# Transgressive Ravinement versus Depth of Closure: A Geological Perspective from the Upper Texas Coast

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# Transgressive Ravinement versus Depth of Closure: A Geological Perspective from the Upper Texas Coast

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**ABSTRACT**

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The upper Texas coast is one of the most populated areas along the Gulf of Mexico. Three dynamic barriers along this section of coastline (Bolivar Peninsula, Galveston Island, and Follets Island) have a well-documented history of shoreline change. Numerous engineering studies incorporating both sedimentological data and numerical models have been established for this system to understand sediment fluxes. However, rarely have previous studies examined sediment fluxes for the upper Texas coast in light of certain fundamental concepts of coastal geology. Here, we discuss the current theory and understanding of barrier island dynamics from a geologic standpoint as they relate to sediment budgets for the upper Texas coast. From sediment cores, we quantify both shoreface and washover sand fluxes, which previously were not incorporated as sand sinks into sediment budgets for this system. Shoreface sand fluxes represent a sizable portion of the total budget, whereas modern washover sand fluxes are minimal. Until now, a depth of closure (beyond which sediment transport is negligible) of 4 m has typically been used; however, our data suggest a depth of at least 8 m would be more appropriate. We show that the combined upper and lower shoreface has the potential to sequester ~160,000 ± 39,000 m$^3$/y of sand, equaling ~17% of the entire calculated sediment flux and ~37% of the total longshore transport flux for the upper Texas coast, based on previous studies. Therefore, we recommend revised approaches to future sediment budget studies in order to establish more robust analyses. Ultimately, it will be crucial to use both engineering principles and geologic concepts to construct an accurate and realistic scenario for coastal restoration projects.

**ADDITIONAL INDEX WORDS:** *Shoreline response, sand budget, sediment, transgressive ravinement, erosion, closure depth, Texas.*

## INTRODUCTION

### Rationale for Study

Several previous studies have established the sand budgets for a wide range of coastal systems (Best and Griggs, 1991; Bowen and Inman, 1966; Carter, 1988; Kelley *et al.*, 2005; Komar, 1983; Schwab *et al.*, 2000). The upper Texas coast is one of the most developed sections of the Gulf Coast. Every year, millions of dollars are spent toward coastal nourishment projects aimed at combating coastal erosion. The study area spans some 150 km of coastline and includes both progradational and regressive barrier systems (Figure 1).

Gibeaut *et al.* (2006) present shoreline and bayline erosion rates for the upper Texas coast ranging from stable to about −4 m/y. To better understand this variability and ultimately quantify the long-term contributions of different coastal change mechanisms, an accurate sediment budget for the upper Texas Coast is needed. Previous research has focused on engineering practices as they relate to sediment budgets, but few have considered this work in light of geological principles. Specifically, there is a need to better constrain the sand flux at a range of timescales using information gained from sediment cores (Figure 2). Since rates of sea-level rise are expected to increase this century, quantification of coastal change mechanisms over decadal and centennial timescales allows us to better predict coastal change and to establish coastal preservation and planning scenarios.

### Geologic Setting

Prevailing winds from the southeast create a dominant westward flow along the upper Texas coast, although eastward flow does occur during cold fronts and winter months. Along this section of coastline, a microtidal regime exists, and the tidal range is ~30 cm. Average fair-weather wave heights for the system are ~1.0 m, but they can exceed 7 m during tropical storms and hurricanes.

#### Bolivar Peninsula

Bolivar Peninsula formed in its current location between 1500 and 1700 YBP by westward spit accretion (Morton, 1994; Rodriguez *et al.*, 2004). As Bolivar Peninsula migrated westward over the ancestral Trinity River incised valley, the barrier's thickness increased toward the west. It is up to ~15 m

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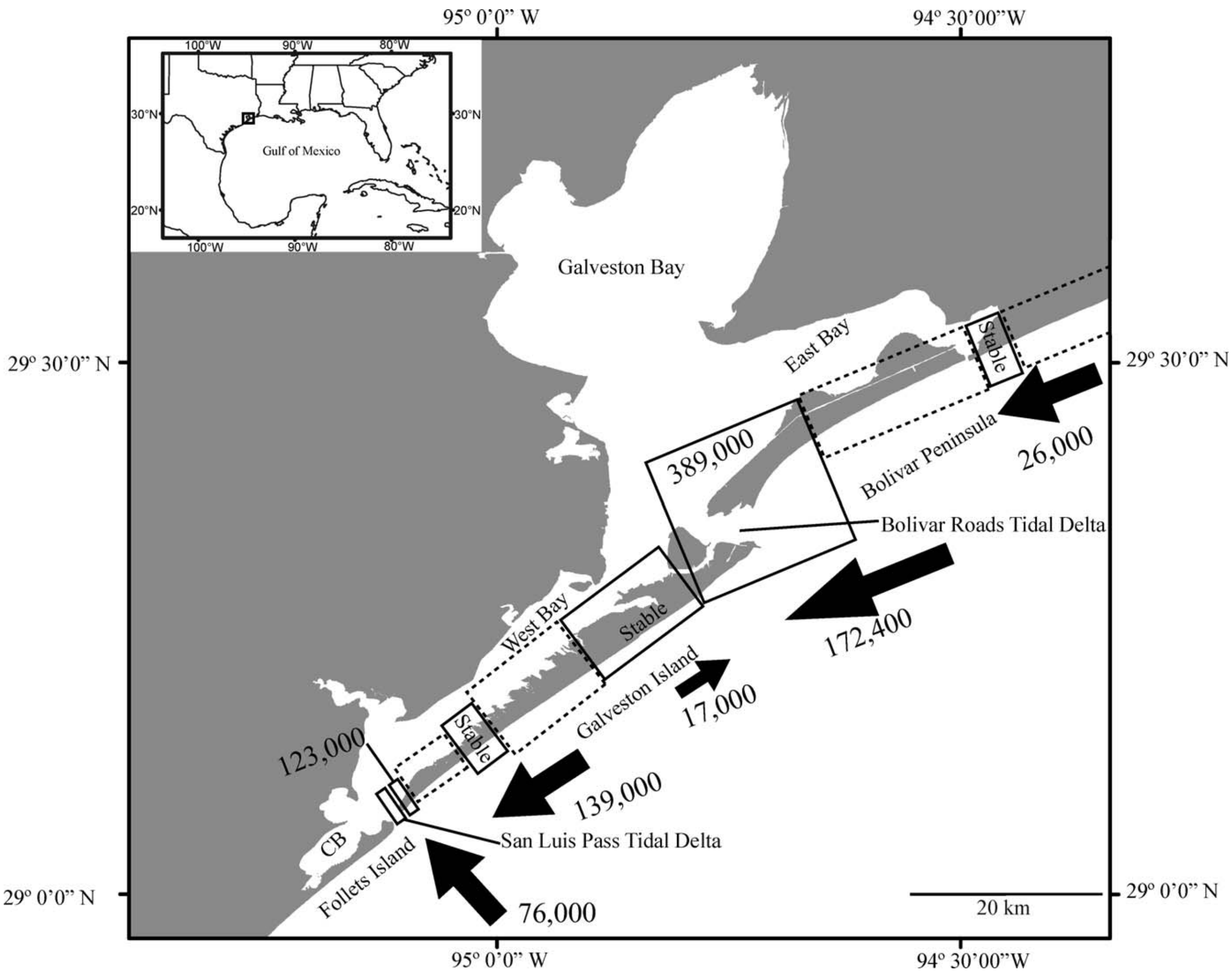


Figure 1. Study area map of the upper Texas coast. Also shown are approximate summarized results from an Army Corps of Engineers sand budget analysis (Morang, 2006). Numbers are the approximate flux in m³/y. Solid black boxes are approximate progradational shoreline sections, solid boxes marked stable are approximate stable shoreline sections, and dashed boxes represent approximate erosional shoreline sections (from Gibeaut *et al.*, 2006; Morang, 2006). Numbers adjacent to arrows represent approximate longshore transport fluxes. CB = Christmas Bay.

thick over this valley and ranges between ~3 and 8 m thick along the flanks (Figure 3). Currently, Bolivar Peninsula's shoreline change rates vary from about −1.95 m/y to +3.63 m/y, while the bayline is eroding at rates from about −1.5 m/y to −3 m/y (Gibeaut *et al.*, 2006).

### Galveston Island

Galveston Island is an elongate barrier, which began to form ca. 6000 YBP (Bernard, Major, and Parrot, 1959; Bernard *et al.*, 1970; Morton, 1994; Rodriguez *et al.*, 2004). Seaward progradation of the barrier island ended ~2000 y ago. Since that time, it has been eroding. The island is younger toward the west because the prevailing longshore currents deposit sand in this direction. It ranges in thickness from ~12 m to 2 m from east to west (Figure 3). Currently, Galveston Island's shoreline change rates vary from about −1.70 m/y to +2.70 m/y, and between about −0.35 m/y to −13.7 m/y for the bayline (Gibeaut *et al.*, 2006). The island is currently drowning in place.

### Follets Island

Follets Island rests on ca. 3000 YBP paleo–Brazos River sediments (Bernard *et al.*, 1970; Morton, 1994). This thin transgressive barrier ranges in sand thickness from ~1 to 4 m (Figure 3), and the backside of the island is dominated by washover deposits. Currently, Follets Island's shoreline change rates vary from stable to about −3 m/y, while the bayline varies from stable to about +1 m/y (Gibeaut *et al.*, 2006). We consider this island to be in its "rollover phase" because the rate of shoreline retreat is roughly equal to the rate of landward bayline movement.

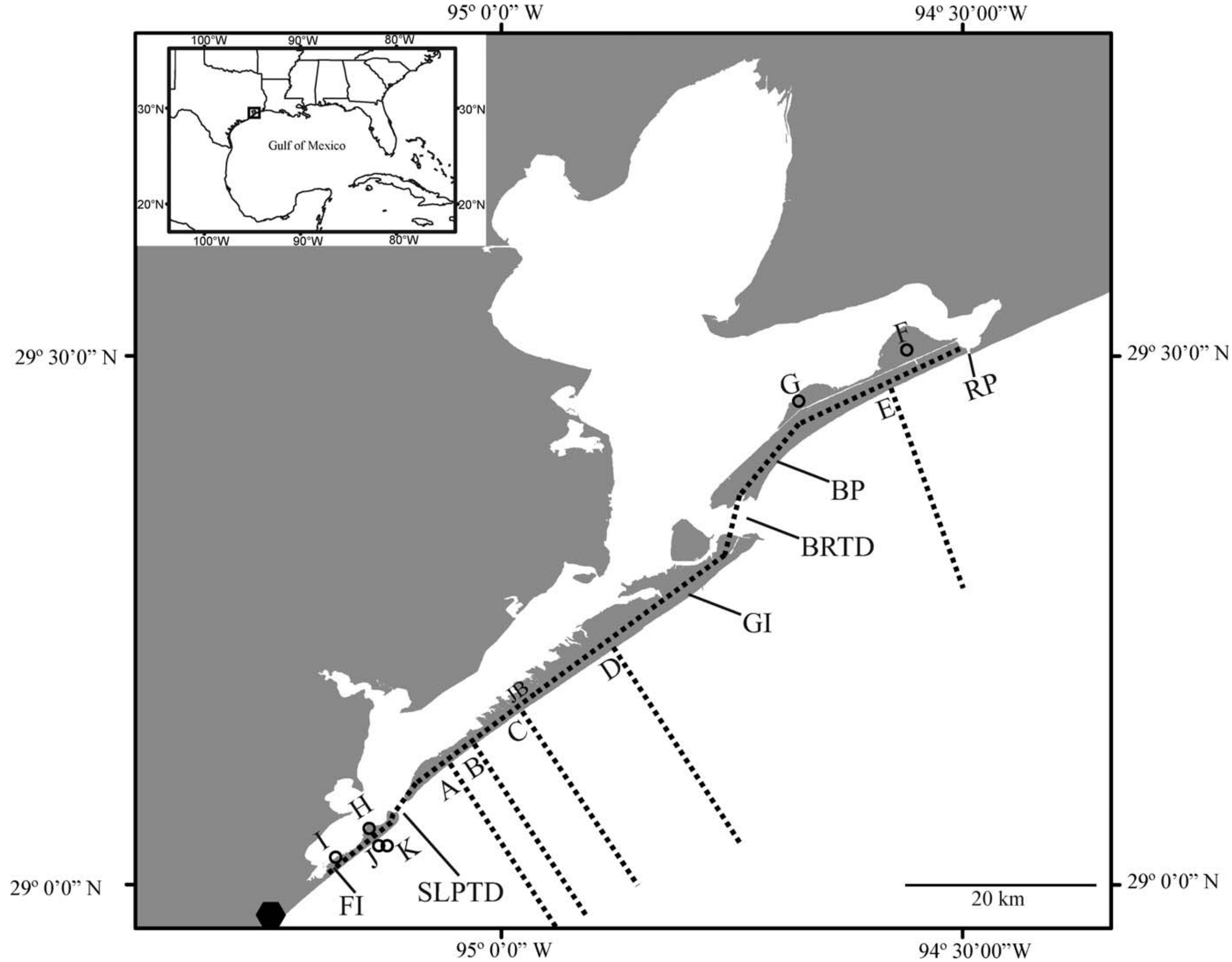


Figure 2. Map showing locations of core transects used for this study. Onshore and offshore core transects (dashed lines, letters A–E; data from Anderson *et al.*, 2008; Rodriguez *et al.*, 1999; Rodriguez, Fassell, and Anderson, 2001; Siringan and Anderson, 1993, 1994; Wallace, Anderson, and Rodriguez, 2009) and back-barrier core transects (open circles, letters F, G [both from Rodriguez *et al.*, 2004], H, and I) and nearshore cores (open circles, letters J and K) are shown. Black polygon represents the approximate location of Figure 7. RP = Rollover Pass, BP = Bolivar Peninsula, BRTD = Bolivar Roads Tidal Delta, GI = Galveston Island, JB = Jamaica Beach, SLPTD = San Luis Pass Tidal Delta, FI = Follets Island.

### Tidal Deltas

Two prominent tidal deltas exist along the upper Texas coast: Bolivar Roads Tidal Delta (BRTD) and San Luis Pass Tidal Delta (SLPTD) (Figures 1 and 3). The Bolivar Roads Tidal Delta system formed ca. 3300 YBP between the western end of Bolivar Peninsula and the eastern end of Galveston Island and had both a prominent ebb- and flood-tidal delta before jetties were constructed in 1846 (Rodriguez, Anderson, and Bradford, 1998; Siringan and Anderson, 1993, 1994). San Luis Pass Tidal Delta is a smaller delta between the west end of Galveston Island and the east end of Follets Island. SLPTD has both a prominent flood- and ebb-tidal delta (Israel, Ethridge, and Estes, 1987). Today, BRTD is highly anthropogenically influenced by jetties and dredging, while SLPTD is almost entirely natural.

### Transgressive Ravinement

Along Galveston Island, shoreface sands extend on average ~5 km offshore and rarely into more than ~12 m water depth, where there is clear onlap of distal lower shoreface deposits by marine mud (Figure 4) in most cases. These shoreface sands date back to ca. 2,660 YBP and rest atop Pleistocene-aged sediments (Rodriguez, Fassell, and Anderson, 2001; Siringan and Anderson, 1994); this significant hiatus indicates that the entire shoreface profile is migrating in accordance with the shoreline. Thus, reworking of sand during transgression (transgressive ravinement) occurs to water depths up to ~12 m, within a distance of ~5 km from the Galveston Island shoreline (Rodriguez, Fassell, and Anderson, 2001; Siringan and Anderson, 1994). On Bolivar Peninsula, shoreface sands are restricted to water depths up to 8 m, or within 2.5 km of the

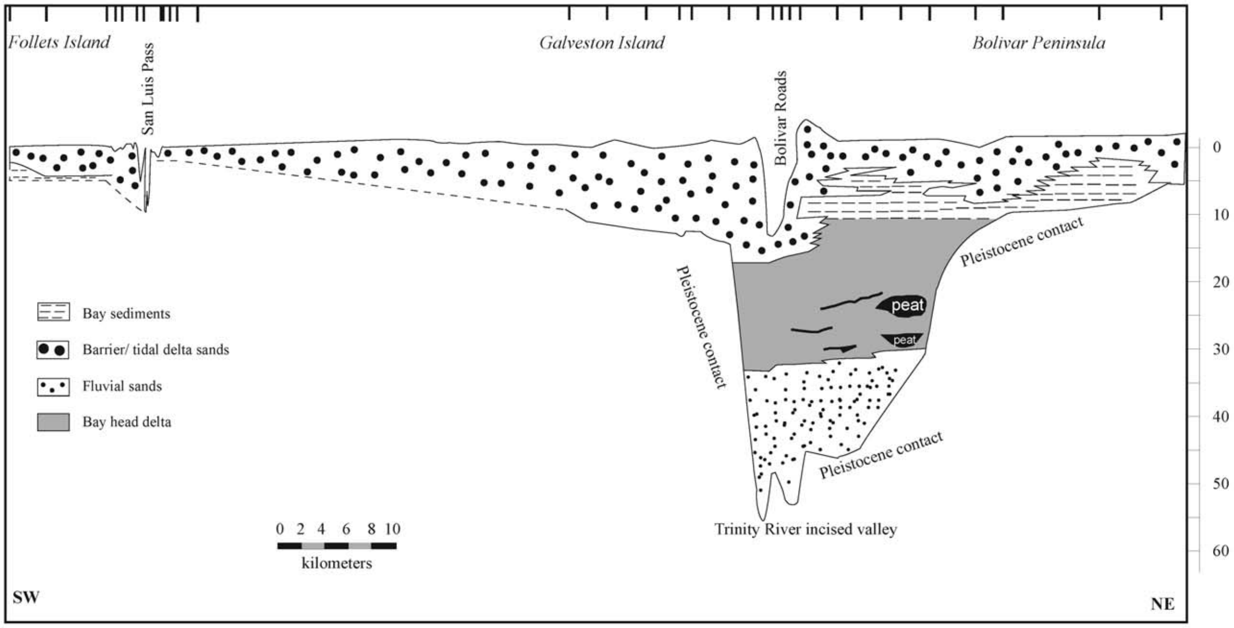


Figure 3. Coast-parallel cross section from Bolivar Peninsula to Follets Island (modified from Anderson *et al.*, 2008; Israel, Ethridge, and Estes, 1987; Rodriguez *et al.*, 1999; Siringan and Anderson, 1993; Wallace, Anderson, and Rodriguez, 2009). Note the thinning of sand from Galveston Island westward and on Bolivar Peninsula eastward, which is controlled by the antecedent topography of the Pleistocene surface, the most prominent feature being the ancestral Trinity River incised valley. Vertical lines at the top of the diagram represent core locations.

shoreline (Figure 4). Hence, the system is more sand deficient, and transgressive ravinement occurs at shallower depths, mainly because of this sand deficiency (Rodriguez, Fassell, and Anderson, 2001; Siringan and Anderson, 1994). On Follets Island, nearshore core data suggest that the system is sand starved (Figure 5), because the upper and lower shoreface contain only ~2 m and ~1 m of sand, respectively. Ravinement occurs to the Pleistocene surface (Figure 3), which is more resistant to erosion than the softer Holocene sediment.

Transgressive ravinement has removed old fluvial channels, deltas, and coastal deposits on the inner shelf. At the same time, cannibalization of these fluvial, tidal, and coastal deposits has yielded most of the sand that makes up the modern barriers of the upper Texas coast (Anderson *et al.*, 2004).

## Equilibrium Profile and Depth of Closure

The equilibrium profile model describes a beach profile that is bounded seaward by the depth of closure, beyond which there is negligible sediment transport (Bruun, 1962; Swift, 1976), although the existence of such a profile has been debated (Pilkey *et al.*, 1993; Thieler *et al.*, 2000). As the shoreface and shoreline migrate, sand that is removed from the barrier can be deposited into the back-barrier environment by storm washover and/or offshore by storm return flow.

Previous studies have determined that storms can transport sediment out to the edge of the continental shelf (Hayes, 1967; Morton, 1981; Pilkey *et al.*, 1993; Snedden, Nummedal, and Amos, 1988). Offshore Bolivar Peninsula, a thin (~2 cm) storm sand layer has been associated with Hurricane Ike based on data collected 1 mo after the impact (Goff, Allison, and Gulick, 2010). However, the source of the sand (*i.e.*, beach, upper shoreface, and/or lower shoreface) remains unclear as grain size analyses were not reported. Furthermore, the lateral extent of this event bed has not yet been established, so the volume of sand lost offshore from the coastal system cannot be accurately determined. Since previously collected core data rarely reveal modern sand beds beyond ~12 m water depth for the upper Texas coast (Siringan and Anderson, 1994; Rodriguez, Fassell, and Anderson, 2001), the timescales at which this sand remains offshore are uncertain. Over geologic timescales, the existence of late Holocene upper and lower shoreface sands directly overlying Pleistocene sediments also suggests that the toe of the shoreface migrates in accordance with the shoreline position (Figures 4 and 6).

The process of storm overwash transports sand from offshore, shoreface, and barrier environments into the back-barrier environment. Evidence of past storm deposition is seen on the backsides of Bolivar Peninsula, Galveston Island, and Follets Island as washover fans (Figure 2, cores F, G, H, and I). Washover fans generally form when barrier islands are narrow, thin, and can easily be overtopped. A recent study showed that the intense hurricane landfall probability for the Gulf Coast over the late Holocene is ~0.46% (annual landfall probability) for south Texas, and the current rate does not seem unprecedented (Wallace and Anderson, 2010). However, little

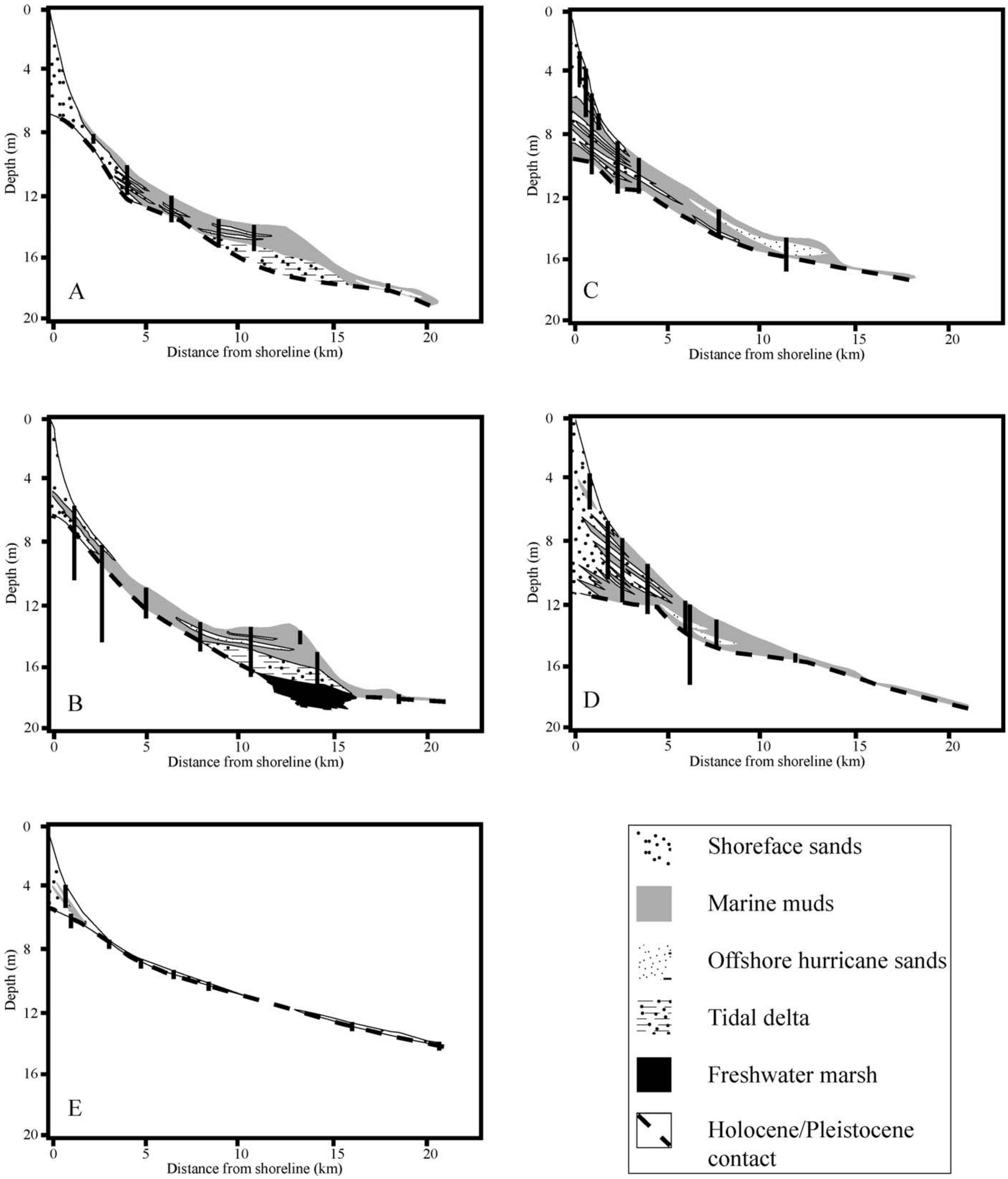


Figure 4. Core transects used to approximate sand volumes for the upper Texas coast (modified from Rodriguez, Fassell, and Anderson, 2001; Siringan and Anderson, 1993, 1994) (see Figure 2 for transect locations). A shoreface age of 2660±75 YBP is used, based on the maximum age of onlapping marine mud along the upper Texas coast (Rodriguez, Fassell, and Anderson, 2001; Rodriguez *et al.*, 2004). Vertical black lines represent core locations. Sand area between 4 and 8 m was determined for each profile. These profiles were then extrapolated between core transects for each barrier, and a shoreface sand volume was estimated for each barrier island system.

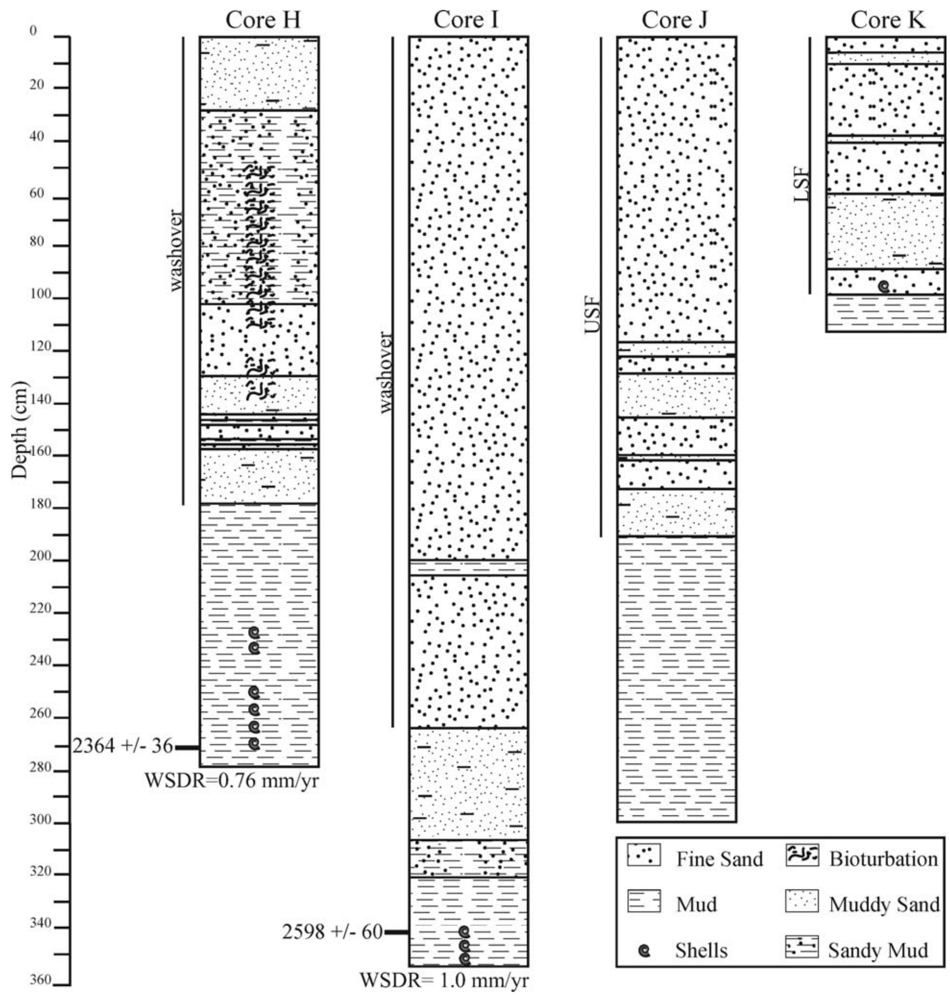


Figure 5. Lithologic descriptions and radiocarbon ages from core transects across Follets Island. Locations of cores are shown in Figure 2. Radiocarbon ages are calibrated from radiocarbon to calendar years using the average one-sigma ranges from Marine04 (Hughen *et al.*, 2004). Cores H and I represent hurricane washover sands, and cores J and K represent upper shoreface (USF) and lower shoreface (LSF), respectively. Note the minimal washover sand deposition rates (WSDR) for approximately the past 3000 y (~0.76–1.0 mm/y) in cores H and I. There is also minimal sand present in the upper and lower shoreface, suggesting it is likely being eroded and transported further west. The mud at the bottom of each core is fluvial sediment from the Bastrop channel, described by Bernard *et al.* (1970).

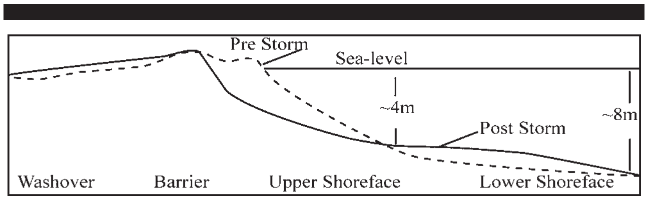


Figure 6. Equilibrium profile model for the upper Texas coast (modified from Bruun, 1962; Pilkey *et al.*, 1993; Swift, 1976). The dashed line represents the prestorm cross-sectional profile, while the solid line represents the poststorm cross-sectional profile. Recent sand budgets for the upper Texas coast only consider sediment within 4 m water depth to be part of the active coastal system (*i.e.*, depth of closure). However, geological studies suggest that a depth of at least 8 m would be more appropriate (Anderson *et al.*, 2004; Rodriguez, Fassell, and Anderson, 2001; Siringan and Anderson, 1994).

is known about the long-term storm sand fluxes associated with each barrier island along the upper Texas coast.

The change in sand volume for any length of beach is proportional to shoreline change ($\Delta s$) and the depth of the active beach sediment transport from an equilibrium profile (*i.e.*, the sum of the berm height, $D_b$, and the depth of closure, $D_c$) (Dean and Dalrymple, 2002; Ravens and Sitanggang, 2007). Both shoreline change and the berm height are well established from beach profile data, aerial photography, and satellite images (Gibeaut *et al.*, 2006; Ravens and Sitanggang, 2007). The depth of closure, however, is highly controversial. Morang (2006) and Ravens and Sitanggang (2007) both use a $D_c$ value of 4 m, based on negligible changes in before and after bathymetric profiles (*i.e.*, about <1 m). Beumel and Beachler (1994) calculated a depth of closure for Galveston Island of ~5 m. Numerous studies based on seismic, core, and bathymetric data

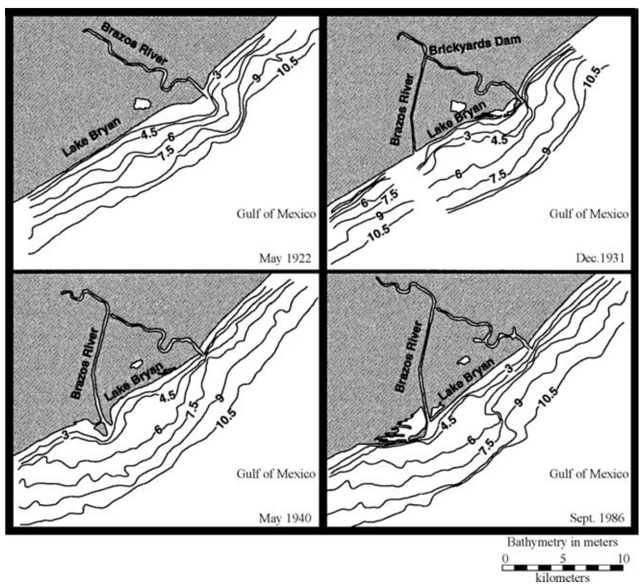


Figure 7. Bathymetric data (NOAA, 1989) of the Brazos Delta showing changes in the location of the delta from 1922 to 1986 (modified from Rodriguez, Hamilton, and Anderson, 2000). Approximate location is shown in Figure 2. The Brazos River was diverted in 1929, and the old delta was quickly eroded. Note that erosion of the old delta occurred at depths of at least 10.5 m.

indicate that a $D_c$ value of at least ~8 m would be more appropriate along the upper Texas coast (Anderson *et al.*, 2004; Rodriguez, Fassell, and Anderson, 2001; Siringan and Anderson, 1994). There are several lines of evidence that point to this deeper value. First, the physiographic toe of the shoreface (Siringan and Anderson, 1994), the defining geological factor in determining the $D_c$, is at least 8 m deep (Figures 4 and 6). Second, several Holocene offshore sand banks show a ravinement surface in at least 9 m water depth (Rodriguez *et al.*, 2004), so sediment transport and reworking is active to at least this water depth. Lastly, the fact that transgressive ravinement occurs at these deeper water depths indicates that sand transport during storms and hurricanes is a common process.

The best example of transgressive ravinement at depths well below 4 m is the erosion of the pre-1929 Brazos Delta. Prior to 1929, there was a prominent delta located at Surfside, Texas, that extended ~5 km offshore into at least 10.5 m of water (Figure 7). After the Brazos River diversion in 1929, the delta eroded within a matter of a few decades.

Most of the sand that was eroded from the old delta was transported westward and accreted to a new delta that formed at the new river mouth within a few decades (Rodriguez, Hamilton, and Anderson, 2000) (Figure 7). This example illustrates that wave erosion and redistribution of sand occur to water depths well below 4 m, and over timescales relevant to coastal nourishment projects. Therefore, we suggest using a $D_c$ value of at least 8 m as a better estimate of the depths of sediment transport. The Brazos Delta example provides a stark reminder that ravinement associated with $D_c$ is a very efficient process and should be taken into account for any sediment budget analyses.

## ASSESSING THE SAND BUDGET APPROACH

Several recent studies have attempted to develop a sediment and/or sand budget for the upper Texas coast. Ravens and Sitanggang (2007) used a numerical modeling approach to understand and develop a strategy to combat coastal erosion along Galveston Island. This study incorporated shoreline change data with the GENESIS model to determine that approximately 100,000 $m^3$/y of sand might be needed to maintain the 2001 shoreline on Galveston Island, and ~300,000 $m^3$/y would be needed to nourish the more depleted West Beach. A recent U.S. Army Corps of Engineers study (Morang, 2006) developed a sediment budget for the upper Texas coast from the Texas-Louisiana border to SLPTD. This study relied on bathymetric profiles, sediment grab samples, dredging records, aerial photographs, and elevation data.

These studies provide two independent approaches for establishing a sediment budget for the upper Texas coast. However, neither study incorporates data beyond 4 m water depth. Furthermore, neither study incorporates known sand contributions from storm impacts nor potential sources from reworking of sediment. Quantification of these previously overlooked components would provide the necessary information to accurately describe a sediment budget for the entire system and determine the volume needed for nourishment purposes.

### Methodology

Since sand-sized material is the most relevant to coastal nourishment scenarios, we focus the discussion on this size fraction. Currently, new sand delivery from fluvial systems to the upper Texas coast is minimal (Anderson, 2007; Morton, Gibeaut, and Paine, 1995). Therefore, it is critical to examine all available potential sources and sinks. The volume of sand within part of the coastal system (*i.e.*, barrier proper, littoral drift, and fluvial sediment supply) for Bolivar Peninsula, Galveston Island, and Follets Island has been established by previous studies (Morang, 2006; Ravens and Sitanggang, 2007). From core data, we determined the previously unaccounted volume of sand within the active coastal system (*i.e.*, between 4 and 8 m water depth) (Rodriguez, Fassell, and Anderson, 2001). The volumes were accurately estimated based on previously collected offshore profiles (Rodriguez *et al.*, 2001; Siringan and Anderson, 1994) (Figure 4). These profiles are ~20 km in length and are spaced ~15 km apart on average. We then estimated volumes from this information, and a shoreface age was determined from an articulated *Abra aequalis* bivalve shell (Rodriguez, Fassell, and Anderson, 2001; Rodriguez *et al.*, 2004). Radiocarbon ages were calibrated from radiocarbon to calendar years using the average one-sigma ranges from Marine04 (Hughen *et al.*, 2004). The upper Texas coast has a ~400 y radiocarbon reservoir (Milliken, Anderson, and Rodriguez, 2008), which is the built-in reservoir used in Marine04. Additionally, we examined the storm sand flux from

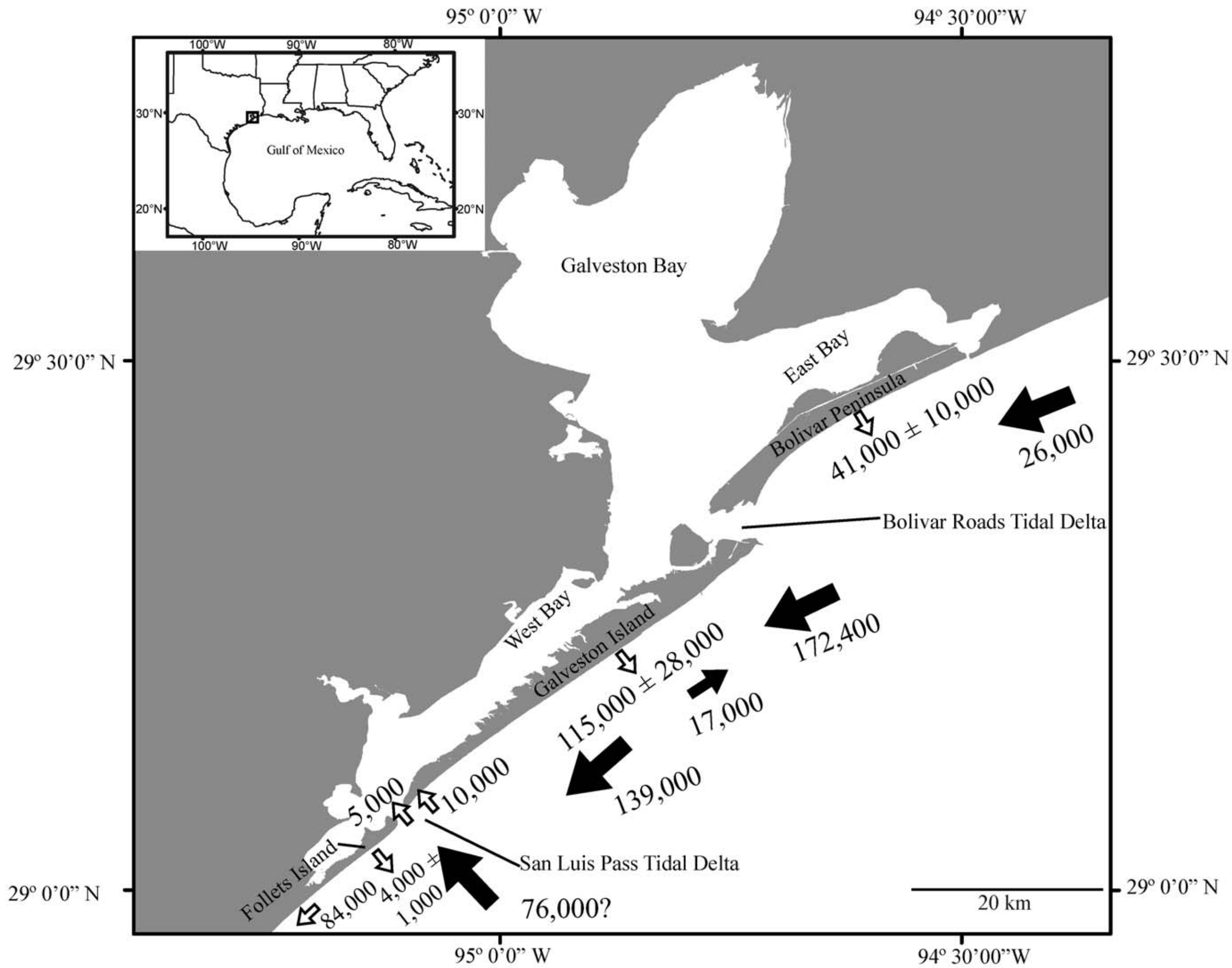


Figure 8. Previous approximate longshore transport estimation (solid arrows are data from Morang, 2006) with new data (hollow arrows are from this study) for the annual flux of sand to between 4 and 8 m water depth (arrows pointing offshore), into San Luis Pass Tidal Delta, and further west (84,000 $m^3/y$). Note that the estimated shoreface flux is equal to ~17% of the entire calculated sediment flux (Figure 1) and ~37% of the total longshore flux for the upper Texas coast from previous studies (Morang, 2006).

sediment core data (Figures 2, 4, and 5) both over historic and geologic time.

## RESULTS

The volume of sand sequestered within the shoreface environment was accurately estimated from core transects (Figures 2, 4, and 5). First, the sand area between 4 and 8 m was determined for each profile. Next, these profiles were extrapolated between core transects for each barrier, and a shoreface sand volume was estimated for each system. Based on the spatial distribution of core transects (Figure 2), this method yields a robust estimation of shoreface sand sequestration. From Rollover Pass to Follets Island (Figure 2), the upper and lower shoreface contains an estimated 426 million cubic meters of sand between 4 and 8 m depth. For Bolivar Peninsula and Galveston Island, the volume was then time averaged by 2660±75 YBP, the age of the shoreface deposits, based on the age of onlapping marine mud and the average age of barrier island deposits for the upper Texas coast (Rodriguez, Fassell, and Anderson, 2001; Rodriguez *et al.*, 2004), while the Follets Island shoreface sand volume was averaged by ~3000 YBP (Bernard *et al.*, 1970; Morton, 1994) to arrive at a total flux of ~160,000 $m^3/y$. Additionally, the error was calculated to be ± one standard deviation from the average area of Galveston Island profiles. Finally, the percentage of the total of this standard deviation (24%) was used to estimate error for all other shoreface profiles (*i.e.*, Bolivar Peninsula and Follets Island).

### Bolivar Peninsula

The sand volume within the shoreface from Rollover Pass to the west end of Bolivar Peninsula (Figure 2) was determined to be approximately 109,000,000 $m^3$. The shoreface sand is only ~6 m thick here because the underlying Pleistocene topography is shallow in this location (Figure 4). The time averaged sand flux to the Bolivar Peninsula shoreface was thus determined to be ~41,000 ± 10,000 $m^3/y$ (Figure 8).

### Galveston Island

The sand volume within the shoreface from the east end of Galveston Island to San Luis Pass was determined to be ~306,000,000 $m^3$. The shoreface sand is thickest near the east end (~12 m) and thins toward the west (~2 m) (Figure 4). The total time-averaged sand flux to the shoreface was determined to be ~115,000 ± 28,000 $m^3/y$ (Figure 8).

### Follets Island

Cores collected up to a kilometer offshore show minimal sand in the shoreface of Follets Island (between 1 and 1.7 m thick) (Figure 5). We estimate ~11,000,000 $m^3$ stored within the shoreface environment, meaning the flux is ~4000 ± 1000 $m^3/y$ based on an age of ~3000 YBP (Bernard *et al.*, 1970; Morton, 1994) (Figure 8).

Follets Island has yet to be incorporated into any previous sediment budgets for the upper Texas coast. Using an erosion rate of ~3 m/y for roughly 10 km of shoreline (Gibeaut *et al.*, 2006) averaging 3 m thick (Morton, 1994), we determine an annual sand flux of ~90,000 $m^3/y$.

### San Luis Pass

Previous studies suggest that the sand flux into the flood-tidal delta of the SLPTD is at least 76,000 $m^3/y$ (Morang, 2006). This number was determined based on the residual flux needed to close the budget from further east. A prior study by Israel, Ethridge, and Estes (1987) used an extensive collection of sediment cores to map proximal and distal facies and stratigraphic relationships of the SLPTD. Based on this work, we derive an approximate volume of 9,000,000 $m^3$ of sand within the flood-tidal delta of San Luis Pass.

This volume can be time averaged by the age when most of the sediments were deposited into San Luis Pass (between ca. 2100 YBP and 200 yr ago), which yields an annual sand flux of ~5000 $m^3/y$ (Figure 8), which is more than an order of magnitude lower than previous estimates (Morang, 2006). From core data, along with historical charts, we estimate that ~2,000,000 $m^3$ of sand has been stored along the far west end of Galveston Island due to the infilling of San Luis Pass over the past 200 y (Bernard *et al.*, 1970), equaling an average sand flux rate of ~10,000 $m^3/y$ to the far west end of Galveston Island (Figure 8).

### Bolivar Roads Flood-Tidal Delta

The sand flux for BRTD can be measured from annual dredging records. Both the north and south jetties on the west end of Bolivar Peninsula and the east end of Galveston Island, respectively, have accumulated a significant volume of sand since they were constructed.

Morang (2006) suggests that the sand flux for this system equals ~389,000 $m^3/y$, of which ~189,400 $m^3/y$ (172,400 $m^3/y$ + 17,000 $m^3/y$) can be attributed to longshore transport from further to the east and west (Figure 1). Morang (2006) suggests that since the dominant longshore transport direction is from northeast to southwest, sand is transported and deposited directly adjacent to the north jetty (far west end of Bolivar Peninsula). During winter months and approaching fronts, the dominant longshore transport direction switches to northeast, and thus some sand also accumulates directly against the south jetty (far east end of Galveston Island) (Morang, 2006). Since they are porous, the author suggests that sand moves through the jetties into the channel. However, this estimate does not take into account the large volume of sand sequestered in both the ebb- and flood-tidal deltas prior to jetty construction (Morton, 1977; Siringan and Anderson, 1993). Morton (1977) suggests a flux of ~470,000 $m^3/y$ on both Bolivar Peninsula and Galveston Island from 1867 to 1974 that could be attributed directly to destruction and reworking of the Bolivar Roads ebb-tidal delta. Therefore, it is likely that the sediment source reported by Morang (2006) to the western end of Bolivar Peninsula and the eastern end of Galveston Island was likely derived from cannibalization of the natural BRTD after jetty construction, with only minimal input from longshore transport.

### Washover Sands

Over historical time, Light Detection and Ranging (LIDAR) has been used to measure the elevation of subaerial land to within decimeters. Coupled with core data, comparison of pre- and posthurricane LIDAR data is the most accurate way of understanding the sand fluxes associated with storms. When both pre- and poststorm (Hurricane Ike-2008) LIDAR data for Bolivar Peninsula are compared (U.S. Geological Survey, 2009), it is clear that the majority of sand is transported only a few hundred meters landward of the shoreline, so washover into East Bay is minimal.

Wallace, Anderson, and Rodriguez (2009) suggest that hurricane washover accumulation rates are ~0.4 m/100 y for Galveston Island, and vary from 0.154 m/100 y to 0.095 m/100 y for Bolivar Peninsula (using radiocarbon data from Rodriguez *et al.*, 2004). Recently collected core data on the backside of Follets Island suggest washover rates of ~0.1 m/100 y (Figures 2 and 5). Therefore, from both core and LIDAR data, we conclude that the majority of washover sands in East, West, and Christmas Bays (Figure 1) accumulated earlier in the histories of the three barriers, when they were significantly lower and narrower, and that current rates of washover are minimal. These low accumulation rates are consistent with results from south Texas (Wallace and Anderson, 2010).

Bernard, Major, and Parrot (1959), Bernard *et al.* (1970), and Rodriguez *et al.* (2004) determined that beach ridges extending from the east end of Galveston Island to approximately the location of Jamaica Beach (Figure 2) formed ~1800 YBP based on radiocarbon ages (isochron interpolation). The continuity of these ridges along much of the coast suggests that hurricane sand transport from the island into West Bay has been minimal throughout modern times.

We quantified the washover sand fluxes by first estimating the area from satellite imagery, then calculating a volume based on known sand thicknesses from cores (Figure 2), and finally using the age of the deposits (Rodriguez *et al*., 2004) to derive a time-averaged flux. On Bolivar Peninsula, washover deposit F (Figure 2) formed ca. 1800 YBP, and washover deposit G (Figure 2) formed ca. 2800 YBP (Rodriguez *et al.*, 2004). Rodriguez *et al.* (2004) suggest that these features likely have not been active since ca. 700 YBP, based on the continuity of beach ridges of this age and younger on the peninsula. Therefore, the sand flux for washover F was ~23,000 $m^3$/y (2,300,000 $m^3$/100 y), and ~3000 $m^3$/y (300,000 $m^3$/100 y) for washover G from the time they both respectively formed until ca. 700 YBP.

On Follets Island, there are no preserved beach ridges, suggesting that during storms, the island is frequently overtopped and the washover fans on the back side of the island have recently been active. Washover H formed ca. 2400 YBP, meaning that the washover sand flux is ~300 $m^3$/y (30,000 $m^3$/100 y). Washover I formed ca. 2600 YBP, and the sand flux in this location is ~2000 $m^3$/y (200,000 $m^3$/100 y). It appears as though bayline stability on Follets Island is the result of organic marsh accretion and not washover sand deposition. Thus, while washover was an important means of removing sand from these barriers during their early evolution, this process can be considered negligible for sand budget purposes.

## DISCUSSION

By incorporating both hurricane washover and shoreface sand sinks into previous sand budget studies for the upper Texas coast, a more accurate sand and sediment budget is established. We show that the shoreface environment from the east end of Bolivar Peninsula to the west end of Follets Island sequesters ~160,000 ± 39,000 $m^3$/y of sand. This is the time-averaged flux over the late Holocene, and it is used to estimate long-term annual changes. This number represents ~17% of the entire calculated sediment flux onshore, longshore, and offshore from previous studies (Morang, 2006) based on historic data. Additionally, this flux equals ~37% of the previously calculated longshore transport flux (Morang, 2006) for the entire region. Most of the error in prior budget analyses stems from using a 4 m depth of closure, which geological evidence indicates is at least half the depth of active sediment transport in the region.

Previous sediment budgets have yet to concretely establish the sand flux into SLPTD, and to incorporate Follets Island. The flux of SLPTD was previously thought to be at least 76,000 $m^3$/y (Morang, 2006). However, our data suggest that a flux of ~5000 $m^3$/y is more reasonable. For Follets Island, it appears as though a unique scenario is taking place. A sand flux of ~90,000 $m^3$/y is determined based on current erosion rates. However, only ~6000 $m^3$/y is being sequestered in both the shoreface and washover environments (Figure 8), and there have been no notable elevation changes on the barrier itself. Therefore, since Follets Island is currently sand starved, longshore transport is likely removing and transporting ~84,000 $m^3$/y of sand further west (Figure 8).

The magnitude of this volume shows that the current estimates of longshore sand transport west of SLPTD (Morang, 2006) are significantly underestimated, and it highlights the importance of taking all possible sand sequestration environments into account for sediment budgets.

## CONCLUSIONS

Several recent studies have relied on engineering principles to establish sand budget estimations for the upper Texas coast (Morang, 2006; Ravens and Sitanggang, 2007). They have determined that the majority of sand is either deposited along jetties and beaches, or it erodes and is transported west with the prevailing longshore currents. These studies estimate the total sand flux along the upper Texas coast to be ~942,000 $m^3$/y (Morang, 2006), and that nourishing the seawall and West Beach along Galveston Island would likely require ~400,000 $m^3$/y to maintain the 2001 shoreline (Ravens and Sitanggang, 2007). However, these studies use a closure depth of 4 m, when a depth of at least 8 m is more appropriate based on many lines of geological evidence. Incorporation of this new shoreface sand volume equals ~17% of the entire previously estimated sediment flux, and ~37% of the previously calculated total longshore flux (using previous estimates from Morang, 2006). Additionally, extending the closure depth to a more geologically reasonable depth increases the volume needed to successfully nourish beaches on Galveston Island by at least ~115,000 ± 28,000 $m^3$/y. Taking sand from the shoreface for beach nourishment is unacceptable.

We also show that the modern washover sand flux into the bays behind Bolivar Peninsula, Galveston Island, and Follets Island is quite minimal, and thus not a significant annual contributor to sand sequestration. We determine a sand flux for San Luis Pass that is an order of magnitude lower than previous estimates (Morang, 2006). Consequently, longshore sand transport from the west end of Galveston Island past SLPTD is significantly underestimated. This translates into significant errors in the estimates of sand needed for coastal nourishment projects.

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