

Linking backbarrier lacustrine stratigraphy with spatial dynamics of shoreline retreat in a rapidly subsiding region of the Mississippi River Delta

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ABSTRACT

The northern Gulf of Mexico shoreline is rapidly retreating, and coastal features of the abandoned Mississippi River delta complexes are eroding and subsiding. Bay Champagne is located in the Caminada-Moreau headland, a region located west of the currently active delta that has one of the highest rates of retreat and land loss globally. As a result, the shoreline at Bay Champagne has retreated more than two kilometers in the past 130 years, causing a gradual transition from a stable, circular freshwater lake to a frequently disturbed, semi-circular backbarrier lagoon. Analyses of clastic layers in a series of sediment cores collected at this site over the past decade indicate the lake was less perturbed in the past and has become increasingly more sensitive to marine incursion events caused by tropical cyclones as the shoreline retreated. Geochemical and pollen analyses of the cores also reveal profound changes in environmental and chemical conditions at Bay Champagne over the past century. Through relating stratigraphy to spatial changes observed from satellite imagery, this study establishes a timeline of the transition of Bay Champagne from an inland lake to a backbarrier environment, and demonstrated that these changes have not occurred at a constant rate. These results provide a case-study of changing local environmental conditions in response to rapid shoreline retreat, and therefore serve as a model for future coastal changes for Louisiana and other Gulf coastal areas.

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1. Introduction

Many coastlines around the world are currently impacted by shoreline retreat. Over the past several decades, an estimated 28,000 km² of coastal land area globally has been eroded or lost through a combination of anthropogenic factors, relative sea level rise, and natural hazards (Mentaschi et al., 2018). Eastern North America is no exception, where coastal land loss outpaces land aggregation (Mentaschi et al., 2018), particularly along the Gulf of Mexico coast (Luijendijk et al., 2018). Notably, shoreline retreat rates along the Louisiana coast are currently among the highest in the world (Penland and Suter, 1988; Penland and Ramsey, 1990; McBride and Byrnes, 1997; Penland et al., 2005; Dietz et al., 2018; Luijendijk et al., 2018). Several factors are responsible for this rapid shoreline retreat, including sea-level rise, subsidence and compaction of Holocene deltaic sediments, and reduced sediment supply due to the construction of dams and levees (Kulp et al., 2005; Blum and Roberts, 2009). One region of the Louisiana

coast with a particularly high rate of shoreline retreat is the Caminada-Moreau headland (Harper, 1977; Penland and Ritchie, 1979; Penland et al., 1986; Penland and Suter, 1988; McBride and Byrnes, 1997; Penland et al., 2003; Penland et al., 2005; Henry and Twilley, 2013; Dietz et al., 2018; Yao et al., 2020). Located west of the active Mississippi River delta, this stretch of coastline was once part of the Lafourche Delta lobe that was abandoned by the Mississippi River within the last 1000 years (Harper, 1977; Penland and Ritchie, 1979; DeWitt et al., 2007). Since then, erosional processes have altered the morphology of the Caminada-Moreau headland considerably, and significant land loss has occurred (Harper, 1977; Penland and Suter, 1988; Penland et al., 2005; Penland and Ritchie, 1979; Penland et al., 2003).

The average annual rate of shoreline retreat for the Caminada-Moreau headland over the past century has been estimated at approximately 12.5 m/yr (Penland et al., 2005). However, modern rates of shoreline retreat at Bay Champagne, a backbarrier lagoon located on this stretch of coast (Fig. 1), have been shown via satellite imagery analysis to vary considerably, particularly in response to increases in Gulf of Mexico hurricane activity (Dietz et al., 2018). Approximately 300 m of shoreline retreat occurred during the past 35 years alone, and rates of

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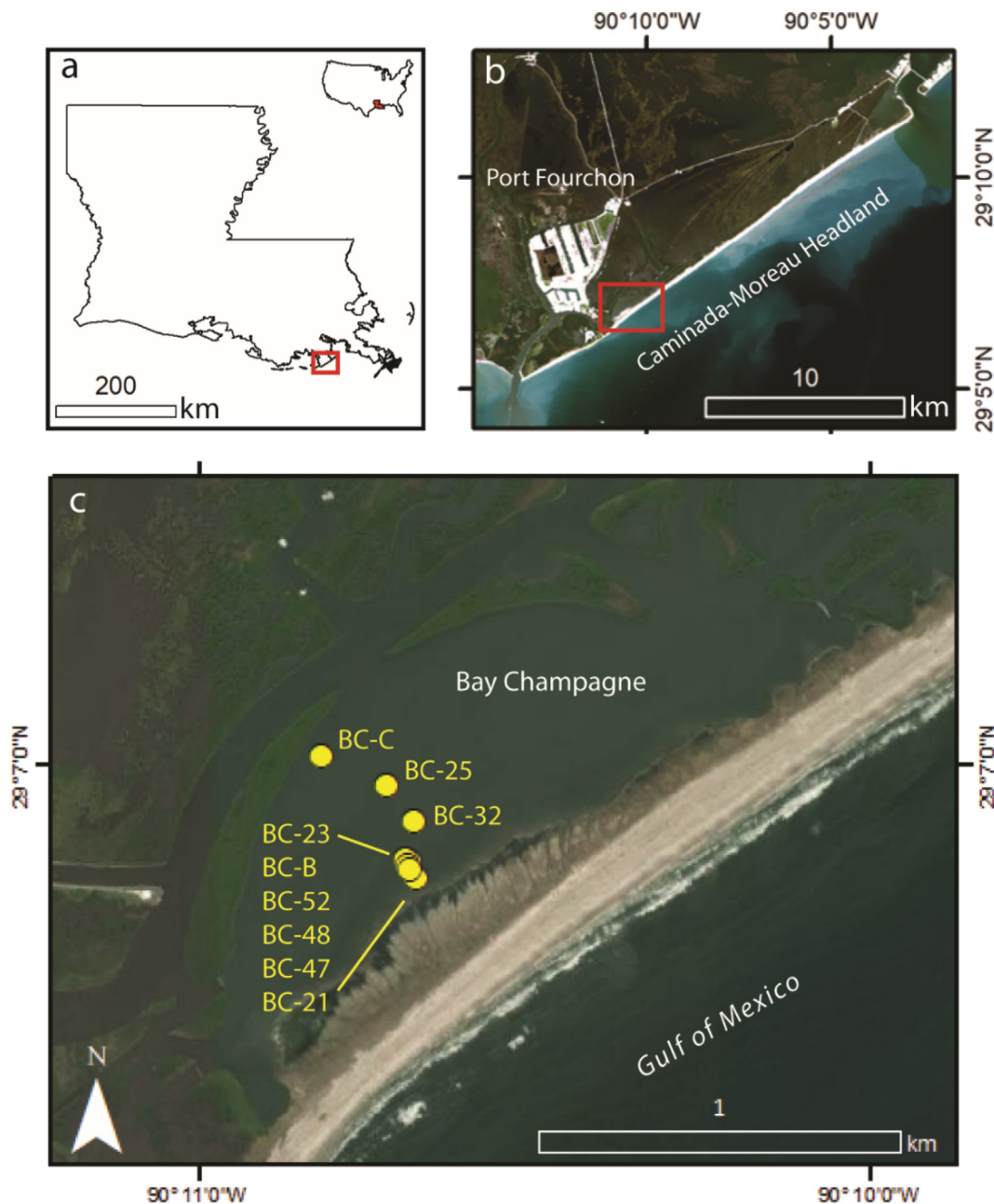


Fig. 1. Bay Champagne is located on the coast of south-eastern Louisiana (a), on the southwestern part of the Caminada-Moreau Headland (b). Bay Champagne is a shallow, semi-circular coastal lagoon separated from the Gulf of Mexico by a barrier beach (c). Collection locations for the nine sediment cores analyzed are shown as yellow dots. Cores BC-21 through BC-23 are listed in order from SE to NW. Image credits: Landsat 8 (b), and Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community (c). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shoreline retreat were five times higher than normal during a 16-year period (1998–2013) of above average hurricane frequency (Dietz et al., 2018). Such variability in shoreline retreat rate during modern times suggests that past movement may not have occurred at a constant rate. However, the lack of annual detailed information on shoreline position prior to the 1980s makes the completion of a high temporal-resolution study of Louisiana shoreline retreat difficult.

Land surveys of the Caminada-Moreau coast during the late 1800s show the regional shoreline was several kilometers seaward of its present location, with Bay Champagne existing as a circular inland lake (Penland et al., 2003; Penland et al., 2005). Subsequent shoreline retreat has resulted in significant loss of lake area and transformation of the circular lake to the semi-circular backbarrier lagoon that is present today.

This process likely caused changes to the local environment and vegetation over time, as the site became more saline. This transition makes Bay Champagne an ideal location to study the environmental effects of long-term shoreline retreat.

As shoreline retreat occurred, Bay Champagne would have become increasingly vulnerable to hurricane impacts. When the lake was located further inland, only the strongest and/or most direct hurricanes would have generated the storm surge sufficient to transport marine water and sediment over that distance. Erosion of coastal land between the lake and the Gulf of Mexico indicates Bay Champagne gradually became more susceptible to marine inundation through storm surge overwash processes. The further the shoreline retreated, the frequency of such inundations would have increased, since weaker storms that

previously may not have impacted the site would become capable of doing so (Liu, 2004). Thus, Bay Champagne is expected to have become more sensitive to hurricane impacts in conjunction with shoreline retreat. An environmental reconstruction is therefore needed to accurately interpret hurricane events recorded in sediment cores from this lake.

Coastal lakes, like Bay Champagne, are natural sediment traps for terrigenous runoff and marine incursion events, and are thus an archive of depositional events. Sediments at Bay Champagne likely document the gradual transition from inland lake to coastal lagoon, and may indicate when this transition occurred. Inorganic sedimentary chemical composition can be investigated through X-ray fluorescence (XRF) analysis to indicate marine- and terrestrially-derived sediment origins (Rothwell and Croudace, 2015) and to reconstruct paleoenvironmental conditions (Kylander et al., 2011; Chawchai et al., 2015; Larson et al., 2015; Orme et al., 2016). The general source of organic material in sediments can be examined by measuring the stable isotopic values of carbon, which differ between marine organic matter and terrestrial plant organic matter (Meyers, 1994; Lamb et al., 2006). Pollen analysis can be used to reconstruct vegetation changes over time (Liu et al., 2008; Yao et al., 2015; Yao et al., 2020).

With the aid of historic maps and aerial photographs, this study presents a 130-year record of shoreline retreat for a single site on a rapidly retreating stretch of the Louisiana coast. Previous studies have investigated shoreline retreat at a state or regional scale (Harper, 1977; Penland and Suter, 1988; Penland et al., 2003; Martinez et al., 2009) but significant variations in shoreline retreat rates have occurred even within a single stretch of this coastline (Martinez et al., 2009). Therefore, multi-decadal reconstructions of shoreline retreat are likely more accurate on a local scale rather than a regional scale.

The main objective of this study is to investigate how the impacts of spatial changes in shoreline position over the past 130 years have altered the local environment at Bay Champagne, and whether those alterations are captured in the sediment record. We examine how local environmental conditions and vegetation evolved in response to long-term shoreline retreat through analyses of several sediment cores. Similar trends observed from multiple geochemical and sediment proxies are used to establish a timeline of the transition of Bay Champagne from freshwater lake to brackish lagoon. We also seek to identify evidence that this site has become more sensitive to storm surge during the last century as a result of rapid shoreline retreat.

2. Study site

Bay Champagne is a semi-circular coastal lake situated on the southwestern end of the Caminada-Moreau headland, near Port Fourchon (Fig. 1b). The lake is brackish and shallow with a mean depth of ~2 m. Currently, Bay Champagne and the rest of the Caminada-Moreau headland are not directly influenced by the Mississippi or Atchafalaya Rivers. The site is microtidal with an average tidal range of less than 0.4 m, and is surrounded by mangrove and saltmarsh vegetation. Limited freshwater sources are from local precipitation and input from Bayou Lafourche; these freshwater inputs are assumed to have remained relatively constant over the study period. Navigation channels provide access between Bay Champagne and the Port Fourchon area, but there is no direct connection to the Gulf of Mexico. Intermittent connections to the Gulf have occurred in the past through breaching of the relatively narrow coastal barrier beach and dune (Whitehurst and Self, 1974). The relatively low dune separating the lake from the Gulf has one of the lowest elevations on the Caminada-Moreau headland (Ritchie and Penland, 1988) and can be overtopped by storm surge in excess of 1.2 m (Penland and Ritchie, 1979). Evidence of overwash at Bay Champagne is visible in satellite imagery as a large depositional fan immediately inland from the barrier beach, and as sand layers preserved in sediment cores from the lake's interior (Fig. S1, supplemental material) (Liu et al., 2011; Naquin et al., 2014).

3. Methods

3.1. Historic map analysis

Shoreline position was reconstructed using ten historic maps and aerial photographs collected from the Louisiana State University Cartographic Information Center. These maps and photos covered the past 130 years; the oldest available map was a land survey completed in 1887 (Table 1). After 1983, Landsat imagery (30-m spatial resolution) was used to determine shoreline position. Maps and photographs were digitized and georectified using ArcMap (v10.5). Shoreline positions and lake boundaries were manually delineated for each map and image. Shoreline retreat distance was determined by measuring the change in these positions over time along a transect drawn in the center of the lake.

The number of historic maps and aerial photographs for this region is limited, with no documents available from the early twentieth century. Since the lack of shoreline position data creates a gap of more than 50 years between available maps, it is necessary to use spatial interpolation to estimate decadal-scale shoreline positions throughout the study period. Ten different shoreline positions from 1887 to 2017 were used as the basis for this analysis. A nearest neighbor interpolator was implemented to create a raster surface estimating shoreline position for each year during the study period. Contour lines were drawn on this surface delineating the shoreline position at each decade. Estimated annual rates of shoreline retreat were then calculated by dividing the estimated change in shoreline position between decades by ten years.

3.2. Sediment stratigraphy and geochemistry

Sediment geochemistry were analyzed from nine sediment cores. These cores were collected between 2008 and 2016 (Table 2) from sites that were selected to represent a relatively shore-normal transect (Fig. 1c). Many of the cores were collected near the barrier beach to capture hurricane deposits from storm surge overwash events. These cores were also expected to reflect a brackish environment due to their proximity to the beach and the Gulf of Mexico. The cores collected further from the beach were expected to show a stronger fluvial influence compared to the cores collected near the beach, and also less disturbance by shoreline retreat processes and hurricane overwash. The nine cores range in length from 41 cm to 240 cm, and were collected via Russian peat borer or aluminum push coring methods. The entirety of each sediment core was used in this study, with the exception of BC-32. Due to the length of this core (over 2 m), only the top 50 cm was analyzed for comparison with the other cores.

Each core was visually inspected. Loss-on-ignition (LOI) analyses were performed at 1-cm intervals in each core. Samples were burned

Table 1

List of historic maps and aerial photographs used to establish changing shoreline position at Bay Champagne over the past 130 years.

Year	Source	Name	Type
1887	U.S. Coast and Geodetic Survey	From Grand Pass Timballier to Bayou Moreau, LA	Map
1892	U.S. Coast and Geodetic Survey	Cheniere Caminada Sheet	Map
1945	USGS	New Orleans, LA	Map
1949	USGS	Belle Pass Quadrangle	Map
1953	USGS	Belle Pass Quadrangle	Map
1957	USDA	CPV-2T-5	Aerial Photo
1963	USGS	New Orleans, LA	Map
1966	USGS	New Orleans, LA	Map
1979	USGS	Belle Pass Quadrangle	Map
1980	USDA	22057 278-128	Aerial Photo

Table 2

Collection locations and date of collection for the nine sediment cores analyzed in this study. Only data from the top 50 cm were used from core BC-32.

Core ID	Length (cm)	Lat	Long	Date Collected
BC-21	41	29° 6'51.88"N	90° 10'41.20"W	9/19/2008
BC-23	45	29° 6'52.38"N	90° 10'41.12"W	9/19/2008
BC-25	48	29° 6'58.39"N	90° 10'43.25"W	9/19/2008
BC-32	240	29° 6'55.51"N	90° 10'40.80"W	12/2011
BC-47	42	29° 6'52.67"N	90° 10'41.45"W	9/12/2012
BC-48	45	29° 6'52.06"N	90° 10'41.41"W	9/12/2012
BC-52	62	29° 6'51.84"N	90° 10'41.12"W	9/12/2012
BC-B	93	29° 6'51.19"N	90° 10'40.62"W	11/11/2016
BC-C	72	29° 7'00.70"N	90° 10'49.00"W	11/11/2016

at 105°, 550° and 1000 °C, to determine the relative percentages of water, organic matter, and carbonates, respectively, present in each sample (Dean, 1974).

Samples from cores BC-B and BC-C were submitted for radiocarbon and ^{137}Cs dating. However, establishing a sediment chronology through traditional dating techniques for this site has proven challenging. The ^{14}C date from the bottom of BC-C was deemed too old to be relevant for the time frame of this study; the ^{14}C date for BC-B came back as post-1950 (modern). Results for ^{137}Cs dating were inconclusive, as the concentration of this isotope was too low to be measured in several samples. Such dating challenges are commonly encountered in dynamic coastal environments (Stanley and Chen, 2000), particularly shallow-water lagoonal sediments that are subjected to storm overwash, bioturbation, and resuspension. Additionally, precisely dating recent, multidecadal sediment stratigraphies that are known to have been interrupted by thick storm deposits is even more problematic due to the episodic dilution of Cs isotopes and disturbance and reworking of sedimentary processes. These challenges highlight a need for alternative methods of establishing chronological control for deltaic sediment stratigraphies such as those explored in this study.

Geochemical profiles were determined with a handheld Innov-X Delta XRF scanner. Each core was scanned at 2-cm intervals, the smallest possible interval for this instrument. Results were reported in ppm and converted to weight percent. Calcium is used as a proxy for marine-derived sediments (Bianchette et al., 2016) and marine incursion to the study site. Titanium is a commonly used indicator of terrestrial sediment sources and deposition via fluvial processes (Kylander et al., 2011; Rothwell and Croudace, 2015). The ratio between Ca and Ti has often been used as an indicator of the relative importance between marine and terrestrial input in coastal sedimentary studies (McCloskey et al., 2015; Bianchette et al., 2016; Bianchette et al., 2017; McCloskey et al., 2018).

Three sedimentary zones (modern, transition, lacustrine), were identified based on the lithologies of the sediment cores. The modern zone, occurring at the top of most cores, is composed of modern storm deposits attributable to two recent hurricanes, Gustav and Ike of 2008 (Liu et al., 2011). Storm overwash event layers were also identified as unique stratigraphic layers interspersed within most of the cores. Ca and Ti concentrations for the samples contained within each zone in each core were averaged to create one value per zone per core, resulting in a maximum of four values per element per core. In order to determine relative changes in the provenance of the dominant sediment source into Bay Champagne, the average concentration of Ca (marine source) was compared with the average concentrations of Ti (terrestrial source) for each zone. The relative changes in concentrations between Ca and Ti were interpreted as shifts in the dominant sediment source to Bay Champagne.

3.3. Organic geochemistry

Core BC-C, collected from the back of the lake near a mangrove-covered island that forms the lake's northern shoreline and presumably

minimally affected by shoreline retreat processes, was selected for sedimentary organic matter analysis. Due to the minimal disturbance in this area from hurricane overwash and human activities, this core location is most likely to contain a complete sediment record of past environmental conditions in Bay Champagne. Two parallel aluminum push cores were collected at site BC-C in 2016. One core (71 cm long) was kept intact for XRF and LOI analysis. The other core (72 cm long) was sub-sampled in the field in 1-cm increments and kept frozen for organic analyses.

Total organic carbon (TOC) analyses were conducted at 1-cm intervals for the entire length of BC-C (72 samples). Samples were run on a Costech 4010 elemental analyzer (EA) in the Wetland Biogeochemistry Analytical Laboratory at Louisiana State University. Prior to analysis, sediment samples were packed in silver capsules and acidified via fumigation with hydrochloric acid (HCl) for 24 h to remove carbonates. After fumigation, samples were dried and repacked into tin capsules for analysis on the EA.

Stable carbon isotopic analysis was conducted at 1-cm intervals for the entire length of core BC-C. Samples were run in the Marine & Coastal Trophic Ecology Laboratory at Louisiana State University on an elemental analyzer (Costech) interfaced with an isotope ratio mass spectrometer (Thermo Scientific DeltaV). Samples were analyzed without acidification due to interference with the isotopic values. Two standards (USGS 40 and USGS 41) were used for calibration. Standard deviation for carbon for both standards was very low (USGS 40: 0.063‰; USGS 41: 0.187‰). Sediment samples were run in duplicate to account for sedimentary organic matter heterogeneity. Results for duplicate samples had almost no variability; the precision among replicates was $\pm 0.11\text{‰}$.

3.4. Pollen

Core BC-C was selected for pollen analysis using conventional methodology (Liu et al., 2008). Nineteen sediment samples (1.8 cc each) were collected from every third centimeter in the core and transferred to test tubes for chemical processing. The samples were treated with a solution of 10% hydrochloric acid (HCl), 10% potassium hydroxide (KOH), and 49% hydrofluoric acid (HF) to remove calcium carbonate, break down organic molecules, and dissolve silicates, respectively. An acetolysis mixture was used to remove cellulose, and samples were gently stirred to homogenize the sediment and remove clumps. One *Lycopodium* tablet was applied to each sample as a standard in order to determine pollen concentration (Stockmarr, 1971). A minimum of 300 pollen grains were counted within each sample. Special attention was paid to five pollen taxa (*Typha*, *Cheno-am*, *Taxodium*, *Batis maritima*, *Avicennia germinans*) as representative examples of freshwater and brackish environments. *Cheno-am* is an abbreviation for *Chenopodiaceae-Amaranthaceae* pollen.

4. Results and discussion

Analysis of historic maps and aerial photographs revealed dramatic changes at Bay Champagne due to shoreline retreat. Land surveys from the late 1800s showed Bay Champagne as a circular, inland lake with a direct riverine connection to the Gulf of Mexico (Fig. 2). At this time, the lake was located approximately one kilometer inland. By 1949, the shoreline had retreated nearly to the edge of the lake; by the mid-1960s, the southern lake shoreline had begun to erode. By 1979, nearly half of the original lake area had disappeared.

Over the last 130 years, the shoreline moved landward a total of 2252 m between 1887 and 2017, yielding an overall average annual rate of shoreline retreat of approximately 19 m per year. This retreat rate is higher than the average rate of shoreline retreat of approximately 12.5 m/yr determined by Penland et al. (2005), which used only four intervals between 1887 and 2002 to calculate the average rate of shoreline retreat. Shoreline changes at Bay Champagne occur rapidly and

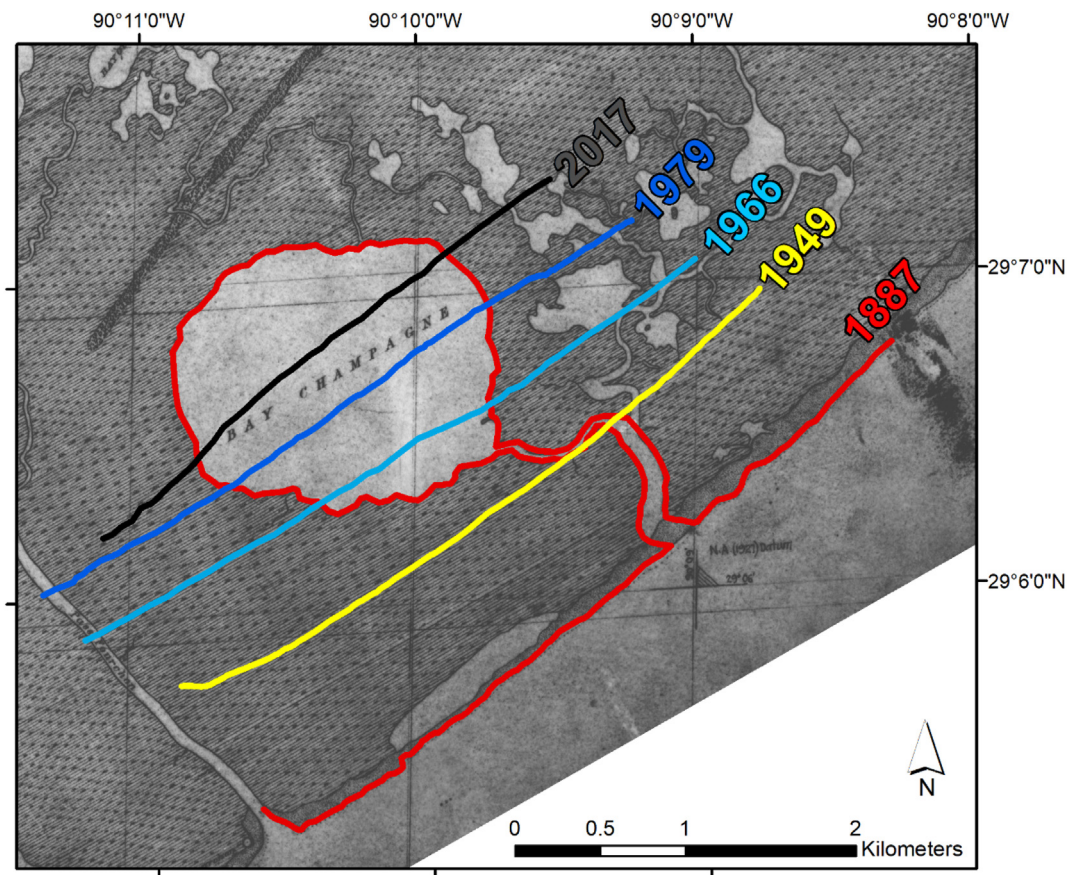


Fig. 2. Shoreline positions in five selected years from which historic maps were available, including the first year (1887) and the last year (2017) of the study period. Shorelines are shown in reference to the earliest available historic map for this area from 1887, when Bay Champagne existed as a circular freshwater lake. Subsequent landward migration of the shoreline in excess of two kilometers highlights the change in shape and spatial extent of the lake over time.

episodically as a function of decadal variations in hurricane activity, and long-term averages may not always capture these changes (Dietz et al., 2018). Penland et al. (2005) also calculated average shoreline retreat for the entire Caminada-Moreau headland, where rates have been shown to vary even within a small coastal stretch (Martinez et al., 2009). Therefore, the results presented in this study should be considered more accurate for Bay Champagne.

Spatial interpolation was implemented to estimate shoreline positions during periods where data were limited or unavailable (Fig. 3). The estimated decadal shoreline positions indicate that the average rate of retreat has varied considerably over the study period (Fig. 4). During the late 1800s, the annual rate of shoreline retreat was estimated at just under 20 m/yr. The rate decreased to 10 m/yr during the early 1900s and remained almost constant until the 1940s. The rate of shoreline retreat increases in the 1940s and rapidly accelerates in the 1950s. The highest rate of shoreline retreat occurred between 1950 and 1960, when the shoreline migrated nearly 600 m at a rate of nearly 60 m/yr. Over a quarter of the total amount of shoreline retreat in the last 130 years occurred during this time period. The estimated average retreat rate decreased during the 1960s and 1970s to over 20 m/yr, and slowed considerably after 1980 to less than 5 m/yr. In the 1990s, shoreline retreat was estimated at 10 m/yr and remained relatively constant for the three most recent decades.

During the early part of the record, shoreline retreat was relatively constant across the length of the shoreline of interest. After 1960, shoreline retreat increased more rapidly on the northeastern portion of the shoreline at Bay Champagne. By the 1980s, the northeastern portion of the shoreline was retreating more rapidly than the southwestern section. This trend is likely due to the presence of breakwaters and shoreline control structures in that area.

The major physical mechanisms driving shoreline retreat at Bay Champagne, such as relative sea level rise and deltaic sediment compaction, have likely remained relatively constant over the past century. However, a major factor that accelerated shoreline retreat at Bay Champagne was increased Gulf of Mexico hurricane activity (Dietz et al., 2018). Atlantic hurricane activity has fluctuated during the twentieth century (Elsner et al., 1999; Webster et al., 2005; Mann et al., 2009), and periods of frequent landfalling hurricanes are known to increase shoreline retreat rates (Dietz et al., 2018). Hurricane activity in the Gulf of Mexico was higher than average during the 1950s and 1960s (Landsea et al., 1992; Elsner et al., 2000), and may have been a driving factor of shoreline retreat at Bay Champagne during that period (Fig. 4a).

Another possible driver of shoreline retreat at this site is local oil and gas development. Bay Champagne is located near Port Fourchon, an important support facility for the majority of oil and gas activities in the Gulf of Mexico. The port was completed in 1960, after the sharp increase in shoreline retreat rates (Fig. 4a), but construction activity could have influenced shoreline retreat prior to this date.

4.1. Stratigraphy

To illustrate sedimentological processes at Bay Champagne, the detailed stratigraphy of a representative core (BC-48) is presented here (Fig. 5). A 17 cm-thick sand layer is present at core top, with fine sand and trace silt and clay in the upper 10 cm and coarser sand from 10 to 17 cm depth. A sharp contact exists at 17 cm between the bottom of this sand layer and darker, finer-grained sediment beneath it. Multiple alternating layers of sand and clay were deposited between 17 and 35 cm. The rest of the core below 35 cm was comprised of a stiff gray

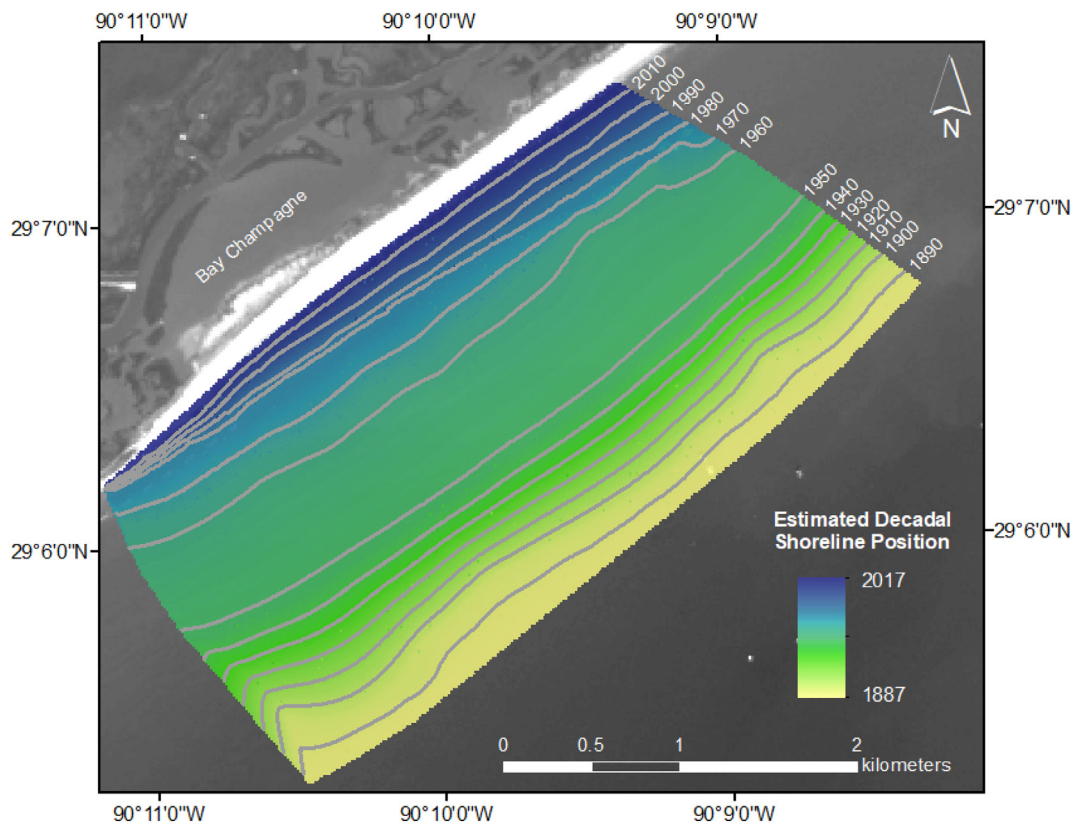


Fig. 3. Estimated decadal shoreline positions at Bay Champagne from 1887 to 2017. These positions were determined through spatial interpolation of historic maps and photographs dated from 1887 to 1980; Landsat imagery was analyzed to estimate shoreline position from 1980 to 2017.

mud. LOI results indicate that layers with higher sand content tend to contain less water than layers comprised of finer-grained sediments. Notable decreases in water content were observed at 10–17 cm, 24–25 cm, and 28–34 cm; each of these depths correspond with layers that are sand-rich. Sediment water content can exhibit similarities to organic content (Bianchette et al., 2017) and particle size (Menounos, 1997), and can aid in correlating different cores (Menounos, 1997). Conversely, organic matter content is low in these regions of the core, and higher in layers that have low amounts of sand. Carbonate content was low throughout this core with little variability among samples.

Stratigraphic features similar to those in BC-48 are observed in most of the other cores in this study (Fig. 6; Fig. S3, supplemental material). The most notable feature in all but one core (BC-C) is the presence of a number of sand layers, visually distinct clastic layers low in water and organic contents which typically contain shells and shell fragments. These deposits are most likely formed through marine incursion events into Bay Champagne and are interpreted to be storm deposits formed by hurricane overwash. These layers are typically comprised of coarse sand and are lighter in color than the surrounding sediment layers. Nearly all of the cores (with the exception of BC-C) exhibit two thick sand layers at the top and a sharp contact with mud-rich sediment beneath. These layers are attributed to Hurricanes Gustav and Ike in 2008 (Liu et al., 2011) and are interpreted as “modern” storm deposits (Fig. 5, blue box). Additionally, several similar sand layers are present in the middle and lower portions of the cores; these layers are referred to as “older storm deposits”. Based on the sediment stratigraphy and LOI results for these cores, three stratigraphic zones are identified: modern, transitional and lacustrine (Fig. 6). These zones can be considered “time windows” to compare geochemical changes in different core sections, deposited at different times and under different environmental conditions. The characteristics of each zone (time window) are described below:

- **Modern:** This zone is characterized by coarse sand and is entirely composed of two thick storm deposits attributed to Hurricanes Gustav and Ike in 2008 (Liu et al., 2011). This layer is present at the top of almost all cores and is delineated by a sharp contact with finer-grained mud located below. The core tops show a decrease in the average water content in each core, indicative of the sand layer present. This zone is considered to be a representation of modern environmental conditions in Bay Champagne.
- **Transition:** This stratigraphic zone consists of alternating layers of mud and sand, with the latter representing older storm deposits. These layers are located in the middle sections of the cores and likely represent a combination of several depositional processes (marine and fluvial) occurring during and after an overwash event. The transition zone is present in almost all cores, but fewer sand layers are observed in cores taken further from the beach (BC-25 and BC-32).
- **Lacustrine:** Present at the bottom of all cores, this zone consists of gray to dark brown dense silt and clay particles (mud) that is distinct from younger stratigraphic layers and almost completely devoid of sand. Sediments are dark brown in color, may contain plant fragments and/or peat, and exhibit relatively high organic and water content. As the oldest section of each core, this zone represents sediment deposition typical of a coastal lake or lacustrine environment driven by fluvial processes depositing fine-grain, terrestrial-derived sediment. Cores collected farthest away from the beach (BC-25, BC-32, BC-C) are comprised mostly or entirely of this type of sediment.

One core, BC-C, is unique in that it is devoid of sand layers (Fig. 6). This core, collected from an area of Bay Champagne furthest from the beach, is comprised completely of dark brown mud and plant material, and was not expected to contain storm overwash layers. The amounts of water and organic material present in BC-C are higher than any other

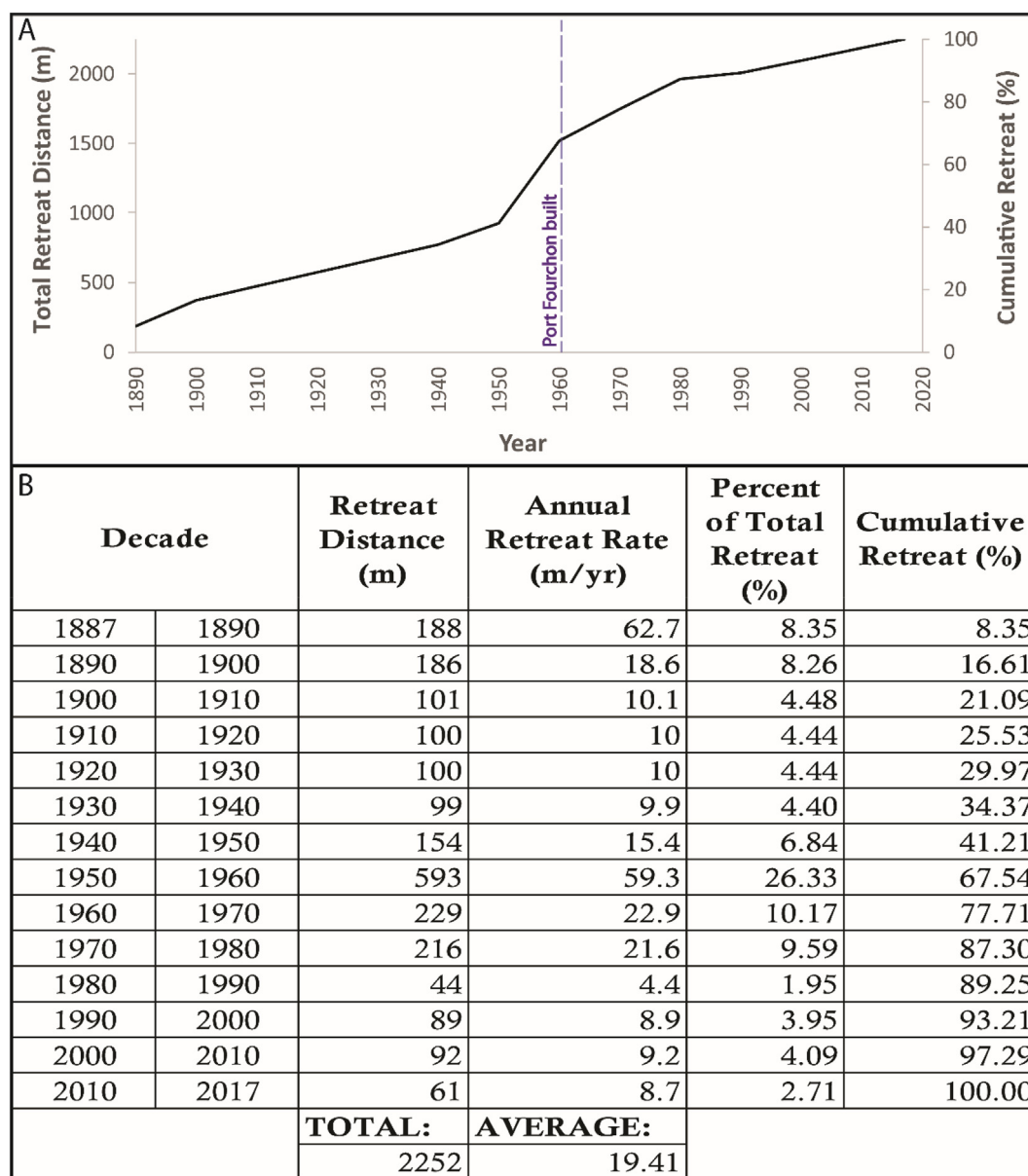


Fig. 4. Shoreline retreat distances and annual retreat rates based on estimate decadal shoreline positions from 1887 to 2017 (a). Cumulative shoreline retreat at Bay Champagne since the late 1800s shows that rates of shoreline retreat have varied dramatically (b). Shoreline retreat increased dramatically during the 1950s and remained high during the 1960s and 1970s before returning to a slower, more constant rate. The sharp increase in retreat rate may be partly related to oil and gas development activity in the region in conjunction with an increase in Gulf hurricane activity.

cores from this study and show little variability throughout the core, with the exception of two peat layers comprised of large plant fragments at 7 cm and 68 cm depth. This lack of variability suggests that environmental conditions at this core site have remained relatively stable.

4.2. XRF

Ca and Ti concentrations in each core were compared to investigate relative changes in sediment sources at Bay Champagne over time. Ca (marine indicator) and Ti (terrestrial indicator) concentrations generally show a gradual progression from a terrestrial-dominant sediment source to increased marine influence over time (Fig. 7, Fig. S2, supplemental material). Ca and Ti concentrations for the samples contained within each stratigraphic zone in each core were averaged to create one value per zone per core, resulting in a maximum of four values per element per core. A scatterplot was created to compare the average

Ca and Ti concentrations within each zone across all nine cores (Fig. 7). The oldest section of the cores, representing lacustrine conditions, consists of higher Ti concentrations and relatively low Ca concentrations. The transition samples and storm deposits were generally higher in Ca values and slightly lower in Ti values than the lacustrine samples. The older storm deposits were slightly lower in Ti values, albeit with significant overlap, than the transition and modern samples. The modern samples contained the highest average Ca element concentrations, but exhibited significant overlap with those of the storm deposits and transitional zones. The positions of the centroids show a gradual shift from higher Ti concentrations in the older (lacustrine) core sections to higher Ca concentrations in the younger (modern) core sections.

In the late 1800s, Bay Champagne was a circular, inland lake, located more than a kilometer from the Gulf of Mexico; thus, it was likely fresh with minimal marine influence. Given its distance from the coast, Bay Champagne would likely have been protected from all but the most

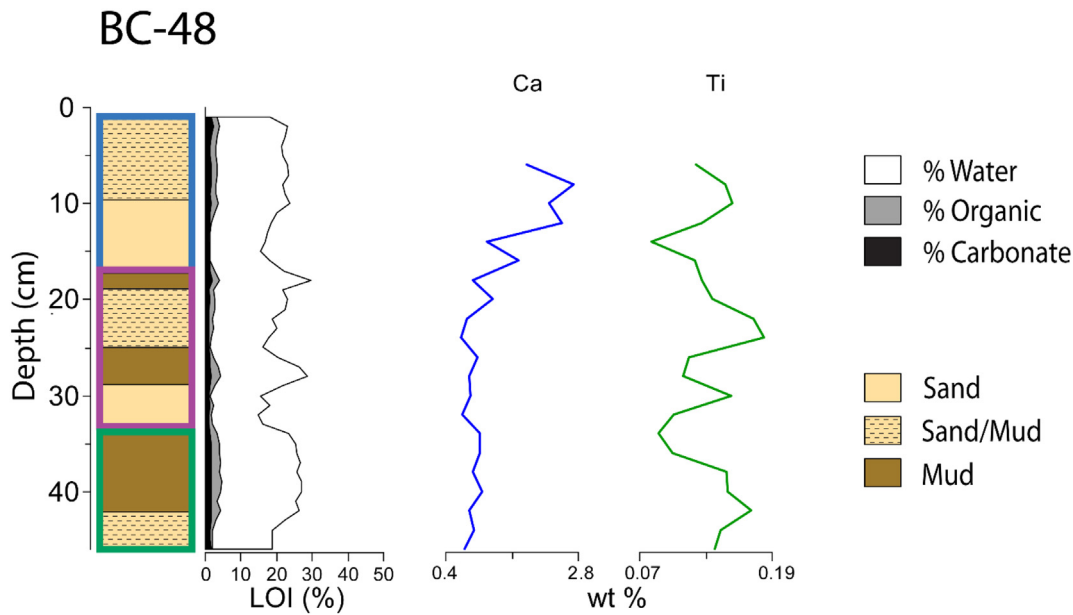


Fig. 5. Stratigraphy, LOI and XRF results for core BC-48. Colored boxes show the delineations of each of the three stratigraphic zones; sand-rich storm layers are visible within the top two zones.

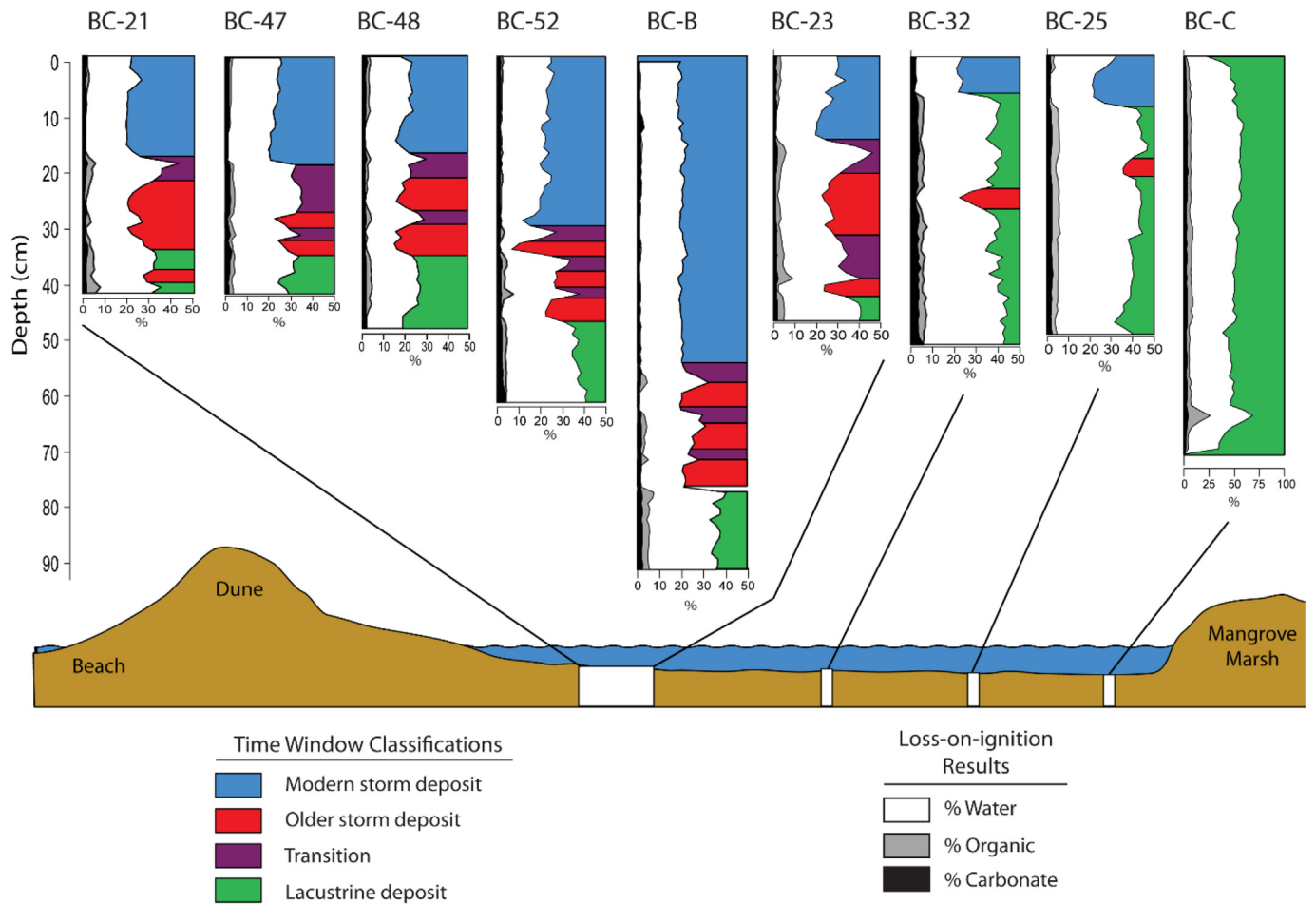


Fig. 6. Relative locations and LOI results for the nine sediment cores in this study. Three different time windows were identified based on sediment composition and stratigraphy. The time window classifications are overlain in this figure on the LOI data as colored blocks.

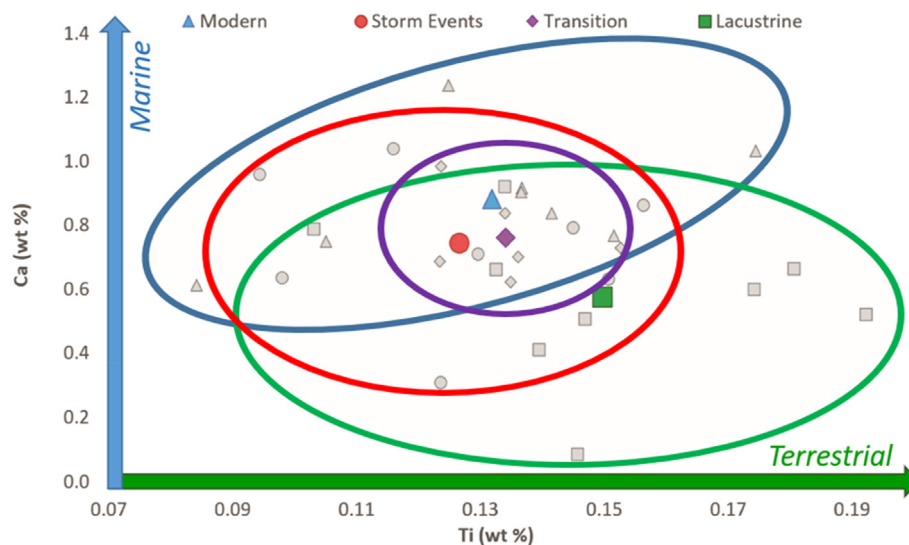


Fig. 7. Scatterplot of calcium and titanium values for the time windows in nine sediment cores. Titanium concentrations (a proxy for terrestrial sedimentary input) are listed on the x-axis, and calcium concentrations (a proxy for marine sedimentary input) are listed on the y-axis. The centroids for each of the time window groups are displayed as colored shapes; the spread of data points for each group is bounded by colored ovals. The average time window values for the individual cores are displayed in gray. The oldest portions of the cores (lacustrine window) contain higher concentrations of terrestrial material, while younger portions of the cores contain progressively higher concentrations of marine-derived material.

severe storm surge events, making it less disturbed by hurricane impacts than the current state. Sediment deposition in Bay Champagne during this time would have been representative of a lacustrine environment: fine-grained, terrestrial-derived sediment deposited through fluvial input observed in the oldest sections in the nine sediment cores. Samples consisting of lacustrine sediment were higher in Ti concentrations and lower in Ca concentrations of than samples from other core sections. This suggests that deposition during this time was driven mostly by fluvial (terrestrial) processes with minimal marine influence.

Progressively younger sections in most of the cores exhibited an increase in Ca concentrations, suggesting a shift in sediment provenance. These transition zones also contain significant amounts of sand that likely originated on the barrier beach. This suggests that deposition at this time was dominated by overwash of the barrier beach at Bay Champagne. For this to occur, the shoreline must have migrated enough for hurricane storm surge to transport and deposit sand within the lake. Samples from these core sections also contain high amounts of terrestrially-derived material and seem to represent a gradual shift from fluvial-dominant depositional processes to a mixture of fluvial and marine processes. These transitional samples were found in all but three of the nine sediment cores used in this study (BC-25, BC-32, and BC-C); these three cores are located furthest from the beach.

Embedded in and lying above the transition zones are sand-rich layers interpreted as storm-surge overwash deposits. Samples from these layers were high in Ca concentrations and relatively low in Ti concentrations, which suggests sediments of marine-origin. The thick top sand layer is known to be deposited by Hurricanes Gustav and Ike in 2008 (Liu et al., 2011) and is representative of modern environmental conditions. Samples from this layer had lower concentrations of Ti than older storm event layers, suggesting an increase in the relative dominance of marine depositional processes at this site. These results support the general trend towards increasing marine influence at Bay Champagne, corresponding to shoreline retreat.

It is important to note that some variability exists in the average elemental values for each time window, resulting in overlap among samples of different categories. For example, several cores had modern samples with high concentrations of Ti (BC-32, BC-47). Conversely, one of the cores (BC-21) had lacustrine samples with low a Ti concentration and higher Ca concentration. Significant overlap also exists between the modern, storm, and transitional values. This overlap could be attributed to ambiguous sediment layer boundaries caused by

bioturbation or sediment disturbance during storm event deposition. This would homogenize the elemental concentrations at stratigraphic boundary layers and result in some higher or lower than expected values.

4.3. Pollen

Relative changes in five pollen taxa (*Typha*, *Cheno-am*, *Taxodium*, *Batis maritima*, *Avicennia germinans*) support the transition from a freshwater to brackish environment and delineate three stages of ecological succession (lacustrine, transition, and lagoon/mangrove) in core BC-C (Fig. 8). The oldest portion of the core (72–55 cm) consists of high percentages of *Typha* (24.8%), *Cheno-am* (32.7%), and *Taxodium* (7.3%) pollen (Fig. 8). This section of the core represents a lacustrine environment based on high percentages of pollen characteristic of freshwater marshes (*Typha* and *Taxodium*) and almost no pollen from salt-tolerant plant species (*Batis maritima* and *Avicennia germinans*). The middle portion of the core (55–25 cm) comprises high percentages of *Typha* (22%), *Cheno-am* (40.9%), and *Taxodium* (13.7%). The percentages of *Batis maritima* increases up to 2.6% at the upper end of this section. This section represents the transitional period as Bay Champagne was becoming more saline, marked by the co-dominance of pollen from freshwater taxa and increasing frequencies of salt-tolerant taxa (*Cheno-am*), particularly towards the top of this section. The top portion of the core includes low percentages of *Typha* (4.6%), *Taxodium* (4.6%), but relatively high percentages of *Cheno-am* (22%) and *Batis maritima* (24.3%). *Avicennia germinans* pollen first occurs at 9 cm and increases in percentages up to 2.6% towards the top. These recent sediments represent the lagoon environment as it exists today, with very low percentages of freshwater pollen taxa and higher frequencies of salt-tolerant taxa. The abundance of *Batis maritima* is particularly high in the top 15 cm of the core and corresponds with the appearance of *Avicennia germinans* pollen.

4.4. Organic geochemistry

Stable carbon isotopic values show a gradual shift in values from the bottom of BC-C to the top (Fig. 8), which likely reflects a change in the source of sedimentary organic matter. $\delta^{13}\text{C}$ values are lowest at the bottom of the core ($\sim -24\text{‰}$) and increase to the highest values ($\sim -16\text{‰}$) at about 20 cm. A steady decrease in $\delta^{13}\text{C}$ is evident from 20 cm to the

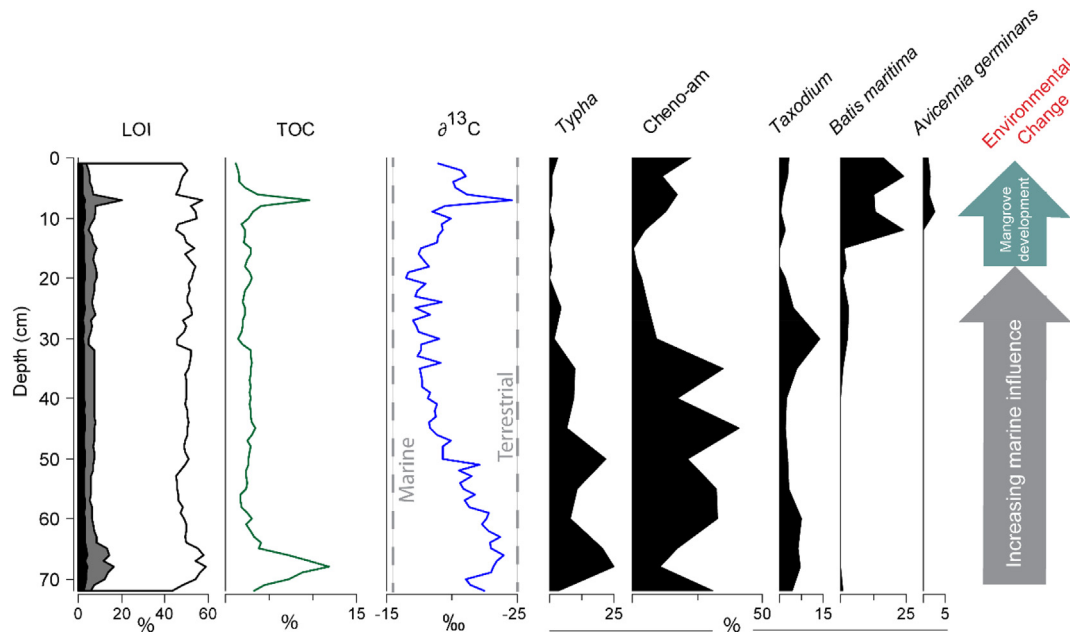


Fig. 8. Results for core BC-C. Lithology and stratigraphy remain relatively constant throughout this core, with two peat layers at 7 cm and 68 cm as notable exceptions. Stable isotopic ratios of carbon show a gradual shift from the bottom of the core to the top. A gradual decrease in $\delta^{13}\text{C}$ at the very top of the core may be linked to local black mangrove (*Avicennia germinans*) expansion. Pollen results show a gradual change from freshwater dominant vegetation to more salt-tolerant species.

top of the core, where isotopic values average -20‰ from 20 cm to 10 cm, whereas a sharp decrease (-24‰) in isotopic values occurs at 7 cm. Values increase from this depth to the top of the core. Multiple similar but smaller decreases of about 1–2‰ in isotopic values occur throughout the record, but do not affect the overall trend.

The increasing $\delta^{13}\text{C}$ values indicate a shift from terrestrial plant values (-25‰) in the lower parts of the core towards isotopically heavier values indicative of marine algae and/or C4 plants (-15‰) near the top (Fig. 8). This change in carbon isotope values suggests a relative increase in the amount of marine algal and/or C4 plant biomass, which likely reflects an increasing marine influence on Bay Champagne over time. Small fluctuations in $\delta^{13}\text{C}$ towards isotopically lighter values may indicate fluvial flooding events that deposited an influx of terrestrial plant material in the lake. A major depositional event at 7 cm in the core is evident in TOC and $\delta^{13}\text{C}$ results, and most likely records a major fluvial flooding event.

The gradual shift evident at the top 20 cm of the core towards more negative $\delta^{13}\text{C}$ values more indicative of terrestrial plant matter, coupled with the presence of *Avicennia germinans* pollen, represents local colonization by black mangroves. Bay Champagne is located within the northernmost extent of this species (Rodríguez et al., 2021), which has been expanding as the local climate has grown warmer. Mangroves are C₃ plant species that are isotopically similar to inland terrestrial plants. An increase in the amount of mangrove detritus deposited in Bay Champagne could be responsible for the shift in carbon isotopic values indicated at the top of the core. *Avicennia germinans* pollen appeared in the core only in the top portion (Fig. 8), and occurs at the same depth in the core as the transition to lighter carbon isotopic values, suggesting the two trends may be linked. A similar trend was shown in Texas, where the expansion of black mangroves resulted in a local decrease in sedimentary $\delta^{13}\text{C}$ values (Bianchi et al., 2013).

By combining shoreline retreat data with the trends observed in sediment geochemistry at Bay Champagne, a timeframe of the gradual shift from inland lake to coastal lagoon can be determined (Fig. 9, Fig. S5). Sedimentation characteristic of a lacustrine environment would only have occurred when the shoreline was located further seaward from the lake. Therefore, the earliest part of the sediment record represents inland lake stratigraphy isolated from marine influence. The transition from inland lake to lagoon would have occurred while the shoreline

was migrating inland; from decadal estimates of shoreline position, this probably began around 1950. By then, the shoreline would have migrated far enough inland where storm surge overwash was possible, yet rare. This transition period probably continued until the lake shoreline was eroded, which likely occurred between 1950 and 1960 based on historic shoreline positions, and may have continued into the 1970s. By this point, sedimentological conditions at Bay Champagne were probably similar to its current state.

5. Conclusions

Long-term shoreline retreat has resulted in profound environmental changes at Bay Champagne. These changes are detectable within several sediment cores collected from this lake, indicating that the site underwent a gradual transition from an inland freshwater lake to a brackish backbarrier lagoon. As this transition occurred, Bay Champagne was subjected to increasingly frequent marine inundations, likely from storm surge overwash processes. This indicates that this site has become more sensitive to hurricane impacts over time, meaning that hurricane overwash affects this site differently today than in the past. This change is evident in the sediment record and is important for reconstructing past hurricane activity and interpreting pre-historic hurricane records (Liu, 2004), since increasing site sensitivity could lead to inaccurate storm counts. These results also provide a case-study of changing local environmental conditions in response to rapid shoreline retreat, which can be used as a model of future coastal changes for Louisiana and other areas of the Gulf of Mexico Coast.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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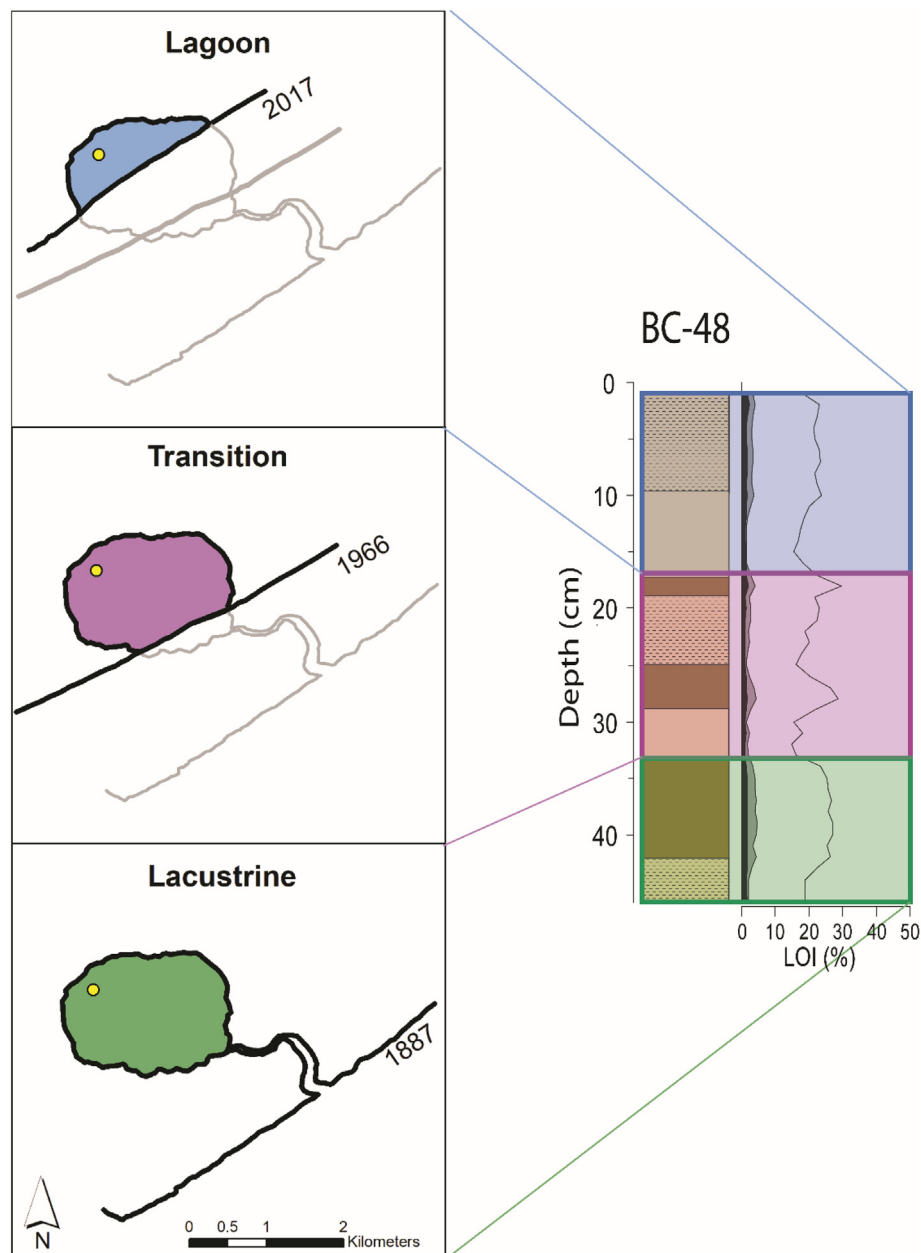


Fig. 9. Landward migration of shoreline position is reflected in stratigraphic changes in the sediment stratigraphy and geochemistry of Bay Champagne. The stratigraphy and LOI results for core BC-48 shown here as an example. Core location for BC-48 is shown as yellow dot. Sediments indicative of lacustrine environments (bottom panel) would have been deposited while the shoreline was still far from Bay Champagne (shoreline positions of ~1880–1950). The transition from inland lake to modern coastal lagoon likely occurred as the shoreline retreated during ~1950–1970 (middle panel). Modern lagoonal conditions are represented in the sandy top portion of the core (top panel). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.geomorph.2021.108008>.

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