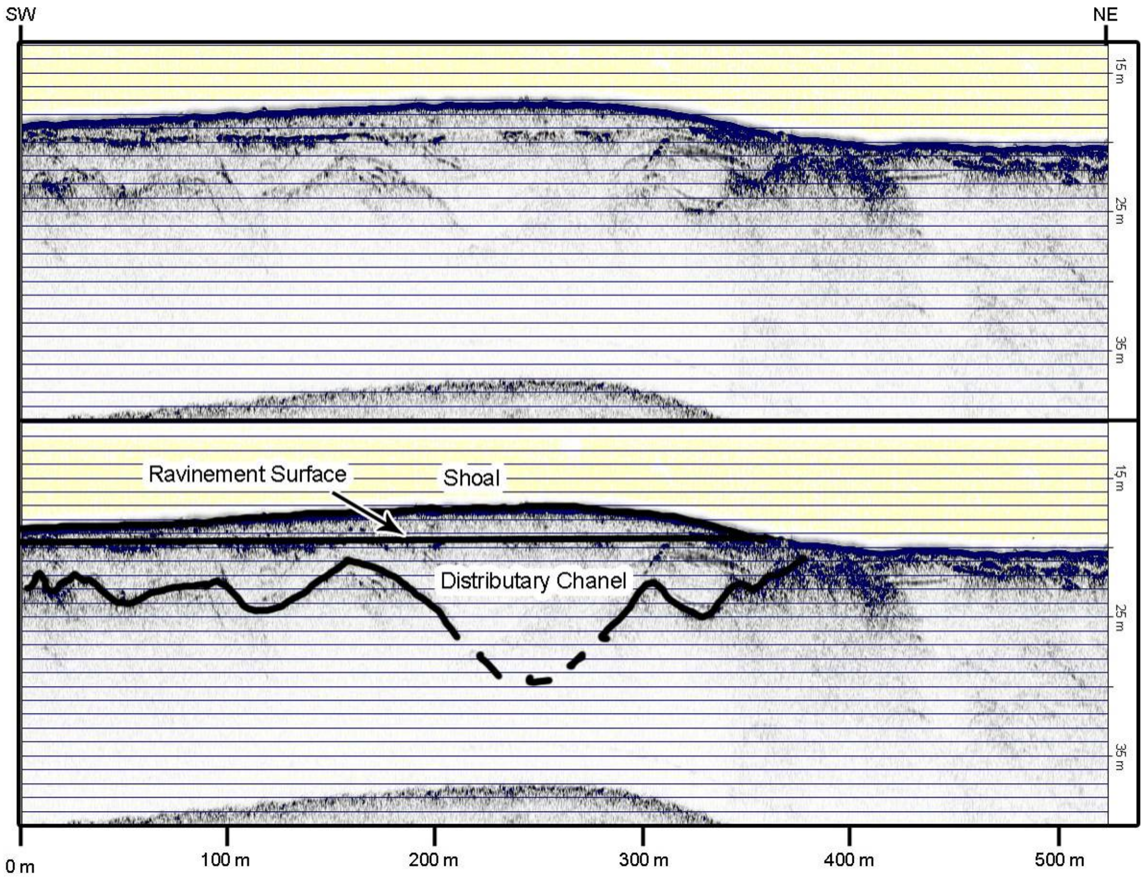


Figure 33. SBS-08 seismic profile and facies interpretation showing the spatial relationships between the transgressive shoal facies and the regressive distributary channel facies. Note the shoal base lies higher than the adjacent inter-shoal sea-floor. This profile also shows the variability in distributary channel fill. The lower portion of the channel form is acoustically transparent, while the top contains higher-amplitude reflectors. Location is shown in figure 28.

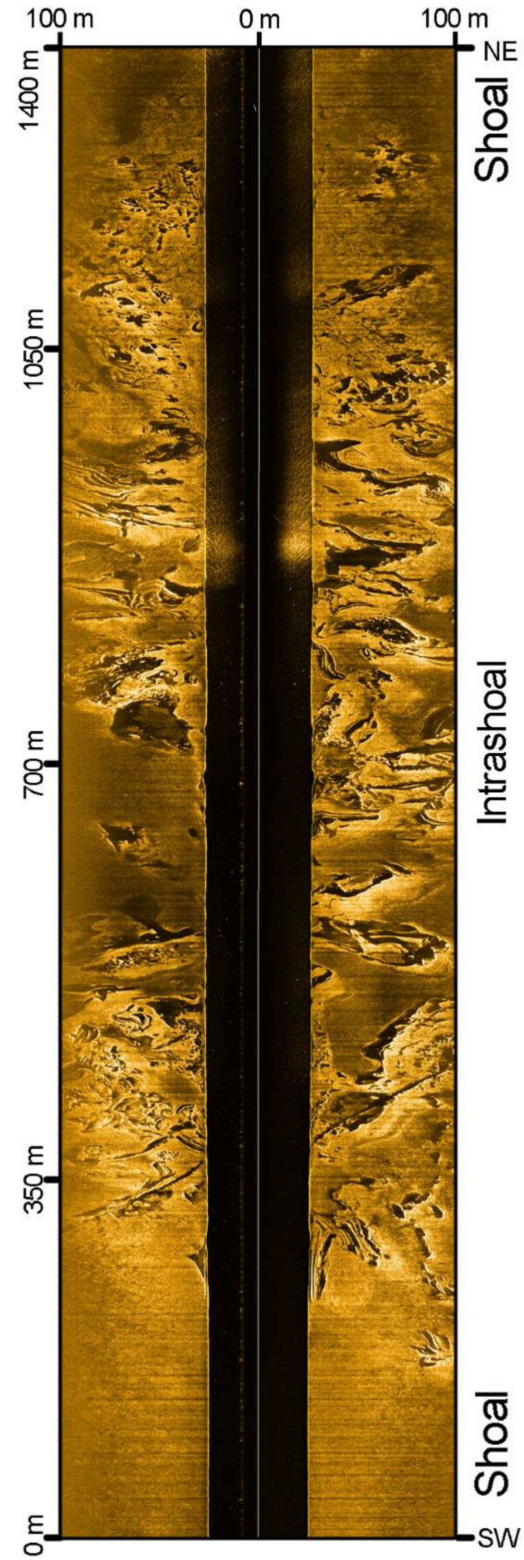


Figure 34. Side scan imagery across two shoals and the intervening intershoal sea-floor. The shoal deposits are the flat featureless areas at the top and bottom of the image. Notice the highly irregular intershoal area, which is suggestive of surface deformation resulting from scouring or sediment mobility. Elevation information from the seismic data in this area also shows an irregular seafloor elevation. Location is shown in figure 28.

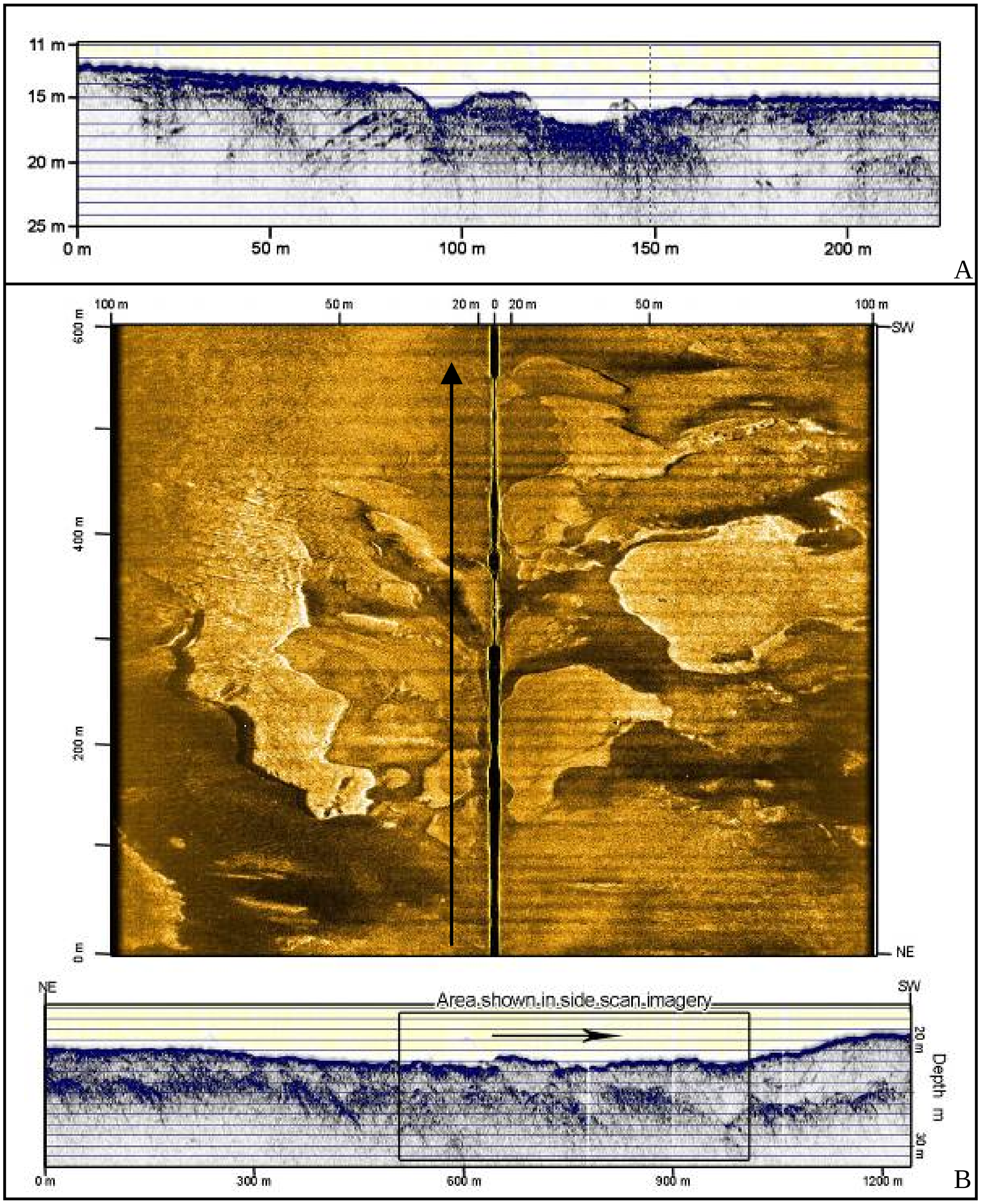


Figure 35. Side scan and sub bottom profiles showing the steep shoal edges (15˚ - 60˚) and pedestals amongst the St. Bernard Shoals. A) In the top seismic profile note how a straight line could be drawn along the entire seafloor if the two intrashoal lows were not present. B) The bottom image shows the sidescan and subbottom data showing pedestal. The arrow in the side scan imagery shows the approximate trend of the seismic data and the direction of travel. The location of theses profiles is shown in figure 28.

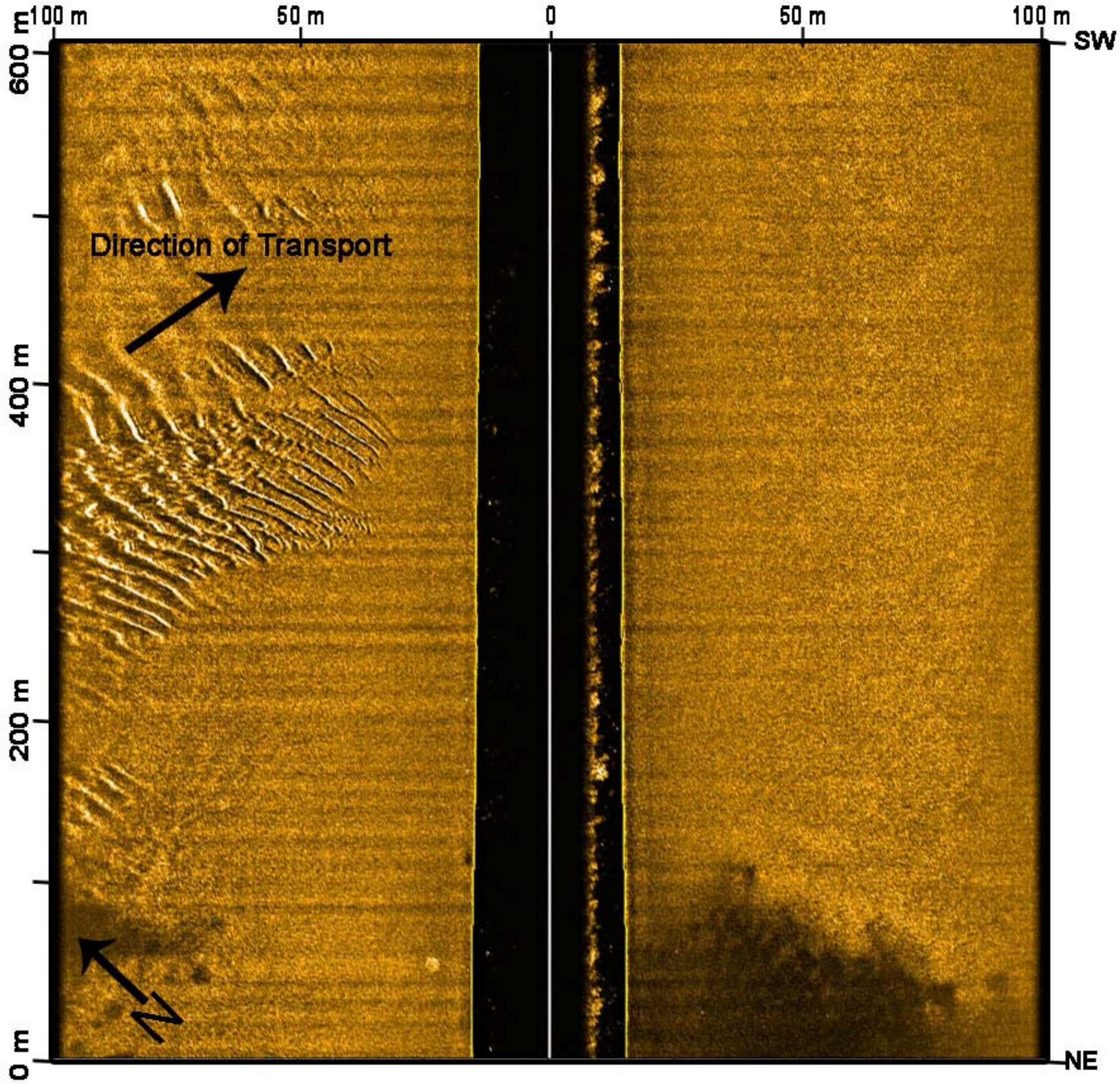


Figure 36. Side Scan imaged using the Klein 300 system. A field of sands wave on the top of a shoal reflect an net eastward direction of transport. The direction of transport is interpreted to be east. The larger sandwaves have wavelengths up to 8 m and are 2 - 3 m high. Location of sand wave is shown in figure 28.

Discussion

The St. Bernard Shoals have a morphology unique from other shoals of the Louisiana continental shelf. Stratigraphically the shoals lie above a recently transgressed delta complex (~1,800 yrs BP). The St. Bernard Shoals consist of numerous, individual, relatively coarse-grained sand lithosomes. The shoal platform sits in deeper water compared to the other shoals, except Outer Shoal. The following discussion focuses on the development of a Holocene evolutionary model for the eastern Louisiana continental shelf using facies, stratigraphic relationships, and surface morphology. This conceptual model captures the sequence of events involved in the formation and continuing evolution of the shoal system.

Distributary Advancement Across the Eastern Louisiana Shelf

The distributary channel map developed from the available data suggests that a complex network of distributary channels extended across the study area from the northeast (Fig. 31). The terminal extent of the distributaries that were mapped is 1 km southeast of the outermost modern shoal. In some locations the depth of the distributaries exceeds 30 m below sea level; as much as 10-m thick distributary channel deposits are present below the modern sea floor. The updip extent of the mapped distributary network closely correlates to the distributary channels mapped by Suter et al. (1988), Penland et al. (1989) and Twichell et al. (2009) seaward of the Chandeleur Islands. Uniting these data with those of this study provide the first understanding of deltaic deposition on this part of the Louisiana shelf. Extension of the mapped distributary channel network toward the mainland suggests an approximate connection to the updip Bayou La Loutre, which is still an extant distributary that crosses the southern Biloxi marsh of the mainland

(Fig 37). Bayou La Loutre was the main distributary channel that supplied sediment and fresh water to lobe 8 of Frazier's (1967) delta model.

La Loutre Progradation and Beach Ridge Construction

Figure 31 indicates the location and orientation of the prograded beach ridges discussed previously. Penland et al. (1989) mapped a beach ridge plain in the same area and showed it extending much farther north, but here the extent of the beach ridge plain is depicted on the basis of the data available for this study.

The northwest dip direction of the prograded shoreface facies identified seaward of the Chandeleur Islands suggests they formed against the southern extension of the Bayou La Loutre distributary channel that supplied the sediments to the regressive deltaic stratigraphy below the St. Bernard Shoals (Figs. 25 and 31). Delta plain regressive beach ridges have been shown to develop as sediment is transported alongshore from an updrift erosional headland source and is deposited against the flank of prograding distributaries (Gerdes, 1985; Bhattacharya and Giosan, 2003; Kulp et al., 2005). As the active distributary progrades seaward a "groin effect" results in successive progradational beach ridge sets abutting the active distributary. Beach ridges within a delta plain represent the geomorphic vestiges of deposition associated with temporally and geographically offset distributary progradations, longshore transport processes, and marine reworking of abandoned deltas (Kulp et al., 2005). The resultant relative relationships of the beach ridges and distributary network morphology therefore provide a means to establish a relative chronology of associated delta lobes, progradation, and erosional reworking of abandoned headlands.

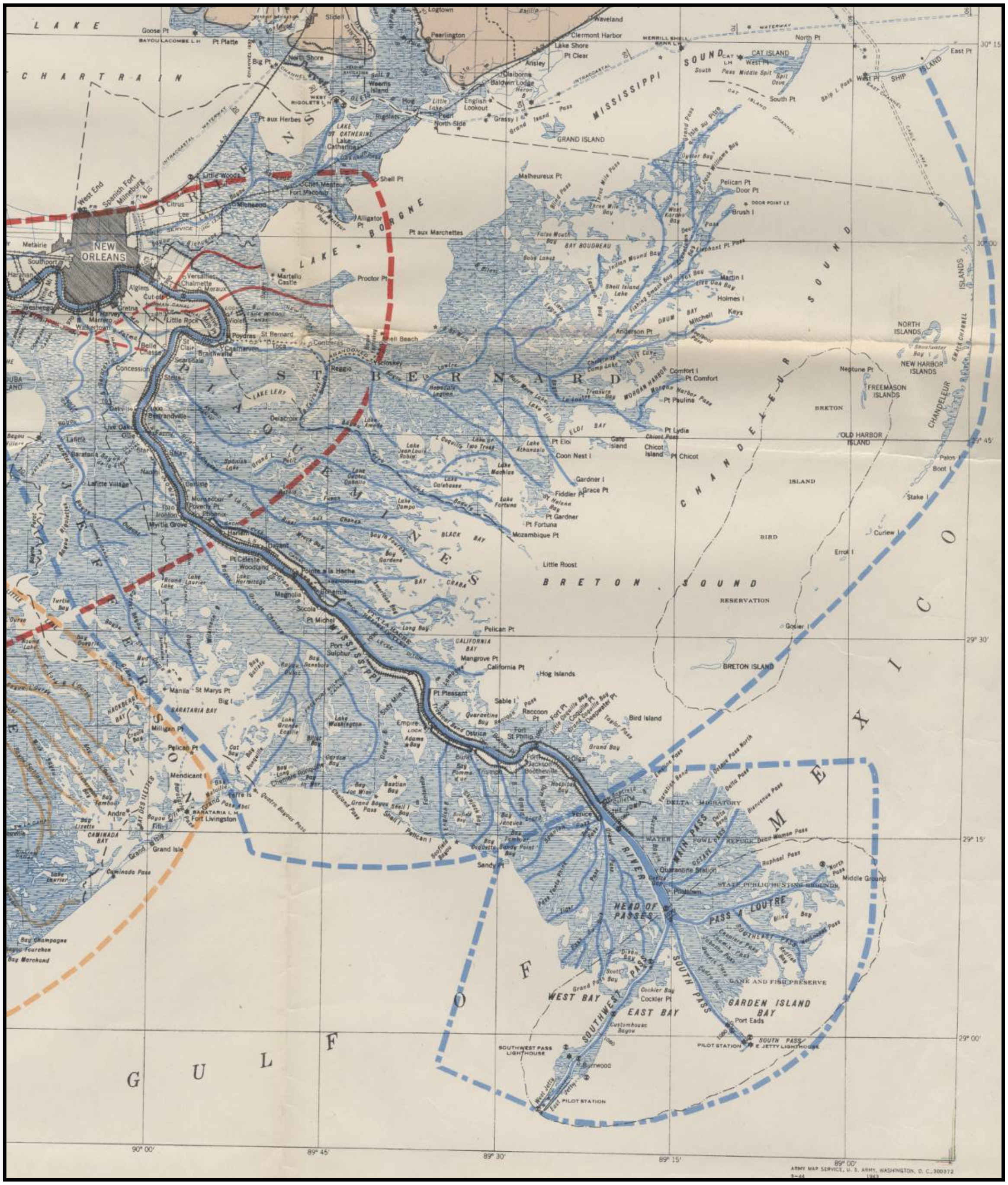


Figure 37. Eastern section of a map depicting the active and abandoned distributaries in the Mississippi River delta (Fisk 1943). The Distributaries in the Biloxi Marsh are now recognized as originating from 2 main progradational lobes. The progradation of Bayou Terre aux Boeufs to the south and the progradation of Bayou La Loutre in the north. The La Loutre lobe is recognized in this paper as occurring in two separate phases, a northern and a southern progradation. The more southern distributaries of Bayou La Loutre are used as the updip connection to distributary channels mapped in the study area.

The juxtaposition of the beach ridges against the La Loutre distributary requires a transgressive shoreline updrift of the prograding distributary. According to the distributary map of Twitchell et al. (2009), the transgressive shoreline was located farther north and perhaps slightly seaward of the modern Chandeleur Islands. The sediment from this transgressive shoreline was transported south and formed against the simultaneously prograding La Loutre distributary channel. The formation of the northern transgressive shoreline likely resulted when the La Loutre distributary channel bypassed the more northern distributaries of Frazier's (1967) Lobe 8. This sequence of events suggests the fluvio-deltaic deposits that underlie the St. Bernard Shoals are the seaward extent of the La Loutre distributary and the most recent lobe of the St. Bernard delta complex, Frazier's (1967) delta lobe 9. Figure 38 shows previously proposed chronologies of the Eastern Louisiana continental shelf and the chronology proposed here.

Penland et al. (1989) indirectly suggested that the St. Bernard Shoals were of early Holocene age (~8,000 – 9,000 yrs BP) on the basis of the water depth (similar to Outer shoal) in which they are located and the assumption that the shoals represent a former shoreline position of a deltaic headland and flanking barrier islands that underwent transgressive submergence. However, the delta lobe chronology of Frazier (1967), the delta lobe and beach ridge facies associations, the stratigraphic relationship between the transgressive and regressive facies, and the distributary network mapped updip all suggest that the St. Bernard Shoals sit upon deposits that are associated with the most recent delta lobe progradation of the upper Holocene St Bernard Delta complex.

Transgression of the St. Bernard Bathymetric High

Shoals of the St. Bernard Bathymetric High directly overlie, within all available

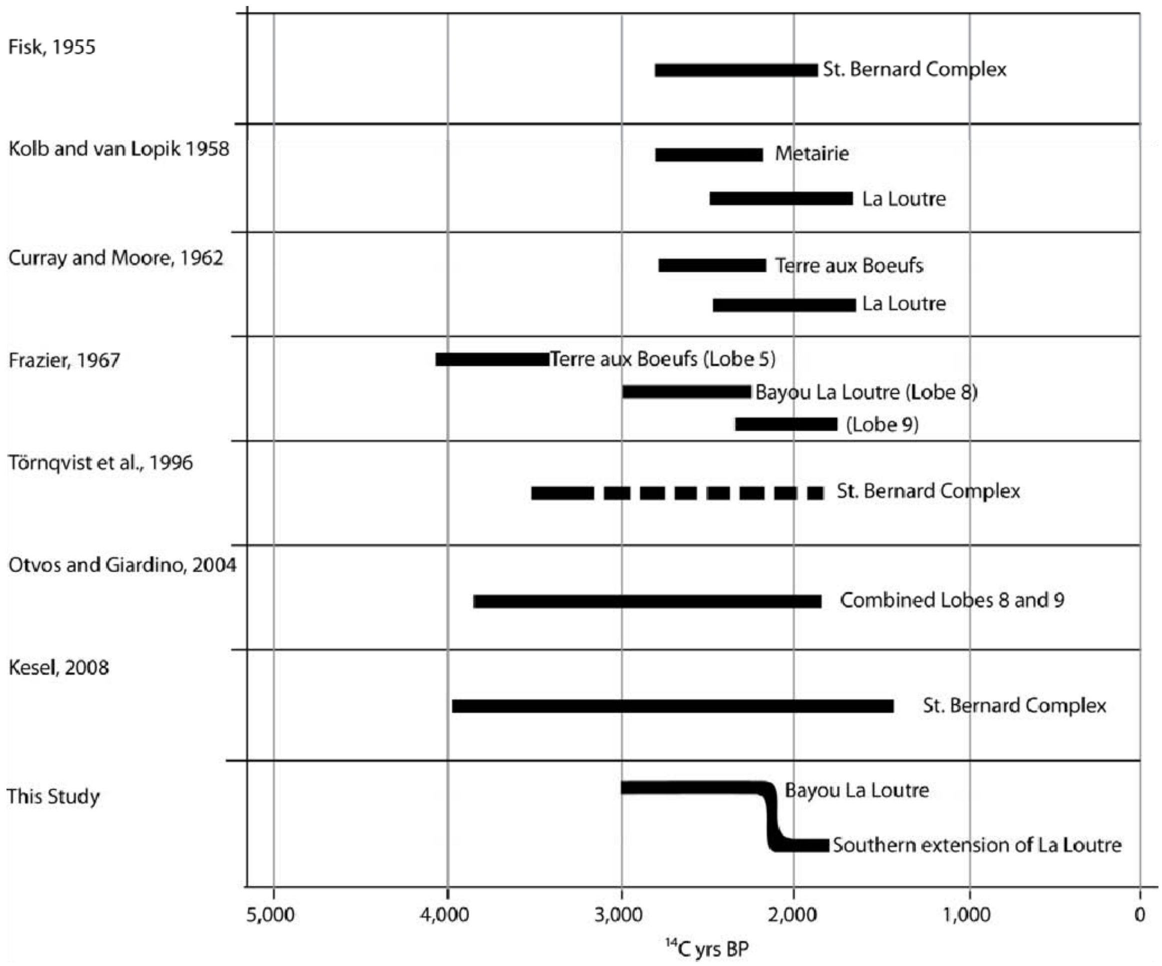


Figure 38. Proposed ages for the St. Bernard Delta complex and individual lobes from this study and others. Note that most ages are centered between 3,000 and 2000 yrs B.P.

core and seismic data, regressive facies that are lithologically similar to distributary, deltaic front, and prodelta facies encountered elsewhere within the Holocene stratigraphy of the north-central Gulf of Mexico Shelf. The Holocene progradational deltaic sediments underlying the St. Bernard Shoals are as much as 45-m thick in 15 to 20 m modern water depth (Fig. 5) (Kulp et al., 2002). Seismic profiles show individual shoals separated from the underlying regressive facies by a shoal base ravinement surface that can be mapped across the study area as a semi-continuous high amplitude reflector (Figs. 23 and 33). This surface is truncated by the modern seafloor in locations between shoals but otherwise represents a highly traceable reflector at the base of the shoals across the shoal platform. Underlying the shoal base ravinement, typically directly below the shoals are numerous, deeply incised (as much as 30 m below mean sea-level) distributary channels.

The model of transgressive submergence (Penland et al., 1988) predicts that shoals formed through transgression of a deltaic package will be separated from the underlying progradational facies by transgressive paralic facies deposited in a subsiding back-barrier lagoon. However, the St. Bernard Shoals are bound at their base by a shoal ravinement surface and lie directly upon progradational facies associated with the St. Bernard delta complex (Figs. 23, 29, 30, and 33). This facies relationship, marine sand overlying fluvio-deltaic deposits with no paralic interval in between, has important implications for the evolution of these inner shelf sand bodies. On the basis of the stratigraphic interpretations, facies relationships, morphology, and their position on the inner-shelf it is proposed here that rapid relative sea-level rise and accompanying shoreface ravinement resulted in the truncation of the upper deltaic deposits, paralic

transgressive deposits, and beach ridges with little overall deposition (Fig 39). Cattaneo and Steel (2003) have similiarly shown that high rates of relative sea-level rise across a low-gradient commonly results in a nonaccretionary transgression where few to no transgressive deposits are produced. The low gradient shelf with little transgressive strata suggests a rapid relative sea-level rise led to shoal development. Rates and mechanisms are not yet identified.

Several authors have discussed mechanisms by which shelf sand bodies form. Subaqueous shoals can be the remnants of an ebb tidal delta or shoreface-attached ridges, (McBride and Moslow, 1991; Snedden and Dalrymple, 1999; Snedden et al., 1999) or they may originate from shoreface processes transporting sandy sediment to the lower shoreface. They later became detached as the transgressive shoreface shifted farther updip (Neidoroda and Swift, 1984; Sneden et al., 19894). In the case of the St. Bernard Shoals however it is proposed that the shoals developed from sea floor irregularities that were created by differential transgressive reworking of the sandy distributary channels. The lower, sandy portions of the distributary channels that were not truncated by shoreface erosion remained exposed on the inner shelf and were excavated and reworked by marine process and built into the present day St. Bernard Shoals. The orientation of the larger shoals is a product of the underlying distributary channel's orientation. The underlying distributary channels are also being continually reworked by marine currents and likely continue to supply the St. Bernard Shoals with sediment.

Marine Forces Driving the St Bernard Shoals Evolution

The end product of transgressive submergence is described as a continuous shoal that can consist of more than 90% sand, which migrates shoreward (Penland, 1989).

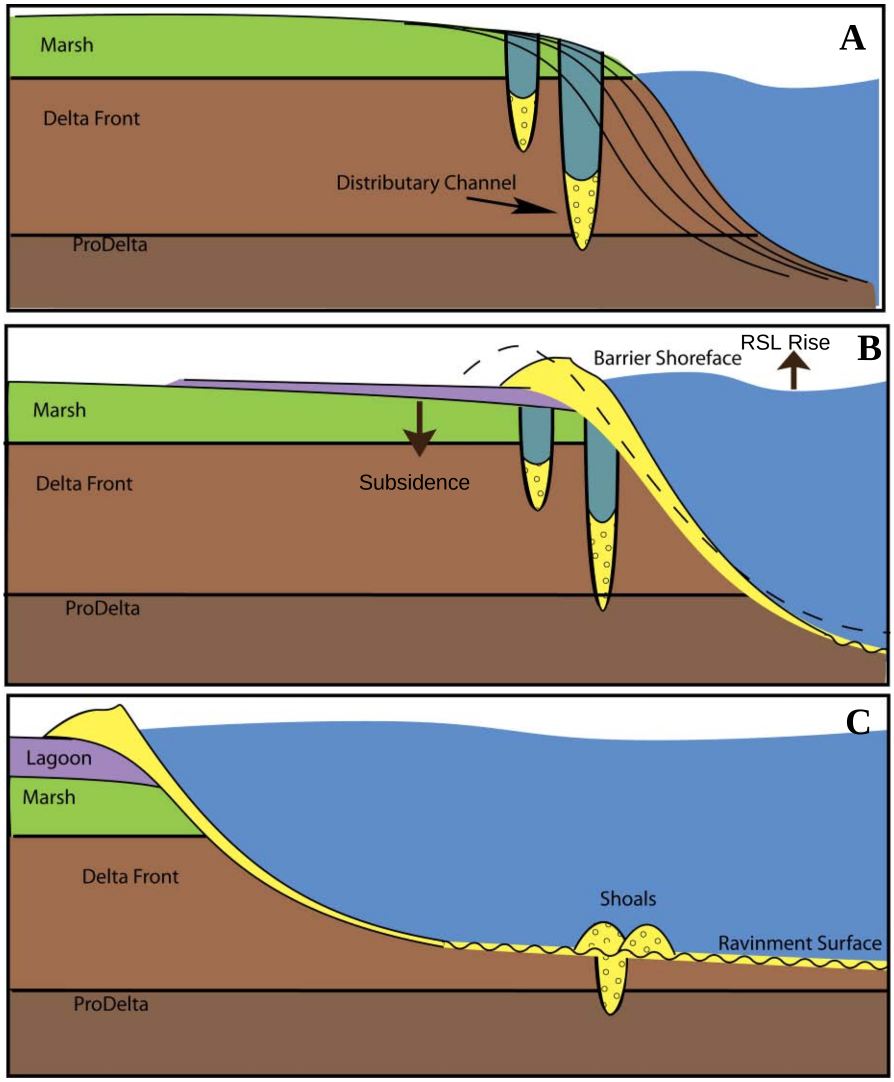


Figure 39. The delta lobe (A) experienced rapid relative sea-level rise which resulted in the formation of a barrier shoreace (B). As the transgression continued the shoreface retreat shifted updip truncating the upper deltaic, paralic, and transgressive facies (C). Coarse grained sediment was excavated from the underlying distributary channels by marine process forming the St. Bernard Shoals. The shoreface ravinement continues today along the shoreface of the modern Chandeleur Islands.

However, the St. Bernard Shoals consists of numerous, discrete, coarse-grained deposits. The largest of which are oriented shore normal and appear to migrating north to northeast. Marine currents associated with large hurricane driven waves are suggested to be a force controlling the shoals morphology and direction of migration

Hurricanes can produce abnormally large waves and strong wind-driven currents in the Gulf of Mexico. Georgiou and Schindler (2009) modeled near bottom wave orbital velocities on the eastern Louisiana shelf for 100-yr, 10-yr, and 1-yr storms and exhibited velocities energetic enough to erode and transport sand-sized sediment in storms with a 1-yr recurrence interval (Fig. 40). Georgiou and Schindler (2009) also demonstrated that significant deep-water wave dissipation takes place along the seaward edge of the St. Bernard Bathymetric High (Fig. 41). Other authors measured near-bottom wind-driven current velocities greater than 2.0 ms^{-1} in depths of 60 to 80 m southeast of the St. Bernard Shoals, and currents with velocities of 1.2 ms^{-1} in 500 m of water at the shelf-slope break during Hurricane Ivan (Teague et al., 2006; Teagure et al., 2007). Teague et al. (2006) also observed bottom scour of as much as 36 cm in 60 m of water during Hurricane Ivan. The scour indicated that the currents were flowing offshore, and may have led to the erosion of as much as 100 million m^3 of sandy sediment from their study site and transported southwest. Keen and Glenn (2002) modeled 0.02 m of erosion and scour on Ship Shoal during Hurricane Andrew, and observed as much as 10 cm-thick storm beds with hummocky cross stratification in cores taken after Katrina. Keen et al. (2006) also produced a quantitative model suggesting that storm beds would reach a maximum thickness (14 cm) on the St. Bernard Shoals.

The position of the shoals on the continental shelf, and their elevation above the

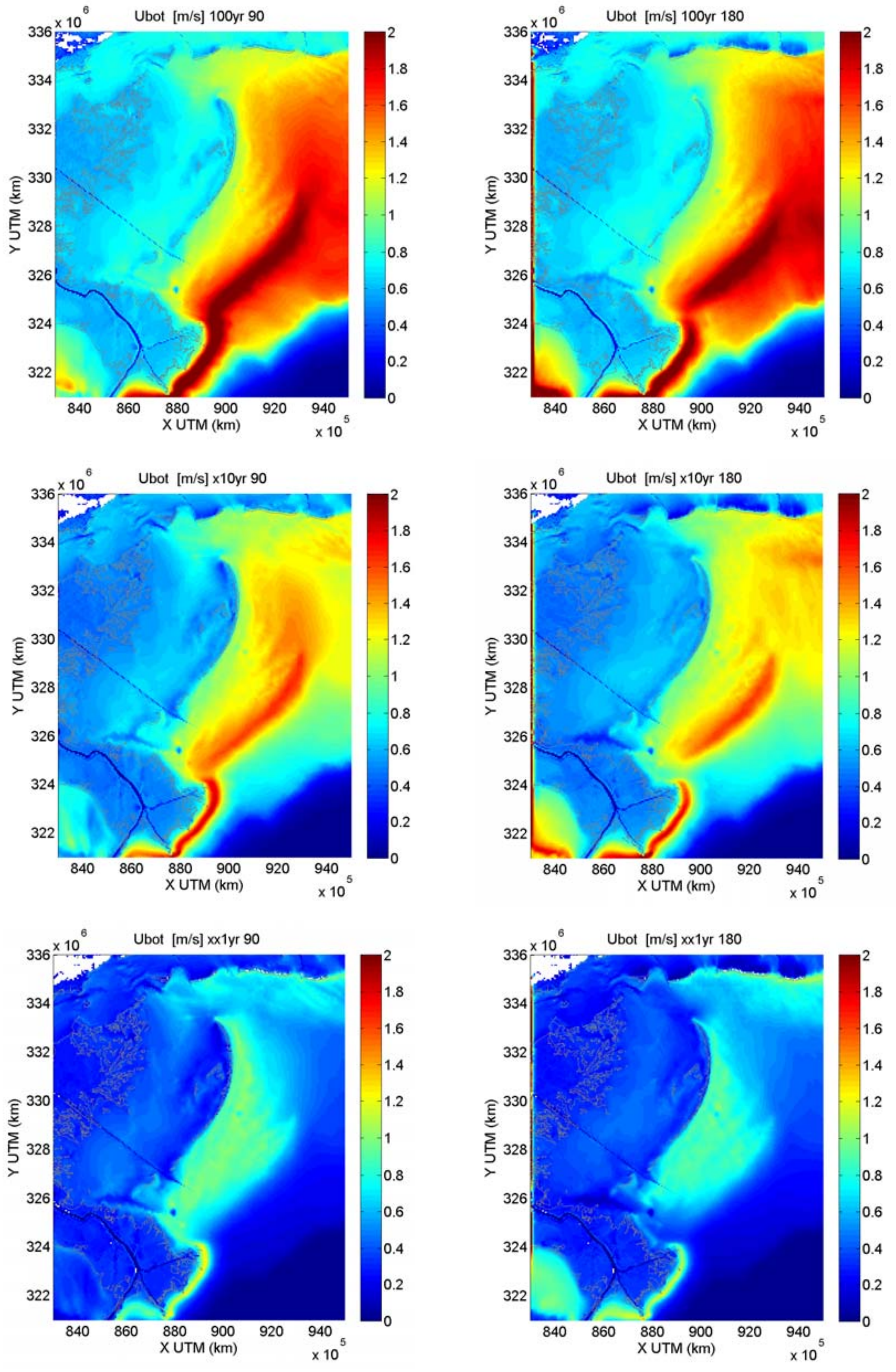


Figure 40. Modeled bottom velocity (m/s) for incoming waves of 90 and 180 degrees for the 100 yr, 10 yr and 1 yr return period storms. From Georgiou and Schindler (2009).

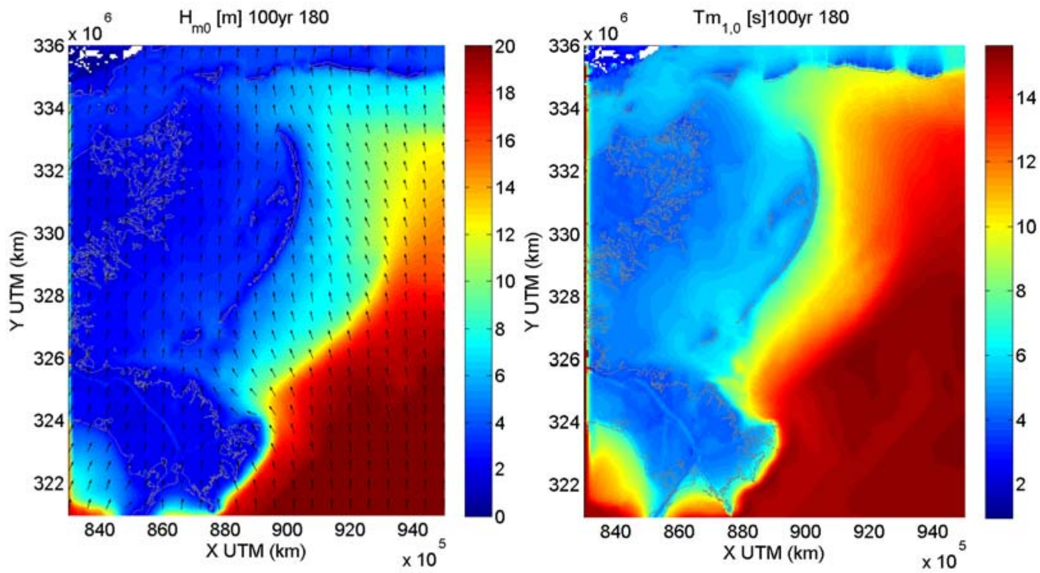


Figure 41. modeled wave height H_{m0} (left panel) and wave period $T_{m-1,0}$ (right panel) of SWAN results of grid "GridLarge" for a return period of 100 yrs and an incoming direction of 180 degrees. From Georgiou and Schindler (2009).

sea floor likely results in a focusing of the wave energy and wind-driven bottom currents as they refract and reflect around the elevated shoal platform. The unique morphology of the St. Bernard Shoals is likely a direct result of these marine currents reworking the shoals. The most widely accepted model for shelf sand body maintenance is the Huthnance (1982) model.

Huthnance (1982) has shown that strong bottom currents can grow and maintain subaqueous shelf sand bodies as they flow over and around shoals. The currents shift obliquely to the dominant flow direction and accelerate as they pass over the top of the sand body. This acceleration causes erosion of the stoss side and after the flow passes the crest of the shoal the velocity decreases and sediment is deposited on the lee side (Snedden and Dalrymple, 1999). This process also excavates sandy sediment in the underlying substrate which can subsequently be deposited on the growing sand body. Another model proposed by Hayes and Nairn (2004) suggests that the convergence of shoaling waves along a shore parallel shoal results in sediment deposition along its crests and landward migration of the shoal.

Cold fronts during the winter months and hurricanes are the two forces driving large waves and strong current in the northern Gulf of Mexico and are likely responsible for driving the evolution of the St. Bernard Shoals. While these models may generally describe large-scale processes for shelf sand body evolution, the St. Bernard Shoals morphology suggest a greater complexity to the process controlling the shoals evolution. It is recommended that further study be undertaken to understand the marine process driving the continued evolution of the St. Bernard Shoals.

Despite a poor understanding of the marine forces driving the ongoing morphologic evolution of the St. Bernard Shoals, two important conclusions can be reached. First, the strong currents caused by tropical cyclones affect the shoals orientation and direction of migration. The larger shoals longitudinal axis is oriented sub-parallel to the dominant flow across the shelf (Ellis and Stone, 2006; Georgiou and Schindler, 2009). Also, most of the larger shoal bodies have steeper slopes on their northeast sides (Fig. 10). SBS-08 side scan imagery also shows fields of sand waves migrating eastward (Fig. 36). These three characteristics are likely caused by storm-induced wave and wind-driven currents traversing the shoals. Second, the swale scour that has been identified across the entire shoal platform suggests that sediment is resuspened and transported significant quantities of coarse grained sediment from the St. Bernard Shoals and from the deltaic sediments exposed in the swales (Figs. 33, 34 and 35). Sharp scarps along the edges of several shoals and the presence of pedestals suggest that the shoals have been locally truncated by erosion. The pedestals are herein considered to be the remnant of the initial shelf sand body or larger shoals that were differentially eroded. The strong currents also resulted in several other erosional features, including slumps, debris flows, and channels. Models of shoal maintenance propose that the sediment eroded in the adjacent swales is then deposited on the shoal crest and slip face (Huthnance 1982; Snedden and Dalrymple, 1999; Hayes and Nairn 2004; Thieler et al., 2001).

Model of Shelf Development

The evolutionary model for the eastern Louisiana continental shelf proposed by this study is shown in figure 42 and described in detail below. The chronology presented here relies

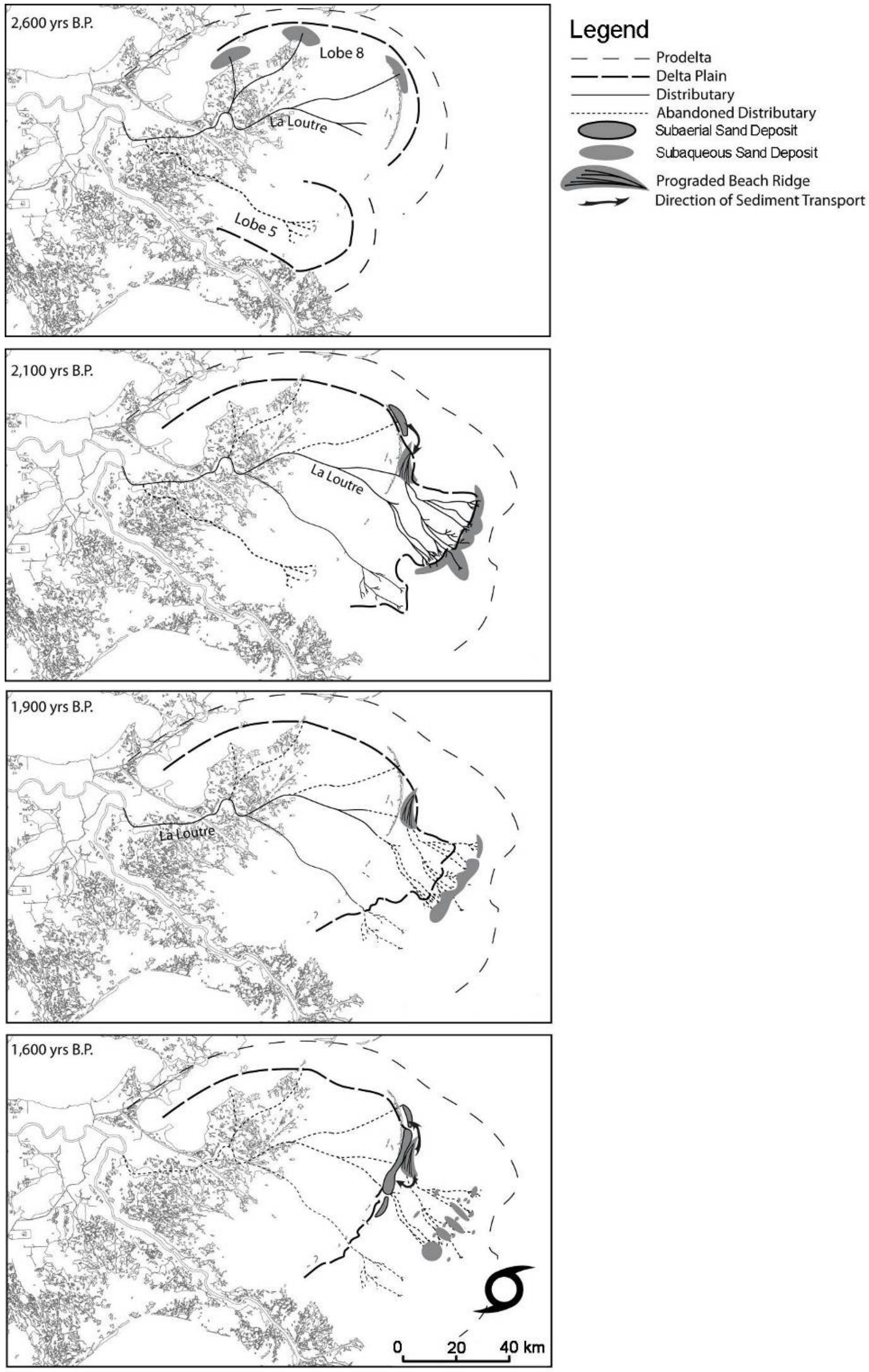


Figure 42. Four-stage Holocene evolution of the eastern Louisiana continental shelf. Stage 1: progradation and abandonment of Terre aux Boeufs lobe (*sensu* Frazier,1967) and progradation of the La Loutre lobe across the northern section of the shelf forming an inner to mid-shelf delta. Stage 2: the La Loutre distributary system bypasses the northern distributary network and extends to the outer shelf. Sediment for the northern distributary channels is transported south and beach ridges are built against the new distributary channel. Stage 3: Abandonment and marine reworking of the southern delta lobe. Sediment for the prograded beach ridges and delta lobe is reworked into the precursor deposit of the Chandeleur Islands. Stage 4: St. Bernard Shoals form from reworking of distributary channel deposits at the lower shoreface and inner shelf.

principally on stratigraphic relationships and published chronologic constraints presented in figure 41. The dates provided are based upon Frazier's (1967) chronology.

Stage 1. The Terre aux Boeuf lobe (Frazier's lobe 5) was initiated ~4,000 yrs BP and built a narrow delta lobe across the southeastern Louisiana continental shelf. It is not clear how far this system extended, but possibly to the area of modern Breton Island. The Terre aux Boeuf lobe was abandoned ~3,500 yrs BP, and the depocenter switched to a position farther to the west. The La Loutre lobe (Frazier's Lobe 8) became active ~3,000 yrs BP after channel avulsion took place toward the northeastern Louisiana shelf. By ~2,600 yrs BP Frazier's (1967) Lobe 8 had reached its maximum extent. This period of deposition contributed toward the construction of the present day northern Biloxi Marsh and the deltaic lobe that would later be reworked to form the northern tip of the Chandeleur Islands.

Stage 2. Approximately ~2,500 yrs BP the northern distributaries of the La Loutre distributary network were largely abandoned or bypassed and discharge to the southern distributary channels increased. The southern distributary channels prograded across the shelf, approached the shelf edge, and likely reached their maximum extent around ~2,100 yrs BP. Despite being considered a distinct delta lobe of the St. Bernard delta complex by Frazier (1967) this deltaic package was likely a near-shelf edge extension of the more northern lobe 8. The southern La Loutre extension developed a 40-m thick, narrow, near-shelf edge lobe with a complex distributary network of deeply incised channels. During this time sediment within the abandoned distributaries farther north was probably reworked by marine process. Similar to the modern shoreface it was mobilized by tropical cyclones and cold fronts and transported south. Simultaneously, the prograded

distributary channels associated with the southern La Loutre extension interrupted the southern transport of this sediment creating a local sediment sink favorable to the development of the beach ridges along the northern side of the prograding distributary network.

Stage 3. Updip of the active depocenter the Mississippi River avulsed again, switching to the Lafourche and Plaquemines-Modern channel, and discharge in the La Loutre channel was greatly reduced. The southern La Loutre extension was rapidly transgressed as a result of overextension and relative sea-level rise and was rapidly reworked by marine processes. The shoreface ravinement truncated the upper section of the delta lobe and any overlying deposits. After the shoreface shifted farther updip at ~1,900 yrs BP, only the bases of deep distributary channels remained. These sediments were reworked into the St. Bernard Shoals.

Stage 4. At ~1,600 yrs BP the transgressive shoreface retreated to the area occupied by the prograded beach ridge plain and the Chandeleur Islands were beginning to form. Distributary channels outcropping on the shelf in the area of the St. Bernard Shoals continued to be reworked by lower shoreface-inner shelf processes. Since then the St. Bernard Shoals have continued to evolve and be reworked by marine processes during storm events.

Conclusion

The results of this study suggest that the St. Bernard Shoals are transgressive remnants of an over-extended delta lobe, but did not form through transgressive submergence. These marine sand bodies are bound at their base by a shoal ravinement surface and sit directly upon prodelta, delta front, and distributary channel deposits. This underlying regressive stratigraphy is suggested to be the result of deltaic deposition associated with the progradation of the St. Bernard delta complex. This facies relationship — marine sand overlying fluvio-deltaic deposits with no paralic interval in between — conflicts with the model of transgressive submergence (Penland et al., 1988) and has important implications for the evolution of a deltaic occupied shelf and the formation of midshelf sand bodies in such settings. The results of this study show that shelf shoals can form through the subaqueous excavation and reworking by strong marine currents of locally available coarse-grained sediment during rapid sea-level rise.

High-resolution seismic reflection profiles and vibracores indicate that the shoals are derived from sediment that was deposited by deltaic depositional systems similar to those that contributed to the formation of the Chandeleur Islands. The data show that the distributary network stratigraphically below the shoals is chronologically younger than distributaries located farther north that were the primary suppliers of sediment that became the Chandeleur Barrier Islands. The supplying river system apparently abandoned the northern distributaries leading to sedimentation farther south, in the vicinity of the modern St. Bernard Bathymetric High. This progradation into a deeper water setting led to an outer-shelf deltaic depocenter. Evidence for this system exists in the form of subshoal regressive stratigraphy and deeply incised, sand rich distributaries.

The distributary network mapped suggests a morphology and facies framework similar to the modern shelf edge Balize delta. Deltaic switching to the south at ~2,500 yrs BP may have resulted from the presence of a more favorable gradient in that direction. The gradient to the south was enhanced by the infilling to the north during the initial deltaic progradation, and previously the lobe 5 construction of Frazier (1967)..

After abandonment the extended delta lobe in the south was rapidly transgressed as relative sea level rose rapidly. A transgressive headland and barrier island may have formed during this period, however the ensuing shoreface ravinement in a regime of rapid sea-level rise, would have removed any evidence of this paleogeography. The distributary channels that remained were eroded, and reshaped by marine currents to form the modern St. Bernard Shoal system. Today, marine currents continue to rework the St. Bernard Shoals, most likely still partially sourced from the underlying distributary deposits. Waves and marine currents driven by the passage of large tropical cyclones provide a considerable force, that drives numerous physical processes involved in the reworking and mobilization of sediment around the St. Bernard Shoals. The relative role of gravitational and kinetic forces remain unqualified.

Future Work

It is recommended that several approaches be taken to further understand the early evolution of the St. Bernard Shoals. First, it is recommended that vibracores be collected across the shoals and absolute dates should be obtained in order to determine the date of the underlying deltaic package. Second, the mechanism responsible for the intershoal erosion needs to be identified to better understand these outer shelf transport processes. This could be accomplished by measuring local current velocities during calm conditions

and if possible during a tropical storm. The intra-shoal swale should also be mapped at higher resolution to determine if any morphologic patterns emerge that could constrain the reworking processes. Third, a model needs to be developed to describe the forces affecting the shoals during hurricanes and how the shoal system responds.

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Vita

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