
Geological Processes and Sedimentation Rates of Wind-Tidal Flats, Laguna Madre, Texas

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ABSTRACT

Coastal flats worldwide that are periodically exposed to arid climates and periodically flooded by marine waters are unique depositional environments because they receive sediments surficially and interstitially from both land and sea. The wind-tidal flats bordering Laguna Madre, Texas, which fit this unique category, are modified by eolian processes when subaerially exposed, and by wave and current processes when submerged. Floodwater is derived from the lagoon and driven onto the flats by strong and persistent winds during the passage of cold fronts and tropical cyclones. Low surface gradients of the flats prevent rapid drainage and promote seawater evaporation. The depositional products of these processes are interbedded and interlaminated sand, mud, marine shells, algal mats, and evaporites. This assemblage of sediments is geologically diagnostic evidence for intertidal marine deposition and the same assemblage of sediments have been reported for modern marginal-marine flats in the Middle East.

The wind-tidal flat surface at Laguna Madre is constantly changing. However, the net effect of natural changes during the past century is either negligible or the changes occur at such a slow rate that they are almost imperceptible. Sediments are repeatedly added to and removed from the surface of the flats in minor increments and in different areas at different times. Preservation potential is enhanced at a particular site by the development of thick mats of blue-green algae.

The ¹⁴C ages of buried algal mats yield average long-term (centuries to millennia) sedimentation rates for the wind-tidal flats that range from 0.13 to 0.96 mm/yr and average 0.57 mm/yr. The ²¹⁰Pb profiles yield average short-term (150 yr) sedimentation rates that are an order of magnitude higher, ranging from 0.7 to 8.3 mm/yr and averaging 2.9 mm/yr. The minimum present rate of relative sea-level rise in Laguna Madre (3.4 mm/yr) exceeds the historical sedimentation rates for most of the flats. If future sea-level rise is faster than the rates of aggradation, then the wind-tidal flats will progressively become more frequently flooded and will eventually become permanently submerged.

INTRODUCTION

Broad, barren coastal flats that are periodically exposed and periodically flooded by marine water are common where the climate is hot and relatively dry, the tidal range is low, strong winds drive seawater onshore, and there are no large streams or rivers emptying into the coastal waters. The conditions that promote periodic flooding of coastal flats by saline water are met not only in the Persian Gulf (Kinsman, 1969; Kinsman and Park, 1976; Patterson and Kinsman, 1981), Red Sea (Friedman et al., 1973), and eastern Mediterranean Sea (Levy, 1977), but

also in south Texas (Fisk, 1959; Miller, 1975). All the marginal-marine coastal flats in the Middle East and in south Texas are either barren or covered by mats of blue-green algae, and they contain authigenic sulfate and carbonate minerals that form from the evaporation of seawater. Alternating layers of sand, mud, algal mats, and evaporites are diagnostic sedimentary components of these coastal-flat environments.

The wind-tidal flats of Laguna Madre, Texas (Figs. 1 and 2), have been the focus of several geological investigations because they represent an anomaly compared to other coastal depositional environments. The Texas flats are located between a barrier island (Padre Island) to the east and a vast complex of sand dunes (eolian plain) forming uplands to the west. Margins of the flats and eolian plain are also aligned with the predominant southeasterly wind direction, and they coincide with the ocean-shoreline embayment where average northerly-directed and southerly-directed alongshore currents converge near 27°N latitude in the western Gulf of Mexico.

The primary objectives of this study were to investigate the geologic history of the Laguna Madre flats over the past few hundred yr, to determine if significant surficial changes had occurred in and around the flats since the late 1800s, and to provide data for predicting the future condition of the flats, considering anticipated rates of sea-level rise. These tasks required understanding the dominant physical processes responsible for constructing the flats, examining the sedimentary sequences beneath the flats, estimating the time-averaged and most recent rates of sedimentation, and interpreting the geological significance of the results. To achieve the study objectives, we (1) examined historical documents, (2) made aerial and ground field observations, (3) collected, described, and sampled sediment cores, (4) analyzed physical and chemical properties of the sediments, and (5) interpreted the integrated data.

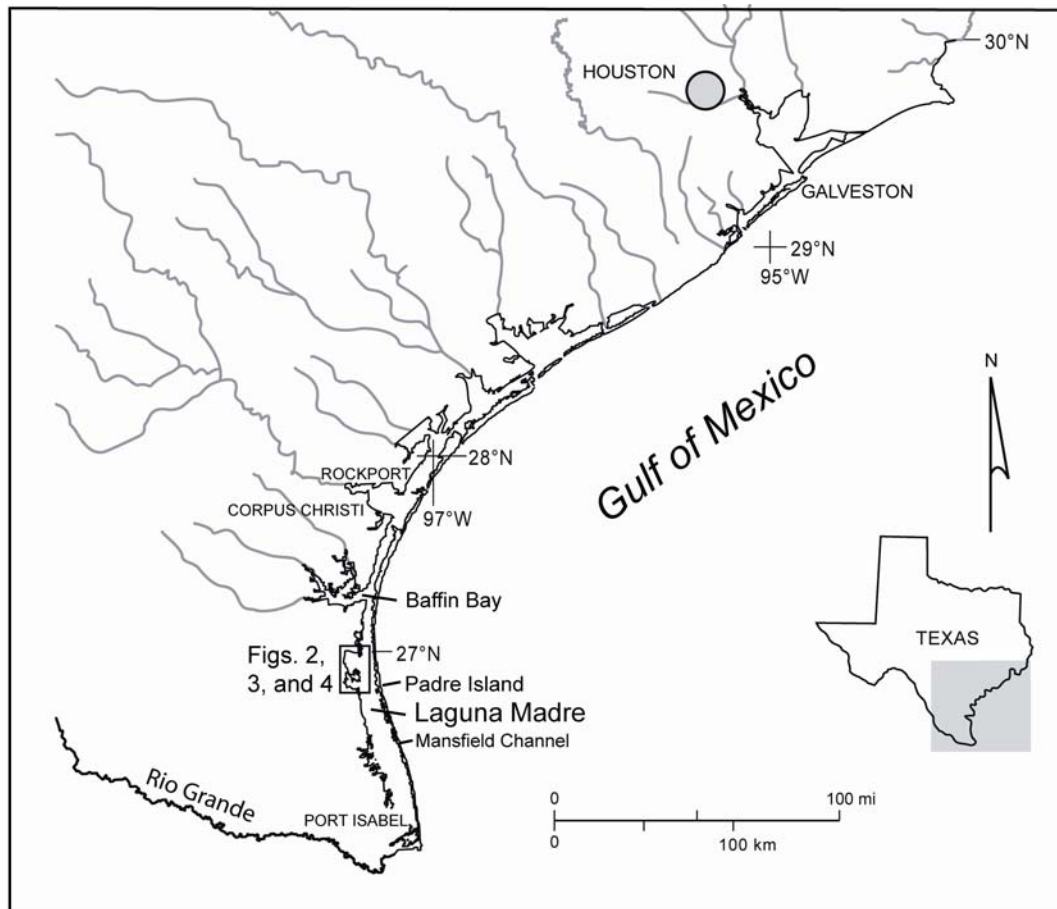


Figure 1. Map of the Texas coast, showing location of the wind-tidal flats of Laguna Madre near 27°N latitude and locations of Port Isabel and Rockport where interior tide gauges are located.



Figure 2. 1996 aerial photograph showing the natural and man-made geomorphic features of the wind-tidal flats of Laguna Madre. Location shown in [Figure 1](#).

DATA SOURCES AND METHODS

Historical Records and Field Operations

The U.S. Coast Survey prepared the oldest reliable topographic map of the wind-tidal flats of Laguna Madre (Fig. 3). This map meets federal accuracy standards, so it can be compared with recent photographic images and orthophoto maps to determine if significant geomorphic changes have occurred on the flats during the past 130 yr. Ten sets of aerial photographs taken between 1937 and 2005 also were examined and compared to evaluate the stability of features on and around the flats. A topographic contour map prepared in 1948 by the Humble Oil and Refining Company (Fisk, 1959) was used to estimate elevations at the coring sites (Fig. 4). The relative differences in elevations across the flats probably have not changed significantly since the 1948 survey.

Aerial reconnaissance and ground observations showed that the degree of algal-mat development at a particular site could be broadly categorized as dense, sparse, or absent (non-algal). Coring sites were selected to represent the major physiographic subdivisions of the flats and to sample each category of algal-mat density at several different locations. Geographic coordinates of the coring sites were determined by Global Positioning System surveys conducted by the Texas General Land Office.

Both push-core and vibracore (Lanesky et al., 1979) techniques were used to penetrate and retrieve unconsolidated sediments to a depth of about 2 m. The core barrels consisted of standard 7.5 cm diameter aluminum irrigation pipes. Each core was cut into 1 m sections, and each section was split lengthwise (Fig. 5). Two continuous sediment cores were obtained at each of the 13 core sites. Each replicate core was located within 5 m of the first core taken at a site. The replicate cores were collected to test the repeatability of the sampling method, to provide ample material for the physical and chemical analyses, and to offer a choice of the core that was selected for extensive physical and chemical analyses. One half of each core was cleaned, photographed, and described in detail. The core descriptions and photographs provided a basis for identifying the predominant sedimentary facies and for selecting stratigraphic units to sample for isotopic analysis.

At several coring sites, a 1 m deep trench was excavated, cleaned, and photographed. The trench photographs provided an independent record of the sediment composition and lateral continuity of laminations in the wind-tidal-flat deposits. Trenches avoid the potential sediment deformation caused by the coring process, but vehicles in transit or other surface activities before trench excavation could deform the sediments.

Nearly all cores taken in unconsolidated sediments undergo some compaction that typically ranges between 10% and 40% (Molnar and Smith, 1993; Morton and White, 1997). The percent compaction for the cores from the Laguna Madre wind-tidal flats is well within this range. The amount of compaction normally depends on the type of material being cored. Sand with abundant air pockets, such as the sponge-cake texture, or soft mud with high water content, are easily compacted. In contrast, well-sorted sand is not easily compacted. Most of the wind-tidal-flat cores penetrated sediments that are laminated, and the laminations are composed of layers that are alternately more compactable (mud or algal mats) and less compactable (sand or evaporites). Detailed correlation of the replicate cores at each site reveals the zones of strata that have undergone the most compaction. Correlation of laminations in the cores with those observed in the trenches also helps identify the zones that have undergone compaction.

Magnitudes of core shortening and total core length were the primary considerations used to select a core for physical and chemical analyses. Minimizing the amount of shortening is important because it affects the relative depths of the laminations and the data derived from those laminations. Core shortening also causes calculated sedimentation rates to be lower than the actual rates because the strata are closer together. Core depths can be corrected for shortening if measurements are made during the coring operation (Morton and White, 1997). Most of the cores used for the detailed analyses were shortened less than 15%.

Laboratory Analyses

Chronology of the wind-tidal flats was measured using ^{210}Pb and ^{14}C isotopic analyses of core samples. For the ^{210}Pb analysis, cores were sampled at 1 cm intervals for the uppermost 15 cm, then at 5 cm increments to the bottom of each core. Holmes et al. (2001) presented a detailed description of analytical methods. Briefly, a homogenized wet sample was placed in a clean, weighed porcelain evaporating dish, dried at 40°C, cooled, and

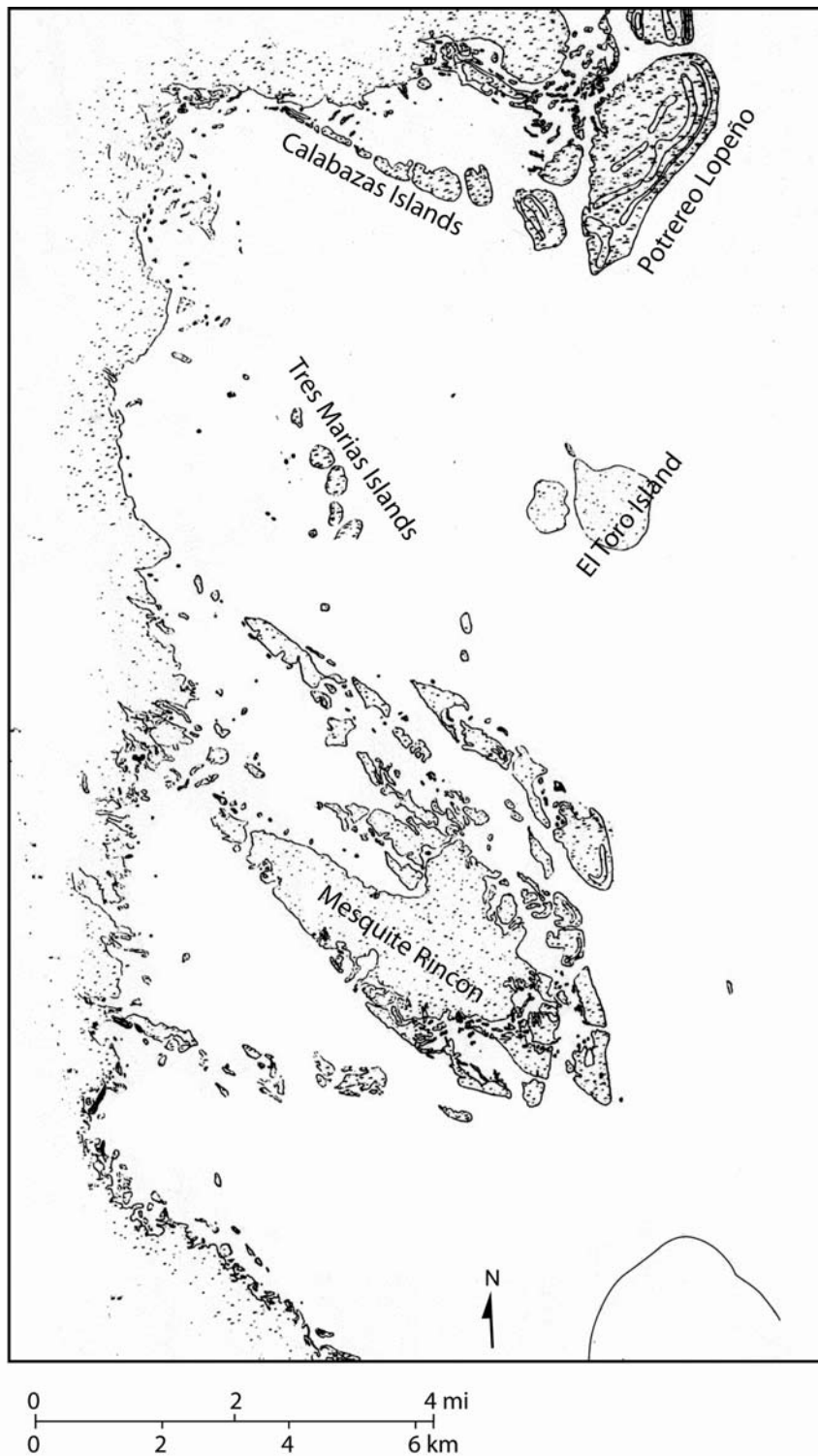


Figure 3. Topographic maps T-1677 and T-1678 of central Laguna Madre surveyed by the U.S. Coast Survey in 1879-81 showing the natural geomorphic features of the wind-tidal flats.

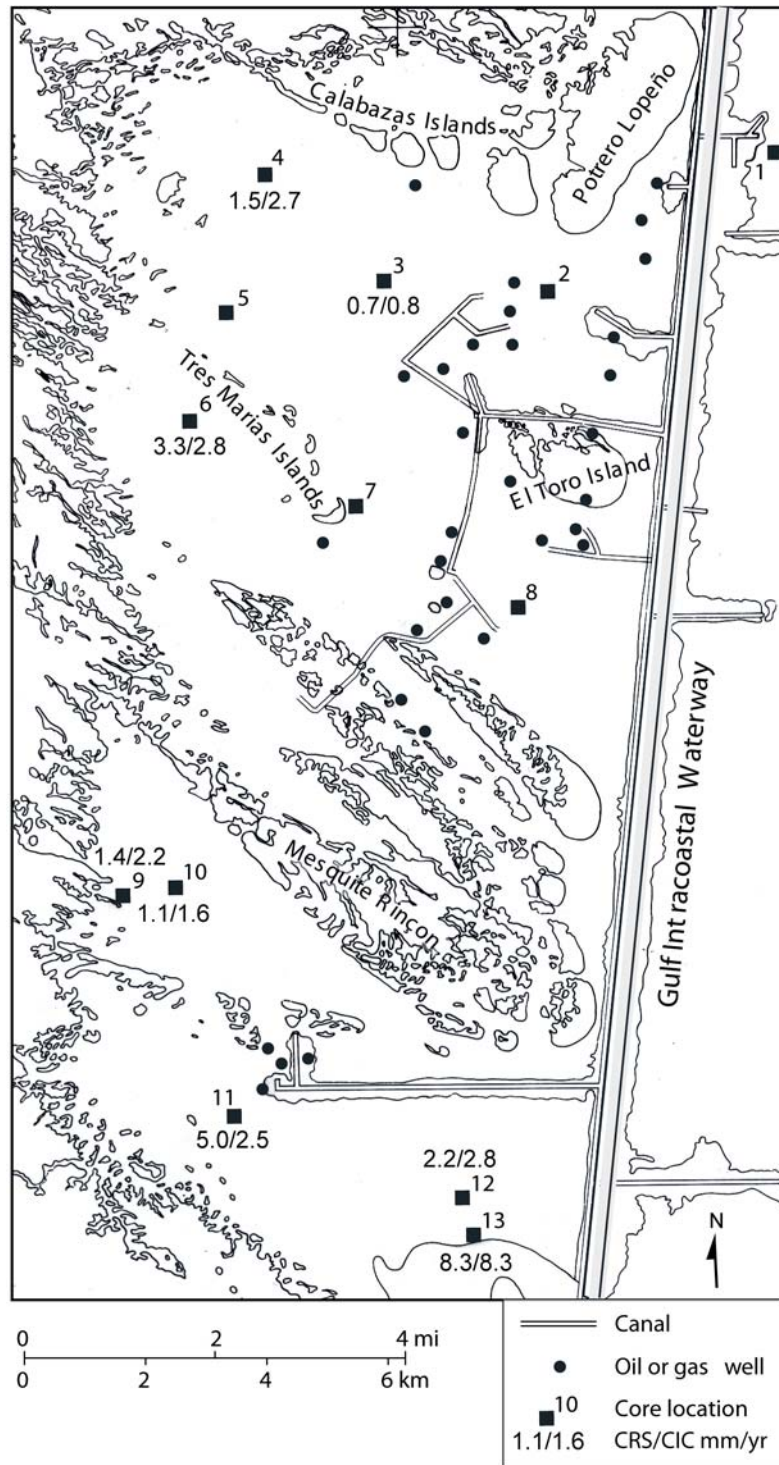


Figure 4. Locations of sediment cores collected from the wind-tidal flats of Laguna Madre, Texas, and associated average sedimentation rates from the ^{210}Pb analyses using the constant rate of supply (CRS) and constant initial concentration (CIC) models.

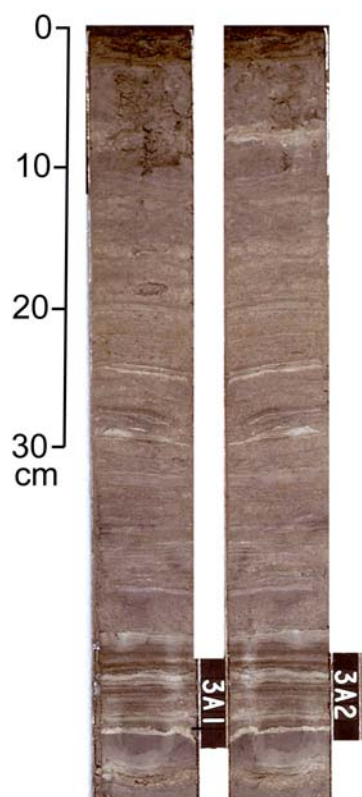


Figure 5. Representative split-core section (core 3, section A, twin halves 1 and 2) from the Laguna Madre wind-tidal flats showing laminations formed by alternating sediment compositions. See Figure 4 for location.

reweighed to determine the water loss. Loss on Ignition (LOI) was determined by heating the sample at 450°C for 6 hr and reweighing. Activity of ^{210}Pb was determined by alpha spectroscopy (Flynn, 1968). The results were expressed in disintegrations per gram.

Lead-210, with a half-life of 22.3 yr, is an ideal chronometer for most ecosystem studies where changes have occurred within the last century. Its capacity to provide age information, especially with regard to sedimentation rate, makes ^{210}Pb an excellent tool for assessing recent natural and sociogeographic impacts in depositional environments. Theoretically, the total ^{210}Pb should decrease at depth until it reaches a uniform concentration, which represents the background level of ^{210}Pb (Appleby and Oldfield, 1992). The excess ^{210}Pb is the total ^{210}Pb minus the background level of ^{210}Pb .

Two models commonly used to estimate the sediment ages with ^{210}Pb are: CIC (Constant Initial Concentration) and CRS (Constant Rate of Supply). For in-depth critiques and descriptions of these models, see Robbins (1978) and Appleby and Oldfield (1992). The simplest model, CIC assumes a constant flux of excess ^{210}Pb from the atmosphere and a constant dry-mass sedimentation rate. Where these assumptions are satisfied, the ^{210}Pb concentration will vary exponentially with depth in accumulating sediment. When applying this model, it is assumed that these conditions are met within the sampled interval. The dry-mass rate of accumulation is obtained from the excess ^{210}Pb , cumulative dry mass, and decay constant for ^{210}Pb . The sedimentation rate can be obtained graphically from the mean slope determined by a least-squares best fit. For our analyses, the best-fit curve of the ^{210}Pb data was calculated by least-squares optimization using the Marquardt-Levenberg (M-L) method (Press et al., 2007).

The CRS model assumes a constant ^{210}Pb flux but permits the sediment supply to vary. Intuitively, this model seems to apply to most sedimentary systems where the sediment supply may vary in response to climatic or anthropogenic changes. In addition to determining excess ^{210}Pb , this model requires contiguous sampling and bulk density of the sampled interval. The program of Binford (1990) was used to calculate the CRS ages in this investigation. An informative parameter derived from the data is the isotopic inventory, which is defined as the concentration of lead isotopes in a sediment deposit. Inventory is measured in disintegrations per minute per unit area (decays per minute [dpm] / cm^2). Sites greatly exceeding the theoretical inventory value, as determined by

the flux, indicate that the sediment acquired additional lead during transport. Baskaran et al. (1993) estimated that the atmospheric flux of ^{210}Pb at Galveston and College Station, Texas, was 1 dpm/cm^2 , which equates to a value of $32 \text{ dpm/cm}^2/\text{yr}$. They also demonstrated that most of this flux occurred during rain events. Because average precipitation in the Galveston region is 130 cm/yr , and average rainfall in the Corpus Christi region is 75 cm/yr , the flux of ^{210}Pb in the Laguna Madre region is estimated to be about 60% of that at Galveston, or about $20 \text{ dpm/cm}^2/\text{yr}$. Core sites with inventories that exceed the theoretical value, as determined by the flux, indicate that the sediment has been focused into that site from the surrounding region, whereas sites with less than the theoretical value indicate missing sediment as a result of either periods of non-deposition or erosion.

For the ^{14}C analysis, selected algal-mat samples were cleaned of carbonate material and submitted to Beta Analytic Inc. The ^{14}C analysis was determined by the Accelerator Mass Spectrometry (AMS) method, which required measuring the stable-carbon isotopic ratio ($\delta^{13}\text{C}$). Reported results contained both $\delta^{13}\text{C}$ and the conventional radiocarbon age (CRA), which is the age corrected for carbon isotopic fractionation as established by the $\delta^{13}\text{C}$. Calibrated ages were then determined by the OxCal 5.0.1 program using the Marine04 correction (Hughen et al., 2004).

X-radiographs of the core half selected for isotopic analysis were made by a commercial lab in Denver, Colorado. Organic analyses (carbon and nitrogen isotopes and fatty acids) were conducted by Dr. Pat Parker at the Department of Marine Studies, University of Texas at Austin, and chemical, textural, and x-ray diffraction (XRD) analyses were conducted by the Bureau of Economic Geology, University of Texas at Austin. The common siliciclastic and authigenic minerals were identified using a binocular microscope and XRD techniques. Eleven representative samples from eight different cores were selected for XRD analysis based on appearance, crystal form, and sample depth.

GEOLOGICAL SETTING

Climate and Physical Processes

The wind-tidal flats of Laguna Madre are in a semi-arid climate zone, wherein annual average evapotranspiration normally exceeds precipitation (Bomar, 1995). The deficit in rainfall has a profound influence on plant assemblages, physical processes, and landforms of the region. Coastal waters historically have been hypersaline because average annual temperatures are high, evaporation is high, rainfall is low, and freshwater inflow to the lagoon is low. However, salinities in Laguna Madre have not been abnormally high since the late 1940s, when construction of the Gulf Intracoastal Waterway (GIWW) connected northern and southern Laguna Madre (Fig. 1). Opening Mansfield Channel in the early 1960s also increased water circulation between the lagoon and the Gulf of Mexico and moderated salinity fluctuations (Hansen, 1960).

Large dune fields and wind-tidal flats dominate the landscape surrounding Laguna Madre. Every few decades, prolonged droughts lower the water table, reduce the internal moisture of the sediments, weaken or kill the stabilizing vegetation, and accelerate onshore eolian transport of sand.

Wind is responsible for shaping the south Texas coastal plain and controlling erosion and deposition on the wind-tidal flats and in other coastal environments. The predominant southeasterly onshore winds generally do not reach high velocities, but they persist from spring through fall. In contrast, northerly winds associated with the passage of winter cold fronts are strong but brief; however, their total energy dissipated at the coast is less than that of the predominant southeasterly winds (Price, 1958).

Water-Level Fluctuations

Astronomical tides in Laguna Madre are mixed (diurnal and semi-diurnal) and extremely small, ranging from 0 to 30 cm (Gill et al., 1995). The absence of substantial tidal influence on water levels in Laguna Madre is attributed to the low tidal range in the western Gulf of Mexico, the large area and small number of tidal inlets intersecting the lagoon, and the long distances from inlets to the center of the lagoon. Meteorological forces (wind speed and direction, barometric pressure) largely control water-level fluctuations near the wind-tidal flats

and the astronomical tides explain only a few percent of the water-level variability (Fisk, 1959; Gill et al., 1995). The flats have such low relief that wind is capable of pushing water out of the lagoon and up onto the flats. Field observations and daily monitoring (Fisk, 1959) showed that the flats are inundated by non-channel sheet flow.

Both winter storms and tropical cyclones can rapidly change water levels in Laguna Madre and generate moderately high waves and strong currents that erode and transport small volumes of sediment. Cold fronts with associated north winds cross the Texas coast about every six days throughout the winter. Because of this frontal activity, several strong winter storms occur each year. Before a cold front passes the coast, strong winds blow onshore from the southeast in response to the low-pressure system that is farther inland. Strong onshore wind drives water onto the southern part of the flats and off the northern part of the flats (Fisk, 1959). After the frontal boundary passes the coast and moves over the Gulf of Mexico, the wind changes direction and blows from the north, driving water onto the northern and off the southern part of the flats. A hurricane crosses the Texas coast about once every three yr, but the probability of a major hurricane striking at any particular site is much lower and on the order of once every 10 to 12 yr (Simpson and Lawrence, 1971). The climate and geographic setting of Laguna Madre ensures that it has been influenced by several hundred hurricanes since it was formed several thousand yr ago. Hurricanes flood the flats and generate high-velocity, wind-driven currents that locally erode and deposit sand on the flats (Fig. 2).

Flooding frequency of the flats generally decreases to the west and northwest because of surface gradient and orientation with respect to the lagoon and predominant wind directions. This means that core sites near the western margins (core sites 4, 5, 6, and 9) are less frequently flooded, whereas core sites near the open lagoon (core sites 1, 12, and 13) are more frequently flooded.

Relative Sea-Level Changes

Tide-gauge records in interior coastal waters of south Texas all show interannual and decadal sea-level variations that coincide with droughts and periods of abnormally high rainfall. The relative rise in sea level (Fig. 6) currently averages from 3.4 mm/yr at Port Isabel, which is the lowest for the entire Texas coast, to 4.6 mm/yr at Rockport (Zervas, 2001). The rate of relative sea-level rise in Laguna Madre (3.4 mm/yr) is about twice as fast as the eustatic rise of 1.8 mm/yr for the past century (Douglas, 2001) or nearly comparable to the average global eustatic rate (3.1 mm/yr) between 1993 and 2003 (Intergovernmental Panel on Climate Change, 2007).

When examined for temporal trends, tide gauges within or near Laguna Madre reveal significant increases in water level beginning in the early 1960s (Fig. 6). Some of the historical relative rise in sea level is due to subsidence (Swanson and Thurlow, 1973) caused by sediment compaction, with additional regional contributions from subsurface-fluid withdrawal (Paine, 1993).

Sediment Transport and Deposition

Most of the sediments that compose the flats were transported to the area by marine water. Evidence of a lagoon origin includes the presence of (1) marine shells in most of the cores, (2) relatively thick layers of homogeneous mud that is transported in suspension in flood waters, and (3) abundant layers of evaporite minerals that are products of hypersaline seawater.

When the flats are dry, wind is the only physical agent that delivers sediment to or removes sediment from the flats. The wind entrains sand grains, small particles of mud, and fragments of algal mats from the tidal-flat surface. The eroded sediments are transported landward by the predominant southeasterly wind and either relocated on the flats or transferred farther inland depending on the speed and duration of the wind. If deflation persists, wind erosion will lower the land surface until sediment moisture prevents further erosion. Thus, the land-surface elevation near sea level is controlled by the height of the water table. Deflation maintains the broad, nearly horizontal surface even as additional sediments are deposited on the flats.

During and after heavy rains, water draining onto the flats from higher elevations transports some sediment eroded from the upland areas. However, slope-wash deposition is minor and areally restricted to a narrow zone along the extreme western margin of the flats where they merge with the uplands. Internal drainage on the upland surface prevents formation of an integrated network of streams, which restricts slope wash to a local process.

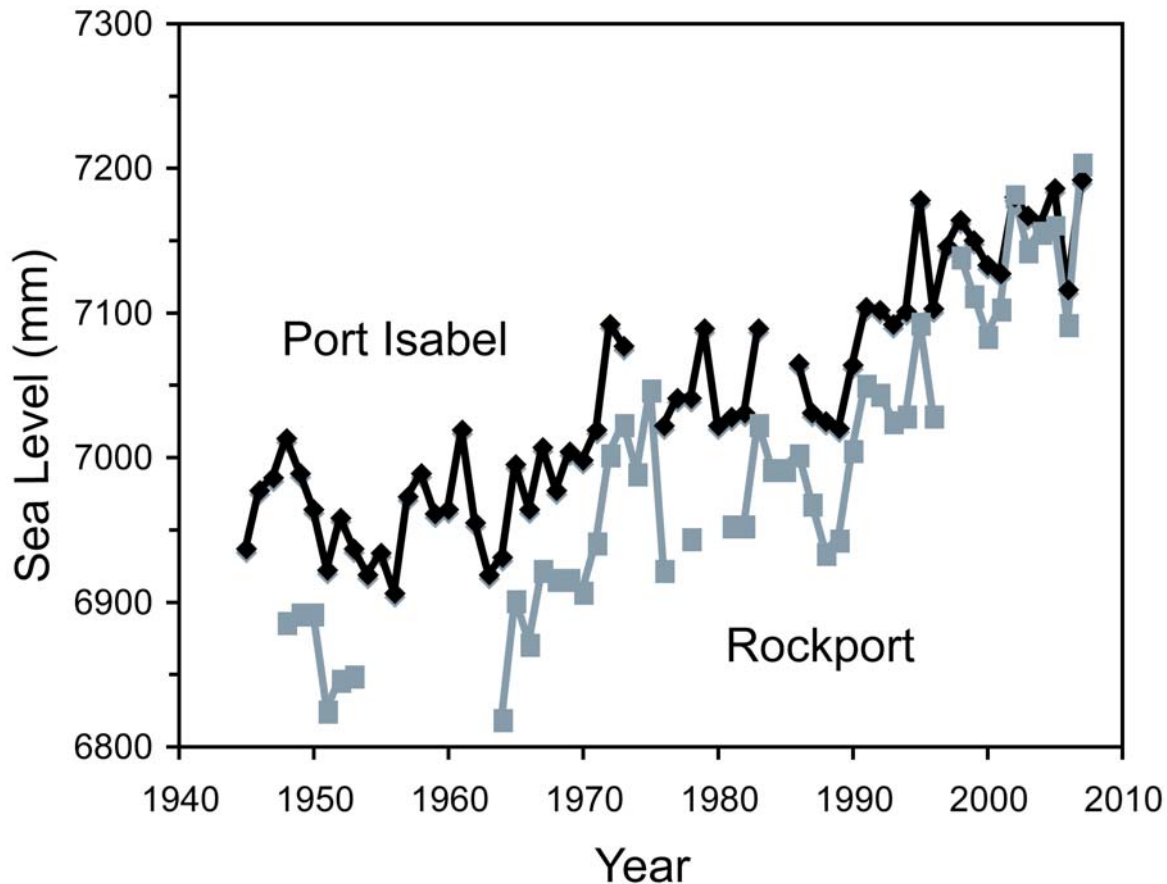


Figure 6. Historical record of relative sea-level rise at National Ocean Service tide gauges that encompass the wind-tidal flats of Laguna Madre. Data from the Permanent Service for Mean Sea Level (PSMSL; <http://www.pol.ac.uk/psmsl/>). Locations of Port Isabel and Rockport are shown in Figure 1.

GEOMORPHOLOGY OF THE FLATS

The largest features of the wind-tidal flats were examined to determine the nature and extent of morphological changes since the late 1800s. The primary features compared historically were Potrero Lopeño, Calabazas Islands, Tres Marias Islands, El Toro Island, and Mesquite Rincon (Figs. 2 and 3). The 1879-81 map (Fig. 3) displays less detail than the 1937 aerial photograph (not shown), so comparisons between 1879-81 and 1937 are limited. However, it is evident that the positions, shapes, and general outlines of the features remained the same, and no large-scale changes occurred on the wind-tidal flats during that period.

Comparing the largest geomorphic features on the georeferenced aerial photographs showed that no systematic erosion or deposition occurred around the features between 1937 and 1996 (Fig. 2) or 2005 (not shown). The most obvious small-scale morphological changes were local scour-and-fill features (Fig. 2) produced by hurricane currents around topographic mounds (erosion) and on the margins of dredged channels (deposition). The most significant tropical cyclones directly impacting the flats were hurricanes Allen in 1980, Bret in 1999, and Dolly in 2008.

Results of the sequential geomorphic comparison indicate that the primary natural features of the flats are relatively stable, and the appearance of the flats has remained essentially the same since the late 1800s. The most obvious changes since the late 1940s are related to dredging of the Gulf Intracoastal Waterway and channels to hydrocarbon well sites (Figs. 2 and 4).

Eolian Plain

The eolian plain refers to the sand sheet (Forman et al., 2009) that covers the western margin of Laguna Madre near the wind-tidal flats (Fig. 2). Price (1958) classified the eolian plain as a banner-dune complex because the sharp angles sculpted by the wind create a pattern that is similar to a banner. The banners are oriented northwest-southeast, which is parallel to the predominant wind direction. Mesquite Rincon exhibits the same banner patterns, indicating that it is an erosional remnant of the eolian plain that once covered the area now occupied by the wind-tidal flats.

Potrerros and Rincons

The potrerros and rincons of the Laguna Madre flats (Potrero Lopeño, El Toro Island, and the eastern margin of Mesquite Rincon, Fig. 2) are compound geomorphic features that record a complex history of erosion and deposition by wind and water. Both landforms exhibit parallel construction of sand ridges that outline the former shapes and positions of the features. Both the potrerros and rincons are attached to remnants of the eolian plain, so they formed after the eolian plain. Sand ridges of the potrerros and rincons are oriented nearly perpendicular to the banner dunes, indicating that processes responsible for the formation of the potrerros and rincons were different from those that formed the eolian plain. In contrast to the eolian plain, the northeast-southwest trending sand ridges of the potrerros and rincons are oriented normal to the predominant wind direction, and they were shaped primarily by water when the flats were flooded.

Surficial Disturbance of the Flats

Despite their remote location, the wind-tidal flats have been the site of cattle ranching, seismic surveys, and hydrocarbon exploration, production, and transmission. The northern part of the flats also was a bombing range during World War II. Because of these activities, the surfaces of the flats have been disturbed in some areas. The impacts of cattle trails, roads, pipelines, drilling sites, and spoil disposal are limited to narrow linear bands or relatively small areas, whereas remnant vehicle tracks could be present almost anywhere on the flats.

Surface disturbances potentially can alter the calculated rates of sedimentation and subsequent geological interpretation of the flats. Activities that compressed the sediments would decrease the estimated sedimentation rates. Deposition of dredged material has the greatest potential for invalidating rate results. Dredged material can alter the natural order of strata and create an artificial stratigraphy of disturbed sediments whereby older dredged sediments are deposited onto younger sediments at the surface. The most common disturbances on the flats have been excavation and backfilling of pipeline trenches and dredging of well locations, access channels, and the GIWW. Fortunately, the impacts of these activities are areally restricted, and the disturbed areas are easily identified and were avoided when cores were collected.

Dredged Channels and their Hydrodynamic Effects

Construction of the GIWW through the flats (Figs. 2 and 4) in 1948 altered the hydrodynamics of the flats by reducing both their frequency and duration of flooding (Rusnak, 1960). Before the GIWW was dredged, strong or persistent winds from either the south or north would force water onto the flats where it would remain until it either gradually drained back into the permanently flooded part of Laguna Madre or it evaporated. However, since its construction, the GIWW provides an alternate route for the wind-driven water, and some water flows through the dredged channel rather than onto the flats (Breuer, 1957; Rusnak, 1960). In addition, water that is driven onto the flats probably remains a shorter time because it can drain into the GIWW rather than having to flow back across the flats.

Several shallow canals were dredged from the GIWW to the interior of the flats to provide access to hydrocarbon well sites (Figs. 2 and 4). These well canals also operate as conduits for water flowing onto or off of the flats. Their long-term influence on frequency and duration of flooding on the flats is uncertain, and these effects

have likely changed as more canals have been dredged. Field evidence indicates that the canals act primarily as drains; water draining off the flats erodes branching channels at the heads of the canals and locally lowers elevations of the flats around the canals.

SEDIMENT CHARACTERISTICS OF THE FLATS

Composition

The wind-tidal flats of Laguna Madre are composed primarily of siliciclastic sediments derived from the land and transported to the flats by physical processes; however, some of the sediments are authigenic evaporites or precipitates. Results of the XRD analyses show that the most common minerals are quartz, feldspar, gypsum, halite, aragonite, calcite, dolomite, and smectite. These results agree with the mineral compositions that were previously reported by Fisk (1959) and Miller (1975). The clastic sediments, which include quartz, feldspar, and clay minerals (primarily smectite), are not unique to the wind-tidal-flat deposits; therefore, greater emphasis for geological interpretation is placed on the authigenic sediments, shells, and algal mats.

The flat deposits also contain crystals and thin layers of aragonite, calcite, dolomite, gypsum, and halite. The gypsum occurs in three forms: (1) layers or lenses of granular gypsum, (2) single-bladed crystals or small interlocking crystalline aggregates (gypsum rose), and (3) discrete nodules without any crystalline shape. The continuous thin beds and lenses of gypsum were deposited at or near the surface by evaporating seawater (Fisk, 1959; Masson, 1955; McBride et al., 1992). In contrast, the discrete nodules, crystalline aggregates, and single-bladed crystals were precipitated in the porous sand by highly saline groundwater that is periodically recharged by marine water flooding the flats (Fisk, 1959; Long and Gudramovics, 1983).

Chemical analyses show that organic matter is normally a minor component of the flat deposits; however, organic matter can be concentrated in algal mats that form continuous laminations and thin beds. The algal mats form at the surface and grow when the flats are flooded, but they become desiccated and may be destroyed when the flats are dry. In those areas that are frequently flooded, the algal mats form layers that are leathery and resist erosion. Algal mats form where the flats are frequently flooded, and they are diagnostic indicators of the intertidal zone of coastal deposition (Kinsman and Park, 1976; Schreiber, 1986).

Marine molluscs are commonly present in the wind-tidal-flat sediments, occurring either as disseminated whole valves or fragments, or as concentrated lenses. The most abundant molluscs are the marine species *Anomalocardia auberiana* and *Mulinia lateralis*, which also are abundant in Laguna Madre (Fisk, 1959; Rusnak, 1960; White et al., 1989).

Sedimentary Structures

Most of the sediments from the wind-tidal flats are preserved as laminations that conform to the surface of the flats. In some of the cores, laminations are disrupted by processes that were contemporaneous with deposition. However, some of the disruptions occurred long after the sediments were deposited. Contemporaneous lamination disruption can be caused by desiccation of the sediments and algal mats, which forms mud cracks and causes the algal mats to curl up. Gas formation in the shallow sediments also can cause sediment disruption. Gas generated as the algal mats decompose migrates to the surface and causes the sediments and algal mats to heave or form blisters. Air trapped in the sandy sediments while they are flooded produces another common sedimentary structure known as “gas-bubble” or “sponge-cake” structure.

BRIEF GEOLOGICAL HISTORY

The relations of eolian-plain sediments to underlying Pleistocene deposits and the relatively young age of the dunes (Forman et al., 2009) indicate that the eolian plain formed during the Holocene. Wind erosion (deflation) of the area south of Potrero Lopeño (Fig. 2) removed most of the eolian landforms except Mesquite Rincon, a remnant landward of El Toro Island, scattered mounds such as Tres Marias Islands, and smaller un-

named islands southwest of Mesquite Rincon. Sea level rose and began flooding the former upland area several thousand yr ago. This major geological event marked a change from dominantly wind erosion to dominantly marine deposition near the flats. The periodic flooding resulted in deposition of the interbedded sand, mud, algal mats, and evaporites that form the wind-tidal-flat deposits. The remnant islands were wave modified, and concentric accretion ridges began to form around the islands. Sediments that caused accretion of the potreros and rincons were transported by the wind and later shaped by the water that periodically flooded the flats. Clay dunes that form the western margin of the flats also began to form about this time by accreting against remnant upland mounds. The potreros and rincons accreted seaward, whereas the flats aggraded vertically.

ISOTOPIC AGE DATING AND SEDIMENTATION RATES

Carbon-14

The wind-tidal-flat deposits contain algal material, shells, and carbonate sediments that can be used to obtain radiocarbon ages of the sediments and for estimating rates of sedimentation. The primary sources of error that could invalidate the ^{14}C dates are sediment reworking and geochemical contamination, including the well-known marine-reservoir effect (Hughen et al., 2004). Fisk (1959) reported anomalously old and stratigraphically inconsistent ^{14}C dates for relatively shallow sediments beneath the flats. Fisk attributed the erroneous dates to reworked shell material. Contamination probably explains why dates derived from shells and carbonate material are slightly older than those derived from algal material taken from similar horizons beneath the wind-tidal flats (comments by J. A. Miller in Valastro et al., 1972). Friedman et al. (1973) also found an older age bias in shells compared to algal material.

All the ^{14}C dates reported for this study were obtained from discrete algal mats in growth position in cores 5, 7, 8, 10, 12, and 13 (Fig. 4; Table 1). The algal mats were processed to remove all carbonate material. Therefore, the algal mats should be free of contamination by recycled older carbon and should provide accurate dates for the wind-tidal flat sediments.

Average geological rates of sedimentation for the wind-tidal flats were estimated using the radiocarbon ages and depths of algal samples (Table 1). For those cores with more than one dated sample, two different rates of sedimentation can be calculated using the same data. Dividing sample depth by sample age gives the simplest but least accurate estimate. This end-point calculation yields an average rate of sedimentation for the total thickness of sediments. A more accurate method of calculating sedimentation rates recognizes that different rates of sedimentation can occur at different times. For the second method, the difference in depths and difference in sediment ages at the top and bottom of an interval are used to calculate an interval rate of sedimentation. The interval method does not average the rate of sedimentation for the entire depth of the sample but restricts the averaging to only the interval of interest. Sedimentation rates calculated using the end-point method range from 0.13 mm/yr to 0.71 mm/yr and average 0.57 mm/yr. Sedimentation rates calculated using the interval method are higher, ranging from 0.50 mm/yr to 0.96 mm/yr and averaging 0.77 mm/yr. Although composite plots of radiocarbon ages with depth (Fig. 7) or sedimentation rates (Fig. 8) do not show pronounced changes in sedimentation rate with time, values in individual cores (5B, 7A, 12B, and 13B) show consistent decreases in end-point sedimentation rate for younger sediments (Table 1).

Delta Carbon-13

The $\delta^{13}\text{C}$ values for the wind-tidal-flat algal mats in Laguna Madre fall within a relatively narrow range between -12.6‰ and -15.2‰ (Table 1). The $\delta^{13}\text{C}$ values greater than -15.2‰ indicate that the algal mats are entirely marine in origin, and there is no apparent terrestrial influx of organic carbon that would make them isotopically lighter. Time- and depth-dependent geochemical changes in the depositional environment are indicated by the shift toward more positive $\delta^{13}\text{C}$ values for older mats (Fig. 9). The enrichment of $\delta^{13}\text{C}$ with time (depth) is partly related to the oxidation-reduction state, with sediments in a reduced state having slightly heavier isotopic values (Table 1).

Behrens and Frishman (1971) reported depth-related isotopic variations in algal mats from Baffin Bay, Texas, an estuary located about 30 km north of the study area (Fig. 1). They determined that organic carbon

Table 1. Average sedimentation rates for selected cores based on the intercept calibrated radiocarbon ages and depths of algal samples. Eh state was determined visually by sediment color. Calibrated ages were calculated by the program OxCal 5.0.1 using the Marine04 correction (Hughen et al., 2004).

Core Number	Sample Depth (cm)	Eh State	$\delta^{13}\text{C}$ (‰)	Conventional ^{14}C Age ± 1 sigma	Calibrated Radiocarbon Ages (YBP) @ 1 sigma (95% probability)			End-Point Rate (mm/yr)	Interval Rate (mm/yr)
					Intercept	Lower	Upper		
LM-5B	-5.5	Oxidized	-15.2	770 \pm 80	425	379	464	0.13	0.87
LM-5B	-37.0	Transition	-14.8	1240 \pm 70	785	721	846	0.47	
LM-7A	-34.0	Oxidized	-15.2	1420 \pm 60	920	910	1038	0.37	0.91 0.62
LM-7A	-66.0	Reduced	-16.1	1720 \pm 60	1270	1228	1322	0.52	
LM-7A	-105.0	Reduced	-13.8	2300 \pm 70	1900	1853	1978	0.55	
LM-8B	-131.0	Reduced	-12.9	2250 \pm 60	1850	1812	1896	0.71	
LM-10A	-54.0	Reduced	-13.5	2070 \pm 10	1645	1596	1691	0.33	
LM-12B	-48.0	Reduced	-13.7	1560 \pm 80	1110	1071	1162	0.43	0.50
LM-12B	-128.0	Reduced	-12.6	2930 \pm 70	2715	2692	2740	0.47	
LM-13B	-58.0	Reduced	-14.3	1370 \pm 70	910	887	953	0.64	0.96
LM-13B	-81.0	Reduced	-14.3	1590 \pm 70	1150	1112	1210	0.70	

within the mats was isotopically heavier than organic carbon in the bay sediments. They attributed the differences to fractionation associated with anaerobic bacterial decomposition of the algal mats. They also demonstrated a slight shift toward heavier (more positive) $\delta^{13}\text{C}$ values with depth. In another study of organic carbon in sediments from Baffin Bay, Anderson et al. (1992) reported cycles of $\delta^{13}\text{C}$ enrichment and depletion and an overall slight shift toward more positive values at depth. They interpreted the cycles and overall trend as the result of mixing two primary sources of organic carbon: seagrass, which is isotopically heavy (-10%), and phytoplankton, which is isotopically light (-20%). Their interpretation also implies that seagrass sources were predominant earlier in the history of Baffin Bay, whereas phytoplankton sources were predominant as the bay continued to fill but under conditions that did not favor establishment of seagrass meadows.

Lead-210

Excess ^{210}Pb decreases downcore in the upper 15 cm of most of the wind-tidal-flat cores (Fig. 10). In some cores, however, excess ^{210}Pb is highly variable below 15 cm. This trend may be caused either by sediment mixing or geochemical reactions. Loading, burrowing, or desiccation can cause in-situ mixing of the wind-tidal-flat sediments. However, trench exposures show that natural disruption of sediment laminations is minor. In addition, comparison of ^{210}Pb vertical trends with core photographs and compaction measurements indicates that there is no clear correlation among sediment disruption, core compaction, and anomalous ^{210}Pb trends. A possible explanation for anomalously high excess ^{210}Pb at depth involves atmospheric lead getting into the groundwater, the groundwater circulating through the porous sediments, and lead in the groundwater exchanging with calcium in the calcite and gypsum minerals in the sediments.

Excess ^{210}Pb profiles indicate that historical rates of sedimentation can be calculated for cores 1, 3, 6, 10, 11, 12, and 13. Excess ^{210}Pb trends for the other cores are considered to be too erratic for accurate determinations of sedimentation rates. The magnitudes and distribution of sedimentation rates calculated from the ^{210}Pb profiles

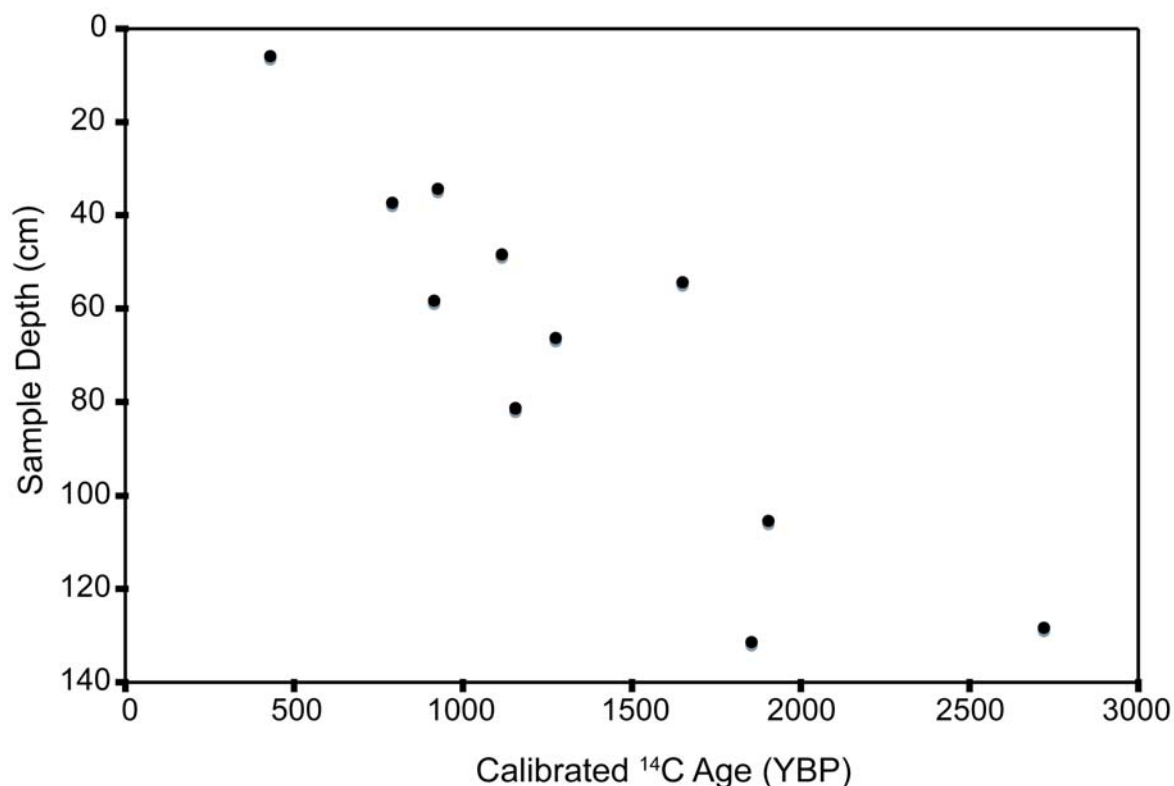


Figure 7. Composite plot of calibrated ¹⁴C dates and depths showing an increase in algal-mat age with depth.

(Fig. 4) indicate that sediment-accumulation rates are variable and seem to be slightly higher in the southern part of the flats compared to rates in the northern part of the flats.

The inventories of excess ²¹⁰Pb in the cores (Table 2) show a wide range of values that likely reflects a variety of sedimentation processes on the flats. Cores 4, 6, and 9 along the western margin of the flats with ²¹⁰Pb inventories that are depleted with respect to expected atmospheric contributions indicate that some sediment is missing. Inventories in cores closer to the intracoastal waterway and lagoon (3, 10, 11, 12, and 13) indicate that these are sites of greatest sediment accumulation. The highest rate of sediment accumulation (8.3 mm/yr) and ²¹⁰Pb inventory (115.9 dpm/cm²) at core 13 is attributed to the low elevation and attendant frequent flooding by lagoon waters.

DISCUSSION AND CONCLUSIONS

Sediment composition, including carbonates and evaporites and $\delta^{13}\text{C}$ values of algal mats, all indicate a marine origin for the wind-tidal flats of Laguna Madre. Miller (1975) used uncalibrated ¹⁴C dates of algal material to calculate sedimentation rates for the wind-tidal flats. He reported that sedimentation rates decreased from 0.5 mm/yr to 0.25 mm/yr during the past 2500 yr. The geological rates of sedimentation calculated for this study and those reported by Miller (1975) from ¹⁴C ages are in general agreement, and they both reveal the same overall trend, a decrease in sedimentation rates at time scales of several hundred to thousands of yr. However, sedimentation rates calculated from the ²¹⁰Pb profiles (Fig. 10; Table 2) are an order of magnitude higher than those calculated from radiocarbon ages of buried algal mats. Comparing sedimentation rates for the radiocarbon end-point and interval methods (Table 1) and for the ²¹⁰Pb models (Table 2) shows progressively faster rates for shorter periods of accumulation. Slower sedimentation rates averaged over millennia and faster rates averaged

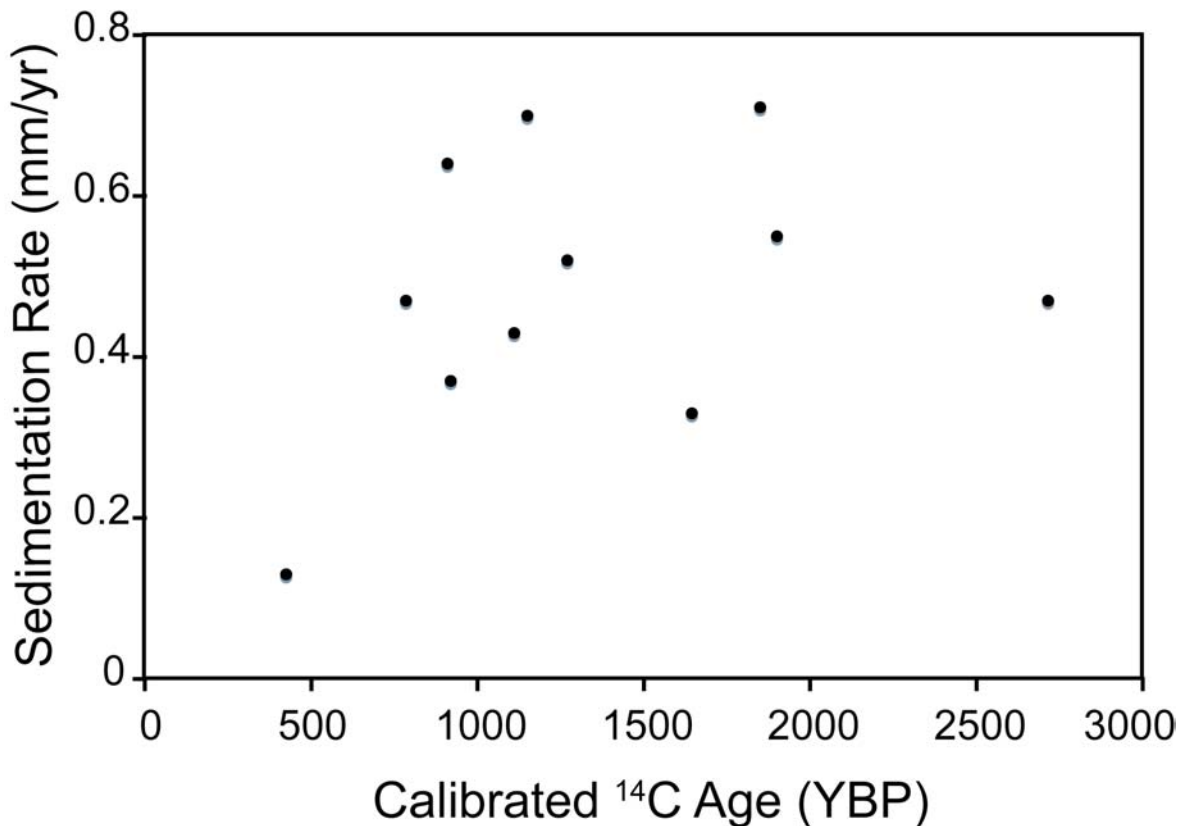


Figure 8. Composite plot of end-point sedimentation rates and calibrated ^{14}C ages of algal mat samples (Table 1) from the wind-tidal flats of Laguna Madre. Except for one outlier, the values show no clear temporal trend in sedimentation rates.

over centuries are the result of sediment erosion or depositional hiatuses and the cumulative missing section that increases over longer periods of observation (Sadler, 1999). Consequently, the sedimentation rates derived for historical and geological time scales cannot be compared directly.

The long-term balance between sedimentation and sea-level rise and the impact of these processes on the future status of the wind-tidal flats of Laguna Madre can be tested with the available data. The relative rise in sea level recorded at Rockport and Port Isabel is about 3 to 4 mm/yr (Fig. 6), whereas the average aggradation rate of the flats calculated from the isotopic data ranges from about 0.6 mm/yr to 2.2 mm/yr (Fig. 4; Tables 1 and 2). Even the historical rates of sediment accumulation (2.2 mm/yr) are substantially lower than the global rates of sea-level rise predicted by the Intergovernmental Panel on Climate Change (2007) as a result of global warming. Because aggradation of the flats likely will not keep pace with the rise in sea level, the flats will slowly be submerged and will eventually become permanently inundated.

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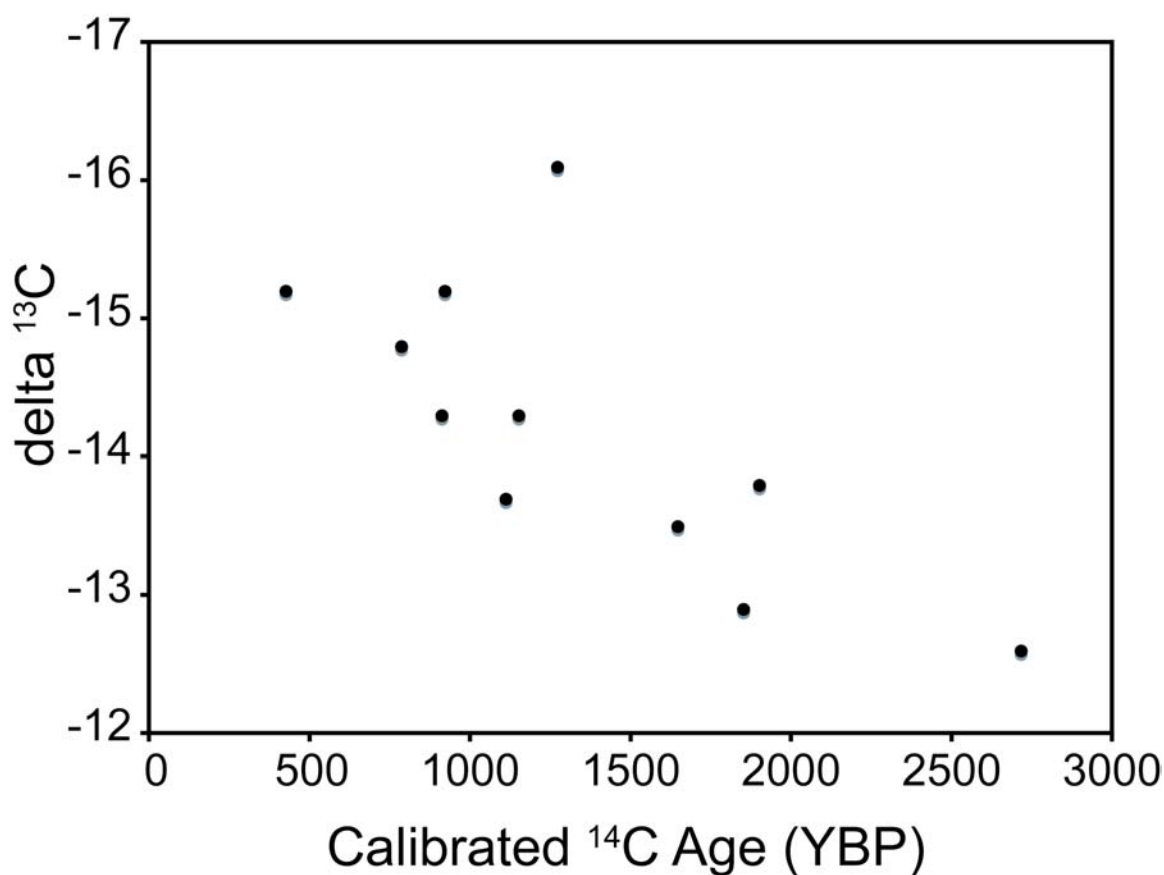


Figure 9. Plot of $\delta^{13}\text{C}$ values and intercept calibrated radiocarbon ages for the wind-tidal flat algal mats showing more negative $\delta^{13}\text{C}$ values in younger sediments.

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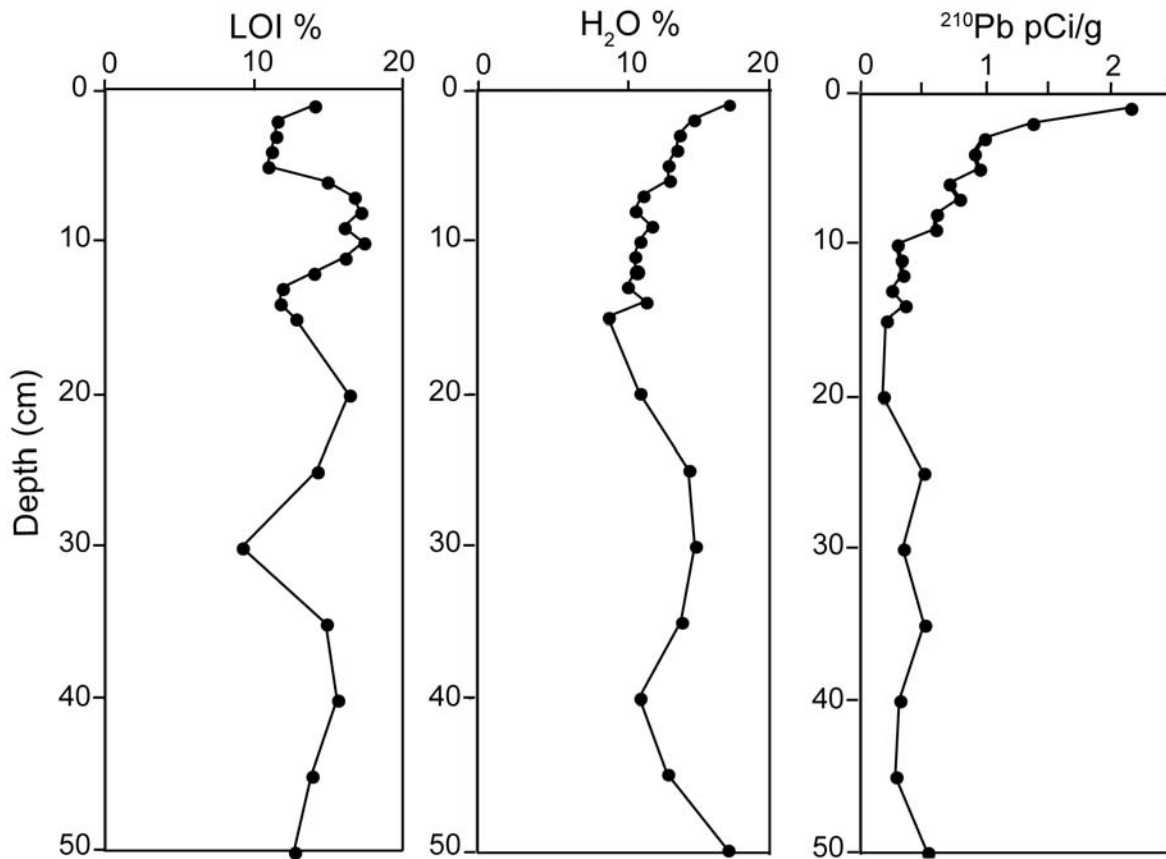


Figure 10. Depth profiles of percent organics (LOI), percent water, and ²¹⁰Pb concentration in core 10 showing systematic decrease of ²¹⁰Pb in the upper 15 cm of sediment.

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Table 2. Average historical sedimentation rates of the wind-tidal flats derived from ^{210}Pb profiles. CRS = Constant Rate of Supply model, and CIC = Constant Initial Concentration model.

Core	X_0 ^{210}Pb activity (dpm/g)	Sedimentation rate			^{210}Pb inventory (dpm/cm ²)
		CRS (mm/y)	CIC (mm/y)	CRS (g/cm ² /y)	
LM 3A	5.8 ± 0.02	0.7 ± 0.3	0.8 ± 0.2	0.97 ± 0.49	28.00
LM 4C	0.9 ± 0.02	1.5 ± 0.6	2.7 ± 0.2	0.35 ± 0.28	11.46
LM 6B	1.3 ± 0.05	3.3 ± 0.5	2.8 ± 0.3	0.48 ± 0.37	11.91
LM 9A	0.9 ± 0.05	1.4 ± 0.4	2.2 ± 0.2	0.25 ± 0.16	11.38
LM 10A	2.1 ± 0.2	1.1 ± 0.2	1.6 ± 0.1	0.18 ± 0.09	51.70
LM 11A	1.9 ± 0.3	5.0 ± 1.3	2.5 ± 0.2	1.64 ± 0.13	31.23
LM 12B	1.62 ± 0.5	2.2 ± 0.4	2.8 ± 0.2	0.40 ± 0.02	23.74
LM 13B	3.31 ± 0.3	8.3 ± 1.4	8.3 ± 0.5	1.21 ± 0.21	115.90

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