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Barrier-island aggradation via inlet migration: Mustang Island, Texas

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Abstract

After establishing its present location around 9.5 ka, Mustang Island aggraded, stacking over 20 m of barrier-island sand in the same location. Throughout Mustang Island's history, tidal inlets shifted within nearly the same location from 7.5 ka to the present, leaving 10–15 m thick deposits of clean, well-sorted, quartz sand deposited within only a few centuries. These deposits lack some of the sedimentary features normally associated with tidal inlets, such as tidal couplets and shell hash. The lack of such features is attributed to the uniform nature of the deposits cut by the inlets during the island's relatively long period of aggradation. Mustang Island was able to maintain an aggradation character throughout most of the Holocene due to the sediment eroded from three sources: Pleistocene headlands, the transgressive Colorado River delta of Texas, and the OIS 3 shoreline of the central-Texas shelf. Each of these sources was exposed to waves and accompanying longshore drift during the island's early history when sea level rose quickly, but was flooded or capped by transgressive muds by the time sea-level rise slowed during the middle Holocene.
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Keywords: Mustang Island; Barrier island; Aggradation; Tidal inlet; Aransas Pass; Texas coast; Grain size; Environmental interpretation

1. Introduction

Dickinson et al. (1972) suggested the presence of three types of barriers: 1) prograding 2) stationary, and 3) landward migrating. Following a similar scheme, Galloway and Hobday (1983) also suggested three types of barrier islands: regressive, aggradational, and transgressive (Fig. 1). Aggradational barriers are the least documented type of barrier islands. Consequently, they are seldom used as models in subsurface and outcrop studies. The purpose of this paper is to describe the history of Mustang Island — a Holocene aggradational barrier island located on the central-Texas coast.

Most of the Texas barrier islands have been studied in great detail (LeBlanc and Bernard, 1954; Fisk, 1959; Shepard, 1960; Bernard et al., 1970; Wilkinson, 1975; Wilkinson and Basse, 1978; Morton and McGowen, 1980; Morton, 1994; Rodriguez et al., 2004) and are often used as analogues to interpret the rock record (Dickinson et al., 1972). One of the more notable barrier sub-environments documented in these studies is a tidal inlet within a microtidal setting. From other studies we learn that tidal-inlet deposits are characterized by shell hash, tidal couplets, and herring-bone cross stratification (Moslow and Tye, 1985; Israel et al., 1987). Within cores, only the first two of these sedimentary features are

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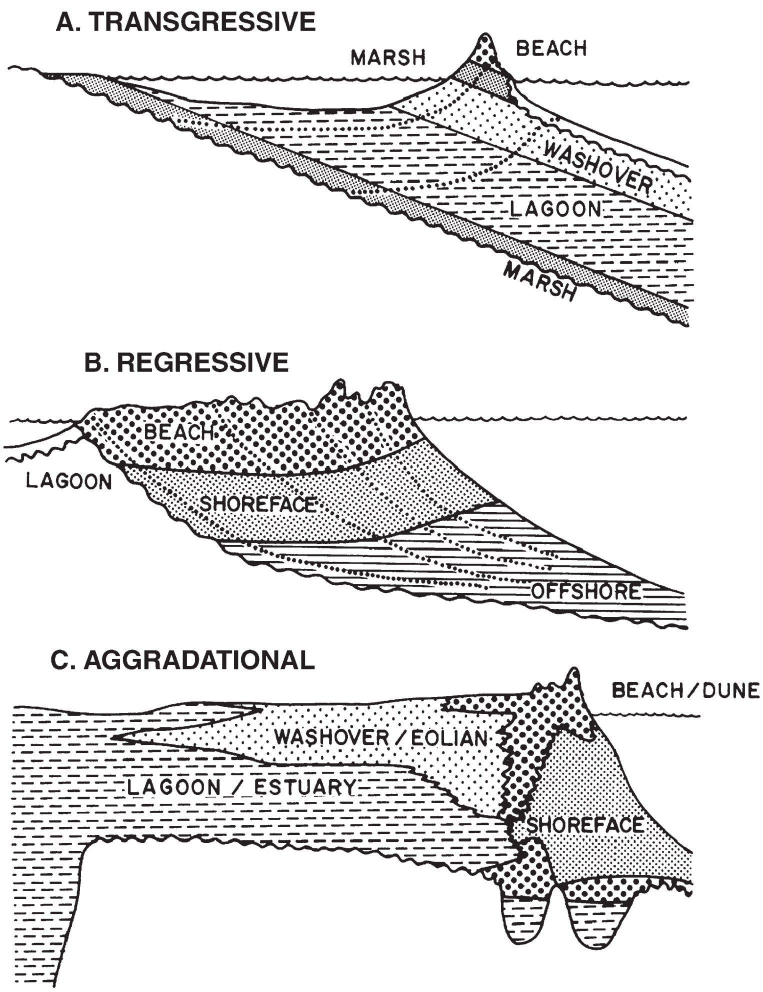

Fig. 1. Three models of barrier-island evolution (after Galloway and Hobday, 1983). A) After Kraft and John (1979), B) after Bernard et al. (1970) and C) after Fisk (1959) and Morton and McGowen (1980).

commonly preserved or identifiable. Another purpose of this paper is to document how reliance on these features alone to identify tidal inlets can lead to a gross underestimation of the amount of tidal-inlet deposits. In addition, a large amount of work conducted on the Texas coast documents the evolution of most of the Texas barrier islands. Mustang Island is a notable exception; in this paper we document the history of Mustang Island.

During this investigation we attempted to distinguish barrier environments with a paucity of sedimentary structures, fossils, and relatively uniform grain size using detailed grain-size analysis as an indicator of depositional environment. It is ironic that some of the first studies using grain size as an indicator of depositional environment were conducted on Mustang Island (Mason and Folk, 1958; Moiola and Spencer, 1973). Since these studies were conducted, newer technology, including laser diffractometry, has lead to techniques with better precision in determining grain size (Sperazza et al., 2004) and some authors have suggested once again that grain size might be a viable method in determining depositional environment. We tested classic methods of distinguishing environments, such as plotting grain size versus skewness and discriminant analysis (Friedman, 1961; Moiola and Weiser, 1969; Greenwood, 1969; Moiola and Spencer, 1973; Taira and Scholle, 1979; Toscano, 1986), with newer grain-size analysis technology. At first glance, the results appear favorable. However, placing the interpreted environments into context with sea-level data from around the region casts doubt on the effectiveness of grain size as a reliable indicator of depositional environment.

2. Study area and previous work

Mustang Island is located above the ancestral Nueces River valley and its tributaries (Fig. 2), which experienced downcutting due to a sea-level lowstand that culminated ca. 18 ka during the Wisconsinian Glaciation (Oxygen Isotope Stage 2) (Wright, 1980; Shideler et al., 1981; Shideler, 1986; Durbin et al., 1997; Simms et al., in press). After a lowstand approximately 18 ka, sea level rose rapidly along the Gulf of Mexico until 6.5 ka when the rate of rise decreased (Fig. 3). Since 6.5 ka, sea level has slowly risen to present levels (Shepard and Suess, 1956; Curray, 1960; McFarland, 1961; Nelson and Bray, 1970; Törnqvist et al., 2004), although some authors have made arguments for a mid-Holocene highstand and slight fall in sea level since 5 ka (Morton et al., 2000; Blum et al., 2001; Blum et al., 2002).

Mustang Island lies within the central-Texas coast (Fig. 2), which is the site of a coastal convergence zone (Lohse, 1956; Curray, 1960; Morton, 1979). Due to the arcuate shape of the Texas Coast and the prevailing southeasterly winds, longshore currents in east Texas generally flow southwest, while longshore currents in

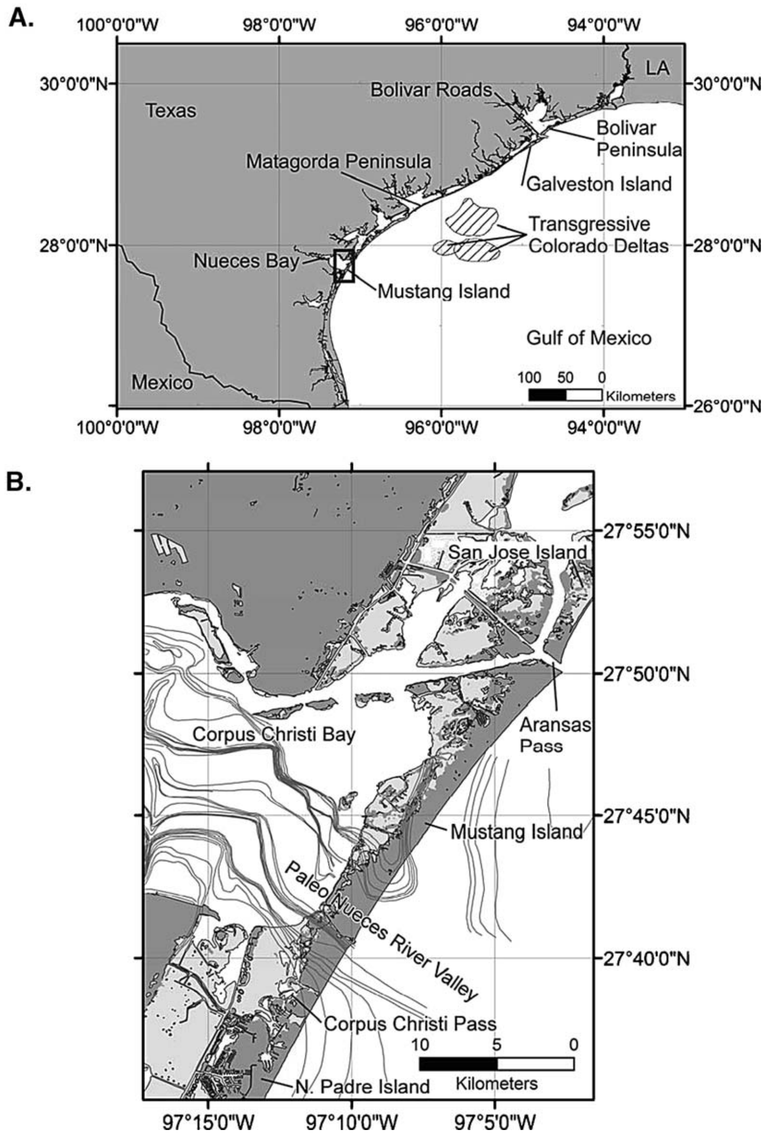

Fig. 2. A) Location of study area and other coastal features along the Texas coast mentioned in the text. B) Study area showing the location of the paleo-Nueces valley. Faint lines are 2 m contours of the Pleistocene/Holocene contact beneath Mustang Island (Simms et al., in press).

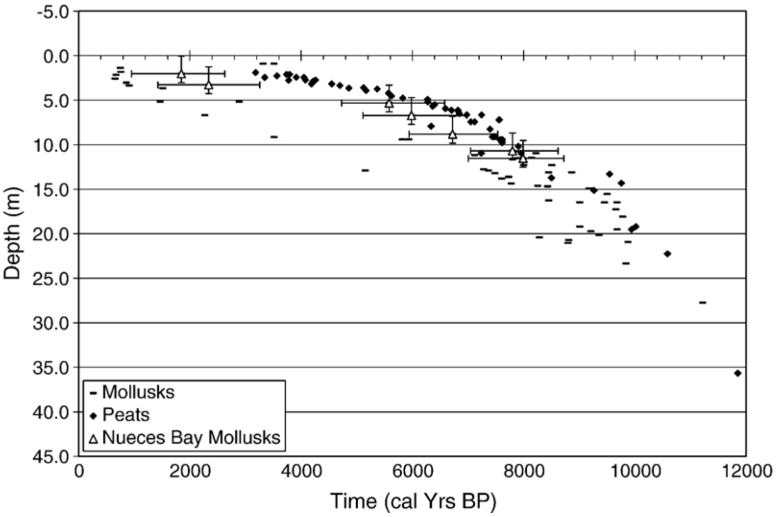

Fig. 3. Sea-level indices from across the coastal areas of the northwestern Gulf of Mexico. Data comes from Shepard and Moore (1955), Curray (1960), Rehkemper (1969), Nelson and Bray (1970), Rodriguez et al. (2004), Törnqvist et al. (2004), and this study. Peats were interpreted by each of the respective authors to represent basal peats. Nueces Bay dates were obtained within a tributary estuary of Corpus Christi Bay behind Mustang Island.

south Texas generally flow north (Curray, 1960; McGowen et al., 1977). The two longshore currents converge south of Mustang Island. Most of the sediment supply for the central-Texas coast is from these longshore currents (Curray, 1960; Watson, 1971). During the winter months, the passage of cold fronts will occasionally shift the winds around and modify longshore currents (Shideler, 1981), as will the passage of hurricanes and tropical storms during the late summer and early fall (Snedden et al., 1988).

The central-Texas coast is considered a microtidal coast (Morton and McGowen, 1980). Tidal range along the open Gulf is less than 0.3 m and even less within some of the estuaries and lagoons. However, the tides do become important agents within tidal inlets between barrier islands and peninsulas. Some of the modern and historically active tidal inlets along the Texas coast, such as Bolivar Roads and Aransas Pass, cut to depths of 10 m (Price, 1963; Morton and McGowen, 1980).

Most past studies of Mustang Island (Mason and Folk, 1958; Moiola and Spencer, 1973; Davis and Fox, 1975; and Davis, 1978) have concentrated on the modern environments. However, Shideler (1986) provided a summary of the Late-Pleistocene and Holocene history of the southern-most portion of the island, but concentrated on the longer-term history rather than the island's Holocene evolution. From Shideler's (1986) work, we know that an ancestral Mustang Island existed offshore of its present location until around 10.5 ka. Sometime after that, but before 9.5 ka, the foundation for the present Mustang Island had formed.

Mustang Island is a high-profile barrier (sensu Morton and McGowen, 1980). A higher profile results in less material delivered to the backbarrier environment, due to the effectiveness of dunes in blocking all but the most severe storms from breaching the barrier. High-profile barriers are generally older, more stable barriers in comparison to low-profile barriers (Morton and McGowen, 1980).

3. Methods and data

Nine new 5.1-cm diameter push cores reaching depths of 31 m were obtained on Mustang Island using the CMT Continuous Sample Tube System (Fig. 4) as well as 8 cores within its estuary, using a hydraulic push coring method aboard the *R/V Trinity.* Three 7.6-cm diameter vibracores up to 3 m in length, eight 7.6-cm diameter hammer cores up to 4 m in length, 41 surface samples from modern environments (16 beach, 12 dune, and 13 eolian or barrier-flat), and roughly 60 km of high-resolution seismic data were also collected (Fig. 4). The seismic data were acquired during two surveys: one sparker survey shot by the USGS in 1978 and one boomer survey shot by Rice University in 1994. No processing of the data other than high and low pass filters and automatic gain control was necessary. In addition, descriptions of 6 long cores up to 62 m in

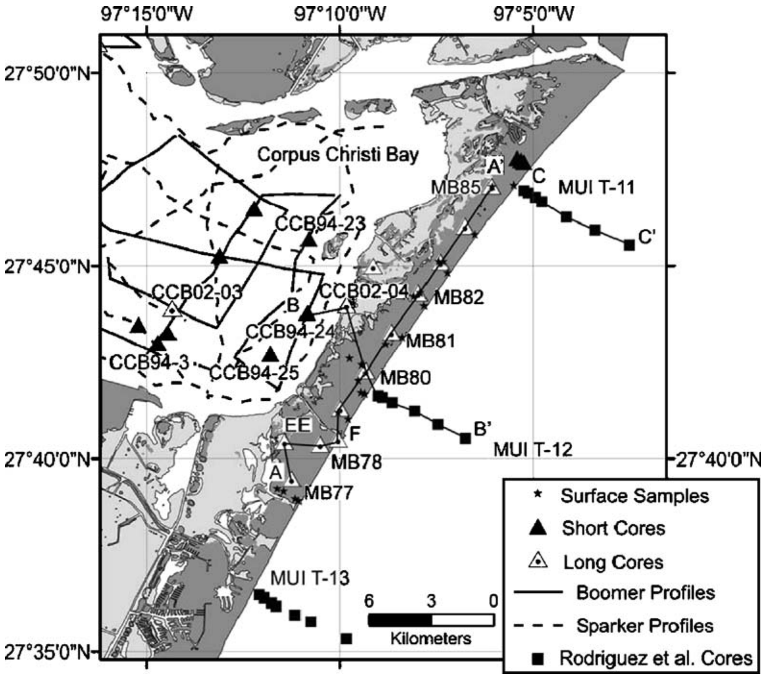

Fig. 4. Data utilized in this study. See Fig. 2 for general location.

length (Shideler, 1986) and three published shoreface transects of six to seven hammer cores up to 3 m in length (Fassell, 1999; Rodriguez et al., 2001) were used to complement the data.

3.1. Grain-size analyses

Grain-size analyses were determined for samples from 25 cm intervals from two of the long cores within the island (MB78 and MB85), one of the shorter vibracores (MUI03-02), and one of the hammer cores used in the Fassell (1999) and Rodriguez et al. (2001) studies (MUI T-1278). In addition, grain-size analyses were obtained from 41 surface samples from modern environments along Mustang Island (Fig. 4). The surface samples were taken from the sidewall of a shovel hole, 5–6 cm below the surface. This procedure was conducted to avoid bias from surface lags, reworking, and anthropogenic disturbances. The samples were analyzed via laser diffractometry using a Malvern Sizemaster 2000. The procedure used is the pipette method as outlined by Sperazza et al. (2004). Approximately 20 mg of sediment was soaked overnight in a 4.4 g/l solution of Calgon soap in order to prevent flocculation. The refractive index was set at 1.544, the index commonly used for quartz (the sediment samples were >95% quartz). Each sample was analyzed twice and if the analysis resulted in a difference greater than 3% sand, they were run a 3rd time. The median grain-size distribution of replicate analysis was used in order to avoid bias from skewed runs.

3.2. Chronostratigraphy

A total of eleven new radiocarbon dates were obtained from mollusk shells for this study (Table 1). In addition, nine published radiocarbon dates where used to supplement these dates (Shideler, 1986; Rodriguez et al., 2001). New dates and dates from older sources were corrected for $^{13}C/^{12}C$ and calibrated using the Calib 4.4 program (Stuiver and Braziunas, 1993; Stuiver et al., 1998). A reservoir correction was applied only to samples obtained from estuarine environments prone to carbon-reservoir problems (Aten, 1983; Raymond and Bauer, 2001). It is assumed that a carbon reservoir does not exist in high-energy shallow-marine environments (nearshore and beach) in which the carbon is abundantly mixed with atmospheric carbon (Stuiver and Braziunas, 1993). In order to obtain a reservoir correction for estuarine environments for this region, we radiocarbon dated an articulated barnacle that was attached to a wood fragment found in an estuarine facies within a core taken in Nueces

Table1
Radiocarbon dates used in this study

Core	Depth (m)	Material	Conventional ^{14}C years BP	Error	Reservoir	Calendar years BP	2σ	Source
MB78	7.5	*Anadara* sp.^{v}	5440	40	0	6240	65	This study
MB78	13.5	*Donax* sp.^{v}	4500	35	0	5170	130	This study
MB78	16.7	*M. lateralis*^{v}	5700	30	0	6480	80	This study
MB78	20.8	*Donax* sp.^{v}	5730	30	0	6520	110	This study
MB85	20.2	*Donax* sp.^{v}	1940	30	0	1890	65	This study
MB85	25.5	*Donax* sp.^{v}	4020	35	0	4480	80	This study
MB85	30.46	? *Tagelus* (frag)?	46,700	870	0	Radiocarbon dead		This study
CCB02-04	5.6	*Anomalocardia cuneimeris*^{v}	2130	30	0	2105	150	This study
CCB02-04	7.01	*Anomalocardia cuneimeris*^{v}	2130	35	0	2106	150	This study
CCB02-04	11.82	*M. laterualus* (hinge)	4620	40	0	5420	70	This study
CCB02-04	14.85	*Anomalocardia cuneimeris*^{v}	2060	35	0	2025	95	This study
MUI T-12 76	1.68	*Oliva* sp.	2840	60	0	2955	190	Fassell, 1999
EE	4	*Chione cancellata*	1520	80	0	1420	140	Shideler, 1986
EE	12.3	*Chione cancellata*	1320	80	0	1230	165	Shideler, 1986
EE	15	*Chione* and *Anadara* shells	1580	70	0	1470	190	Shideler, 1986
EE	18.8	*Macrocallista nimosa*	8460	110	0	9450	280	Shideler, 1986
EE	44.8	*Corbula* and *Rangia*	25,330	680	0	Too old for calibration		Shideler, 1986
EE	60.5	*Crassostrea virginica*	34,900	850	0	Too old for calibration		Shideler, 1986
F	8.5	*Agropectin*, *Donax*, and *Mulinia*	4620	130	0	5310	360	Shideler, 1986
F	14.5	*Anadara*, *Agropectin*, *Cardita*, *Donax*, *Mulinia* and *Tellidora*	6460	100	0 0	7370	205	Shideler, 1986
F	22.3	*Agropectin*, *Chinoe*, and *Mercenaria*	6640	120	0	7520	210	Shideler, 1986
F	34	*Crassostrea virginica*	9840	110	760	10,280	360	Shideler, 1986
F	51.8	Wood fragment	24,640	51.8	0	Too old for calibration		Shideler, 1986

See Fig. 4 for core locations.
v=valve.

Bay (an estuary inland from Mustang Island, Fig. 2A). The barnacle was dated as ~760 years older than the wood fragment. This was assumed to be the reservoir value for the Nueces River estuarine system. The value falls within the range of reservoir corrections found in other estuaries along the Texas coast (Aten, 1983). Table 1 provides a summary of all dates used in this study.

Dating mollusk shells within beach deposits is prone to producing errors as the shells are easily reworked in such a high-energy environment. It is best to use articulated shells for dating. However, none were found within the cores from Mustang Island. The shells submitted for dating were mostly *Donax* sp. The use of *Donax* sp. is a conservative strategy ensuring: 1) the species is endemic to the environment studied and 2) minimal reworking due to the delicate nature of the shells. In addition, the dating of multiple shells from the same core allows for a test of chronostratigraphic consistency. Three dates were not used in the interpretation of the data due to their anomalously old ages in light of other dates within the same core.

4. Facies

Shepard (1960) suggested that barrier islands are composed of four major environments and associated sedimentary facies: beaches, dunes, barrier flats, and inlets. These four environments are found in and around Mustang Island. In addition to these four barrier-island environments, four others exist in the area investigated and each has its unique sedimentary facies. These include upper and lower shoreface, marine muds, and lower-bay deposits (including washover deposits). Two Pleistocene facies were also identified within the cores taken for this study.

4.1. Beach facies

Based on modern samples, beach facies (backshore and foreshore) consist of well-sorted fine to very-fine sand. The mean grain size for these deposits ranges from 2.3 to 2.6 phi. It is predominately quartz in composition, with a few heavy minerals, including magnetite. Sedimentary structures, if present, include gently-dipping laminations. Beach deposits often contain shell material, of which *Donax* sp., *Mulinia lateralis*, and *Lucina multilineata* are most common.

4.2. Dune facies

Based on samples of modern dunes, this facies consists of a clean, well-sorted fine to very-fine sand with a mean grain size ranging between 2.3 and 2.75 phi. This facies is predominately quartz in composition with a few heavy minerals including magnetite. Generally, dune samples contain more heavy minerals and fewer shells than the beach facies (Shepard, 1960). Occasionally, root casts were found within cores interpreted to represent this facies (Fig. 5A).

4.3. Barrier-flat facies

Shepard (1960) showed that deposits from barrier flats have many subfacies. Barrier flats are dominated by two active processes: storm washover and eolian transport. They contain washover deposits composed entirely of sand or lagoonal and palustrine deposits composed of silts and clays. In addition, back island dunes can also develop in this environment (McGowen and Scott, 1975). Within the cores taken on Mustang Island, the presence of interbedded clays or abundant root casts was used to differentiate barrier-flat from beach deposits. Occasionally the mollusk, *Anomalocardia cuneimeris*, which lives in shallow-hypersaline lagoons, was found within this facies.

4.4. Inlet facies

Traditional studies of inlets from a variety of coastlines define two major subfacies of tidal-inlet deposits. The first is a muddy or sandy shell hash with both bay and marine fauna. This facies often grades into or is found in conjunction with a fine to medium sand with abundant shell material. This subfacies is interpreted to represent the inlet itself. The second subfacies is composed of sand and mud laminations. This facies represents the distal portions of the flood- or ebb-tidal delta complex (Fig. 5C). Grain-size analyses obtained from cores within the sandy portions of an ancient flood-tidal delta (Fig. 6) resulted in mean grain-size values ranging from 4.0 to 6.0 phi and skewness values of −0.2 to 0.6. As will be shown, inlet deposits also take on another form very similar to beach, dune, and barrier-flat environments, being indistinguishable in core from these deposits by sedimentological evidence alone. The only clue to their true depositional nature is their relationship to paleo-sea level and, in a few but not all locations, a moderately greater abundance of shells at their bases.

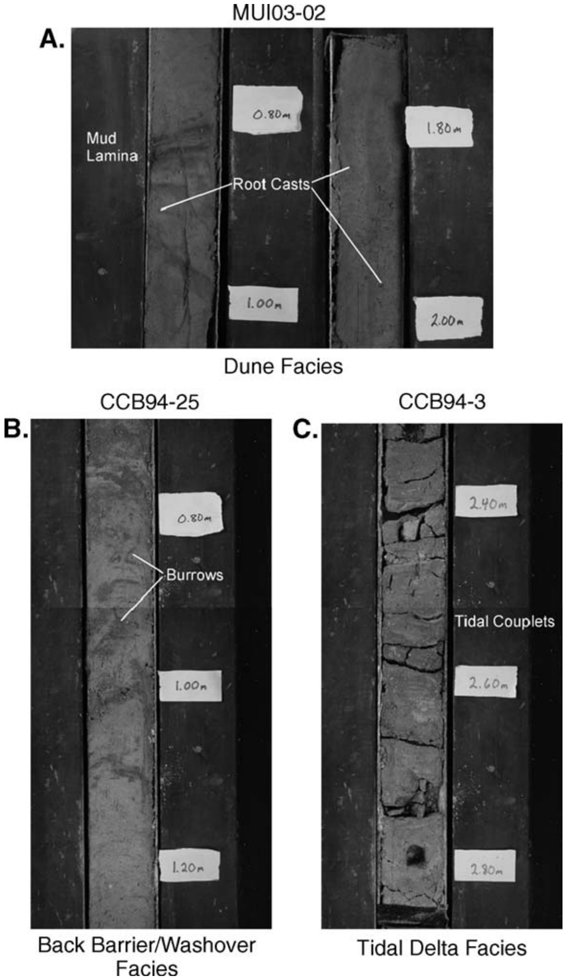

Fig. 5. Examples of sampled facies. A) Dune facies with root casts and mud laminae. B) Backbarrier/washover deposits of sand and occasional burrow, mottling, and muddy lamina and C) Tidal couplets in distal flood-tidal delta facies.

No inlets were seismically imaged. However, several flood-tidal deltas were imaged and are easily identified. They take one of two forms depending on whether they are imaged along depositional dip or strike. As seen along depositional dip they appear as a landward-accreting package of sigmoidal seismic reflectors (Fig. 6). As seen along depositional strike, they appear as broad lobate features (Fig. 7). One ebb-tidal delta was interpreted from a shelly-hash facies located by Fassell (1999) in core transect MUI T-11 (Fig. 4).

4.5. Upper-shoreface facies

Upper- and lower-shoreface deposits and marine muds offshore Mustang Island were originally described and interpreted by Fassell (1999) and Rodriguez et al.

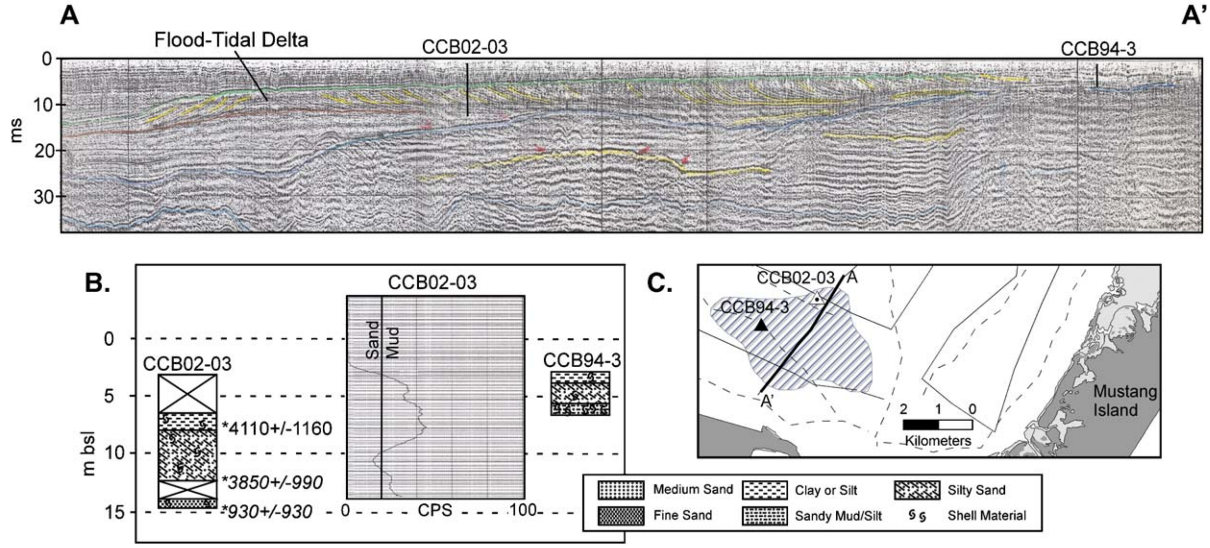

Fig. 6. Seismic line (A) and lithology log and gamma log of cores (B) from an interpreted flood-tidal delta within Corpus Christi Bay. Seismic profile is oriented in a shore-parallel direction (C). In dip transects the forests of the clinoforms dip landward. Core CCB02-03 sampled the sandier flood-tidal delta and was used to constrain its age. Core CCB94-3 sampled the muddy distal edge of the delta. Within the gamma log, intervals measuring less than 20 cps are generally sandy and those over 40 cps are muddy.

(2001). The upper shoreface unit as described by Fassell (1999) and Rodriguez et al. (2001) consists primarily of fine sand with an occasional silt or mud layer. This facies often exhibits moderate to intense bioturbation with common *Skolithos* traces, mostly *Ophiomorpha* (Fassell, 1999). The mean grain size for these units is around 3.0 phi. The finer nature of the sand was used to distinguish this facies from beach, eolian, and barrier-flat environments. The modern-upper shoreface along the central-Texas coast extends to depths around 8 m (Rodriguez et al., 2001).

4.6. Lower-shoreface facies

Facies found to be composed of sandy or clayey silt with interbedded clayey sand and silty sand were interpreted to be lower-shoreface deposits. This facies typically contains the trace-fossil *Glossifungites*. Lower-shoreface deposits were subdivided by Fassell (1999) and Rodriguez et al. (2001) into proximal- and distal-lower shoreface dependent on the relative proportion of interbedded sands and muds and their bedding thicknesses. These units often contain open-

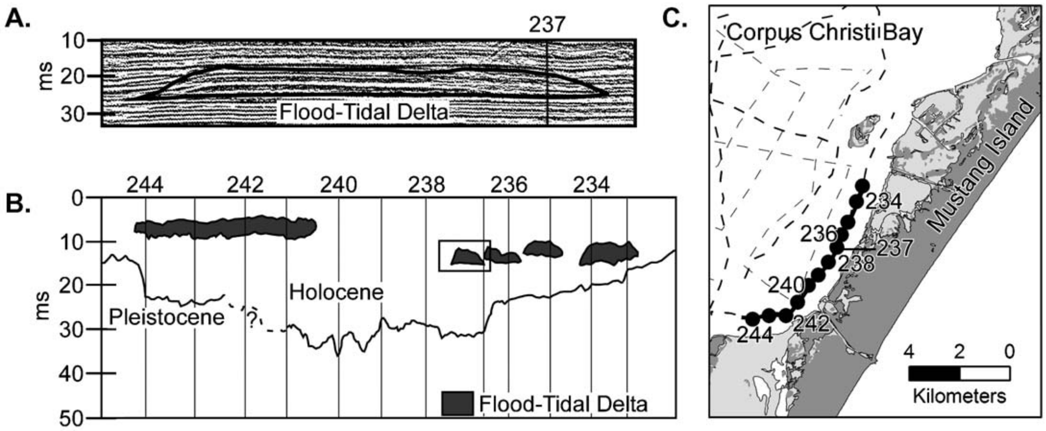

Fig. 7. A) Segment of sparker profile behind Mustang Island illustrating the lobate nature of a flood-tidal delta as seen in a strike direction. B) Line drawing of sparker profile showing the location of several flood-tidal deltas including the feature illustrated in A. Note that the seismic profile through the flood-tidal delta between shot points 244 and 240 is running orthogonal to the shoreline and profile through other flood-tidal deltas is oriented parallel to the shoreline. C) Location of seismic profiles.

marine fauna. This facies was only found in cores taken offshore.

4.7. Marine-mud facies

Like lower- and upper-shoreface deposits, this facies was only sampled in cores taken offshore. This facies consists of massive to mottled clay and silt. Very little sand occurs within these deposits. It is marked by the presence of marine fauna such as *Noetia ponderosa* and *Corbula* sp. (Rodriguez et al., 2001).

4.8. Lower-bay and washover facies

Lower-bay deposits consist of silty sands and sandy silts. They were only found in hammer cores and long rotary cores taken behind the island. Occasionally, a few dispersed laminae and a mottled texture were found in deposits of this facies. Fauna are the most distinctive characteristic of these deposits. The fauna consist of abundant mixed bay (*Crassostrea virginica*, *M. lateralis*, *Ostrea equestris*, *Nuculana acuta*, and *N. concentrica*) and marine forms (*L. multilineata* and *amiantus*, *Crassinella lunulata*, and *Anadara* sp.). Lower-bay deposits grade seaward into washover deposits consisting of more sand than lower-bay deposits. Washover deposits are predominately sand but contain abundant clay-filled burrows and mottling (Fig. 5B).

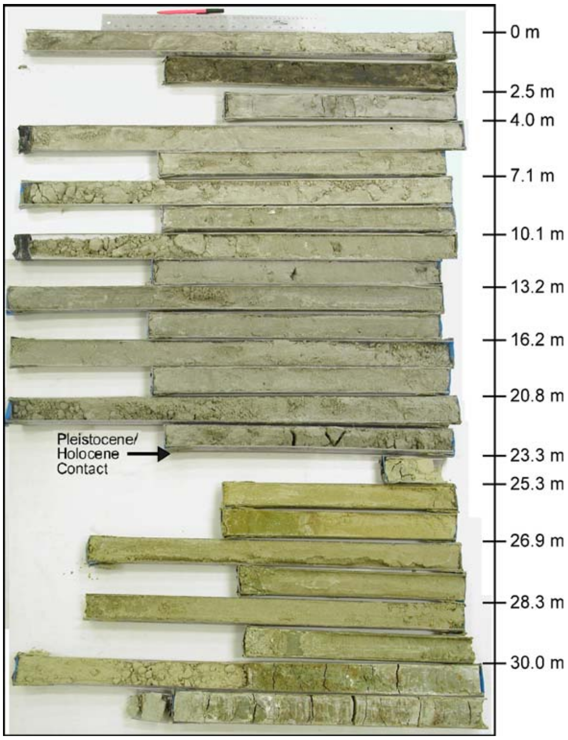

Fig. 8. Photograph of core MB-78 illustrating the color change at the Pleistocene/Holocene contact and the absence of sedimentary structures and homogeneity within barrier-island facies. Metal ruler at top of core photograph is 76 cm long.

4.9. Pleistocene facies

Six long cores bottomed out in Pleistocene deposits: MB77, MB78, MB80, MB81, MB82, and MB85 (Fig. 4). Three of these cores (MB78, MB80, and MB82) contain a poorly cemented, poor- to medium-sorted, fine to medium "yellow" sand with no shell material and a noticeable amount of lithic sand (Fig. 8). These units are interpreted to represent either fluvial "Deweyville" units, often preserved as terraces along the margin of many Gulf of Mexico river valleys (Barton, 1930; Bernard, 1950; Blum et al., 1995; Durbin et al., 1997), or buried remnants of the Ingleside barrier (Wilkinson et al., 1975). Based on the absence of echinoid spines and shell material and the presence of more lithic grains, the authors favor a "Deweyville" interpretation.

The other three long cores (MB77, MB85, and MB81) bottomed out in a stiff, green or brown, mud with carbonate nodules. The stiff-mud facies in core MB85 contained sand-filled burrows or root casts and two mollusk shells in addition to the calcareous nodules. A radiometric date obtained from one of the shell fragments yielded an age of 46,700+ years BP. Core MB81 contains two units above the green-brown stiff clay. At 11.95 m an erosional surface separates the interpreted Holocene barrier sands above from stiff, grey muddy sand with abundant shell material and no carbonate nodules below. It is uncertain if this thin unit is Pleistocene or Holocene in age. Below this unit, but above the stiff green-brown mud, is the same "yellow" sand facies discussed above. When both Pleistocene facies were sampled, the stiff, green-brown mud facies always occurs stratigraphically lower than the sand facies. The stiff, green-brown mud facies is interpreted as the Pleistocene Beaumont Formation, but a "Deweyville" interpretation cannot be ruled out.

5. Grain-size analyses and environmental interpretation

Although some distinctions were made among beach, dune, and barrier-flat deposits, distinguishing the three facies can be very difficult. Distinguishing these facies is most easily done in outcrop using sedimentary structures. However, the long cores taken on Mustang

Island contain very few preserved sedimentary structures (Fig. 8). In some of the shorter cores, plant material or root casts were preserved (Fig. 5A). These features suggested dune or barrier-flat environments and were interpreted as such when present. Frosting of grains has also been suggested as a method of distinguishing beach and dune sand (McKee, 1957). However, Shepard (1960) found that this is not a reliable indicator of an eolian origin within the barrier systems of the Gulf Coast. Within cores MB85 and MB78, no frosted grains were found.

An attempt was made to distinguish the beach, barrier-flat, and dune facies using grain size. Examination of all possible combinations of graphical skewness, graphical kurtosis, graphical mean, and graphical standard deviation was undertaken (Mason and Folk, 1958). From these plots, two populations were found and best distinguished by skewness versus mean (Fig. 9). Cores were resampled to represent each population and grain size was again determined to see if they were reproducible. The same two populations were found in a second analysis of grain-size determinations.

5.1. Modern sediments

Forty-one samples from modern environments (16 beach, 12 dune, and 13 barrier-flat) were also analyzed in an attempt to further test grain size as a means of distinguishing coastal environments of deposition. Barrier-flat samples plot within population 2 on Fig. 9. Of the six barrier-flat samples found in population 1, only three were reproducible. The three samples came from the same location adjacent to a dredged channel. Samples interpreted as barrier flats (population 2) by their greater skewness (skewness > 0.2) were sieved with a 63 μm mesh to determine the composition of the fine tail. The fine tail is composed of silt-sized quartz. The presence of the fine tail is attributed to finer material trapped in this environment by algal mats and other vegetation (Mason and Folk, 1958; Shepard, 1960; Friedman, 1961).

5.2. Discriminant analysis

Both beach and dune deposits inhabited population 1. In order to distinguish beach from dune deposits, a linear discriminant analysis procedure (Krumbein and Graybill, 1965; Moiola and Spencer, 1973; Jones and Cameron, 1976; Alther and Wyeth, 1981) was conducted utilizing the statistical software package SAS. The discriminant analysis was run using mean, kurtosis, skewness, and standard deviation. The method correctly distinguished 15 of the 24 dune samples, and 26 of the 32 beach samples. The method was further tested by running the linear discriminant functions on 26 samples from facies within a core interpreted to be eolian based on root casts and interbedded silts. However, the discriminant function based on four variables only predicted in 11 out of 26 cases that the samples were dune in origin. It was concluded that for this data set, discriminant analysis is not a viable method for differentiating coastal environments based on grain size.

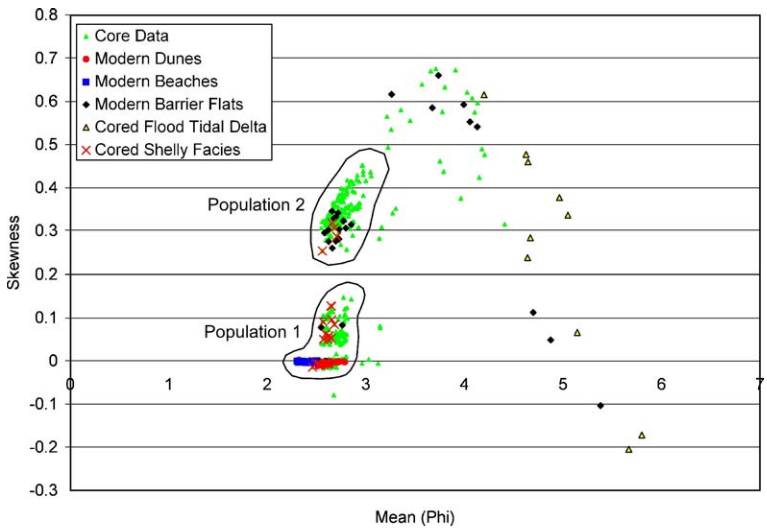

Fig. 9. Skewness versus mean for all grain-size data obtained from cores in this study. Note the two distinct populations. Population 1 is inhabited by modern beaches and dunes. Population 2 is inhabited by only modern barrier flats. “Cored Shelly Facies” corresponds to the basal portions of the episodes of rapid deposition that contain more shell material.

5.3. Regression analysis

In addition to discriminant analysis, a regression equation (Eq. (1)) was determined using SAS from the known samples from all four measured values: kurtosis (K_G), mean (M_Z), skewness (SK_i), and standard deviation (σ). The samples were assigned a value of 1 if collected from a beach and 2 if collected from a dune. Although the correlation coefficient is not significant,

$$y = 95.90 - 96.91(K_G) + 1.95(M_Z) + 86.93(SK_i) - 14.20(\sigma) \quad (1)$$

$R^2 = .5304$, and no single value can be used to distinguish between the two populations, an apparent distinction can be seen between the two populations within the graphed data (Fig. 10). From the data, we felt confident in assigning values less than 1.25 to beach, as no known dune sediment yielded values less than this, and greater than 1.75 to dune, as no known beach sediments yielded values greater than this. To samples yielding values between 1.25 and 1.75, we assumed either a mixed or undetermined origin. This arbitrary cut off correctly identified 13/24 known dune samples as dune and 19/32 beach samples as beach with no samples incorrectly classified. The regression equation was run on 26 samples from a core known to contain dune deposits. This correctly identified the samples as dune in 19 out of 26 cases. Of the 7 not assigned to a dune environment, 5 were undetermined and two were misidentified as beach. In each of the two misclassified samples, the other grain-size determination from the same sample was identified by the regression equation as either dune or uncertain.

6. Results

Stratigraphic cross sections through the island are shown in Figs. 11 and 12. With one exception, no offshore marine muds or estuarine facies are found in the Holocene portion of these cores. The exception is 7 m of estuarine facies in the deepest portion of core F (Fig. 11). An oyster shell from this deposit yielded an age of 10,280±360 cal BP (Shideler, 1986). The presence of estuarine facies with brackish-water fauna points to the existence of an ancestral island further seaward of the modern barrier before 10 ka (Shideler, 1986). The grain-size data from cores MB78 and MB85 suggest that within the barrier-island deposits, deposition did not change from beach, dune, or barrier flat between depths of 0–30 m (Fig. 13).

Isochrons from the available radiocarbon dates suggest extremely rapid deposition of 10–20 m within only a few centuries in several locations on the northern and southern portions of the island (Fig. 11). At the base of three of the four episodes of rapid deposition in our cores and one of the two identified in the cores taken by Shideler (1986) is an interval of core with a moderately greater abundance of shell material. In addition, this facies is found in two undated cores — MB81 and MB83. However, this shelly interval is indistinguishable by grain-size analysis (Fig. 9). The oldest of these rapid-depositional episodes occurred 7.5 ka. The youngest occurred within the last 1.5 ka and within a kilometer of its 7.5 ka equivalent.

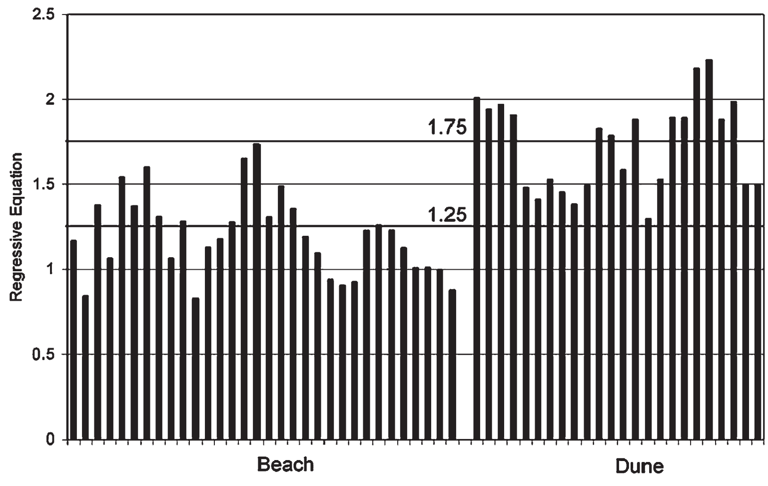

Fig. 10. Regression results of Eq. (1) from surface samples. The first 32 grain-size observations were obtained from modern beach deposits and the last 24 observations were obtained from dune deposits. Horizontal lines with values of 1.25 and 1.75 were the minimum and maximum values for dune and beach deposits respectively.

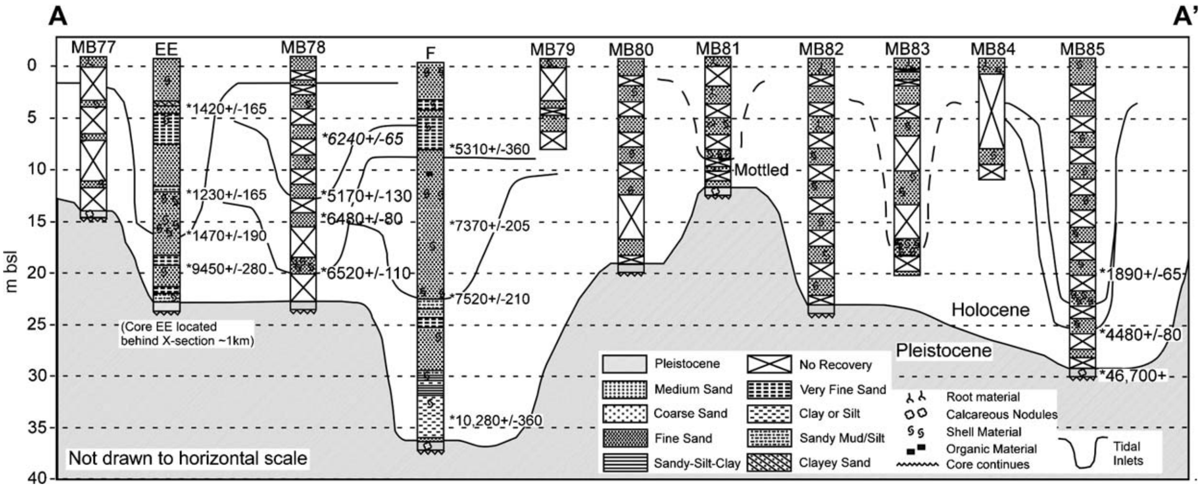

Fig. 11. Shore-parallel core transect through Mustang Island. See Fig. 4 for profile location. Cores F and EE lie approximately 1 and 2 km east and west respectively of a strike line through the other 9 cores (Fig. 4). Cores EE, MB78, and F illustrate a slightly oblique dip transect through the island. Black lines within the Holocene portion of the cores represent isochrones. Note the rapid accumulation of 10–15 m of sand within cores EE, MB78, F, and MB85 without deposits of shell hash at their bases.

Cores taken offshore of Mustang Island sampled shoreface sands above marine muds overlying older shoreface sands suggesting the shoreface retrograded less than 4 km and then prograded seaward the same distance sometime after 2950 ± 190 cal BP (Fig. 12, Fassell, 1999; Rodriguez et al., 2001). Three vibracores taken behind the barrier show a similar pattern with open-bay deposits overlying washover deposits (CCB94-24 of Fig. 12 B–B′). However, this progradation of the shoreface and shifting of environments behind the barrier have no equivalent environmental changes within cores taken along the whole length of the island (Fig. 11).

The seismic profile collected behind the island shows a series of five stacked flood-tidal delta lobes (Fig. 7). Judging by their seismic–stratigraphic position, these flood-tidal deltas were deposited between 5.5 and 2.0 ka. Based on onlapping relationships, the flood-tidal delta lobes do not show a consistent pattern of migration with age, but appear to randomly shift from location to location.

7. Discussion

7.1. Grain size

Placing the depositional environments identified by grain-size analysis into context with sea level poses some problems. The first is illustrated by a radiocarbon date of 4480 ± 80 calendar years BP within a beach deposit in core MB85 located at an elevation of −24 m (Fig. 11). Assuming a similar sea-level history for Mustang Island as found in other coastal Gulf of Mexico sites (Fig. 3) places this beach deposit at least 17 m below paleo-sea level. Supratidal to intertidal deposits at paleo-sea-level depths exceeding 10 m are also found in core MB78 and Shideler's (1986) cores EE and F.

The most plausible explanation for the deep paleo-sea-level depths of these deposits is that these are beach sands that were re-deposited within tidal inlets. The presence of the shelly intervals at the base of some of these rapidly deposited units is also consistent with a tidal-inlet interpretation (Fig. 11). Morton and Pieper (1976) show a rapid migration of Aransas Pass, on the northern edge of the island, of 1–2 km in only 33 years (Fig. 14). Bathymetry from the era suggests depths up to 11 m were in-filled during that migration (Hydrographic Party, 1853). McGowen and Scott (1975) and Morton and McGowen (1980) present a model of historically active Corpus Christi Pass which involves the cutting and filling of an inlet on the southern portion of the island in less than 1 ky. Channel fills of up to 15 m thick were reported (Morton and McGowen, 1980).

The question remains, how does such an inlet cut and fill itself without leaving any clear sedimentological evidence of an inlet (i.e. shell hash, tidal couplets)? Part of the answer for this question can be found in the location of each of the successive episodes of rapid deposition through time. They exist in nearly the same location for at least 7.5 ka (Fig. 11). Most shell hash found in other inlet successions along the Gulf Coast and other areas contain fragments of estuarine (i.e.

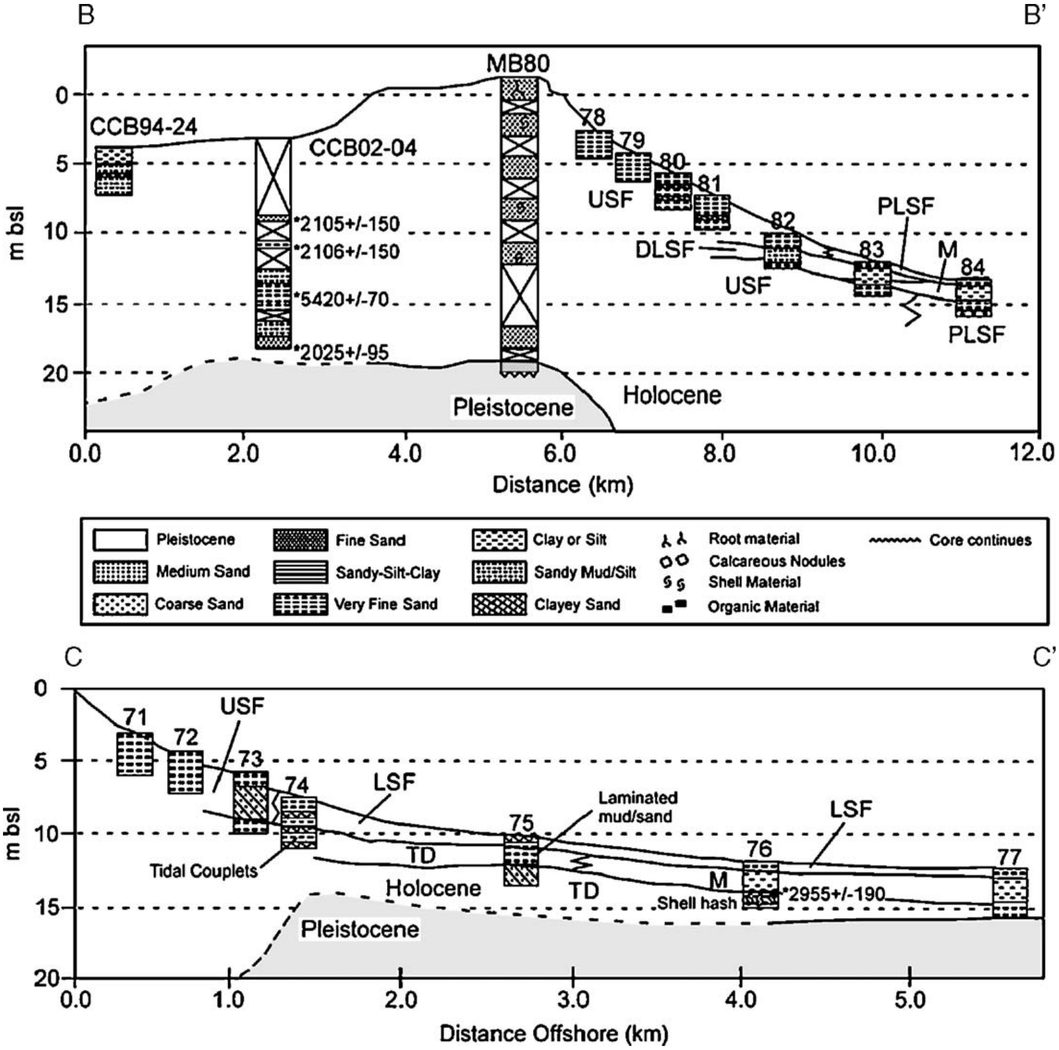

Fig. 12. Two onshore–offshore oriented core transects through Mustang Island. See Fig. 4 for profile locations. Within core MB80 of transect B–B′, note the absence of equivalent facies to that in other cores both landward and seaward of its location. M=marine mud, T=tidal delta, LSF=lower shoreface, USF=upper shoreface.

oysters) and marine fauna (Moslow and Tye, 1985; Israel et al., 1987; Siringan and Anderson, 1993). In order to winnow or deposit a shell hash, an inlet must cut into deposits containing shell material (i.e. estuarine or lower-shoreface deposits). If inlets cut into clean, well-sorted, quartz sands of beach, dune, or barrier-flat origin this is the only sediment available to fill the inlet.

The oldest undifferentiated barrier-island sands within Mustang Island date back to 9.5 ka (Fig. 11). This, coupled with the absence of estuarine or marine deposits beneath the island, suggests the inlets of Mustang Island have been eroding barrier-island deposits for the last 9.5 ka. A similar argument can be made for the lack of tidal couplets within long cores. If the island has stayed in the same location for 9.5 ka, at no time within its history will the more distal portions of the tidal inlets have existed underneath present Mustang Island. This is also supported by the stacked nature of the flood-tidal deltas found in seismic profiles immediately landward of Mustang Island (Fig. 7). Behind other barrier islands and peninsulas along the Texas coast, inlets are marked by lateral accretion (Fig. 15). The accretion fills accommodation as the island or peninsula grows. In contrast, the stacking of flood-tidal deltas behind Mustang Island suggests the island has been at or near its present location throughout much of its history. This scenario is supported by the nearly uniform grain size preserved in every long core taken on Mustang Island (Fig. 13), which contrasts to other inlet successions described by Moslow and Tye (1985) which exhibit fining-upward successions.

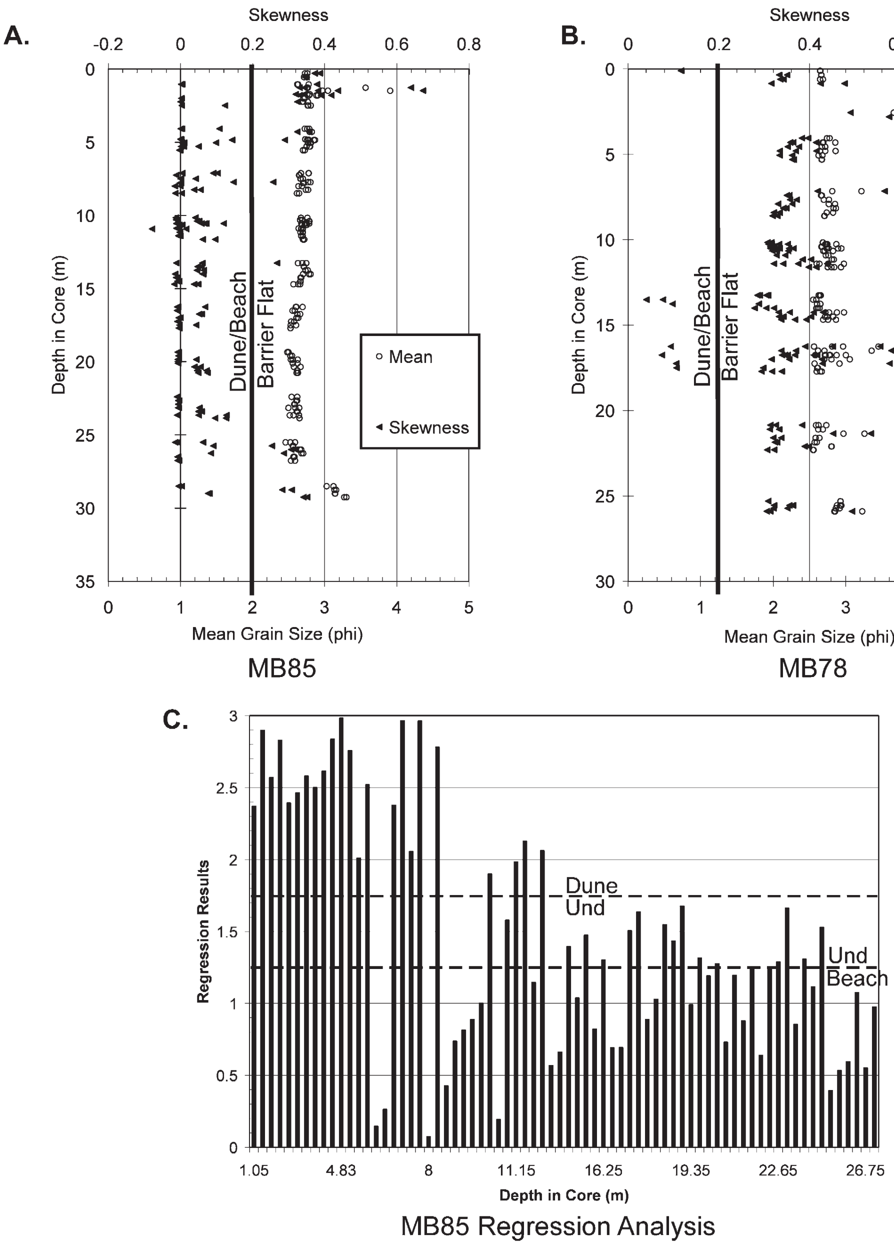

Fig. 13. Grain-size analyses data for cores MB85 (A) and MB78 (B). Dark vertical line with a skewness value of 0.2 separates dune/beach deposits from barrier-flat deposits in accordance with population 1 and 2 respectively within Fig. 9. C) Regression analysis of grain-size data for core MB85 in an attempt to differentiate between dune and beach environments.

7.2. Antecedent topography

Due to Mustang Island's location over the ancestral Nueces River valley and its tributaries (Fig. 2), the Pleistocene surface beneath the southern and northern segments of Mustang Island is deeper than adjacent San Jose Island to the northeast and North Padre Island to the south. Beneath Mustang Island the Pleistocene surfaces reach depths as great as 38 m (Wright, 1980; Shideler et al., 1981; Shideler, 1986; Rodriguez et al., 2001; Simms et al., in press), whereas beneath North Padre and San Jose Island the Pleistocene surface is about 14 m bsl at the present coastline (Andrews, 1970; Shideler, 1986). Beneath Galveston Island to the north, the Pleistocene is only 10 mbsl (Rodriguez et al., 2004).

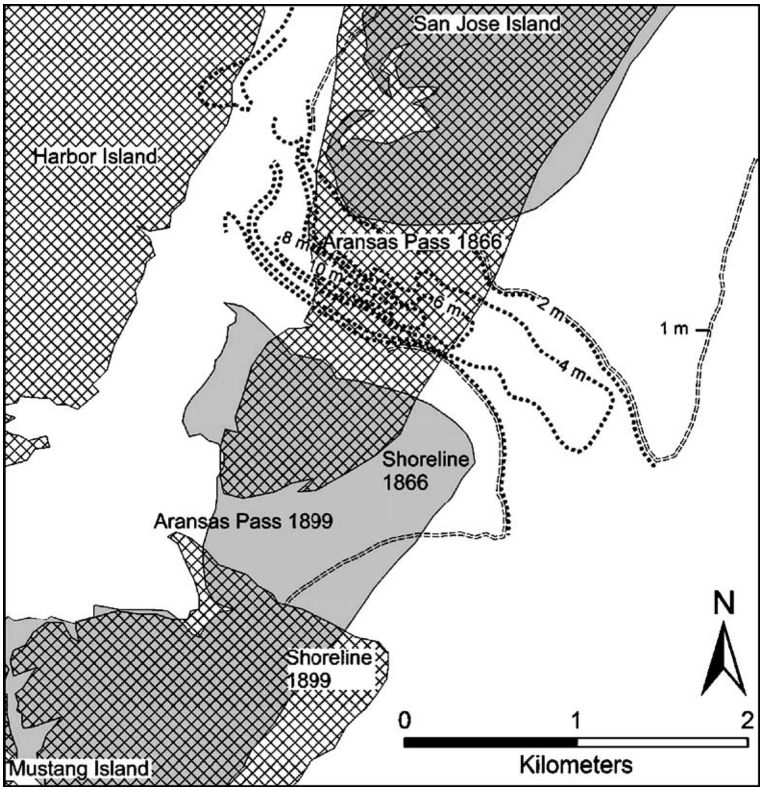

Fig. 14. Historical maps of shorelines and inlet at Aransas Pass. Hashed portions represent Mustang and San Jose Islands in 1899 and solid grey represents the islands in 1866 (modified Morton and McGowen, 1980). Dashed lines represent bathymetry (mbsl) in 1853 (Hydrographic Party, 1853). Contour interval is 2 m unless marked otherwise. Note the depth of the channel that was in-filled with sand within 46 years.

The deeper Pleistocene surface beneath Mustang Island as compared to barrier islands in east Texas is accentuated by the central-Texas shelf's steeper gradient. The slope of the central-Texas inner shelf today is 0.85 m/km compared to 0.32 m/km for the east Texas shelf.

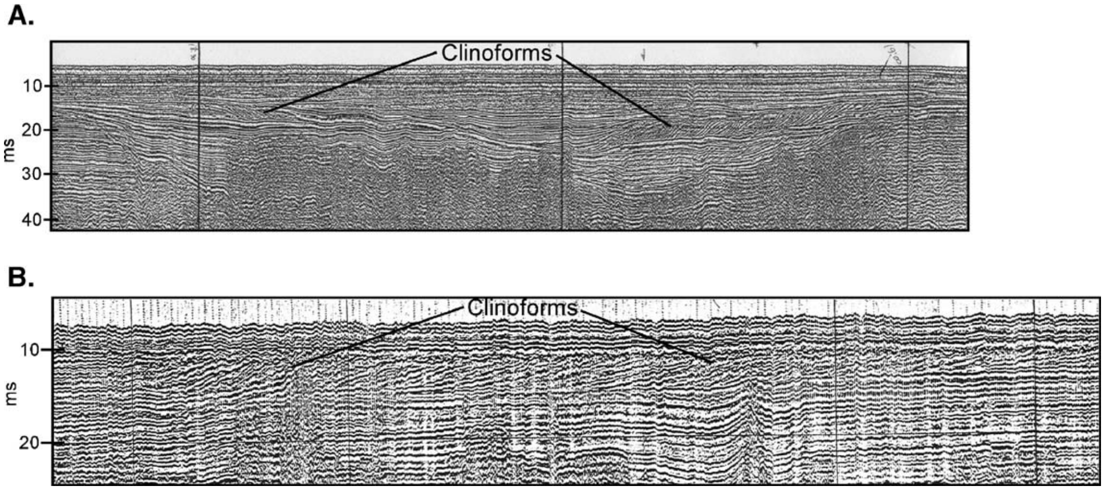

Fig. 15. Seismic profiles along the bayside of (A) Matagorda Peninsula and (B) Bolivar Peninsula showing clinoforms produced by inlet migration in Matagorda and Galveston bays. Note the difference in seismic character between these two features and those from behind Mustang Island illustrated in Fig. 7. See Fig. 2 for location.

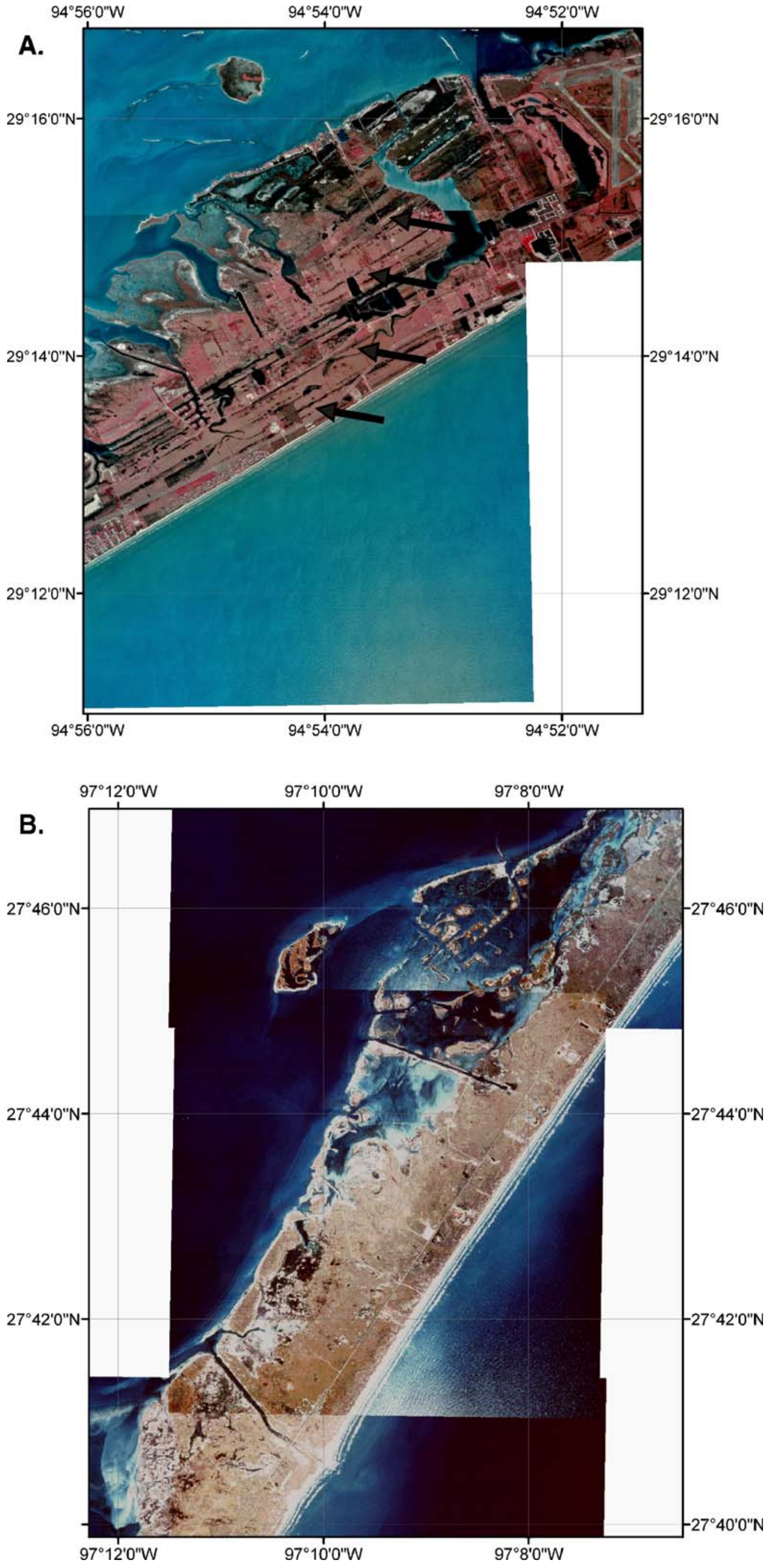

Fig. 16. Aerial photographs showing beach ridges on Galveston Island (A) and absence of beach ridges on Mustang Island (B). See Fig. 2 for location of Galveston Island. Photos courtesy of the Texas Natural Resources Information System (Texas Water Development Board) and the USGS.

The deeper Pleistocene surface within the Nueces incised valley beneath Mustang Island, as compared to North Padre, San Jose, and Galveston Islands, suggests sea level encroached this area earlier, allowing for an earlier establishment of the modern Mustang Island. Thus the modern Mustang Island is older than other modern barrier islands of the Texas coast. San Jose Island, immediately north of Mustang Island, is 6.5 ky old (Shepard, 1960; Andrews, 1970), Padre Island, immediately south of Mustang Island, is only 5.0 ky old (Fisk, 1959; Morton and McGowen, 1980), and Galveston Island of East Texas is only 5.5 ky old (Bernard et al., 1970; Rodriguez et al., 2004).

Antecedent topography may also have influenced the aggradational growth of Mustang Island. Much of the central and northern portions of Mustang Island lie within a near north–south trending tributary of the Nueces incised valley (Fig. 2). The north–south trend to the tributary is also parallel to the depositional strike of the island and the central-Texas coast. The edges of the valley may have played a role in pinning the island in its location during its early phase of growth, inhibiting or at least slowing the rate of retrogradation. The interfluve between the main Nueces paleo-valley and its north–south-oriented tributary may have acted as a headland for spit accretion (Fig. 2). As the headland was eroded, sand would have been introduced to the longshore drift system providing sediment for the continued growth of the spits and a nucleation of the island. The rapid rise in sea level experienced during this time (Fig. 3) would not allow enough time for a complete destruction of the headlands. In addition, once the nucleus for the island was a positive topographic feature, the absence of a backbarrier environment landward of the feature within the tributary of the Nueces valley would inhibit retrogradation. However, behind the island within the Nueces valley proper and the tributary farther to the north, a backbarrier environment would be present.

7.3. Beach ridges

Several of the barrier islands from East Texas (Galveston and Bolivar) exhibit prominent beach ridges that record the seaward growth of the barriers (LeBlanc and Bernard, 1954; Bernard et al., 1970; Rodriguez et al., 2004). However, Mustang Island lacks such features (McGowen and Scott, 1975) (Fig. 16). The absence of beach ridges on Mustang Island is partially attributed to its development. Without a progradational history, beach ridges are less likely to be preserved.

Another possible explanation for the absence of beach ridges is their destruction by eolian processes. Fisk (1959) shows that eolian processes have destroyed the tops of beach ridges on Padre Island located to the south of Mustang Island (Fig. 4). Recent beach ridges may have been created accompanying the recent progradation of the shoreface and subsequently been destroyed by eolian processes. However, two pieces of evidence suggest that progradational beach ridges do not dominate the overall architecture of the island. First, radiocarbon dates from cores lack the seaward younging of depth-equivalent deposits common to progradational islands with beach ridges (Bernard et al., 1970; Rodriguez et al., 2004), although tidal-inlet processes would erase such a trend. Second, seismic profiles taken through the barrier by Shideler (1986) do not show a progradational character.

7.4. Sediment supply

From the data presented, it appears that for most of its history, the modern Mustang Island was an aggradational barrier. This is surprising, considering the great variation in the rates of sea-level rise experienced during this time (Fig. 3) and the behavior of other Gulf of Mexico barriers (i.e. Galveston, Matagorda, etc.). An aggradational character during this time period would require a large source of sand when sea level was rising rapidly from the modern island's inception 9.5 ka to between 6 and 5.5 ka when the rate of sea-level rise slowed. The absence of progradation of the island after 5.5 ka implies a reduction in sediment supply. The Nueces valley was being filled with bayhead-delta and open-bay deposits since 9.5 ka (Simms et al., in press), hence, the Nueces River was not a source of sand during this time interval. Rather sand supply to the barrier was from paleo-Pleistocene headlands, including the underlying sands, the transgressive Colorado Delta (Snow, 1998; Abdulah et al., 2004), and the Oxygen Isotope Stage 3 (OIS 3) shoreline of the central-Texas shelf (Eckles et al., 2004).

Examination of the Pleistocene surface reveals that, due to its location within the Nueces incised valley, ancestral Mustang Island was located between two Pleistocene headlands (Fig. 2). These headlands would have been submerged around 5.5–6 ka when sea level rose to within −5 m of its present level (Fig. 3). Similarly, the Colorado River of east-central Texas produced a large transgressive delta until around 9.5 ka that was subsequently eroded after 9.0 ka (Fig. 2;

Abdulah et al., 2004). Given the present longshore current direction along the central-Texas coast, sands from this delta would have been transported south. The delta was buried by marine muds 5.5–6 ka. The final source of sand is the OIS 3 shoreline of the central-Texas shelf. This large sand body was exposed until it was covered by the "Texas Mud Blanket" around 7.0 ka (Shideler, 1981; Eckles et al., 2004).

Mineralogical work on heavy-mineral assemblages from Mustang Island (Van Andel and Poole, 1960) supports a sediment source from the Colorado River and eroded Pleistocene headlands and shorelines. With time these offshore sources of sand were buried beneath marine muds. Also, a reduction in erosion due to decreased rates of sea-level rise could have slowed the alongshore flux of sand to the barrier (Jennings et al., 1998), preventing any progradation accompanying a reduction in the rate of sea-level rise over the last 6.0 ka.

7.5. Recent contraction and expansion

Core transects from Fassell (1999) and Rodriguez et al. (2001) suggest that a marine flooding event occurred offshore Mustang Island sometime prior to 2955 ± 190 calendar years BP (Fig. 12). Before 4 ka a flood-tidal delta was located 4 km behind the southern portion of the island (Fig. 6). Work on ostracod assemblages from a core taken through this feature by Cronin (1986) suggests connection with the open Gulf; however, macrofauna within this core are devoid of open-marine species. Instead, the macrofauna suggests the inlet connected Corpus Christi Bay with a shallow hypersaline intermediate body of water, not the open Gulf. The cause for the flooding event is unknown but the timing is not the same as the middle-Holocene highstand proposed by Morton et al. (2000) and Blum et al. (2001), which they suggest occurred between 6.8 and 4.8 ka.

Sometime after 2955 ± 190 cal years BP and possibly as late as 1225 ± 230 calendar years BP, based on a radiocarbon date obtained from offshore San Jose Island to the north (Fassell, 1999; Rodriguez et al., 2001), the shoreface seaward of Mustang Island prograded at least 4 km to its present location. Several possibilities could explain this. One possible explanation is a sea-level fall. This is later than the sea-level fall proposed by Morton et al. (2000) and Blum et al. (2001). In addition, studies of the east-Texas coast and the location of the coast with respect to the last great ice sheets suggest a slow rise in sea level during this time, not a fall (Leblanc and Bernard, 1954; Lambeck, 1993; Rodriguez et al., 2004). The second possibility is an increase in sediment supply to this portion of the coast. An increase in sediment supply could be attributed to changes in the longshore drift patterns of the coast. This would fit with the observed enlargement of Padre Island to the south over the last 4 ka (Fisk, 1959).

Three cores located behind the island, which sampled open-bay deposits resting above barrier-flat and lower-bay deposits (core CCB94-24 Fig. 12), also show a prograding of environments. Two possibilities exist for this change. One possible explanation is 1–2 km of progradation of the island, the distance now separating the modern lower-bay depositional environment from the location of the core. The absence of an equivalent change in facies within the cores beneath the modern island does not support this explanation. Another explanation could be a change in the profile of the barrier. If during this period, the island had a lower profile, it would more easily be breached by hurricanes and thus deposits behind the barrier would contain a greater occurrence of overwash deposits. We favor the latter explanation due to the absence of support for a progradation of the island within the cores taken along the modern Mustang Island. In addition, a change from a high-profile barrier to a low-profile barrier would fit an increase in sediment supply as suggested by the shoreface progradation, which commenced between 3.0 and 1.2 ka.

8. Conclusions

The modern Mustang Island was an aggradational barrier island from its inception 9.5 ka. Four observations support an aggradational character for the island. These include 1.) the absence of estuarine or marine deposits underneath Mustang Island, 2.) the presence of five stacked flood-tidal deltas behind the island, and 3.) the presence of tidal inlets for at least the last 7.5 ka. The inlets within the island lack many of the sedimentological features commonly attributed to inlets, such as shell hash, a fining-upward succession, and tidal couplets. The absence of shell hash is attributed to the inlets continual reworking of older barrier-island sands devoid of the shell material required to create shell hash. In addition, without dip-oriented migration of the inlets, the present barrier island was never located above older more distal portions of a tidal-delta complex where tidal couplets are normally found. The fourth and most compelling observation that supports an aggradational history for Mustang Island comes from radiocarbon dates which indicate that the barrier existed in its current location since 9.5 ka.

In order for the island to have aggraded in the same location over the last 9.5 ka, a delicate balance between the rate of sea-level rise and sediment supply must have occurred. During the early history of Mustang Island, when the rate of sea-level rise was great, three sources of sand nourished the island via longshore drift. These include Pleistocene headlands situated along the sides of the Nueces incised valley and its tributaries, the offshore transgressive Colorado delta of central Texas (Abdulah et al., 2004), and the sandy deposits of the OIS 3 shoreline that extends across the central-Texas shelf (Eckles et al., 2004). Each of these sources was either drowned or draped by the Texas mud-blanket when the rate of sea-level rise slowed around 5.5–6 ka. Only during the last 4 ka has the balance between sediment supply and sea-level rise been perturbed. But, instead of retrograding or prograding, the island contracted and expanded around a stable core.

Acknowledgments

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