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Chapter D of
Sand Resources, Regional Geology, and Coastal Processes of the Chandeleur Islands Coastal System: an Evaluation of the Breton National Wildlife Refuge

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Chapter D. Historical (1869–2007) Sea Floor Evolution and Sediment Dynamics Along the Chandeleur Islands

By Michael D. Miner,[1] Mark Kulp,[1] H. Dallon Weathers,[1] and James Flocks[2]

Abstract

Shoreline and sea floor change analyses based on historical hydrographic data (dating back to 1869), shoreline surveys (dating back to 1855), and satellite imagery for the Chandeleur Islands, La., reveal long-term trends of barrier shoreface retreat, barrier thinning, and recently, barrier disintegration. Volume calculations indicate that about 150×10^6 m^3 of sediment has been deposited downdrift (northward) and seaward of the northern terminal spit during the past 125 years. A similar volume of sediment has accreted at the extreme southern limits of the island chain (south of Breton Island). The volume deposited in the backbarrier, however, is only half of that distributed to the flanks, suggesting that the dominant transport mode is alongshore as opposed to cross-shore. The depositional sinks at the flanks of the island arc accreted at rates of more than 1×10^6 m^3 yr^{-1} between 1870 and 2007; however, calculations of potential longshore sediment transport rates based on 20 years of offshore wave data are two orders of magnitude less than the accretion rates. The sediment sources for these accretionary zones at the flanks include (1) relict deltaic deposits eroded from the shoreface where about 790×106 m^3 of erosion has occurred since 1870 and (2) nearshore and subaerial barrier sand. Long-term shoreline erosion and transgressive submergence are primarily event driven and associated with major storms. Rapid land loss accompanies these high-energy events. The islands do not fully recover from storm impacts because sand is transported to the flanks of the arc, removing it from the littoral system. These downdrift sand reservoirs provide a unique, quasi-renewable potential resource for nourishing the updrift barrier system.

Introduction

The processes that govern coastal evolution occur over varied temporal and spatial scales; therefore, significant processes may go undetected in the absence of a regional-scale investigation covering a long time period (Sallenger and others, 1992). In this study of the Chandeleur Islands, La., we used historical bathymetric and shoreline data from the U.S. Coast and Geodetic Survey (USCGS) from the 1870s and 1920s as a basis for comparing bathymetry and shoreline data collected in 2006 and 2007 by the University of New Orleans (UNO) and the U.S. Geological Survey (USGS). The two datasets were used to construct sea floor change digital elevation models (DEMs) for the region, which allowed us to determine zones of erosion and accretion, sediment volumes, and ultimately, long-term sediment transport trends and a sediment budget for the system. This is the first comprehensive coastal evolutionary model for the Chandeleur Islands, and the results demonstrate that processes that occur offshore along the lower shoreface govern sediment supply to the shoreline and, ultimately, long-term coastal evolution. Similar conclusions were reached by List and others (1991, 1994), Sallenger and others (1992), and Jaffe and others (1997) as a result of their study of the south-central Louisiana barrier islands. Hydrodynamic modeling of the Chandeleurs (Jaffe and others, 1997; Georgiou and Schindler, this volume) demonstrates that sediment transport processes along the lower shoreface are active primarily during large storms. Consequently, shoreface retreat and the ensuing large volumes of sediment that eroded from this region, as well as the volume of sediment deposited at the ends of the barrier arc, cannot be accounted for by typical sediment transport equations used for the littoral zone. Prior to the findings presented here, our understanding of the evolution of the Chandeleur Islands suffered from the lack of regional-scale, long-term analyses.

A significant component of this effort included data collected under the Barrier Island Comprehensive Monitoring (BICM) program, a cooperative agreement between UNO and the USGS funded by the Louisiana Coastal Area Science and

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Technology Program (LCA S&T). This chapter was designed to augment BICM findings and provide a framework and basis for planning and designing barrier management projects, for developing operation and maintenance activities, and for assessing the range of impacts from past and future tropical storms along the Chandeleur Islands.

Methods

Bathymetric Data

The bathymetric data employed for the sea floor change analysis were collected and assimilated as a part of the BICM program. What follows is a general methods summary, which is meant to provide a basic understanding of the data collection, processing, and analyses that led to the results and interpretations presented in this report. For a detailed account of the methods and uncertainty calculations see Miner and others (2009) and Baldwin and others (2009).

2006–7 Surveys

During the summers of 2006 and 2007, UNO and the USGS conducted bathymetric surveys of the northern (2006) and southern (2007) Chandeleur Islands as a part of the BICM program (fig. 1). Bathymetric surveys were conducted by using single-beam echo sounders for shallow water and nearshore zones and by using an interferometric swath bathymetric system for the offshore zone. Bathymetric coverage extended from the shoreline to 7 km offshore on the Gulf of Mexico (eastern) side and from the backbarrier shoreline to 5 km into Chandeleur Sound to the west. For the single-beam bathymetry, shore-perpendicular survey transects were spaced at 750 m with shore-parallel tie lines spaced at 1,000 m.

Single-beam bathymetry was acquired and processed by using the USGS-developed System for Accurate Nearshore Depth Surveying (SANDS; see DeWitt and others, 2007, and Miner and others, 2009, for details). SANDS employs post-processed kinematic Global Positioning System (PPK GPS) to incorporate static GPS base station data, survey-vessel GPS navigation, and depth soundings to derive an x,y,z position for each sounding referenced vertically to the North American Vertical Datum of 1988 (NAVD 88) and horizontally to North American Datum of 1983 (NAD 83).

Swath bathymetry was collected by using interferometric sonar, and NAD 83 ship position was recorded by using differential GPS navigation. Tidal corrections were applied by using a discrete tidal zoning model provided by the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service's Hydrographic Planning Team (see Miner and others, 2009, and Baldwin and others, 2009, for details). A correction was applied to shift the data from mean low water tidal datum to NAVD 88 so that the swath bathymetry could be integrated into a single dataset with the single-beam data.

Uncertainty analysis performed on the final processed bathymetric dataset for the entire study area provided an estimate of ±0.11 m vertical uncertainty for each x,y location where empirical data exist (see Miner and others, 2009, for details).

1920s (1917–22)

The 1920s data were acquired digitally from the Hydrographic Surveys Division of NOAA's Office of Coast Survey (table 1; fig. 2). The hydrographic survey smooth sheets (H-sheets) that were used to produce the bathymetric maps are listed in table 1. The smooth sheets associated with these surveys were digitized between 2001 and 2004 by a NOAA contractor. The data were downloaded as an x,y,z file referenced to NAD 83 by using soundings expressed in meters relative to mean low water (MLW) at the time of the survey.

Horizontal positioning was achieved by using a system of triangulations based on a series of towers (up to 100 ft high) and base stations located along the Chandeleur Islands. Beyond the limit of sight from the shoreline, buoys using cuts and fixes from the shore signal were placed at the outer limit of the planned survey lines. Soundings were acquired by using sextant three-point fixes for horizontal positioning when in sight of the positioning signals and by using dead reckoning (estimation of position based on ship speed and heading) when the signals were out of sight. A lead weight handline was used to a depth of 15 fathoms. From the 15-fathom to the 25-fathom depth, a trolley rig consisting of a leadline with copper core was used. In depths greater than 25 fathoms, a mechanical sounding machine was used. A tidal staff at the Chandeleur Islands light, along with automatic tide gages at Bay St. Louis and Biloxi, Miss., and Ft. Morgan, Ala., was used to correct soundings to a common datum of MLW (summarized from USCGS, 1917, 1920, 1922; Hawley, 1931).

1870s (1869–85)

For the 1870s bathymetric data (fig. 3), USCGS H-sheets were acquired through the Hydrographic Surveys Division of NOAA's Office of Coast Survey as high-resolution scanned image files (tagged image file format [TIFF] and Joint Photographic Experts Group [JPEG]). The H-sheets that were used for this analysis are listed in table 1. The H-sheets, originally referenced to a geographical (latitude/longitude) coordinate system based on the Clarke 1866 ellipsoid model, were converted to NAD 83 (see Miner and others, 2009, for details). The depth soundings are reported relative to MLW at the time of the survey and are therefore referenced to an arbitrary vertical datum (more details are given in Sea Floor Change and Volume Calculations section below). Soundings were measured by using the lead weight handline method described above. Horizontal positioning for the soundings was

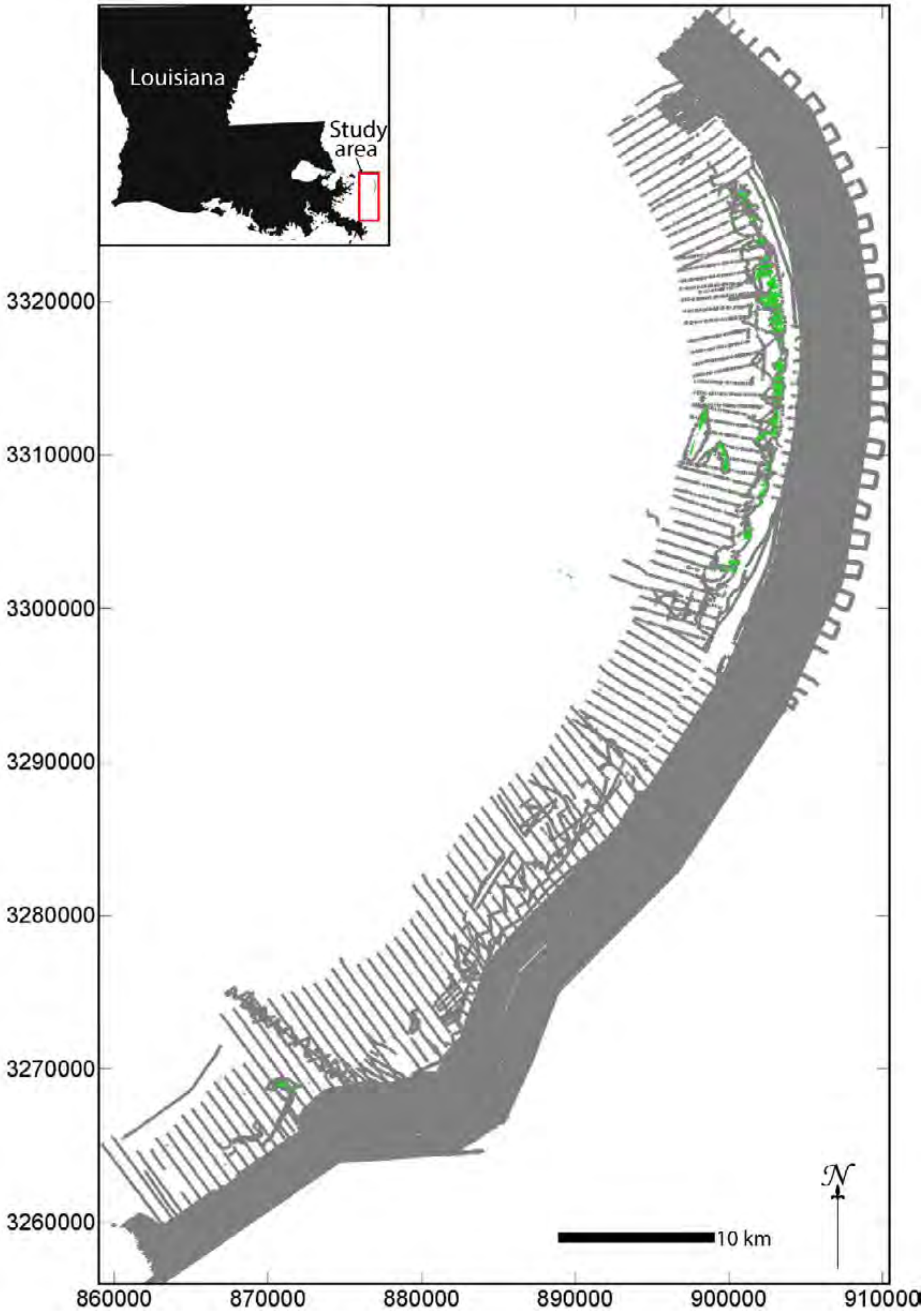

Figure 1. Data coverage for the 2006–7 bathymetric surveys of the Chandeleur Islands, La., conducted by the University of New Orleans and the U.S. Geological Survey. Note the nearly 100-percent swath coverage on the Gulf of Mexico side of the islands. Green polygons indicate 2005 shoreline configuration. Coordinates are in Universal Transverse Mercator Zone 15 N meters.

Table 1. Historical U.S. Coast and Geodetic Survey hydrographic survey smooth sheets (H-sheets) used in this analysis of the Chandeleur Islands, La.

H-sheet	Date	Location
	1870s	
H00999	1869	Breton Island offshore
H01000	1869	Breton Sound
H01171	1873	Chandeleur Sound
H01654	1885	Chandeleur Islands offshore
	1920s	
H04000	1917	Hewes Point
H04171	1920	Northern Chandeleur Islands
H04212	1921–22	Southern Chandeleur Islands (Breton Island)

accomplished by means of recording sextant angles from the ship to known landmarks, recording theodolite angles to the survey vessel from the shoreline positions, and dead reckoning (List and others, 1994).

Adjustment of Historical Datasets for Relative Sea Level Rise

To compare surfaces from two different time periods for calculating sediment erosion and accretion trends, all surfaces must be referenced to a common vertical datum. This requirement presented a problem in the study area because much of the historical data were referenced to an arbitrary datum, MLW at the time of the survey. Because relative sea level rise (RSLR) rates are so high in the study area, the MLW elevation is constantly increasing. Therefore, if RSLR is not taken into account and corrected for, there will be a bias towards erosion in the comparison analysis and sediment volumetric change calculations. This problem was encountered by List and others (1994) when attempting to perform sea floor change analysis in Louisiana. The reader is referred to Jaffe and others (1991), List and others (1994), and Miner and others (2009) for extensive discussion on methods employed to account for RSLR in Louisiana.

For the sea floor change portion of this study, historical data were shifted to reference an elevation relative to NAVD 88 for comparison to the 2006–7 bathymetry. There were two steps to this process. The first involved shifting each bathymetric dataset to a common datum that takes into account the RSLR that occurred between each time period. Both historical datasets were shifted to MLW for the modern tidal epoch by applying a 0.5 cm/yr RSLR correction. Because there are no local sea level rise data that exist for the Chandeleur Islands for the period of study, a value had to be estimated on the basis of tide gage records in the region and depth versus age calculations from radiocarbon-dated peats from the Mississippi River Delta Plain (see Miner and others, 2009). Studies of subsidence-induced sea level rise in Louisiana have shown that there is a direct correlation between RSLR rates and thickness of the Holocene substrates (Kolb and Van Lopik, 1958; Penland and Ramsey, 1990; Kulp, 2000; Meckel and others, 2006; Törnqvist and others, 2006, 2008). On the basis of these findings, sea level rise rates for the Chandeleurs and associated range of uncertainty were estimated by relating RSLR values from tide gages (0.92 cm/yr at Grand Isle, La.; 0.56 cm/yr at Delacroix, La.; and 0.29 cm/yr at Dauphin Island, Ala.) to thickness of Holocene substrate at each location (Miner and others, 2009). On the basis of this relation between relative thickness of Holocene deposits and regional tide gage data, an RSLR value of 0.5 cm/yr for the Chandeleur Islands was applied to shift the historical datasets for comparison to the recent bathymetric surface.

Surface Gridding and Contouring

The final x,y,z bathymetric data were used to construct surface "grids" for the study area. Gridding is the process of taking irregularly spaced x,y,z data and producing a grid file that contains a regularly spaced array of z data at locations called grid nodes (Golden Software, Inc., 2002). Because the x,y,z bathymetric data consist entirely of elevations below the intertidal zone and in order to prevent interpolation across islands (between offshore and backbarrier) during gridding, shoreline representing 0.5-m elevation was included in the bathymetric dataset to constrain the grid algorithm. The shoreline was digitized from a mosaic of USGS digital ortho quarter quadrangles (DOQQs) and/or NOAA Office of Coast Survey topographic surveys (T-Sheets) that were acquired at a time period comparable to each bathymetric dataset (see Martinez and others, 2009).

Final grids for both historical and newly acquired bathymetric data were created in Surfer 8 (Golden Software, Golden, Colo.) and interpolated by kriging with a 100-m grid node spacing (Miner and others, 2009). The grids created by the kriging method became the basis for contouring bathymetry and subsequent grid comparisons for sediment volumetric change calculations.

Sea Floor Change and Volume Calculations

Grid math calculations were carried out between two survey datasets to determine the difference between the historical and more recent z values at each grid node (for example, $Z_{2007} - Z_{1920s}$ = net bathymetric change). Calculations resulted in the creation of a new grid that showed areas of accretion and erosion through positive and negative values, respectively. A new DEM was contoured from these differential z values to show changes (erosion, deposition, or dynamic equilibrium) that occurred during the time period separating the two surveys.

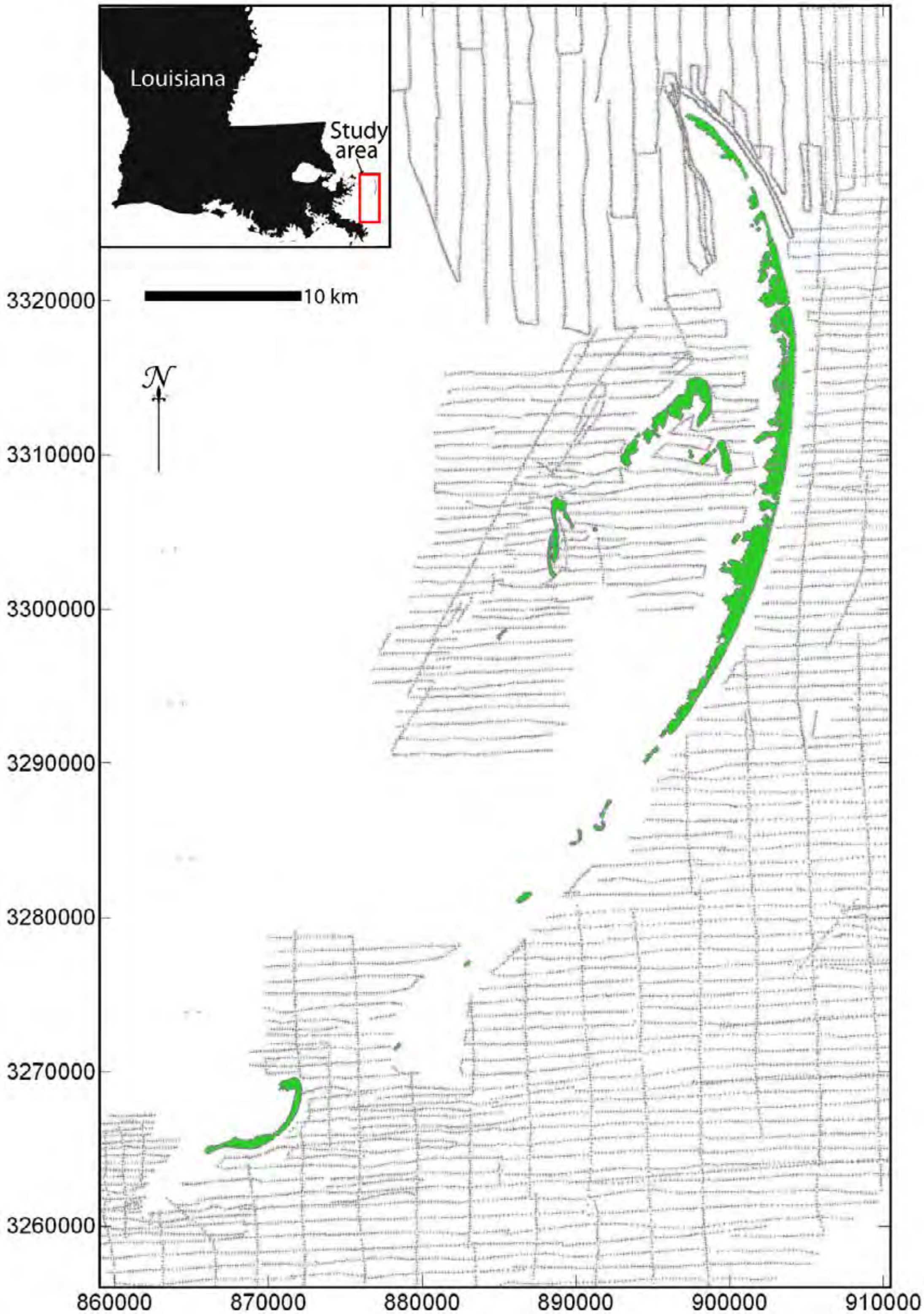

Figure 2. Data coverage for the 1920s U.S. Coast and Geodetic Survey hydrographic surveys of the Chandeleur Islands, La. (see table 1 for a list of hydrographic survey smooth sheets used in this study). Green polygons indicate 1922 shoreline configuration. Coordinates are in Universal Transverse Mercator Zone 15 N meters.

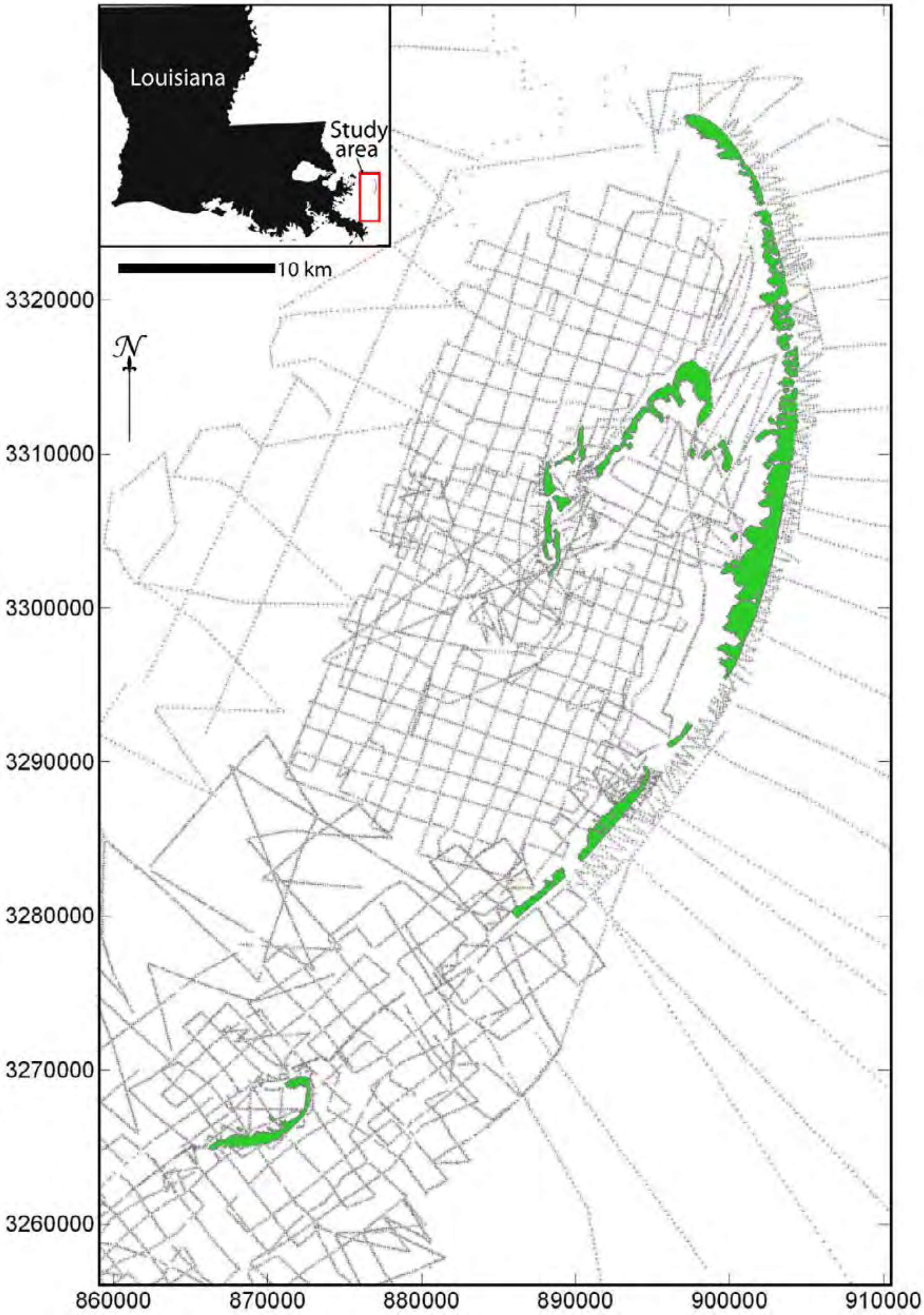

Figure 3. Data coverage for the 1870s U.S. Coast and Geodetic Survey hydrographic surveys of the Chandeleur Islands, La. Green polygons indicate 1855/1869 shoreline configuration. Coordinates are in Universal Transverse Mercator Zone 15 N meters.

Sea floor change DEMs were produced for the 1870s to 1920s, 1920s to 2006–7, and 1870s to 2006–7. Volume calculations of the bathymetric change grids were computed in Surfer 8 to determine positive volume (accretion) and negative volume (erosion). The bathymetric change grids were then broken up into polygons that delineated geomorphically distinct regions of either erosion or accretion. These sea floor change maps and sediment volume calculations form the basis for interpreting long-term sediment transport trends for the study area.

Bathymetric Profiles

While the bathymetric change grid was used to produce a DEM that shows the sea floor change in plan view and quantify volumetric change, it is also optimal to graphically represent changes in profile view to better understand shoreface evolution and estimate cross-shore sediment transport processes. Profiles were selected along transects where 1870s empirical bathymetric data exist because this historical dataset had the coarsest resolution. Profile data were extracted from the interpolated grid data so that each point on the profile represented the x,y,z position of a grid node. Calculations of cross-sectional area difference between profiles along the same transect representing two different time periods were used to estimate the magnitude of localized erosion and/or accretion. When compared along the extent of the island arc, the profiles provide a means for understanding along-strike variations in shoreface progradation or retreat.

Shoreline and Island Area Change

An analysis of shoreline and island area change through time was conducted by Fearnley and others (this volume), Martinez and others (2009), and McBride and others (1992). The results are employed here to relate shoreface retreat magnitude and rates to shoreline change, as well as to relate sea floor sediment volumetric changes to changes in barrier island area.

Results and Interpretation

Sea Floor Morphology and Evolution

Bathymetric data for all three time periods show similar sea floor morphology and document an evolution that is driven by processes associated with the degradation of a relict delta lobe. The geomorphic features documented in the bathymetric data include the shoreface, tidal inlets, backbarrier platform, backbarrier tidal channels, recurved spits, and sandy barrier shoals. The details of these features and their general role in sea floor evolution are presented below. Geographic names are presented on figures 4–6. A more quantitative analysis follows in the Sediment Erosion and Accretion Volumes section.

The Shoreface

The shoreface includes the area seaward of the breaker zone extending offshore to the inner shelf at a depth of approximately 7.5 m (determined from bathymetric data for this study) for most of the Chandeleurs. This is the most dynamic geomorphic region along the Chandeleur Islands. The shoreface slopes relatively steeply seaward until it reaches a break in slope that marks the transition to the more gently sloping inner shelf. The shoreface profile is shaped by storm and fair weather wave activity and associated sediment transport. Along the Chandeleur Islands the shoreface is the geomorphic region that underwent the largest magnitude of erosion during the time of study; however, the relatively sediment-rich northern section of the islands offshore of Hewes Point is a zone where the shoreface has prograded seaward.

Tidal Inlets

A tidal inlet is an opening along a barrier shoreline that connects a gulf with bays, lagoons, marsh, and tidal creeks (Davis and FitzGerald, 2004). Tidal currents maintain the inlet channel by shore-perpendicular flushing of sediment that is transported alongshore by waves (Brown, 1928; Escoffier, 1940). There are four large tidal inlets responsible for the majority of tidal exchange between the Gulf of Mexico and the Chandeleur and Breton Sounds and numerous (more than 60) ephemeral hurricane-cut inlets along the northern island arc.

The two dominant tidal inlets in the system are the channels that flank the terminal spits of the Chandeleurs barrier arc and include an inlet which is north of Hewes Point and an inlet that is south of Breton Island. These two channels are not traditional tidal inlets because they are not bound by a barrier island on both sides of the channel; however, the bathymetry shows a distinct channel form at each of these locations, and current measurements and numerical modeling show that these two flanking channels are responsible for the majority of tidal flow into and out of Chandeleur and Breton Sounds (Hart and Murray, 1978). The inlet north of Hewes Point extends from the backbarrier and wraps around Hewes Point where maximum channel depths are greater than 15 m. Lateral spit accretion towards the north at Hewes Point has forced a northerly migration of this inlet.

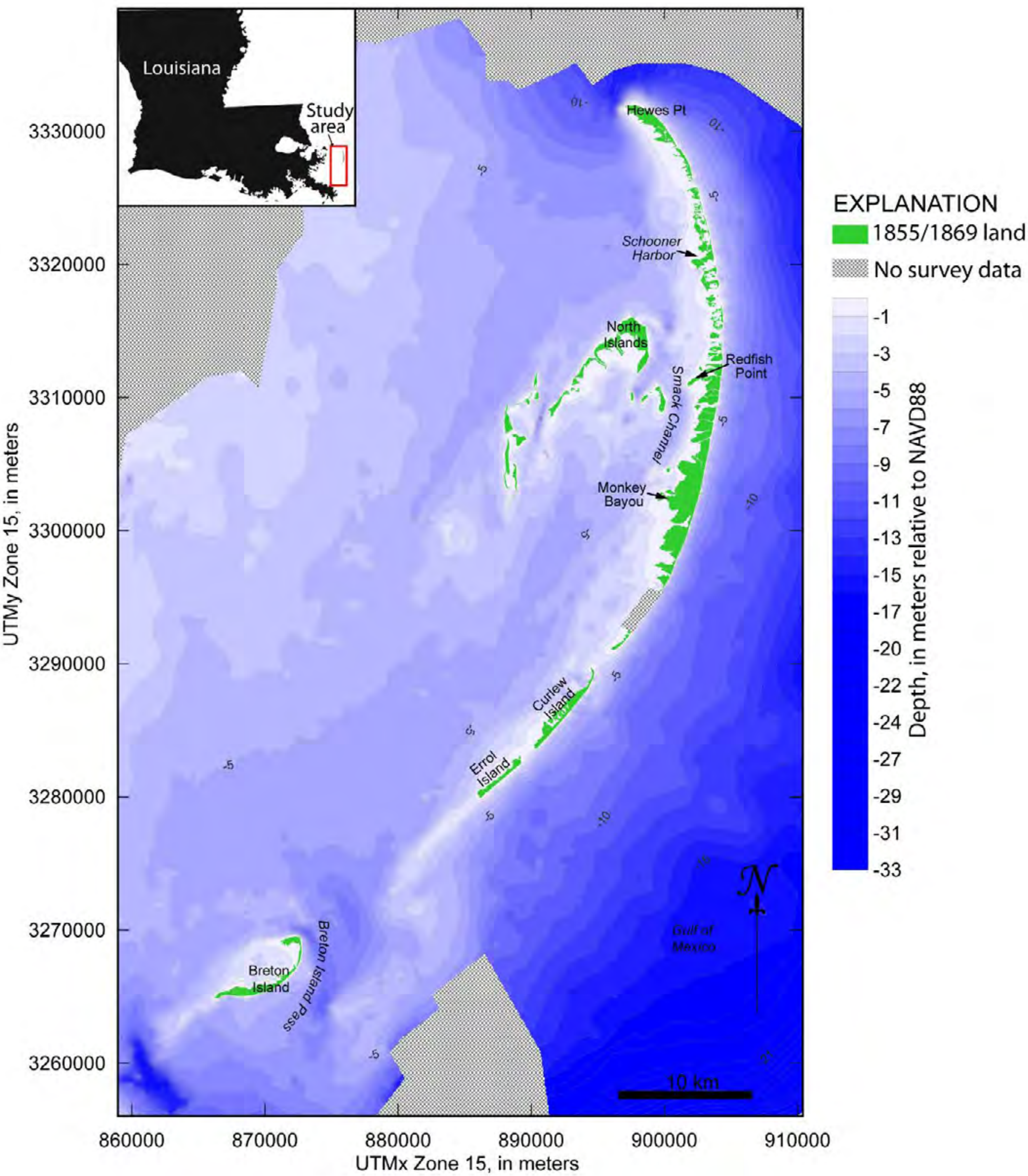

Figure 4. Shoreline configuration and bathymetry for the 1870s for the Chandeleur Islands, La. UTM, Universal Transverse Mercator; NAVD 88, North American Vertical Datum of 1988.

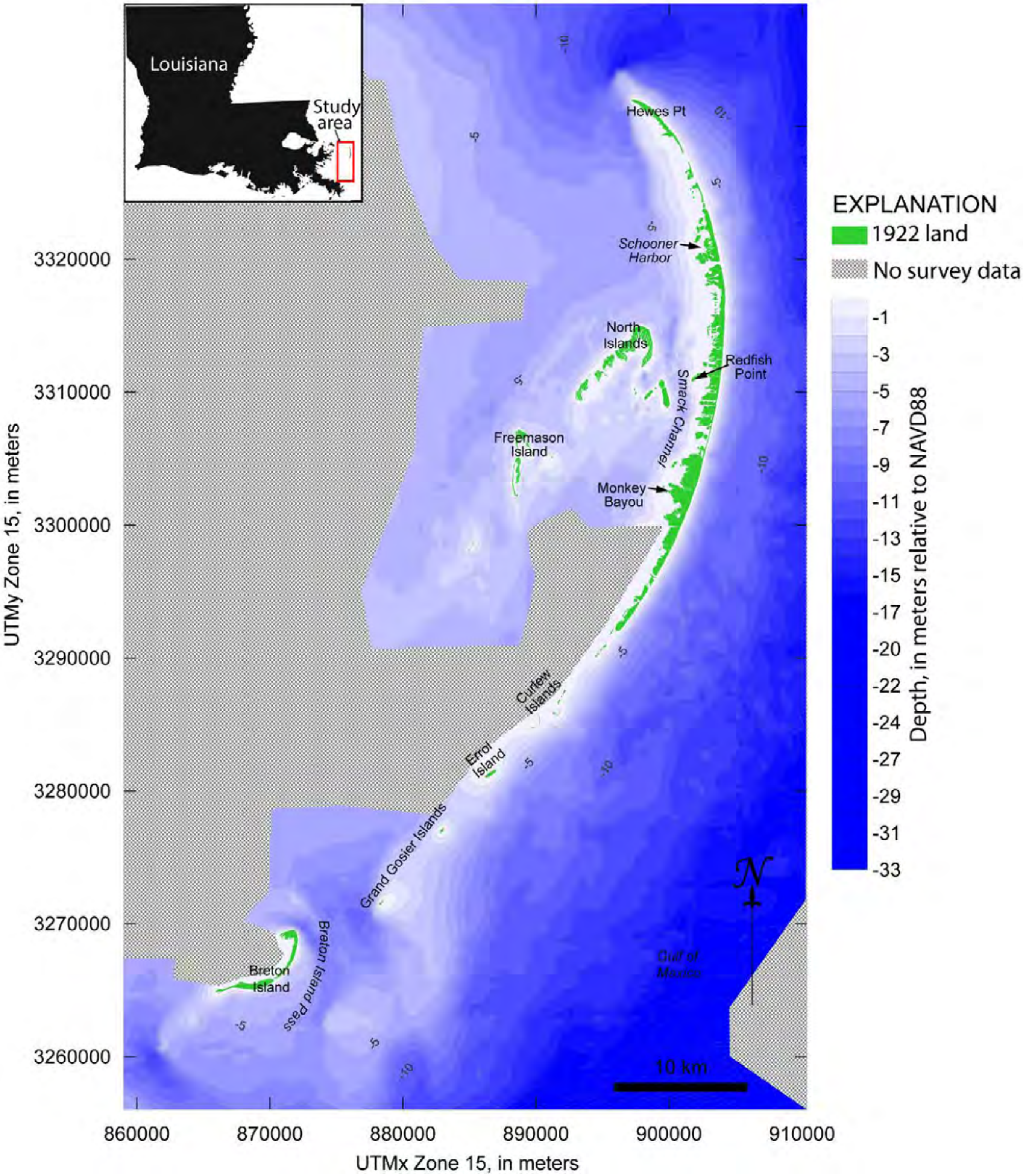

Figure 5. Shoreline configuration and bathymetry for the 1920s for the Chandeleur Islands, La. UTM, Universal Transverse Mercator; NAVD 88, North American Vertical Datum of 1988.

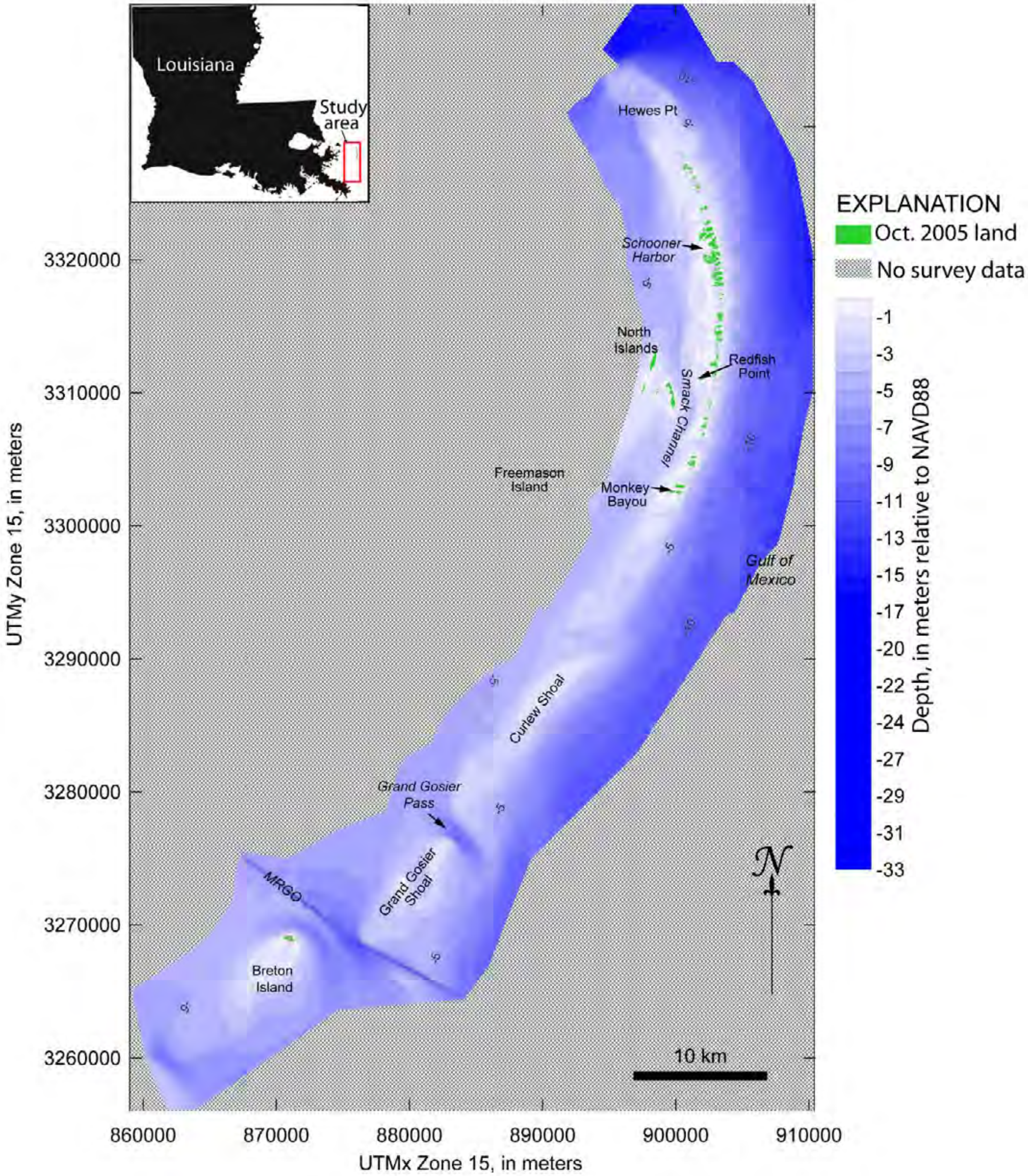

Figure 6. The 2005 shoreline configuration and bathymetry for 2006/2007 for the Chandeleur Islands, La. UTM, Universal Transverse Mercator; NAVD 88, North American Vertical Datum of 1988; MRGO, Mississippi River-Gulf Outlet.

The inlet marking the southern extent of the Chandeleur Islands located south of Breton Island has migrated south and undergone considerable infilling. This may be the result of construction of the Mississippi River-Gulf Outlet (MRGO) and deepening of Grand Gosier Pass by tidal scour, both of which captured tidal prism (the volume of water that passes through the inlet during half of each tidal cycle) from this southernmost inlet. Observations during surveying and subsequent aerial reconnaissance flights confirm strong tidal currents flowing through this broad channel.

The MRGO intersects the Chandeleur Islands just north of Breton Island and was cut through the existing tidal inlet of Breton Island Pass. Although the natural inlet configuration was downdrift offset (the inlet channel was oriented to the south in an alongshore direction), the MRGO trends perpendicular to the shoreline. The MRGO construction did not result in the abandonment of the natural channel in favor of the engineered one, and both channels remained open. The MRGO required frequent maintenance dredging to remove sand before being decommissioned in 2008. Strong tidal currents flow through the MRGO, which is a conduit for tidal exchange for much of the Lake Pontchartrain Basin. The increased tidal prism and strong ebb tidal currents result in seaward transport of sand to distal ebb shoals that would have otherwise bypassed the inlet and nourished downdrift Breton Island.

Grand Gosier Pass is a natural tidal inlet located between Curlew Island Shoal and Grand Gosier Islands Shoal. This inlet was not present in the 1870s bathymetry but, by 2007, had scoured to a depth of more than 9 m. An ebb tidal delta has developed there as indicated by a seaward excursion of the 3-m contour offshore of Curlew Shoal since the 1870s.

Historically, numerous ephemeral hurricane-cut inlets along the barrier chain were active for several years after a storm impact and then filled in to form a continuous barrier shoreline along the northern arc during extended periods of calm weather (Kahn, 1986). Since Hurricane Katrina (2005), more than 60 hurricane-cut tidal inlets have remained open. Based on the 2006 bathymetric surveys, widths range from 80 to 3,100 m, and maximum depths reach 3.5 m.

Backbarrier Platform

The northern island arc (north of Monkey Bayou [see figs. 4–6]) is backed by a broad (maximum width of about 2.5 km), sandy platform that averages less than 1 m in depth and is blanketed by submerged aquatic vegetation. Storm-generated flood tidal deltas have formed landward of deeper hurricane-cut inlets. The backbarrier platform is intersected by channels that were scoured during storms.

Spits

A spit is a ridge of sand attached to the land at one end and terminating in open water at the other (Evans, 1942). Spits are built by lateral accretion that is due to wave-induced sediment transport. Spits accrete laterally over the subaqueous spit platform, which progrades ahead of the subaerial spit. Seasonal variations in wave approach and the refraction of waves bending around the spit end often form a hook-shaped recurve spit that extends into the backbarrier. Lateral accretion of a terminal spit (at the end of a barrier island) usually results in development of a thick sand body because the leading edge of the prograding spit fills a relatively deep inlet channel (fig. 7; Hoyt and Henry, 1967).

Hewes Point is a prominent spit system in the northern end of the Chandeleur Islands. Smaller recurved spits flank hurricane-cut tidal inlets; however, these smaller scale features are not within the scope of this regional-scale report on sea floor evolution. The Hewes Point spit is prograding because of northerly longshore transport into the marginal deltaic basin that flanks the St. Bernard Delta Complex.

The scale of this terminal spit accretionary process is important because it demonstrates how an abandoned deltaic headland is reworked by marine processes to form Stage 1 flanking barriers and eventually a Stage 2 barrier island arc (fig. 8; Penland and others, 1988). Lateral spit accretion remains an important process throughout Stage 2, as shown by the lateral accretion of Hewes Point in a northerly direction (Penland and others, 1988), a concept that is emphasized throughout this report.

Barrier Shoals

The barrier shoals that occur along the Chandeleur Islands are present in the southern portion south of Monkey Bayou and include Curlew Island Shoal and Grand Gosier Islands Shoal. These shoals are actually ephemeral barrier islands that are destroyed during storms and reemerge during extended fair weather periods (Otvos, 1981; Penland and Boyd, 1985; Fearnley and others, this volume); however, recent increased storm frequency and a decrease in sediment supply has inhibited island emergence since Hurricane Katrina (Fearnley and others, this volume). The same factors inhibiting reemergence have also forced other, more stable portions of the Chandeleur Islands into ephemeral island/shoal mode. We predict that this evolutionary behavior will eventually be characteristic of the entire island arc as it is converted to an inner shelf shoal through transgressive submergence (fig. 8).

Sediment Erosion and Accretion Volumes

The sea floor change DEMs and volumetric change calculations for the 1870s to 2006–7 provide a means of tracking sediment dynamics during the 136-year time period covered by this study. Fifteen zones were delineated on the basis of geomorphology and erosion/accretion trends (fig. 9; table 2).

Because the northern Chandeleur Islands are evolving somewhat differently than the islands in the south are, we have

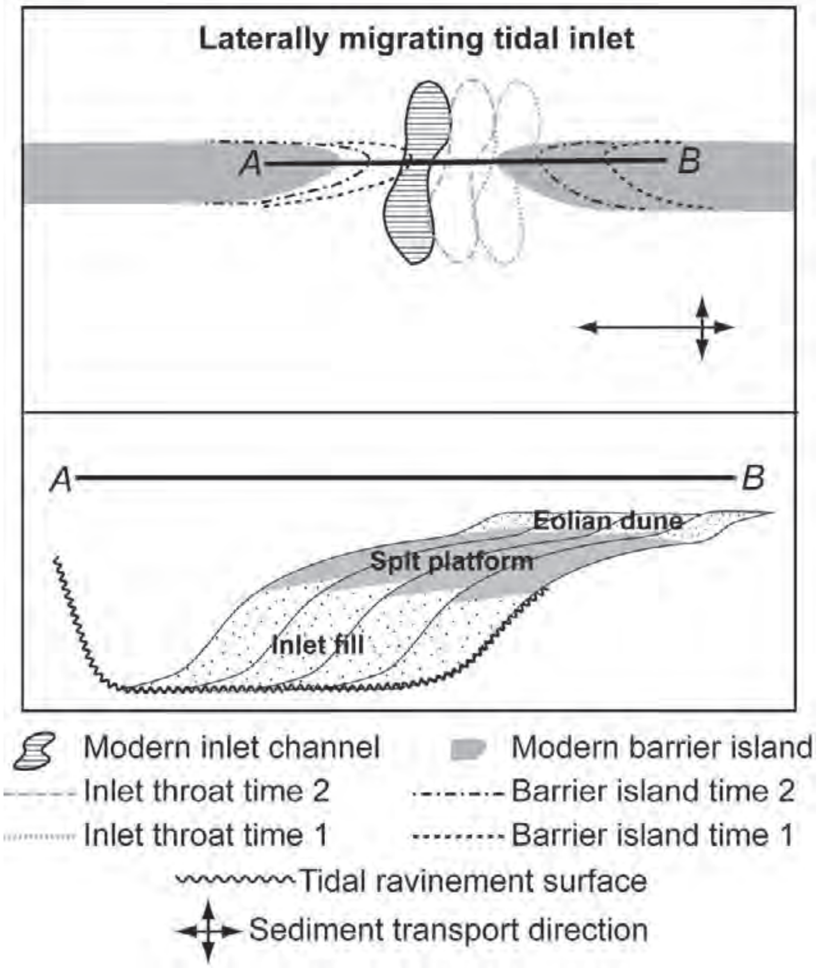

Figure 7. Conceptual model for inlet fill development from lateral spit accretion (modified from Hoyt and Henry, 1967).

divided the island arc into two separate sections (northern and southern) for the purpose of discussing the results of volumetric change analysis. This division is not meant to imply that one section does not have influence on the other or that sediment is retained within a closed system for each section.

Northern Chandeleur Islands (Hewes Point South to Monkey Bayou)

The majority of sea floor change documented in the northern Chandeleur Islands occurred in three geomorphic regions: (1) the shoreface (Zone 2), (2) backbarrier (Zone 3), and (3) downdrift of terminal spit at Hewes Point (Zone 1) (zones are delineated in fig. 9). The shoreface along the northern island arc (Zone 2) is dominated by erosion and underwent a net loss of 285.29 × 10^6 m^3 of sediment between 1870 and 2006, forcing a landward retreat of the shoreface. The maximum vertical erosion was 8.06 m. In a regime of landward shoreface retreat, a net landward transfer of sediment is necessary to maintain a supratidal exposure of barrier islands in a regime of sea level rise. The backbarrier of the northern arc (Zone 3) underwent a net accretion of 84.11 × 10^6 m^3, approximately 29 percent of the total volume eroded from the shoreface. The maximum vertical accretion measured was 5.88 m in the backbarrier. The terminal spit in the northernmost portion of the study area (Zone 1) is a zone of accretion where 128.77 × 10^6 m^3 of sediment has been deposited since 1870 (45 percent of the total volume eroded from the shoreface). The maximum vertical accretion measured in this zone was 10.82 m. This deposit has developed through lateral spit accretion to the north; however, the shoreface is also prograding in a seaward direction (eastward) along this sediment-abundant northern section of the island arc.

To account for the large deficit in the calculated volumes, which is probably attributable to the removal of fine-grained sediment from the coastal system, the percent sand content of the eroded or deposited volume must be determined. To estimate the sand component for each zone, grain-size data from the top 1 m of sediment cores (see Flocks and others, this volume) were analyzed. The percent sand value for each core (vertically averaged from surface to 1-m depth) was then averaged with all cores contained within each zone to estimate a percent sand for that zone. Once the percent sand value was calculated for each zone, a “sand only” volume could be calculated by multiplying the percent sand times the total volume eroded or accreted (table 3). The net volume deficit prior to the sand correction for the northern Chandeleur Islands was -72.41 × 10^6 m^3, and after applying the correction there was a net difference of 1.47 × 10^6 m^3 (more sand deposited than eroded). This excess of sand deposited can be partially explained by the erosion of the subaerial barrier island that was not included in the sea floor volumetric change analysis. Between 1855 and 2005 an area approximately 19 × 10^6 m^2 of exposed island was converted to open water in Zones 1, 2, and 3 (Martinez and others, 2009; Fearnley and others, this volume). The result of this sediment budget for the northern Chandeleurs is not meant to imply that Zones 1–3 are a closed system with regard to sand dynamics. Based on the map in figure 9, it is clear that our study area does not capture the entire depositional area in Zone 1, nor does it capture the

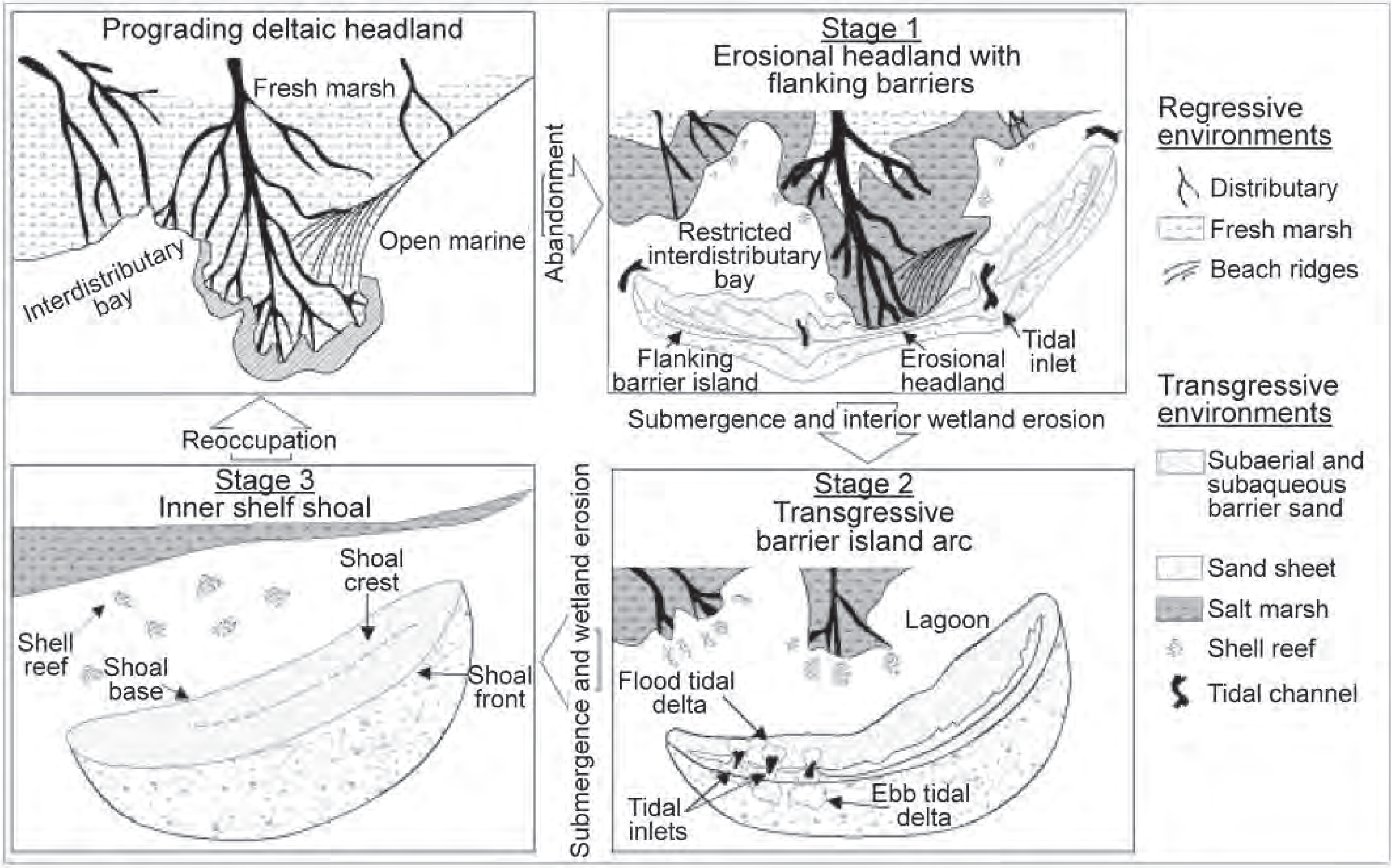

Figure 8. Three-stage model conceived by Penland and others (1988) for the formation and evolution of transgressive Mississippi River Delta barrier islands. Deltaic abandonment leads to marine reworking of the deltaic headland, producing a Stage 1 erosional headland with flanking barriers separated by tidal inlets. Backbarrier marshland loss results in mainland detachment and the formation of a Stage 2 transgressive barrier island arc. Continued relative sea level rise and sediment transport away from the system result in transgressive submergence and the formation of a transgressive inner shelf shoal (modified from Penland and others,1988).

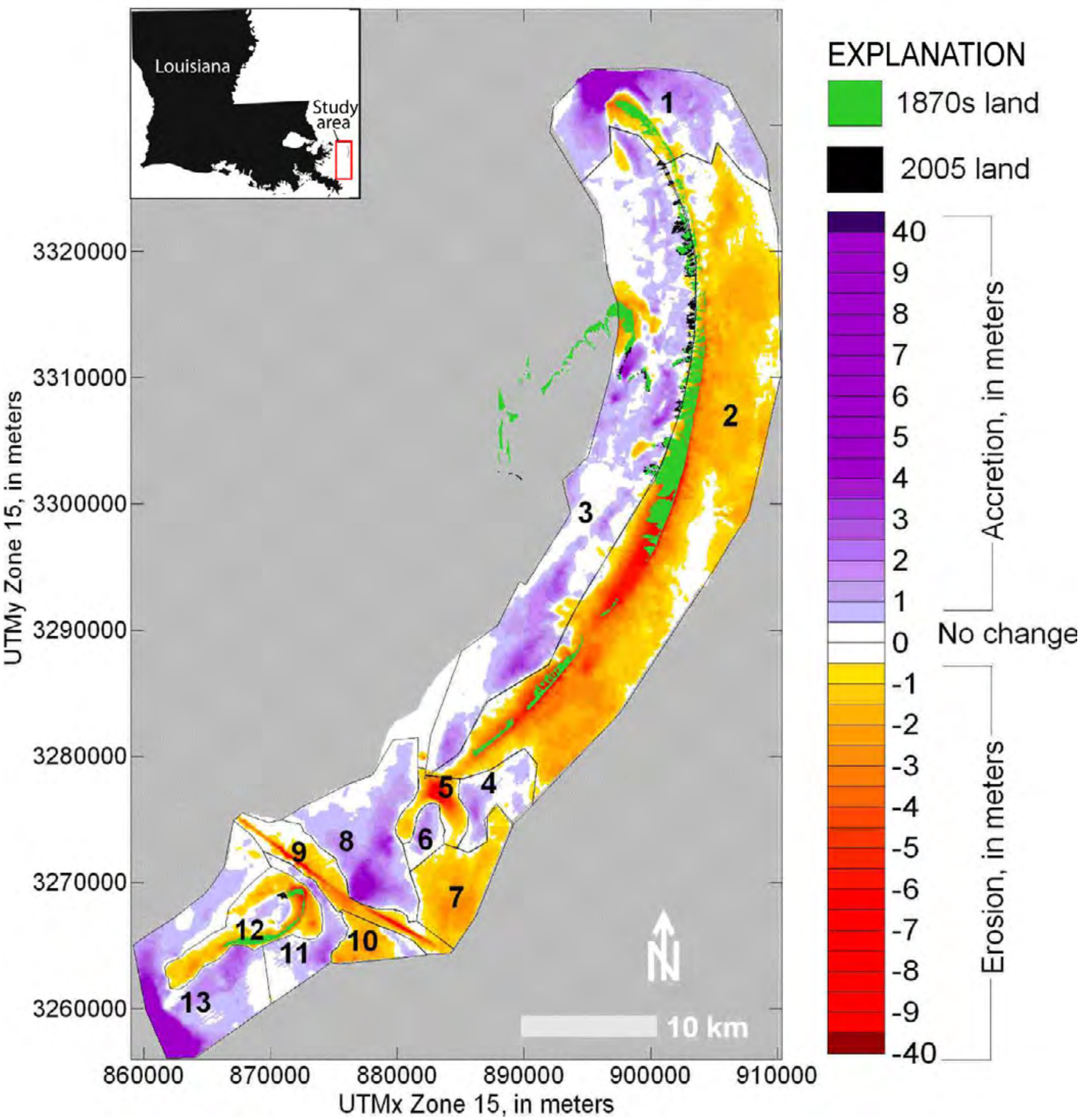

Figure 9. Sea floor change results for the Chandeleur Islands, La. (1870–2007). Numbered polygons delineate erosional or accretionary zones for which volumetric change data are presented in table 2. UTM, Universal Transverse Mercator.

Table 2. Volumetric change results for the Chandeleur Islands, La., 1870–2007.

[Zone location and extent are delineated on figure 9. m, meters; Dz min, maximum vertical erosion; Dz max, maximum vertical accretion; MRGO, Mississippi River-Gulf Outlet]

Zone	Accretion (× 10^6 m^3)	Erosion (× 10^6 m^3)	Net volume (× 10^6 m^3)	Area (× 10^6 m^2)	Net volume error ± (× 10^6 m^3)	Dz min	Dz max
1. Hewes Point/North Inlet	147.03	-18.26	128.77	91.67	25.67	-4.28	10.82
2. Northern Chandeleur shoreface	4.68	-289.98	-285.29	212.19	59.41	-8.06	1.5
3. Northern Chandeleur backbarrier	110.61	-26.50	84.11	166.76	46.69	-3.68	5.88
2a. Southern Chandeleur shoreface	1.49	-406.63	-405.14	163.52	45.78	-8.89	1.70
3a. Southern Chandeleur backbarrier	80.19	-4.72	75.47	84.92	23.78	-2.32	3.30
4. Updrift Curlew Pass ebb delta	14.30	-1.62	12.68	24.78	6.94	-1.20	2.85
5. Curlew Pass inlet scour	0.66	-34.27	-33.61	18.93	5.30	-7.20	1.40
6. Downdrift Curlew Pass ebb delta	7.74	-0.35	7.39	9.33	2.61	-0.64	2.82
7. Grand Gosier shoreface	0.29	-56.29	-55.99	40.61	11.37	-3.43	0.81
8. Updrift MRGO	91.20	-0.16	91.04	70.41	19.71	-1.00	4.67
9. MRGO	0.10	-52.18	-52.08	25.34	7.10	-8.54	1.91
10. Downdrift MRGO shoreface	1.72	-21.35	-19.62	15.88	4.45	-3.43	1.85
11. Breton Island Pass ebb delta and inlet fill	20.17	-0.13	20.04	20.69	5.79	-1.18	3.23
12. Breton Island nearshore/backbarrier	3.45	-51.03	-47.58	39.49	11.06	-7.95	1.33
13. Downdrift Breton Island	176.46	-0.10	176.35	74.98	2.10	-0.59	12.18
Total	660.09	-963.57	-303.46	1,059.5	277.76		

entire erosional area in Zone 2. The absence of sediment core data for the southern Chandeleurs does not allow for a percent sand correction factor to be applied for balancing the sediment budget as was done for the northern Chandeleurs.

Southern Chandeleur Islands (Monkey Bayou South to Breton Island)

The southern Chandeleurs are geomorphically more complex because of the presence of three major tidal inlets along this sector of coast, one of which, the MRGO, was maintained as a navigation channel until 2005. Another complicating factor is the ephemeral nature of the barriers along this stretch. Today there are no subaerially exposed barriers between Monkey Bayou and the northern tip of Breton Island. Instead, this 45-km stretch of former coastline is characterized by a series of subaqueous shoals separated by tidal inlets.

The southern Chandeleur shoreface (Zone 2a [zones are delineated in fig. 9]) that extends from Monkey Bayou south to Grand Gosier Pass underwent the greatest magnitude of erosion in the entire study area. Shoreface erosion resulted in the removal of 405.14 × 10^6 m^3 of sediment between 1870 and 2007, and maximum vertical erosion was 8.89 m. This stretch of coast has also undergone the highest rates (up to 17 m/yr between 1869 and 2004) of shoreline retreat along the entire Chandeleur Island shoreline. Deposition in the backbarrier (Zone 3a) was only 75.47 × 10^6 m^3 for this area. Much of the backbarrier deposition can be attributed to the landward migration of Curlew Island Shoal and Errol Shoal sand bodies.

Grand Gosier Pass, a tidal inlet that separates Curlew Island Shoal from Grand Gosier Islands Shoal, is not present in the pre-2007 survey datasets; however, it is noted on nautical charts dating back to the 1950s. The 2007 bathymetric data show that the inlet had scoured to a depth of more than 9 m, removing 33.61 × 10^6 m^3 of sediment from the inlet channel (Zone 5) since the 1870s. The development and seaward progradation of an ebb tidal delta associated with inlet formation (Zones 4 and 6) increased in volume by 20 × 10^6 m^3 during the time period covered by the study. The sequestering of sand updrift (north) of the inlet reversed the trend of shoreface retreat along this stretch of coast and accounted for 12.68 × 10^6 m^3 (Zone 4) of sediment deposition, and a downdrift lobe accounted for 7.39 × 10^6 m^3 of deposition.

Downdrift (south) of Grand Gosier Pass and north of the MRGO are Grand Gosier Shoals/Islands. These are part of the linear ephemeral barrier shoal/island trend that has migrated to the south since the 1870s by spit accretion. These islands also migrate landward (about 15 m/yr) by a process that involves total island destruction during storms and reemergence at a location landward of the prestorm island position during extended periods of calm weather (Penland and Boyd, 1985; Fearnley and others, this volume). This trend of lateral migration to the south has resulted in the deposition of a large volume of sediment (81.04 × 10^6 m^3) updrift of the MRGO (Zone 8).

The MRGO channel area (Zone 9) has undergone 52.08 × 10^6 m^3 of erosion since 1870, most of which can be attributed to the mechanical removal of sediment during the construction of the navigation channel. Maintenance dredging of this channel after hurricanes complicated sediment dynamics in this area because sediment removed from the channel was deposited in an offshore disposal area downdrift of the channel. Most of this disposal area is beyond the seaward limit of the study area. It should be noted that sand disposal in these offshore locations removed it from the littoral system, depleting the southern Chandeleur Islands of sediment.

Offshore of the MRGO is a zone of shoreface erosion (Zones 7 and 10). Much of this erosion can be attributed to collapse and landward retreat of the Breton Island Pass ebb tidal delta (Zone 11) resulting from natural tidal inlet landward migration in response to RSLR, as well as decreased sediment supply that is due to maintenance dredging. A total of 75.61 × 10^6 m^3 of sediment has eroded from this zone, with maximum vertical erosion of 3.43 m. Between 1870 and 2007 Breton Island Pass migrated to the west, forcing the retreat of northern Breton Island. Deposition in the form of inlet fill and ebb tidal delta growth (Zone 11) resulted in 20.03 × 10^6 m^3

Table 3. Sediment budget for the northern Chandeleur Islands, La., with percent sand corrections applied.

[m, meters]

Zone	Net volume (× 10^6 m^3)	Percent sand	Corrected net volume (× 10^6 m^3)
1. Hewes Point/North Inlet	128.77	80	103.02
2. Northern Chandeleur shoreface	-285.29	58	-165.47
3. Northern Chandeleur backbarrier	84.11	76	63.93

of added sediment offshore of Breton Island. Tidal scour and storm wave reworking of the Breton Island barrier complex resulted in 51.03 × 10^6 m^3 of net erosion in the vicinity of Breton Island (Zone 12). Moreover, only 3.45 × 10^6 m^3 of sediment has been deposited in the backbarrier. Much of this decrease in island area and subaerial sand volume at Breton Island is possibly due to sediment starvation associated with updrift MRGO channel maintenance dredging. Zone 13, which encompasses downdrift of Breton Island and the southern-most limits of the bathymetric data, underwent the greatest magnitude (176.35 × 10^6 m^3) of accretion of all geomorphic zones within the Chandeleur Islands study area. This southern subaqueous terminal spit is characterized by inlet fill development, lateral spit accretion to the south, and shoreface progradation and can be thought of as the southern counterpart to Hewes Point in the north (Zone 1). It should be noted that the limits of the study area do not capture the full extent of the Zone 13 downdrift and offshore depositional sand body.

Bathymetric Profiles

The bathymetric profiles were grouped into five sectors along the length of the barrier island arc on the basis of the shoreface evolution interpreted from the profiles. The sectors include, from north to south, (1) Hewes Point to Schooner Harbor (Profiles Hewes1, 1, and 2), (2) Schooner Harbor to Redfish Point (Profiles 7 and 9), (3) Redfish Point to Monkey Bayou (Profile 11), (4) Monkey Bayou to the MRGO (Profiles 14 and 17), and (5) Breton Island (Profile 21) (profile locations are presented in fig. 10). Typical profiles for each sector were selected for presentation here.

Sector 1: Hewes Point to Schooner Harbor

Sector 1 bathymetric profiles exhibit spit platform development and spit accretion north of Hewes Point and shoreface progradation in a gulfward (easterly) direction. The Hewes Point spit platform accreted 1,439 m laterally to the north (fig. 11) between 1870 and 2006 and broadened by approximately 800 m between 1920 and 2006 (fig. 12). South of Hewes Point, Profile 2 demonstrates that 626 m of shoreface progradation occurred during the period of study (fig. 13). The average rate of shoreface progradation for Sector 1 is 2.5 m/yr. Collectively these profiles illustrate the large volume of sediment deposited (128.77 × 10^6 m^3) in Zone 1 (see fig. 9) and the geometry of this deposit. It is important to note that all of this accretion took place below mean low water.

Sector 2: Schooner Harbor to Redfish Point

Sector 2 profiles an area characterized by shoreface retreat and a decreasing steepness of the shoreface profile. The average rate of shoreface retreat for this sector was 5.6 m/yr with magnitudes ranging from 461 to 902 m for the time period between 1870 and 2006. Many of the profiles in Sector 2 show shoreface erosion in a landward direction and erosion of the backbarrier shoreline in a seaward direction, resulting in an overall thinning of the island (fig. 14). Some of the profiles show barrier landward migration between the 1870s and 1920s with little to no backbarrier deposition between the 1920s and 2006 (fig. 15). The latter situation is typical along the central portion of the island arc and into Sector 3.

Sector 3: Redfish Point to Monkey Bayou

The mean shoreface retreat rate along Sector 3 was 8.8 m/yr, and the average magnitude of net change was 1,196 m between 1870 and 2007 (fig. 16). Shoreface retreat rates increased in a southerly direction. Average shoreface slope decreased from 0.0044 to 0.0031 for the same time period.

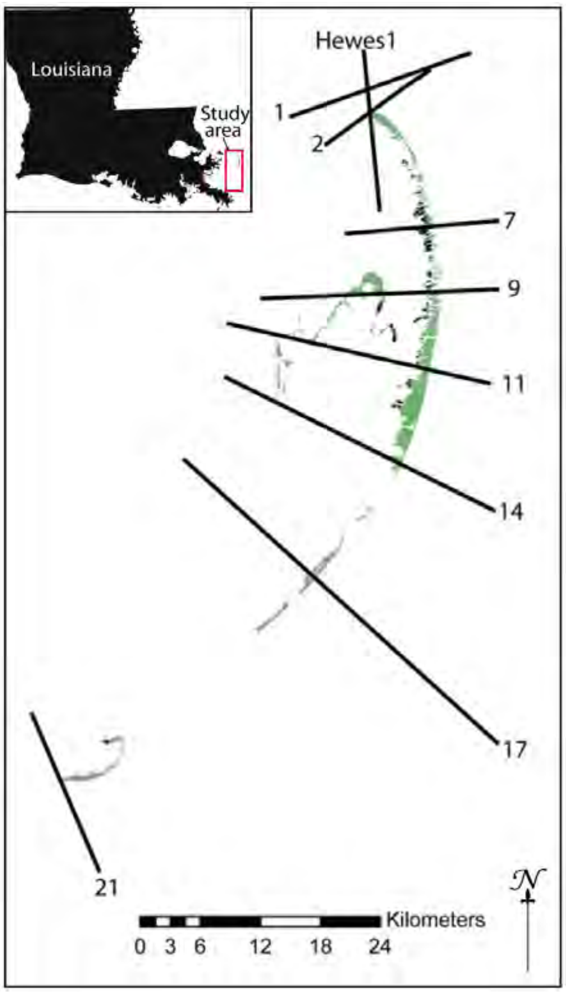

Figure 10. Representative bathymetric profile transect locations for the Chandeleur Islands, La. Shoreline configurations are for 1855/69 (green) and 2005 (black).

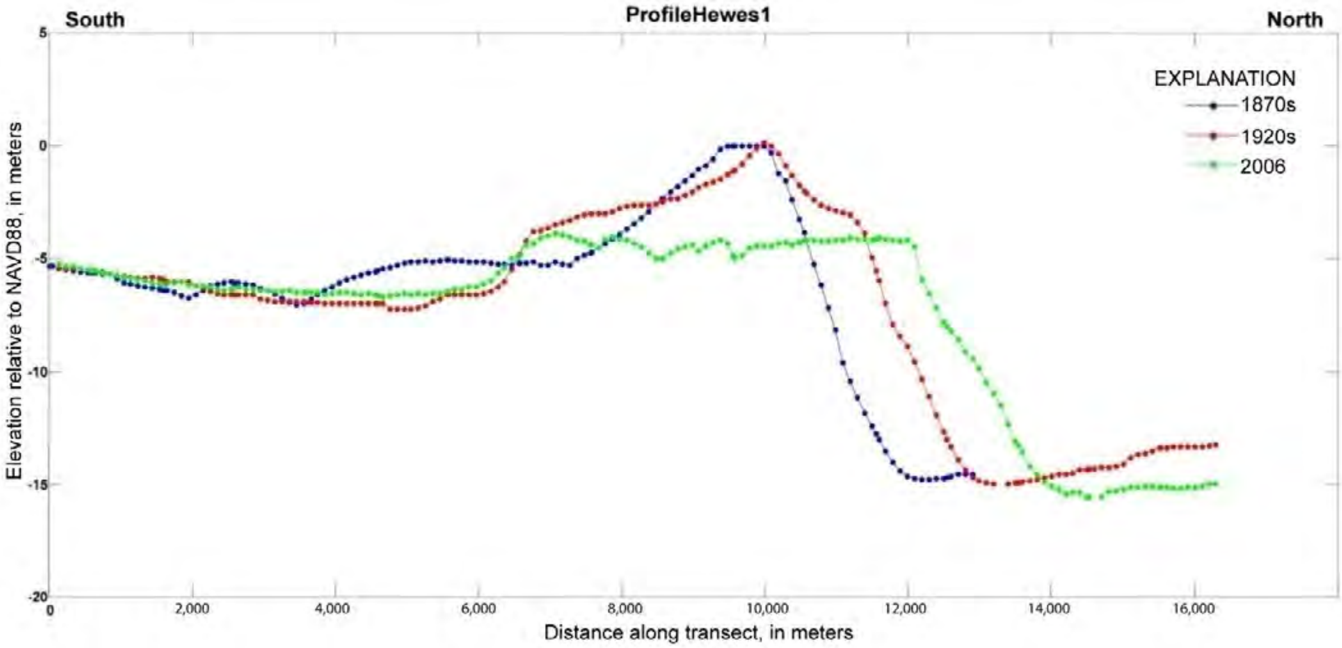

Figure 11. Profile Hewes1 trending north-south across Hewes Point, La. Note the nearly 1,500 m of northerly spit accretion between the 1870s and 2006. NAVD 88, North American Vertical Datum of 1988.

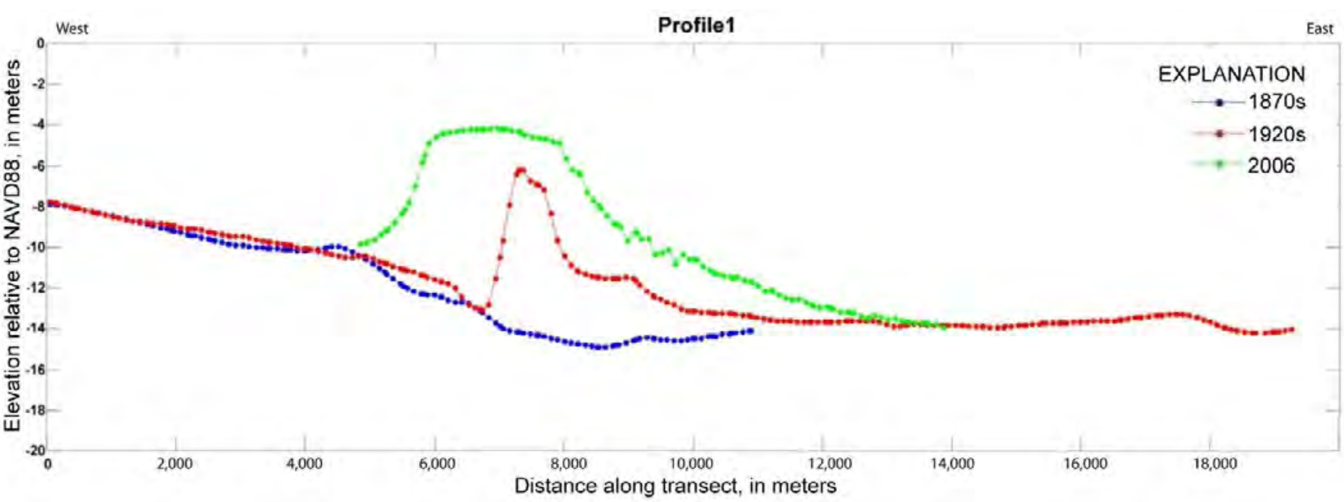

Figure 12. Profle 1 trending from Chandeleur Sound, La. (west), to the Gulf of Mexico (east). Note the vertical shoal aggradation by spit platform development north of Hewes Point, La. NAVD 88, North American Vertical Datum of 1988.

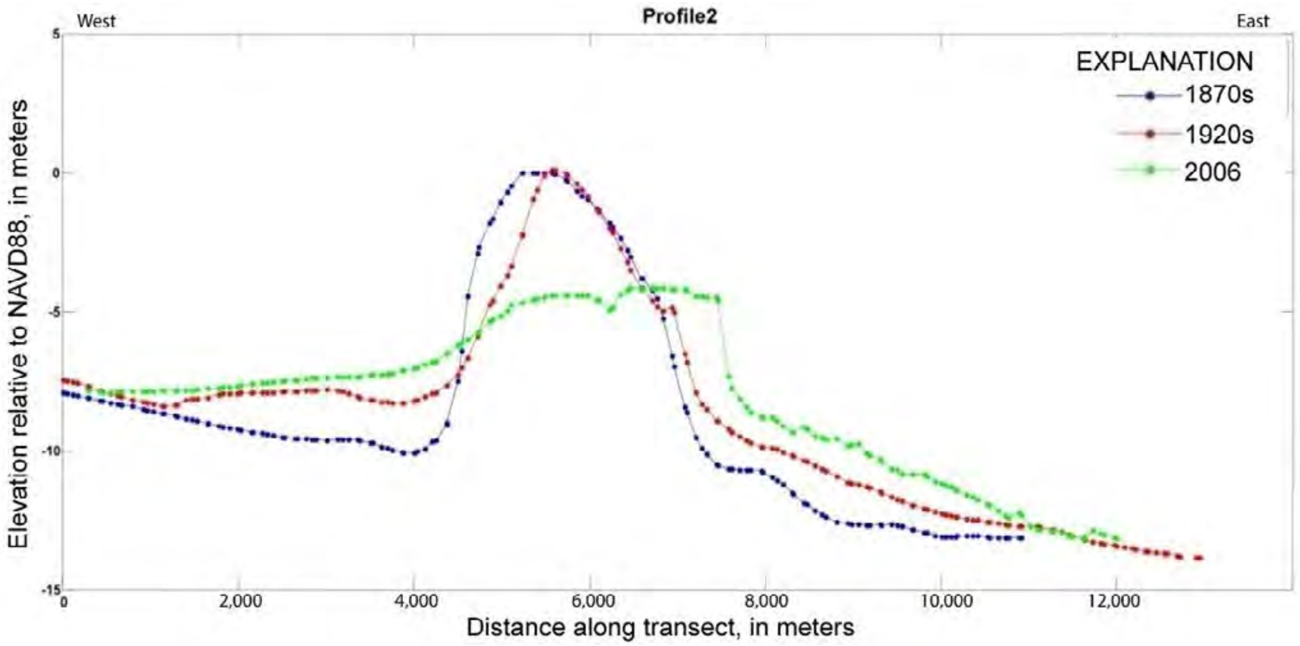

Figure 13. Profile 2 trending from Chandeleur Sound, La. (west), to the Gulf of Mexico (east). While the island became submerged along this northern section after Hurricane Katrina, 626 m of shoreface progradation occurred between 1870 and 2006. NAVD 88, North American Vertical Datum of 1988.

Shoreface retreat profiles show similar trends to the shoreline change trends for this sector (Fearnley and others, this volume): the 1870s and 1920s profiles show landward migration of the barrier (deposition in the backbarrier), but between the 1920s and 2007 there is little to no backbarrier deposition (landward island migration). Most of these profiles intersect shore-parallel backbarrier tidal channels that trend between the Chandeleur Islands and the North and New Harbor Islands in Chandeleur Sound. As the New Harbor Islands degrade, the channels are less constricted and show shoaling in later years. The new hurricane-cut tidal inlets (due to Hurricanes Ivan and Katrina) along the barrier shoreline provide additional pathways for tidal exchange between the sound and the gulf, causing an overall reduction in current velocity in some of the backbarrier tidal channels. The ensuing decrease in tidal current velocity in backbarrier channels allowed overwash sand deposition in some of the deeper channel sections.

Sector 4: Monkey Bayou to the MRGO

Sector 4 is also characterized by shoreface retreat, barrier conversion to shoals (there were no subaerially exposed barriers along this 45-km stretch of coast today), and a decrease in shoreface slope. The average shoreface profile slope decreased from 0.0032 in 1870 to 0.0021 in 2007. The average shoreface retreat was 1,864 m, and the average rate was 14 m/yr. The northern part of Sector 4 showed the greatest difference between the historical and present slopes, highest rates of shoreface retreat along the entire Chandeleur Islands shoreface, and little to no backbarrier deposition (fig. 17). The southern portion of Sector 4, containing the stretch of coast that includes Curlew Island Shoal and Grand Gosier Islands Shoal, exhibited the most consistent shoreface slope angles during the study period and was also characterized by barrier/shoal landward migration (fig. 18).

Sector 5: Breton Island

Shoreface behavior at Breton Island is complex because of the construction and maintenance dredging of the MRGO, migration of Breton Island Pass toward the island, and enlargement of the ebb tidal delta (figs. 1–3, 9). Shore-normal profiles are difficult to interpret because of these complexities. Retreat of the Breton Island shoreface to the south-southwest is driven by the southerly migration of Breton Island Pass at a rate of approximately 9 m/yr. South of Breton Island is a zone of accretion similar to Hewes Point; the shoreface seaward of Breton Island has prograded more than 2 km in a seaward direction since 1870 (fig. 19).

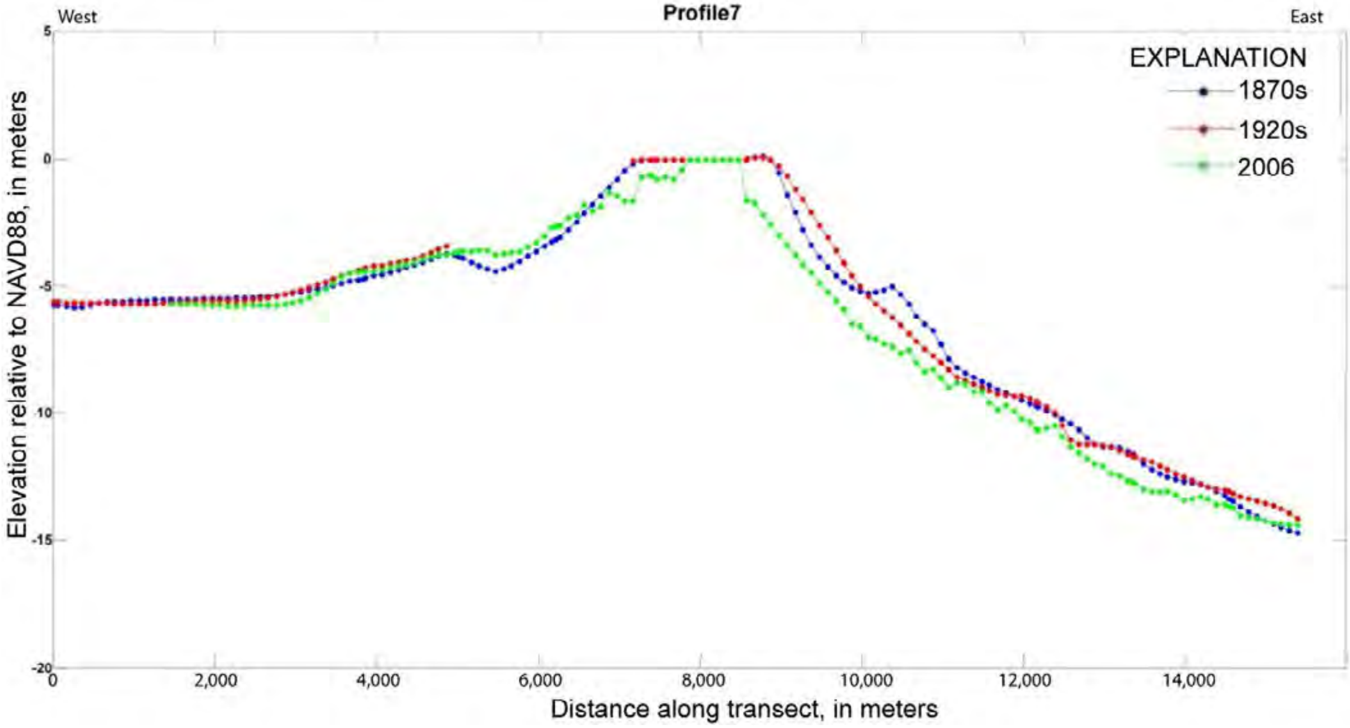

Figure 14. Profile 7 from Sector 2 near Schooner Harbor, La., showing shoreface retreat accompanied by backbarrier shoreline erosion resulting in in-place island thinning. NAVD 88, North American Vertical Datum of 1988.

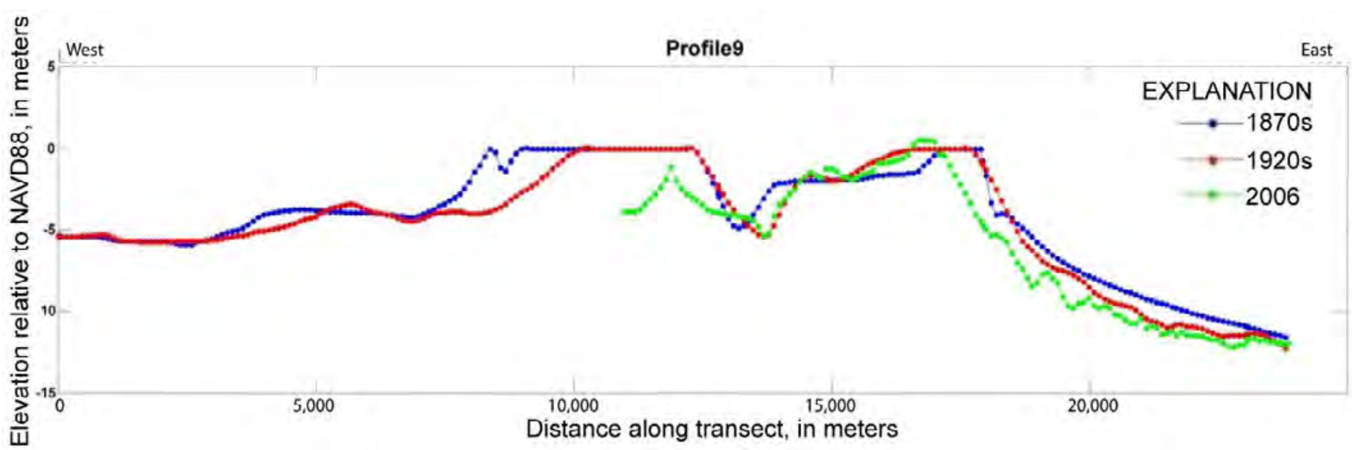

Figure 15. Profile 9 from Sector 2 north of Redfish Point, La., showing shoreface-retreat-accompanied deposition in the backbarrier for the 1870–1920 time period; backbarrier deposition did not occur during the 1920–2007 period. NAVD 88, North American Vertical Datum of 1988.

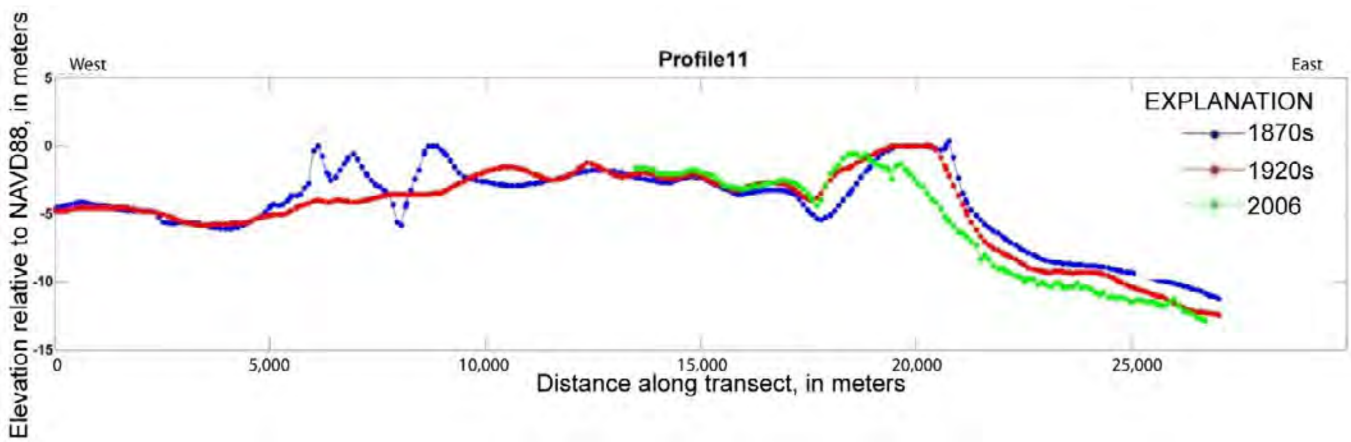

Figure 16. Profile 11 from Sector 3 between Monkey Bayou and Redfish Point, La., showing shoreface retreat accompanied by backbarrier deposition resulting in landward barrier migration. Note the decrease in slope between the 1870s and 1920s profiles and the 2007 profile. NAVD 88, North American Vertical Datum of 1988.

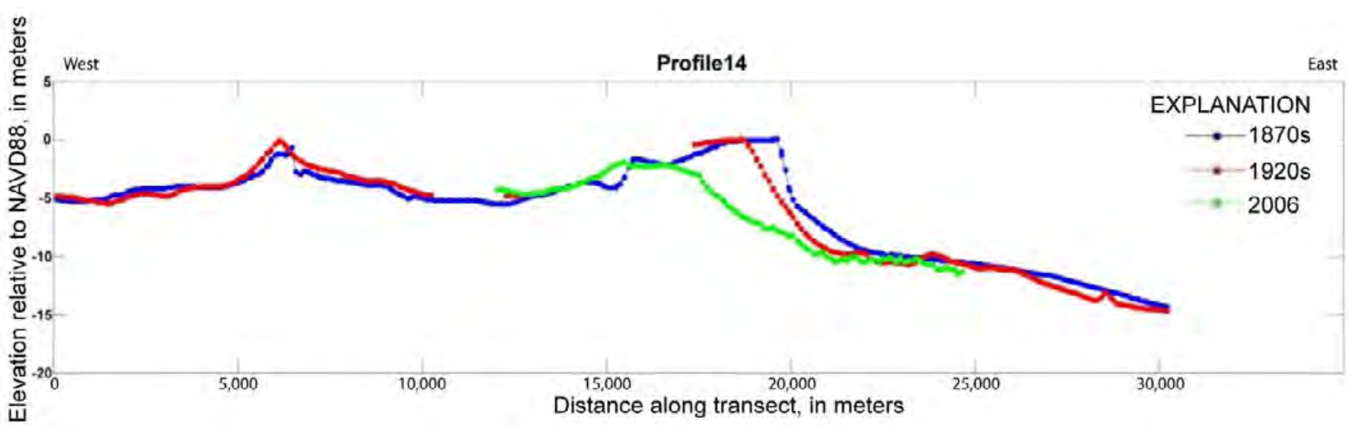

Figure 17. Profile 14 from Sector 4 south of Monkey Bayou, La. Profiles from the northern portion of Sector 4 are characterized by decreasing shoreface slope as islands migrate landward, converting to shoals with minimal backbarrier deposition. NAVD 88, North American Vertical Datum of 1988.

Discussion

Sediment Transport

Barrier island evolution along the Mississippi River Delta Plain involves the reworking of an abandoned deltaic headland by waves, storms, and tidal currents to form a sandy shoreline (fig. 8). Shoreline development and barrier geometry are controlled by orientation of the abandoned deltaic headland relative to the dominant wave approach. Wave-induced lateral transport is the most significant factor in the development of a barrier coastline along the Mississippi River Delta Plain (Penland and Boyd, 1985) and produces sand-rich flanking barrier islands. Because the transgressive shoreline is naturally isolated from the sediment load of the Mississippi River, there is a finite supply of sand for natural island maintenance. In earlier stages of barrier development a significant sand source is derived from erosion of deltaic deposits down to the shoreface. Once the deltaic sediment source has been completely reworked, or has subsided below effective wave base (about 7 m for the Chandeleur Islands; Penland and Boyd, 1985), the barrier and lagoonal deposits are continually recycled at the shoreface during retreat, which for a period of time allows the barrier system to maintain its exposure during RSLR.

Prior to this study, it had been suggested that the net loss of sediment from the Chandeleur Islands system was driven by an imbalance between onshore sediment transport volumes during fair weather conditions and offshore sediment transport volumes during storm conditions (Penland and others, 1988). This net export of sediment in an offshore direction produces a thin transgressive sand sheet offshore of the islands that is too deep for onshore transport by constructive fair weather waves. Based on this model, transgressive submergence eventually occurs because development of this sand sheet constantly removes sediment from the barrier system until a threshold is reached, beyond which the islands cannot maintain exposure (Penland and others, 1988). Here we present findings that show that sand is indeed being lost from the nearshore system to deepwater sinks, but the process is more complicated than previously suggested in the cross-shore sediment budget model. Our updated model includes a large volume of sediment transported to the flanks of the island arc, a condition that is similar to the early stages of barrier island development.

As demonstrated by the sea floor change DEM, the dominant sediment transport trends are shoreface erosion and deposition in deepwater sinks at the flanks of the island arc. Backbarrier deposition is minimal relative to the volumes eroded from the shoreface, indicating that, for the most part, sand is not being transferred in a landward direction for future recycling by means of shoreface retreat. Instead, lateral spit accretion, sourced by island and shoreface erosion, has led to sand being sequestered in downdrift, deepwater sinks and removed from the littoral system.

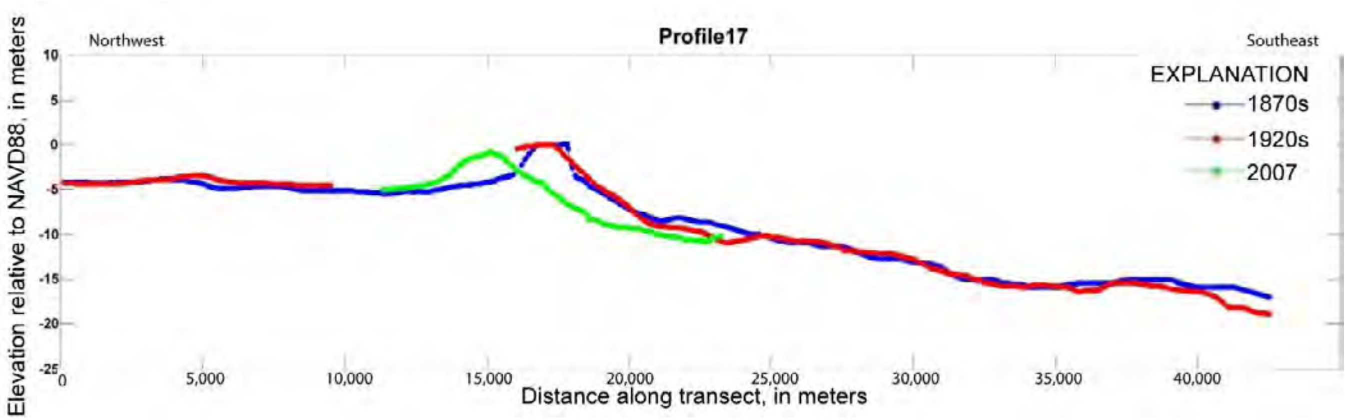

Figure 18. Profile 17 from Sector 4 at Curlew Island/Shoal, La. Profiles from the southern portion of Sector 4 are characterized by low-gradient shoreface slope and landward-migrating islands/shoals. NAVD 88, North American Vertical Datum of 1988.

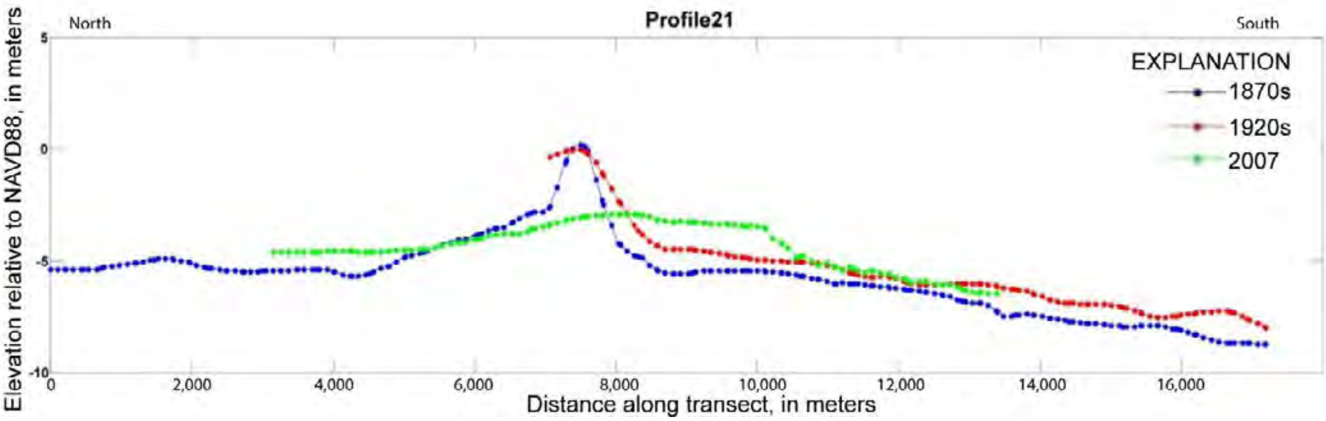

Figure 19. Profile 21 from Sector 4 south of Breton Island, La., showing more than 2 km of seaward shoreface progradation south of Breton Island, La., that is accompanied by island submergence. NAVD 88, North American Vertical Datum of 1988.

Shoreface Evolution and Transgressive Submergence

One of the most apparent trends demonstrated in the profile data is the relation among shoreface retreat rates, shoreline erosion rates, and decreasing shoreface slope through time (fig. 20). There is also a correlation between the shoreface slope angle and barrier evolution during the period of study. The southern Chandeleurs have a relatively gentle shoreface slope and are characterized by barrier landward retreat, barrier shoals, and ephemeral barrier islands with no well-established backbarrier marsh. The northern Chandeleurs have a relatively steep shoreface and are characterized by barriers that are undergoing shoreline erosion that is not accompanied by landward barrier island migration. These islands are backed by a well-established (based on historical maps, more than 150 years) backbarrier marsh. Within the period of study, some sections of coast (for example, central Chandeleurs just south of Monkey Bayou; fig. 17) have converted from the steeply sloping/shoreline erosion category to the gently sloping/ephemeral barrier type.

Along sections of the island chain where a thick backbarrier marsh is present, the shoreline is somewhat anchored by the cohesive sediment and root mat that make up the marsh deposits. These marsh deposits serve as nucleation sites upon which sand can accumulate during storm recovery periods. This more resistant substrate inhibits the total destruction of islands during storms. It serves to slow the rate of shoreline erosion because it forms a barrier beyond which sand transported by waves cannot pass and therefore accumulates as bars weld to the shoreline. In contrast, where no backbarrier marsh is present or where it is destroyed during storms, sand in the nearshore zone can be transported landward by waves, and there is no nucleation site for sand accumulation and the formation of accreting spits.

The parts of the islands that are backed by marsh do not migrate as rapidly, and the shoreface matures and becomes steeper. Parts of the islands that are not backed by marsh are destroyed during storms and reemerge during calm weather in a position landward of their prestorm location.

Results of this study capture a transition from relatively sediment-rich barriers (1870s to 1922) that built new land in the backbarrier by overwash, flood tidal delta, and recurved spit formation to sediment-starved barriers that no longer built new backbarrier land and began to thin in place (1922–2005). Once the thinning reaches the point where no backbarrier marsh exists, the barriers cross the transgressive submergence threshold, becoming mobile sand bodies that migrate landward through a cycle encompassed by storm destruction followed by emergence landward of their former positions during calm weather (fig. 21).

Anatomy of a Threshold Crossing

The Chandeleur Islands are undergoing transgressive submergence by means of a multistage process that involves the following:

- Decreased barrier sand supply restricting new backbarrier marsh development;
- Continued gulf and backbarrier shoreline erosion resulting in barrier thinning and segmentation.

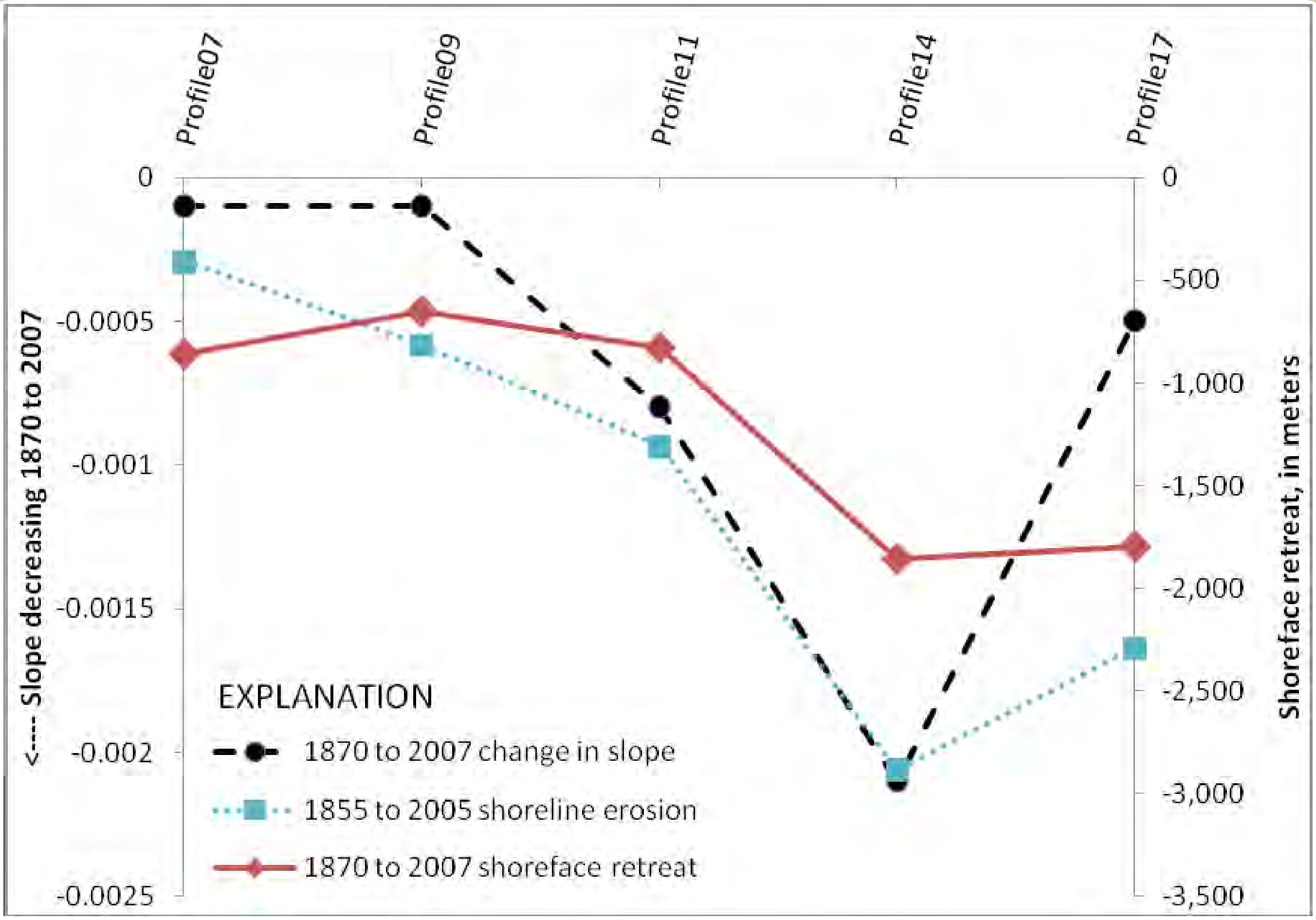

Figure 20. Relation among magnitude of decreased shoreface slope between 1870 and 2007, shoreface retreat rates, and shoreline erosion rates. Note the correlation among decrease in slope magnitude, shoreface retreat, and shoreline erosion. Profile locations are shown in figure 10.

In this multistage process, landward migration is limited because the Chandeleur Islands are stabilized by backbarrier marsh deposits that inhibit landward transfer of sediment by waves. Overwash and eolian processes are not effective at facilitating landward migration of barrier sediment because of the paucity of sand in the subaerial barrier. Fragmented marsh islets that are the remnants of landward protrusions from the backbarrier shoreline (for example, Redfish Point, Schooner Harbor, Monkey Bayou) anchor the longshore sediment transport system. Spits accrete laterally to connect individual islets forming a continuous shoreline.

The gulf shoreline ultimately reaches the backbarrier shoreline, and islands are no longer stabilized by backbarrier marsh, resulting in a sandy ephemeral barrier and the onset of transgressive submergence. The ephemeral barriers are destroyed during storms when the sand is dispersed both offshore and into the backbarrier. During calm weather, landward migration slows, allowing sand that is stored in the gently sloping shoreface to move onshore, forming an equilibrium shoreface profile. This process facilitates the transfer of sand in a landward direction in volumes that are sufficient to maintain island exposure in response to RSLR. The loss of backbarrier marsh forces a shift in the sediment transport regime from the previously dominant longshore direction to one dominated by cross-shore processes. The system becomes more efficient at recycling sediment during landward retreat; however, increased storm frequency inhibits island reemergence and subaerial expansion, processes that occur during extensive calm weather periods. In a regime of frequent storms, the sand that is transported offshore during a storm does not have sufficient time to move onshore and reorganize into a linear shoal

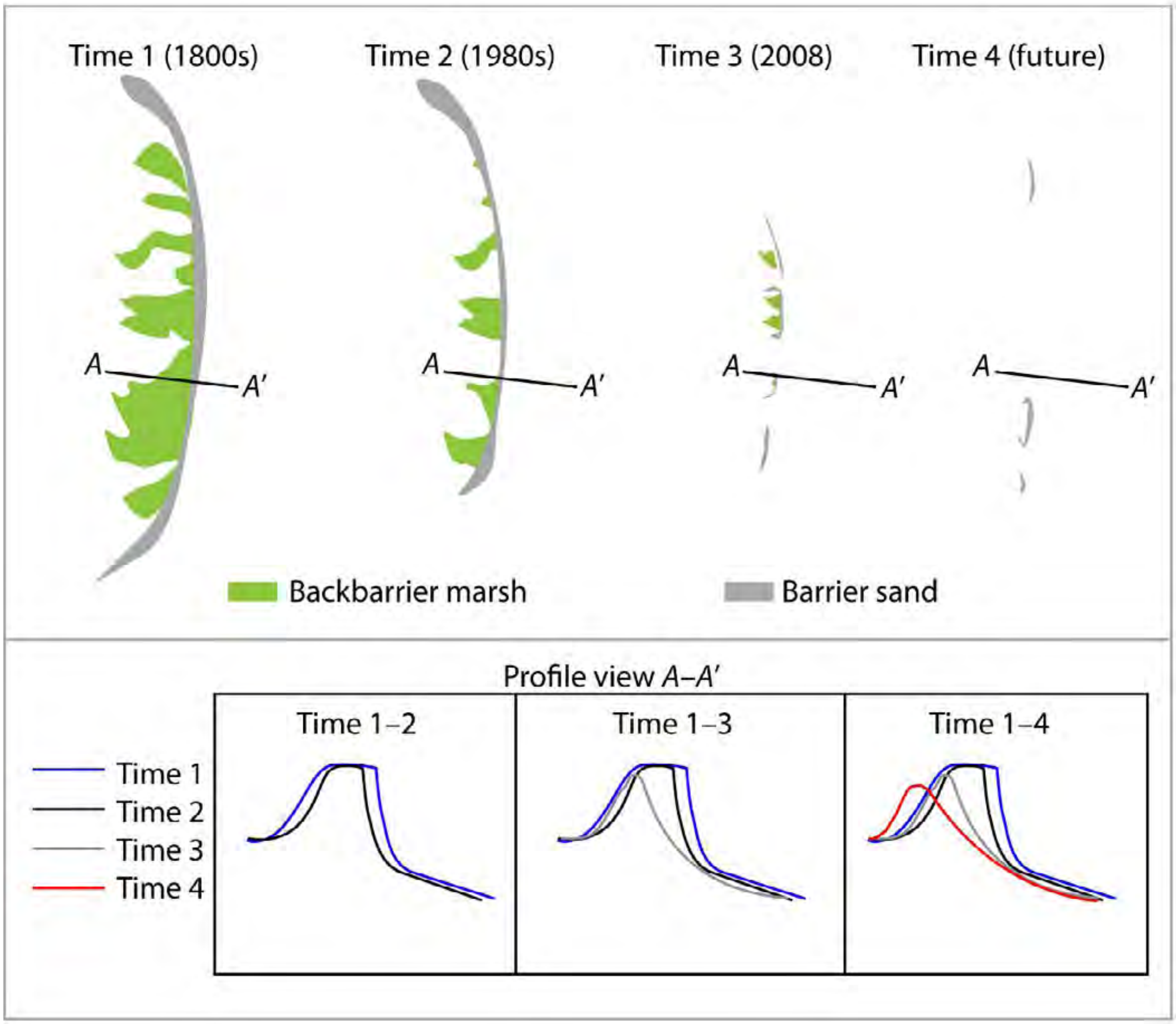

Figure 21. Conceptual model for barrier island transgressive submergence.

before being impacted by a subsequent storm resulting in a net loss of sand offshore and development of an offshore sand sheet in the retreat path of the landward-migrating ephemeral barrier islands/shoals.

Conclusions and Implications for Island Management

1. Long-term reduction in island area is driven by pulses of rapid land loss triggered by storm events. The islands do not fully recover from storm impacts because sand is transported to the flanks of the arc and is thus removed from the littoral system. The remnant marsh islands are the "backbone" that stabilizes the barrier chain. Once this marsh has eroded, the entire chain will begin to behave

similar to the southern ephemeral barriers (Curlew and Grand Gosier Islands/Shoals).

2. Because of long-term volume reduction in the littoral sand budget, a trend that was greatly accelerated by Hurricane Katrina, the islands are incapable of maintaining exposure by means of landward transfer of sand during storm events (overwash processes). It has been observed that during the poststorm recovery period, however, the landward transfer of sand occurs by (a) landward migration of offshore bars that weld to marsh islets, (b) recurved spit formation at hurricane-cut inlets, and (c) eolian processes (dunes, wind tidal flats, and wind-deposited sand on the backbarrier marsh surface). Because of the large volume of sand removed from the littoral system during Hurricane Katrina, the islands have become sediment starved, and the recovery processes described above appear to have exhausted most of the available sand supply, limiting further recovery.

3. The long-term diminished sediment supply, location of sediment sinks, and storm recovery processes documented in this study provide an understanding of what drives early stages of barrier island arc transgressive submergence and the natural sediment dispersal processes at work that prolong submergence. On the basis of this documentation of where the sand is going, how long it takes to get there, and how the islands naturally respond to a rapid introduction of new sediment, we can more confidently formulate barrier management strategies; however, future storm frequency is a major unknown.

4. A modification of the transgressive barrier island evolution model proposed by Penland and others (1988) is an outcome of this study. The finding that lateral transport dominates over cross-shore transport is important because instead of sand being removed and deposited offshore as thin sand sheets we now know that sand is being concentrated as thick spit platform sediment bodies at the flanks of the island arc. These downdrift sand reservoirs may provide a unique, quasi-renewable resource for nourishing the updrift barrier system (that is, the central arc). Barrier island sediment nourishment should be executed with the understanding that gulf shoreline erosion is inevitable, distribution of hurricane-cut passes should be maintained as storm surge/overwash pathways, and well-established (decadal to century scale) sandy backbarrier platform construction and vegetation are crucial to long-term sustainability.

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