Journal of Coastal Research | SI 36 | 65-80 | (ICS 2002 Proceedings) | Northern Ireland | ISSN 0749-0208

Middle Holocene Sea-Level and Evolution of The Gulf of Mexico Coast (USA)

Michael D. Blum, Amy E. Carter, Tracy Zayac, and Ron Goble

Department of Geosciences
University of Nebraska-Lincoln
Lincoln, NE 68588 (USA)

ABSTRACT

New data published in BLUM *et al.* (2001) suggest that middle Holocene sea level along the Texas Gulf of Mexico coast was at –9 m at ca. 7.8 ka, then rose rapidly to +2 m or more by ca. 6.8 ka. This view contrasts with the traditional, widely accepted interpretations of continual submergence until ca. 2-3 ka. or later. A middle Holocene sea level higher than present should have left a significant imprint on the coastal landscape, yet coastal landforms and deposits of middle Holocene age have not been identified in previous studies. Our recent research has now identified extensive Holocene beach-ridge plains on the mainland central Texas coast, landward of Holocene barriers, that may represent the geomorphic manifestation of this highstand. Long considered to be part of the isotope stage 5 interglacial period shoreline, these Holocene beach-ridge plains attain elevations of 2.5-3 m, extend for 10's of km along the mainland shore, and can be 1-3 km in width, roughly the same scale as the Holocene barriers. To further test the concept of a middle Holocene highstand, we have also investigated previously mapped Holocene shorelines along the Alabama coast. A series of optical luminescence ages suggest that some of the shorelines are middle Holocene in age, whereas others represent the earlier part of the late Holocene, prior to ca. 2-3 ka. In aggregate, these data suggest that relative sea level was at, or very close to, present elevations throughout the middle to late Holocene along the Gulf of Mexico shoreline, both to the west and east of the subsiding Mississippi depocenter, and the model of continual submergence until 3-2 ka. or later needs reevaluation.

ADDITIONALINDEXWORDS: *Sea level, Gulf of Mexico, Submergence, beach ridge plains.*

INTRODUCTION

The barrier-dominated western Gulf of Mexico shoreline in Texas has long served as a natural laboratory for the study of coastal depositional systems and their evolution in response to post-glacial sea-level rise. Well-known earlier studies include the work of FISK (1959) on Padre Island, BERNARD *et al*. (1970) on Galveston Island, WILKINSON (1975) on Matagorda Island, and WILKINSON and BASSE (1978) on Matagorda Peninsula. MORTON *et al*. (2000) argue that the Texas shoreline should also be a prime area for renewed studies of sea-level change with a strong globally-coherent "eustatic" component because of its intermediate- to far-field location with respect to Pleistocene glacio-isostatic effects and intrinsic low rates of subsidence. Similar arguments could be made for the entire northern Gulf of Mexico shoreline, away from the rapidly-subsiding Mississippi and Rio Grande alluvial-deltaic depocenters.

Most older studies of shoreline evolution in Texas, and indeed the Gulf of Mexico basin as a whole, have in common the assumption of rapid sea-level rise during the early Holocene, and slower rise with continued submergence through the middle to late Holocene until ca. 2-3 ka. or later. More recent work has refined this general model with seismic data and radiocarbon ages collected from now submerged settings (e.g. THOMAS, 1990; RODRIGUEZ, 1999), noting an overall step-wise pattern that somewhat resembles the "glacio-eustatic" curve developed from studies of Barbados corals (e.g. FAIRBANKS, 1989), and suggested the discontinuous pattern of sea-level rise must reflect variable rates of meltwater and iceberg discharge from Antarctica (e.g. ANDERSON and THOMAS, 1991). Alternative views of sea-level change that incorporate one or more Holocene highstands have been presented over the years as well, most recently for the western Gulf of Mexico shoreline in Texas (MORTON *et al*., 2000; BLUM *et al*., 2001). These differences of interpretation are not trivial when measured with respect to impacts on, and interpretations of, Holocene shoreline evolution. For the beginning of the middle Holocene period, ca. 7-6.5 ka, interpreted sea-level elevations range from – 7-5 m (RODRIGUEZ, 1999) to + 2 m relative to present (BLUM *et al*., 2001).

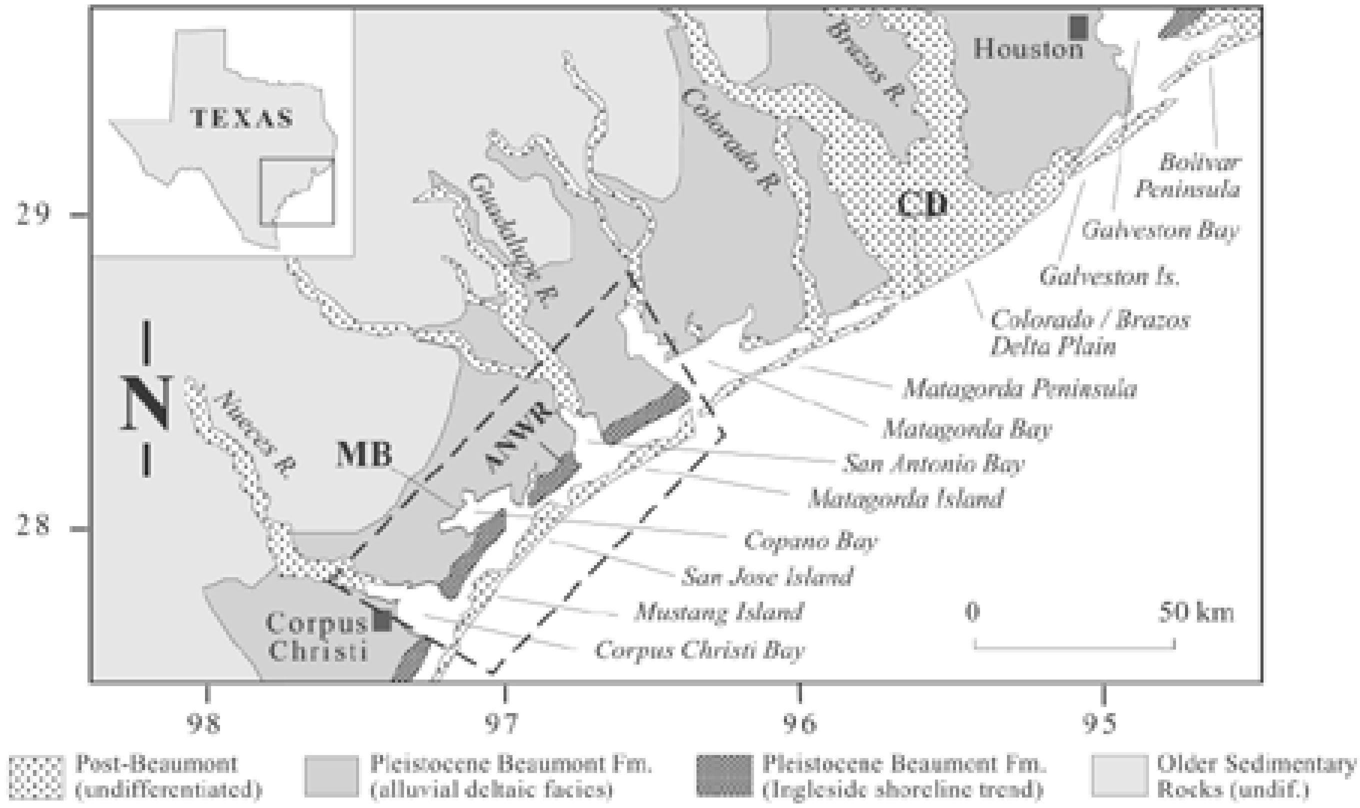

Figure 1. Simplified map of Texas study area, with locations of headlands, bays, and barrier systems discussed in text. CD indicates location of core from the Colorado delta, whereas MB indicates the location of Mullens Bayou, as discussed in the text. ANWR indicates the location of Aransas National Wildlife Refuge and the mainland beach ridge plains discussed in the text.

Three fundamental issues must be addressed to ultimately resolve these different views. First, when did Holocene sea level first reach elevations at, or close to, those of present-day? Second, was sea level ever significantly higher than present during the Holocene? Third, what were the impacts on shoreline evolution? This paper reviews data that pertains to middle Holocene sea-level rise for the western Gulf of Mexico basin in Texas, in between the subsiding Rio Grande and Mississippi depocenters. We then outline the characteristics of previously unrecognised mainland-attached beach-ridge plains of probable Holocene age in that same area that may represent the manifestation of this highstand and subsequent fall. We also briefly summarise new optical luminescence age estimates from beach ridges along the slowly subsiding Alabama coast, east of the Mississippi depocenter, that suggest sea level had reached its present elevation, and was constructing beach-ridge plains, by the beginning of the middle Holocene along that part of the Gulf of Mexico shoreline as well.

BACKGROUND TO TEXAS GULF COAST STUDY AREA

The primary study sites discussed herein are situated on the passive margin Gulf of Mexico coastal plain in Texas, extending from Matagorda to Corpus Christi bays (Figure 1). The coastal plain as a whole consists of a series of Quaternary alluvial-deltaic plains that emanate from each major river valley, as well as correlative estuarine and shore zone landforms and deposits (DUBAR *et al.* 1991). The study area lies between the rapidly subsiding Mississippi delta to the east, and Rio Grande delta to the south.

Sea-Level Change and Coastal Evolution: The Traditional View

The extensive Pleistocene alluvial-deltaic plains of the Texas Coast are referred to as the Beaumont Formation, and represent a succession of valley fills that developed during middle to late Pleistocene oxygen isotope stages (OIS) 10 to 5 (BLUM and PRICE, 1998). The Ingleside shoreline is a distinct sandy barrier island / strand plain trend that

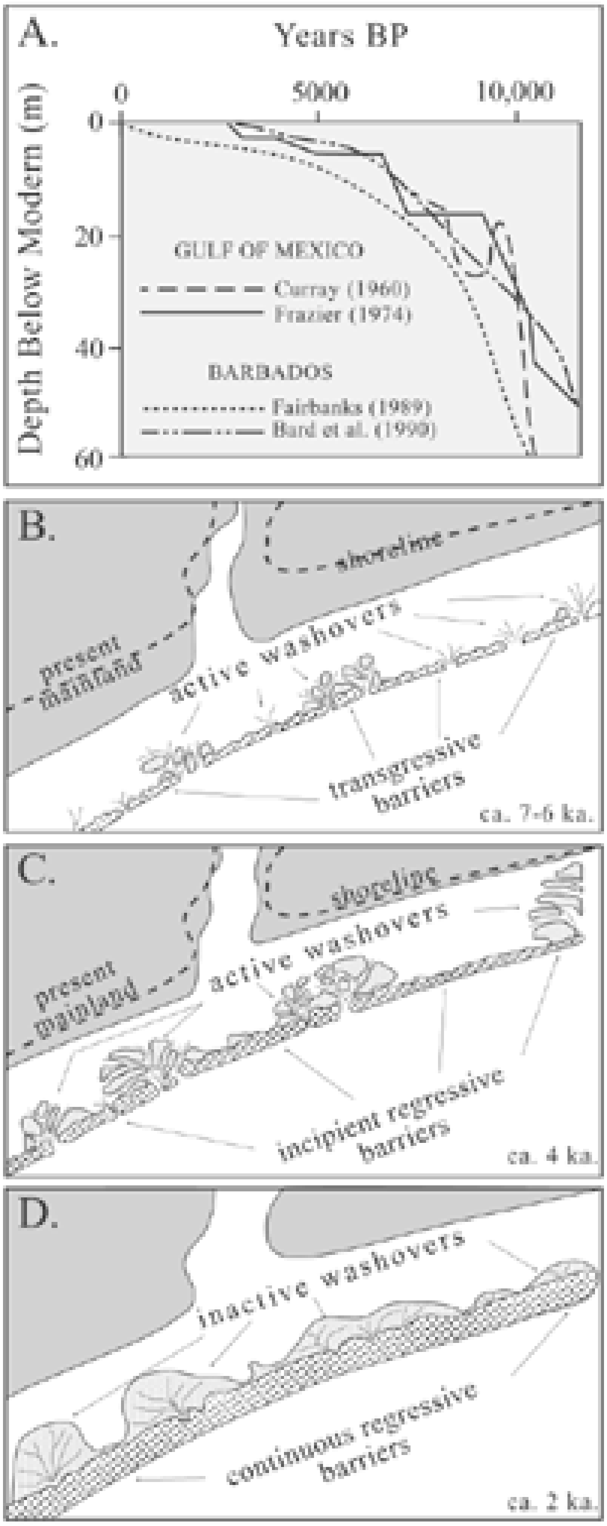

Figure 2. Conventional model for sea-level rise and coastal evolution (modified from BLUM and CARTER, 2000) (A) Sea-level curves from the Gulf of Mexico and Barbados. Note the BARD *et al.* (1990) curve is in calendar years, whereas all others are in uncalibrated radiocarbon years. (B, C, D) Model for evolution of barrier shoreline (adapted and modified from WILKINSON, 1975). Recent model for Sabine Bank, presented in RODRIGUEZ (1999), would place incipient barriers to the east farther offshore than what the original Wilkinson model suggested.

comprises the mainland shore and extends into the now-submerged shelf, is in part genetically related to the youngest Beaumont valley fills, and is well-developed along the central Texas coast between alluvial-deltaic headlands of the Colorado-Brazos and Rio Grande. Traditional views have considered the Ingleside to be from the last "Sangamon" interglacial highstand (now OIS 5e, ca. 125,000 yrs BP; DUBAR *et al*., 1991; OTVOS and HOWAT, 1996), or to represent a middle Wisconsin highstand (OIS 3; WILKINSON *et al*., 1975; SHIDELER, 1986). The latter view is now perhaps unrealistic, given recent data that shows global (CHAPPELL *et al*., 1996; also LAMBECK and CHAPPELL, 2001) and Gulf of Mexico (RODRIGUEZ *et al*., 2000) sea level elevations during OIS 3 were well below present and could not have impacted landscapes at the elevation of the present-day mainland shoreline. Almost by default, this would place the deeply weathered Ingleside sands in the OIS 5 highstand; taking the most detailed "global eustatic" curves at face value (CHAPPELL *et al*., 1996; see ALSO LAMBECK and CHAPPELL, 2001) the last time sea level should have been at present elevations would be OIS 5e.

During the OIS 4-2 glacial period (ca. 70-15 ka.), large coastal plain rivers cut distinct valleys across OIS 5 Beaumont alluvial-deltaic plains and the Ingleside shoreline, and extended their courses to mid-shelf or farther basin-ward positions (BLUM *et al*., 1995; BLUM and STRAFFIN, 2001; ANDERSON *et al*., 1996). Development of the present shoreline is directly coupled to the sea-level rise that accompanied deglaciation. A number of late Pleistocene to Holocene sea-level curves have been published for the western Gulf of Mexico (CURRAY, 1960; SHEPARD, 1963; COLEMAN and SMITH, 1964; NELSON and BRAY, 1970; FRAZIER, 1974; THOMAS, 1990), with each showing continual submergence until ca. 4-3 ka or later (Figure 2A). Most sea-level curves from the eastern Gulf of Mexico and the Atlantic coast of Florida also interpret continual submergence until ca. 3-2 ka or later (e.g. SCHOLL *et al*., 1969; PARKINSON, 1989; TOSCANO and LUNDBERG, 1998; GOODBRED *et al*., 1998). ANDERSON and THOMAS (1991) note that most curves, FRAZIER's (1974) in particular, show discontinuous rates of rise similar to the "eustatic" curve published by FAIRBANKS (1989) using data from Barbados.

During the post-glacial transgression the high sediment yield Brazos, Colorado, and Rio Grande rivers filled their previously incised valleys and prograded delta plains, whereas the lower sediment yield Sabine, Trinity, Guadalupe, and Nueces rivers still discharge to bayhead deltas and "drowned-valley" estuaries that are fronted by barrier island systems (BLUM *et al*., 1995; MORTON *et al*., 1996; DURBIN *et al*., 1997; ASLAN and BLUM, 1999). WRIGHT (1980) used seismic data to estimate that initial flooding of OIS 2 incised valleys to form precursors of present-day bays occurred ca. 8-10,000 yrs BP, and present bay outlines were not reached until ca. 4000 yrs BP. Work by PAINE (1991) in Copano Bay, as well as ANDERSON and THOMAS (1991), ANDERSON *et al*. (1991; 1992), SIRINGIN and ANDERSON (1993), and RODRIGUEZ (1999) in Galveston Bay refined this general model. Most recently, RODRIGUEZ (1999) argued that seismically-identified "flooding surfaces" at –14 and –10 m demarcate rapid landward translation of environments and modification of bay morphologies due to episodic sea-level rise. RODRIGUEZ (1999) further suggested the last event of this kind occurred ca. 4 ka, and that modern sea-level positions were not reached until ca. 3 ka.

A number of studies have been conducted on the large Holocene regressive barriers, such as Galveston and Matagorda Islands. Each is thought to have originated offshore ca. 9-7000 yrs BP, migrated landward late in the transgression, then accreted alongshore during the late Holocene highstand (Figure 2B-D; BERNARD *et al*., 1970; WILKINSON, 1975; MORTON,1994). RODRIGUEZ (1999) also examined sand banks offshore from Galveston Island, the youngest of which is Sabine Bank, now ~30 km offshore and in water depths of –12 m. RODRIGUEZ (1999) used seismic data and a number of 14C ages to suggest that Sabine Bank originated as an early to middle Holocene barrier and has been reworked landward, the Sabine Bank shoreline was active until ca. 4 ka, and that Galveston barrier must have formed after ca. 3 ka. RODRIGUEZ' (1999) view differs from that of earlier workers (e.g. BERNARD *et al*., 1970; WILKINSON, 1975) primarily in that offshore barriers are not interpreted to have migrated landward to form cores to modern barriers, but instead were overstepped during periods of rapid sea-level rise, and new barrier sand bodies formed farther landward during the highstand.

Sea-Level Change and Coastal Evolution: Holocene Highstands?

Views of continual submergence until the very late Holocene are based on data from now-submerged contexts where it would be difficult to resolve relative sea-level positions that were at or above modern. However, there is a long history to suggestions of Holocene highstands for the Gulf of Mexico shoreline as a whole that draw on a variety of land-based data. Older interpretations are linked to high beach ridges south of Rio Grande delta in Mexico (BEHRENS, 1966), subtidal foram assemblages above modern sea level on Rio Grande delta (FULTON, 1975), raised marshes on Rio Grande delta (NECK, 1985), raised wind-tidal flat/clay dune complexes on the central Texas coast (PAINE, 1991), and high beach ridges in northwest Florida (STAPOR, 1975; STAPOR *et al*., 1991; TANNER, 1992; TANNER *et al*., 1989). Previous claims of Holocene highstands have been criticised for a variety of reasons (OTVOS, 1995).

More recently, MORTON *et al*. (2000) discuss a range of Holocene landforms that are significantly higher in elevation than modern analogs, and suggest that they formed when sea level was higher than present. Some key features include (a) higher cores to the regressive barriers, (b) large "washover fans" on the regressive barriers that may actually represent flood-tidal deltas that formed under a higher sea level, and are now emergent due to sea level fall, and (c) sets of accretionary bioclastic beach ridges along bay margins that are 1-2 m higher than modern ridges and storm berms. At the very least, these landforms raise questions concerning the model of continual submergence. However, even though a limited number of 14C ages on shells suggest these landforms are late Holocene in age (< ca. 3 ka), they remain imprecisely dated and difficult to interpret in terms of sea-level change. Interpretations provided by MORTON *et al.* (2000) were criticised by OTVOS (2001).

MIDDLE HOLOCENE HIGHSTAND ALONG THE TEXAS COAST: NEW DATA

BLUM *et al.* (2001) presented new data on middle Holocene sea level along the central Texas coast (Figure 1). The following provides a brief review of these data.

Core Data from Colorado Delta

A continuous core from the late Holocene delta of Colorado River penetrated more than 20 m into the late Pleistocene and Holocene valley fill. OIS 4-2 falling stage to lowstand channel-belt sands are capped by a paleosol at -15.5 m, with the rest of the core consisting of interbedded fine sands and reddish muds that are interpreted to represent valley filling by fluvial and deltaic deposits during the post-glacial transgression (ASLAN and BLUM, 1999). At a depth of -8.75 to -9.25 m, reddish floodbasin mud is abruptly overlain by gray mud with interbedded plant remains, then reddish floodbasin mud. Microfauna within the gray mud are dominated by the agglutinated foraminifera (Trochammina macrescens, Arenoparrella mexicana, Miliammina fusca), which are common to present-day brackish marsh environments within 10 cm of MHW (SCOTT *et al*., 1991; WILLIAMS, 1994). Replicate calibrated AMS 14C ages of 7730 ± 65 and 7795 ± 60 cal yrs BP (calendar years before present) were obtained from two separate carbonised plant fragments at a depth of -9 m.

This key part of the post-glacial valley fill succession is interpreted to represent brackish marsh established ± 10 cm of a contemporaneous sea-level position, which was at –9 m relative to present sea level from ca. 7.7 to 7.8 ka. This depth-age relationship is consistent with previously published data from brackish marsh peats in estuarine and offshore localities in east Texas and Louisiana (REHKEMPER, 1969; NELSON and BRAY, 1970; MORTON *et al.*, 2000), and suggests a regional early to middle Holocene benchmark depth-age relationship for the western Gulf of Mexico, in between the subsiding Rio Grande and Mississippi deltaic headlands.

Other workers have calculated "eustatic" rates of sea-level rise for the early to middle Holocene by merging Barbados and Florida platform data (see TOSCANO and LUNDBERG, 1998), as well as data from Tahiti (see BARD *et al*., 1996). It is interesting to note that beginning with a western Gulf of Mexico benchmark at –9 m at ca. 7.7 to 7.8 ka, and using published "eustatic" rates of rise of ~8 to 10 mm/yr, sea level would have risen to present elevations by ca. 6.9 to 6.6 ka.

Shore-Parallel Ridges in Tributary Valleys

MORTON *et al.* (2000) noted the occurrence of shore-parallel ridges in the mouths of tributaries to major bays along the central Texas coast. BLUM *et al.* (2001) investigated one set of ridges from Mullens Bayou, a small tributary to Copano Bay (Figure 1). Ridges here trace laterally to relict wave-cut bluffs in Pleistocene surfaces and are intermediate in elevation between Beaumont alluvial plains and the active marsh. Ridge crest elevations are typically +2 to 2.5 m relative to present mean high water (MHW), defined as the upper limits to the Spartina alterniflora marsh (Figure 3). Ridges are well-drained and covered by dryland vegetation typical of the uplands, such as mesquite and cacti, with modern high marsh vegetation (mostly Spartina patens) > 1 m below ridge crests.

Trench exposures and a series of shallow cores in shore-parallel ridges at Mullens Bayou show that Holocene strata under the ridge crest are 1.8 m thick, and rest unconformably on erosionally truncated, weathered, reddish-brown Pleistocene Beaumont Formation deposits at an elevation of +20 cm MHW. Holocene sediments under the ridge crest consist of horizontally bedded to lenticular sets of massive to weakly laminated fine sandy silt interbedded with shell hash. Individual strata are 10 to 20 cm in thickness and are bounded by discrete, thin shell hash layers. The upper 30 cm of ridge sediments has been modified by soil formation, especially accumulation of organic matter, minor development of pedogenic structure, and partial leaching of carbonates. Sediments in trenches located on the bayward side of this ridge are similar but more shell-rich, with individual strata dipping gently towards the bay (< 5°), and truncated by a coarse bioclastic strandline and current slope profile. By contrast, shell-hash layers thin and disappear in the trench located farther landward, with individual strata mostly horizontal to very

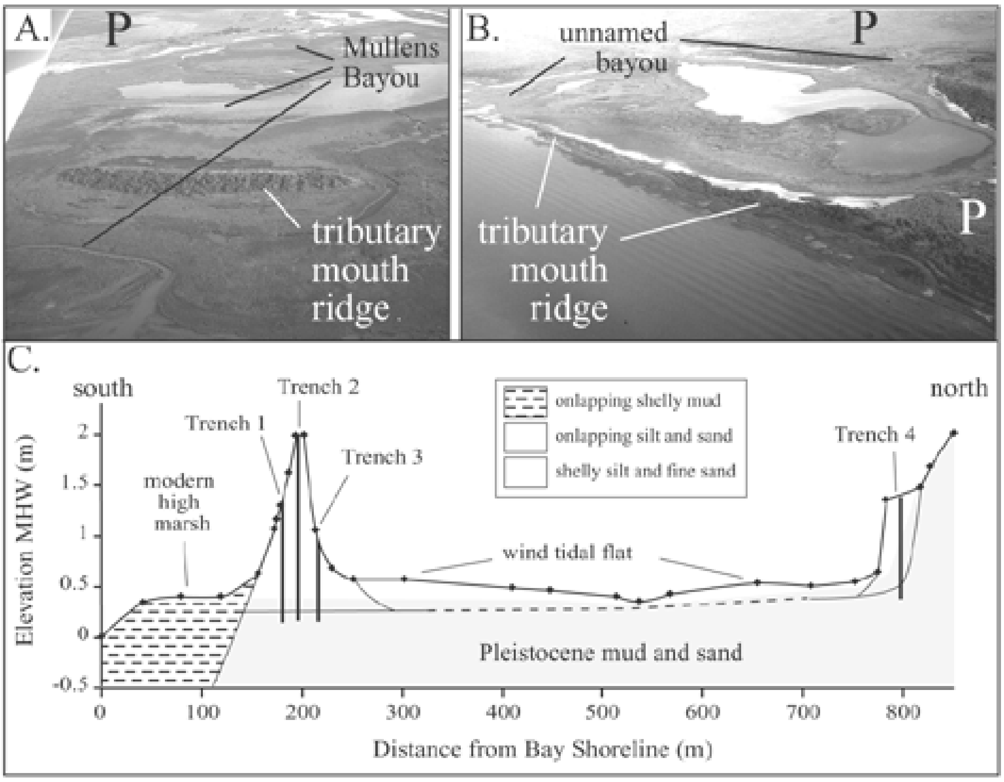

Figure 3. Shore-parallel tributary mouth ridges in Copano Bay. (A) Large ridge in the middle of the Mullens Bayou valley, which has been detached from Pleistocene bluff lines by tidal creek migration. (B) Large ridge in unnamed tributary valley which remains attached to Pleistocene upland surface. (C) Topographic and stratigraphic profile across tributary mouth ridge segment in Mullens Bayou. Positions of backhoe trenches are shown. Pleistocene mud and sand corresponds to the Beaumont Formation (see Fig. 1), whereas shelly silt and fine sand represent sediments underlying shore-parallel ridge or correlative terrace along valley wall. Onlapping shelly mud and onlapping silt and sand are interpreted to represent marsh and wind-tidal flat accretion, respectively, deposited after formation and abandonment of the shore-parallel ridges. The bioclastic strandline developed on the bayward side of the ridge at 120 to 130 cm MHWis present in trench 1 but is not shown here. Adapted from BLUM and CARTER (2000) and BLUM *et al*. (2001).

gently landward-dipping (< 5°), and again truncated by the current slope profile. Ridge sediments are onlapped by younger marsh and/or tidal channel mud in the bay-ward and lateral directions, and wind-tidal flat silt and sand in the landward direction

An abundant microfauna is present in Holocene strata, and dominated by calcareous foraminifera that occupy shallow subtidal to intertidal bay environments (up to +0.2 m MHW; WILLIAMS, 1994). Based on both sedimentological and micropaleontological data, BLUM *et al*. (2001) interpreted these ridges to have formed as low-energy subtidal to intertidal spits and shoals that formed across the mouths of then-flooded bay tributaries when sea level was ≥(?) +2 m relative to present MHW. They suggested the ridges are now emergent due to more recent sea-level fall and are segmented due to tidal channel migration.

BLUM *et al*. (2001) also report six 14C ages from foram tests in Holocene strata at Mullens Bayou. Internal inconsistencies show that more chronological control is needed, but calibrated 14C ages range from ca. 6800 to ca. 4800 cal yrs BP, all within the middle Holocene. BLUM *et al*. (2001) concluded that relative sea level along the central Texas coast had reached modern positions some 2-4000 years before standard interpretations would suggest, and was higher than modern during the middle Holocene.

POSSIBLE MIDDLE HOLOCENE COASTAL LANDFORMS IN TEXAS

A middle Holocene highstand of this magnitude should have had a noticeable imprint on the coastal landscape, yet landforms of middle Holocene age have not been identified in previous studies. Recent field investigations within the Aransas National Wildlife Refuge (ANWR) have now identified extensive beach-ridge plains along the mainland shoreline that deserve consideration in this context (BLUM and CARTER, 2000; CARTER, 2001). These beach-ridge plains extend along the mainland shoreline between the major bays (Matagorda, San Antonio, Copano, and Corpus Christi), and have long been mapped as part of the Pleistocene "Ingleside" shoreline (see Figure 1). However, their crisp, well-defined beach ridge and swale patterns, as well as slightly incised and inset relict shore-normal channels, are very much unlike the degraded and aeolian-modified landscape of the "Ingleside" farther inland (Figure 4), and very much like the grass-covered older ridge and swale topography on modern barriers. Mainland beach-ridge heights reach elevations of +2.7 m MHW (Figure 4B), and these beach-ridge plains attain shore-normal widths of 1-3 km, roughly the same width as the large Holocene regressive barriers like Galveston and Matagorda Islands.

A series of vibracores up to 4 m in depth were collected in two shore-normal transects across this beach-ridge plain on the ANWR (Figures 4 and 5). The most landward core penetrated a truncated deeply-weathered Ingleside paleosol at 1.9 m below the surface, which corresponds to -0.3 m MHW. Other cores did not reach the weathered Ingleside, and were dominated by 3-4 m of massive to stratified, unweathered fine to very fine sand. Most sands are massive and burrowed with no preserved primary sedimentary structures. However, cores taken from ridge crests contain thin (up to 20 cm in thickness) lenses of planar and trough cross-strata interbedded within 3-4 m of mostly massive but clean sand. Planar and trough cross-strata are waterlain and resemble forebeach deposits on the modern barriers. Eolian caps are present on ridges to a depth of 1 m, and aeolian sediments consist of massive fine sands that have been slightly modified by pedogenesis, with A horizons and roots extending to depths of 20 cm. Cores taken from swales more commonly display pervasive green and orange mottling at depths below 0.5 m. Mottling is interpreted to reflect marshy, acidic conditions coupled with a fluctuating water table that promotes alternating oxidising (orange mottling) and reducing (green mottling) conditions. BLUM and CARTER (2000) and CARTER (2001) interpreted the most landward core as proximal to the "shoreline of maximum transgression", with other cores penetrating a prograding Holocene beach-ridge plain with sandbody thickness greater than 4 m. This thickness is signifantly less than that of the modern barriers, but the basal contact with older weathered deposits was not penetrated, so total thickness is not yet known.

The pristine morphology coupled with the unweathered and still-stratified nature of deposits underlying this beach-ridge plain strongly suggests a Holocene age, since sandy deposits of late Pleistocene age in this region are deeply weathered with thick soil profiles (BLUM and VALASTRO, 1994; DURBIN *et al*., 1997). More precise age determinations have remained elusive, however. First,

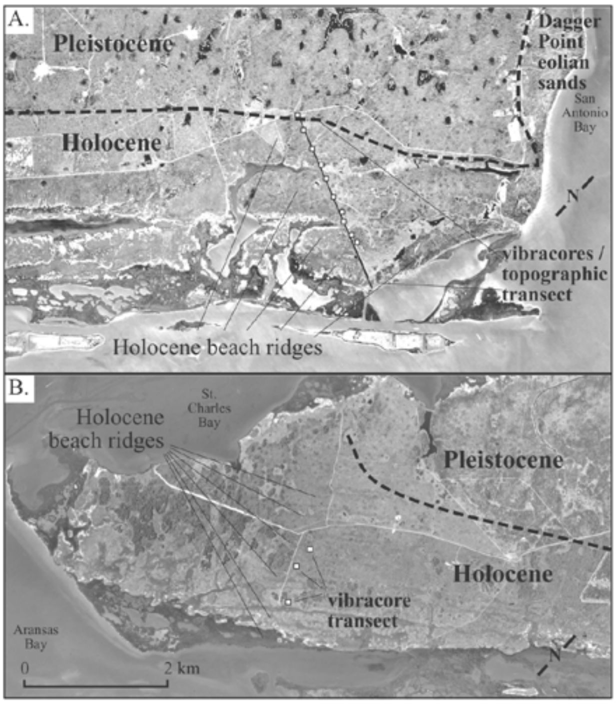

Figure 4 – Air photos of mainland beach-ridge plains on Blackjack Peninsula, Aransas National Wildlife Refuge, Texas. (A) East end of Blackjack Peninsula, with locations of vibracores and interpreted Pleistocene – Holocene boundary. (B) West end of Blackjack Peninsula, with locations of vibracores and interpreted Pleistocene – Holocene boundary. Scale is the same for both photos.

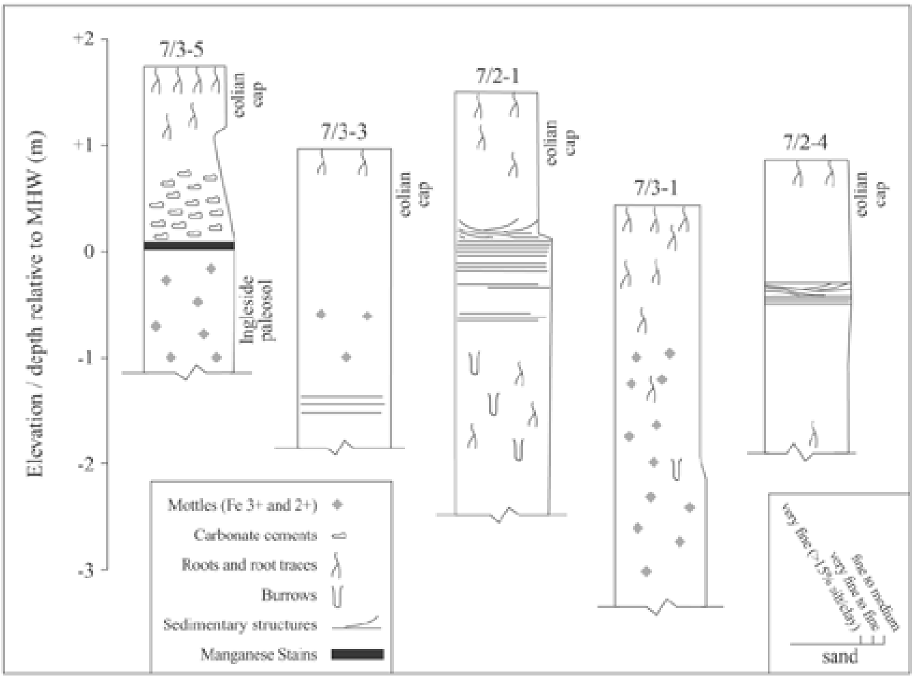

Figure 5. Description of selected vibracores from Holocene beach-ridge plain on Blackjack Peninsula, Texas. See Figure 4Afor core locations.

organic material suitable for radiocarbon dating was not recovered from core. Second, CARTER (2001) attempted to date sandy beach-ridge sediments using optically-stimulated luminescence techniques (OSL; see AITKEN, 1998), focussing on green-light stimulation of quartz and the single-aliquot procedure which can test for partial bleaching (see MURRAY and WINTLE, 1999). Unfortunately, all samples showed considerable data scatter that suggests sand grains were only partially bleached during transport, and produced age estimates that fall within OIS 3 and 2, when sea level was clearly well below present (CARTER, 2001). Hence OSL age estimates should be treated as maximum ages that demonstrate the beach-ridge plain is younger than OIS 3 and 2, and support the general Holocene age assignment based on morphological characteristics and the lack of weathering and soil development.

Topographic survey by CARTER (2001) shows this beach-ridge plain is not significantly higher in elevation than beach ridges on the modern Matagorda barrier, and sedimentary structures typical of swash zone environments occur at elevations that correspond to present sea level (Figure 6). Hence this beach-ridge plain does not require a higher sea level to have formed. However, both ridge crest and swale surface elevations decrease in the seaward direction, and mainland beach ridges and swales seem to disappear below the present lagoon shoreline. This contrasts with ridge crest and swale elevations for the modern Matagorda barrier, which show no such trend. One possible interpretation would be that this beach-ridge plain represents progradation of the mainland coastline following maximum transgression during the middle Holocene, and during sea-level fall to present elevations or lower.

The presence of extensive, large-scale beach-ridge plains of probable Holocene age on the mainland, at elevations corresponding to present sea level, raises a number of questions about overall shoreline development and evolution, but specifically the relationship between offshore barriers and the mainland beach ridge plains. In their present position, proximal to the mainland shore, barriers severely limit fetch and wave set-up in lagoons and along the mainland shore, such that large and continuous features such as the beach-ridge plains described above are not forming today. As a result, it would seem that two possibilities should be considered: (a) the barriers were present when the mainland beach-ridge plain was prograding, but they were much farther seaward and did not severely limit fetch and wave set-up in the lagoons, or (b) the barriers were yet not present along this stretch of the coast, and the mainland beach-ridge plain formed under open marine conditions.

Understanding the significance of these beach-ridge plains must await more data that fully documents (a) the depth to weathered Pleistocene "Ingleside" strata and inferred depth of ravinement of the mainland shore during

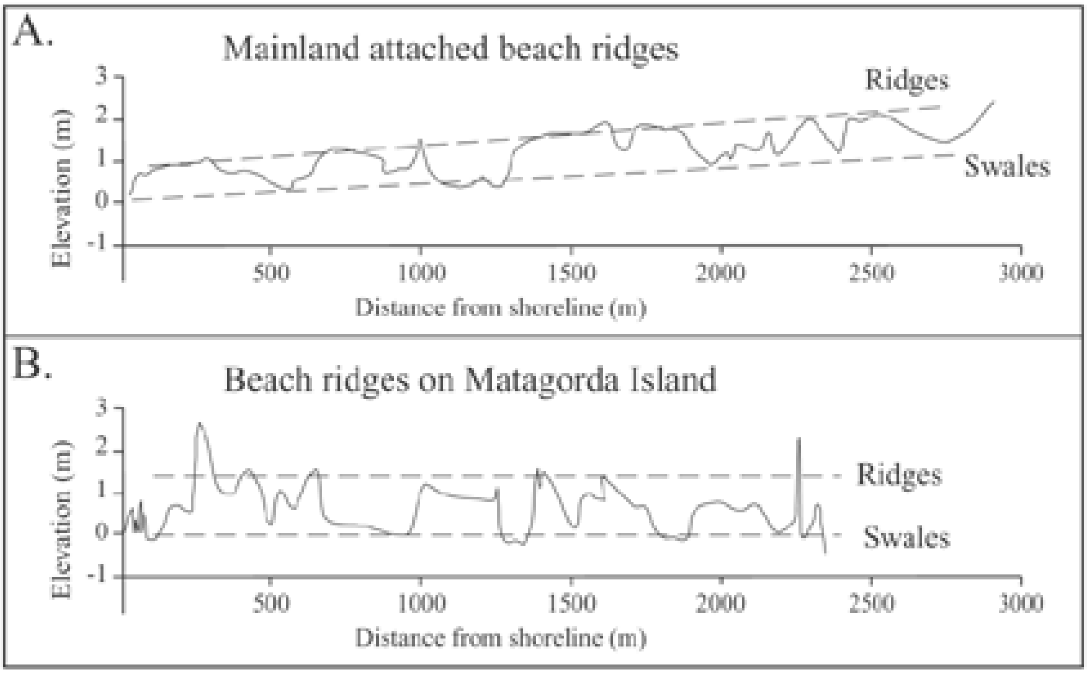

Figure 6 (A) Topographic profile of beach-ridge plain along east side of Blackjack Peninsula, Texas (along vibracore transect in Figure 4A). (B) Topographic profile of beach-ridge plain on the back side of Matagorda Island (after CARTER, 2000).

transgression and highstand, (b) overall sandbody geometries and thicknesses, (c) precise stratigraphic relationships with the Holocene Matagorda barrier-lagoon facies, and (d) the geochronological framework. At the very least, recognition of mainland beach-ridge plains of Holocene age suggests that our understanding of coastal evolution is far from complete. Figure 7 summarises an alternative model for middle Holocene sea level and coastal evolution along the barrier-dominated central Texas coast.

MIDDLE HOLOCENE SHORELINE ALONG THE NORTHEASTERN GULF OF MEXICO COAST?

The Mississippi-Alabama-Florida part of the Gulf of Mexico Coastal Plain is less sediment-rich, and therefore considerably less extensive than in Texas, but also consists of a series of Pliocene through late Pleistocene alluvial, deltaic and shore zone successions (see DUBAR *et al.*, 1991). Holocene coastal landforms and deposits cut across, and rest on, late Pleistocene alluvial-deltaic and shore zone strata, and, as noted above, geomorphic data from the northeastern Gulf of Mexico coast, especially the Florida panhandle, have long been interpreted to suggest a middle Holocene highstand. The most compelling landforms discussed in this context consist of the erosional-scarp and beach-ridge sequences described by STAPOR (1975) and TANNER (1989; 1992) from the beach ridge-dominated Appalachicola deltaic headland. The erosional scarp remains undated, but was cut into the "Pamlico" shoreline (the Gulfport Formation of Otvos in DUBAR *et al*., 1991), presumed to be of last interglacial age and correlative to the "Ingleside" in Texas, whereas adjacent beach ridges are also undated, but higher than, and crosscut by, beach ridges with associated late Holocene archaeological sites.

BLUM *et al*. (2001) noted that paleoenvironmental data from the Alabama coast may also be important in the context of Holocene sea-level change. For example, LIU and FEARN (1993) describe sediments from Lake Shelby, to the east of Mobile Bay (Figure 7A and C). Clay-rich lagoonal deposits with brackish to marine diatoms accumulated in what is now the Lake Shelby basin from ca. 5.6 ka until the present freshwater lake was formed ca. 2.2 ka. (calibrated ages from original uncalibrated ages in LIU and FEARN, 1993). Although not the focus of LIU’S and FEARN’S (1993) study, Lake Shelby is separated from the "Pamlico" shoreline by beach ridges that must be younger than the Pamlico shoreline but predate, or be contemporaneous with, formation of the estuary or freshwater lake basin. BLUM *et al.* (2001) suggested these data call into question the traditional interpretation of continual sea-level rise and coastal submergence until 3 to 2 ka. (e.g. SCHOLL *et al*., 1969; PARKINSON, 1989; TOSCANO and LUNDBERG, 1998; GOODBRED *et al*., 1998).

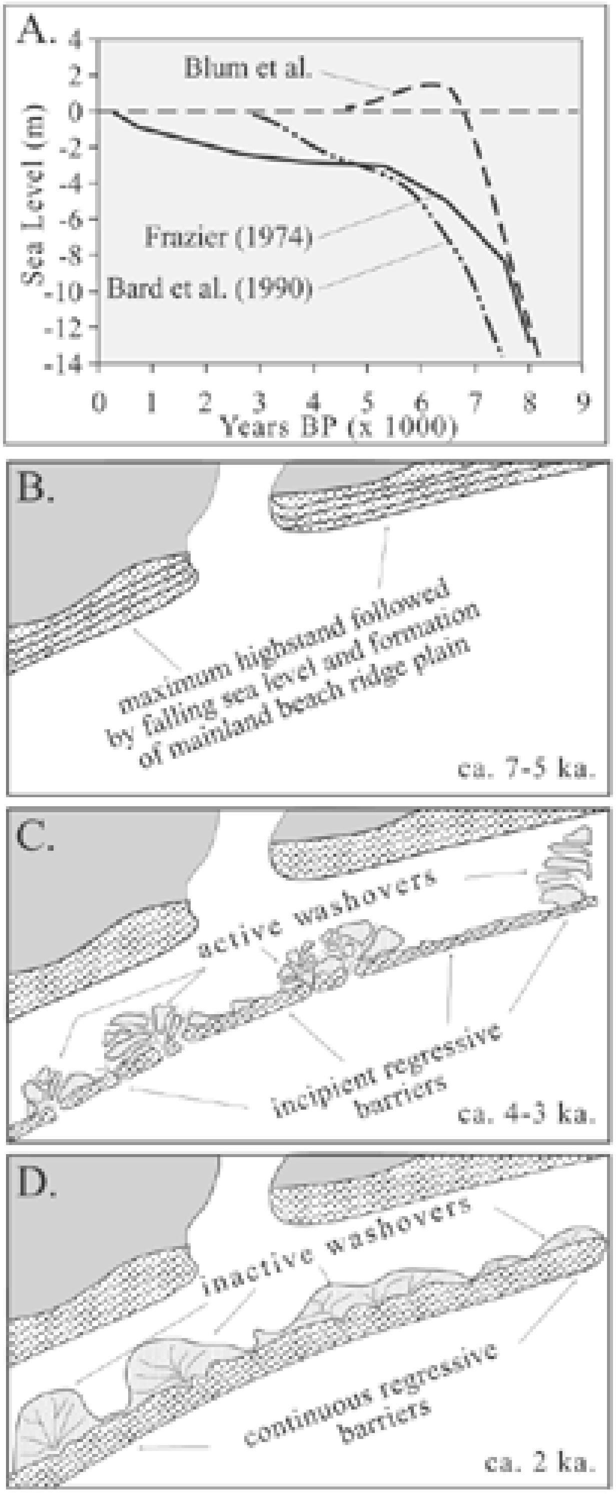

Figure 7 Alternative model for sea-level change and coastal evolution. (A) BLUM *et al*. (2001)'s middle Holocene sea-level position, contrasted with that from FRAZIER (1974) in the Gulf of Mexico and BARD *et al*. (1990) in Barbados. Radiocarbon ages for the Frazier curve have been calibrated to calendar years before present. (B, C, D) Revised model for shoreline evolution, emphasising development of middle Holocene beach-ridge plains on the mainland. Barrier island story is hypothetical only, and it is uncertain as to whether they were present but farther offshore during the middle Holocene, or had not yet formed (see text).

Middle Holocene Shoreline in Alabama: New Data

Multiple Holocene beach-ridge generations were differentiated along this stretch of the Alabama coast, including the Lake Shelby area, by OTVOS (in DUBAR *et al.*, 1991). To further investigate their age and genetic significance, Holocene beach ridge and swale patterns were reexamined from the vicinity of Lake Shelby and to the west along the Morgan Peninsula (Figure 8A). Generations of Holocene beach ridges were differentiated from air photos and topographic maps with field checking, and are for the most part the same as those identified by OTVOS (in DUBAR *et al.*, 1991). Moreover, older beach ridge sediments were examined in natural bluff exposures and a series of vibracores, and samples for OSL dating were collected from specific older beach ridges (Figure 8B and C) and the modern beach.

Holocene beach-ridge sets of interest occur seaward from a distinct erosional scarp cut into the "Pamlico" shoreline, with scarp relief exceeding 4 m, and older Holocene beach ridges are truncated seaward by the continuous beach ridge and dune complex that parallels the present shoreline (Figure 8A). Individual sets occur in cuspate or arcuate patterns with shore-parallel lengths of 5-10 km or more, and shore-normal widths of 1-2 km. Two distinct beach ridge generations lie some 15-20 km west of Lake Shelby. The oldest consists of a series of arcuate ridge and swale patterns that extend into Mobile Bay, and are referred to locally as Little Point Clear. The second oldest set truncates the Little Point Clear set, rests against and truncates beach ridges of Pleistocene age, and has been referred to as the Edith Hammock shoreline (Figure 8B; see SMITH, 1986; also OTVOS in DUBAR *et al.*, 1991). Farther to the east, between the Edith Hammock shoreline and Lake Shelby, beach ridge sets are not present, and the current shore-parallel beach ridge trend is separated from the Pamlico shoreline by a lagoon. However, distinct sets of beach ridges can be differentiated in the vicinity of Lake Shelby, both landward and seaward of the lake itself (Figure 8C; see also OTVOS in DUBAR *et al.*, 1991; LIU and FEARN, 1993).

Ridge crest elevations on the Little Point Clear beach ridge set rarely exceed +1 m elevation, with swales at or below present sea level, and flooded at high tide. However, ridges of the Edith Hammock shoreline commonly exceed

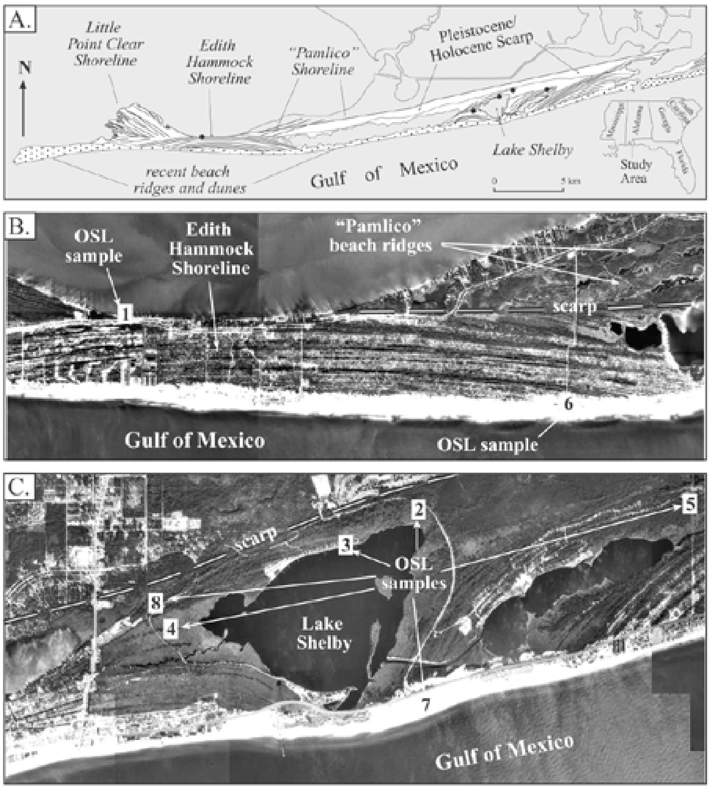

Figure 8 (A) Geomorphic map of the Alabama coast, illustrating cross-cutting beach ridge sets and key locations discussed in text. (B) Air photo of the Little Point Clear and Edith Hammock beach ridge sets on Morgan Peninsula, Alabama. Note the distinct cross-cutting relations between the Edith Hammock shoreline and the Pleistocene "Pamlico" shoreline trend, as well as the location of OSLsamples. (C) Air photo of the Lake Shelby area, Alabama, illustrating cross-cutting relations between beach ridge sets, the location of the Pleistocene "Pamlico" shoreline trend, and the location of OSL samples.

Table 1. OSLresults from the Alabama shoreline. Sample numbers shown correspond to numbers on maps and air photos in Figure 8. Dose rates (in grays (Gy)/1000 years) are calculated from separate contributions of K_2O, U, Th, and H_2O in samples, as measured in the laboratory, and by calculation of the cosmic contribution (following Aitken, 1998). Sample 8 showed clear evidence for partial bleaching, and produced an OSL age estimate that is significantly older than those of surrounding samples, as well as geologically unrealistic.

UNLLab Ref. #	Sample Number	Latitude/ Longitude	Depth of Burial (m)	Equivalent Dose (Gy)	K2O (%)	U (ppm)	Th (ppm)	H2O (%)	Cosmic (Gy/1000 yrs)	Dose rate (Gy/1000 yrs)	Age (x 1000 yrs)
278	1	N30º 14' 19.4" W87º 53' 27.1"	3.0	1.88 ± 0.07	0.012	0.3	0.8	0.97	0.141	0.280	6.73 ± 0.48
156	2	N30º 16' 11.1" W87º 39' 5.2"	1.7	1.09 ± 0.04	0.012	0.4	0.1	23.99	0.167	0.255	4.28 ± 0.29
157	3	N30º 16' 14.1" W87º 37' 4.7"	1.4	0.99 ± 0.02	0.084	0.2	0.4	19.35	0.174	0.291	3.40 ± 0.21
265	4	N30º 15' 34.3" W87º 40' 56.8"	1.3	v1.13 ± 0.04	0.012	0.8	0.3	24.32	0.175	0.351	3.21 ± 0.23
164	5	N30º 16' 30.5" W87º 37' 24.4"	1.0	0.62 ± 0.02	0.012	0.1	0.2	25.45	0.183	0.220	2.82 ± 0.17
275	6	N30º 13' 45.2" W87º 52' 2.0"	0.1	0.04 ± 0	0.006	0.3	0.2	4.20	0.207	0.295	0.14 ± 0.01
167	7	N30º 15' 13.4" W87º 38' 36.7"	0.1	0.04 ± 0	0.006	0.1	0.2	8.23	0.207	0.247	0.16 ± 0.02
166	8	N30º 15' 50.7" W87º 40' 58.4"	2.1	15.74 ± 1.45	0.114	0.3	0.6	23 (est.)	0.158	0.322	49.19 ± 5.42

+4 m, and swale elevations are commonly 1-2 m above present sea level. By contrast, ridge crests farther landward of Lake Shelby rarely exceed 1-2 m above present MSL, whereas swales lie close to the present water table and are commonly flooded. Ridge crests farther seaward of Lake Shelby again commonly exceed +1-2 m, and occasionally reach 4 m or more, but swale elevations remain very close to present sea-level, and are most commonly flooded. Sediments underlying all beach ridges consist of fine to medium quartz-rich sand, mostly massive to weakly stratified, whereas swales also contained thin accumulations (<0.5 m) of partially decomposed plant matter.

Samples for OSL dating were processed using blue-green stimulation of the sand-sized (150-180 _m) quartz fraction and the single-aliquot regenerative protocol (see MURRAY and WINTLE, 1999). In contrast with OSLresults from the mainland beach-ridge plain in Texas, only one sample from the Alabama coast produced a scatter of data that suggests it was partially bleached. Moreover, age estimates from successively younger beach ridges (based on cross-cutting relations) are in the correct geomorphic / stratigraphic order, and modern swash zone deposits produced OSL age estimates of <200 yrs (Table 1). A sample obtained from bluff exposures at the boundary between the Little Point Clear and Edith Hammock beach ridge trends, along the shoreline of Bon Secour / Mobile Bay (Figure 7B), yielded a single OSL age of ca. 6.73 ka. By contrast, samples collected around Lake Shelby (Figure 7C) produced OSL age estimates of ca. 4.28 to 3.21 ka. for beach ridges farther landward of the lake, and 2.82 ka for a beach ridge farther seaward (Table 1).

Further detailed examination, vibracoring, and OSL dating of Holocene beach-ridge sequences in this part of the northern Gulf of Mexico is now in progress. However, these preliminary results suggest that relative sea level along this stretch of the northern Gulf of Mexico coast had reached present elevations by the middle Holocene, the Little Point Clear and Edith Hammock shorelines are of middle Holocene age, and beach ridges in and around Lake Shelby represent the late Holocene. These data further suggest that sea level was at, or very close to, present elevations throughout the middle to late Holocene, and the concept of continual submergence until 3-2 ka or later needs reevaluation for this part of the Gulf of Mexico shoreline as well.

DISCUSSION

BLUM *et al.*'s (2001) interpretation of sea level history along the northwestern Gulf of Mexico shoreline in Texas implies that sea level reached present positions some 3-5 kyr before traditional interpretations would suggest, and raises a number of questions regarding coastal evolution. Among these would be the lack of previously identified landforms and deposits that might represent the imprint of this highstand. However, the newly recognised mainland beach-ridge plains of Holocene age from the Central Texas coast (BLUM and CARTER, 2000; CARTER, 2001) may record the imprint of this highstand and subsequent fall to present elevations or lower. Although traditionally lumped together with the "Ingleside" shoreline of last interglacial age (most recently by OTVOS and HOWAT, 1996), these Holocene mainland beach-ridge plains are similar in scale to the large regressive barriers, yet they must predate or be contemporaneous with the earliest stages of barrier development farther offshore. Their presence clearly implies our traditional views of sea-level change and coastal evolution need revision. New mapping and geochronological data from the Alabama coast lends support to older interpretations of coastal evolution from the nearby Florida panhandle (e.g. STAPOR, 1975; see also TANNER 1989; 1992), as well as to the BLUM *et al.* (2001) view derived from the Texas shoreline, suggesting that beach ridges were forming at, or very close to, present sea-level elevations by ca. 6.7 ka along this stretch of the Gulf of Mexico coast as well.

None of these data, when considered in isolation, provide clear and unambiguous evidence for a middle Holocene highstand, but the composite pattern is beginning to make a more robust case for sea-level positions that were at, or close to, present elevations during the middle Holocene. It is clear that such an interpretation runs counter to older traditional views (see discussion by OTVOS, 1995; 2001), as well as the most recent studies in the Gulf offshore (RODRIGUEZ, 1999). But it is also worth reiterating that views of continual submergence until the late Holocene have been based almost exclusively on data from now-submerged contexts where it would be difficult to resolve relative sea-level positions that were ever at or above modern. Moreover, it has long been recognised that archaeological sites with late Holocene ages occur on beach ridges that are at the same elevation, or slightly higher than, those forming today (STAPOR, 1975; STAPOR *et al.*, 1991), which would seem unlikely if sea level were significantly below present until very recently. These contrasting views should be reconciled through the collection of further empirical data, but for the present time both should be retained as alternative testable hypotheses that have fundamentally different implications for shoreline evolution.

With the above said, the concept of a middle Holocene highstand is far from unrealistic for the non- to very slowly-subsiding parts of the northern Gulf of Mexico coast. Highstands of similar age and magnitude have been interpreted for low-latitude coasts in both hemispheres which are far-field with respect to the isostatic effects associated with deglaciation (see PIRAZZOLI, 1991; 1996). Moreover, earlier versions of the ICE geophysical model of Peltier and colleagues (ICE 3G; TUSHINGHAM and PELTIER, 1992) suggested that glacio- and hydro-isostatic adjustments should have produced a middle Holocene highstand along the northern Gulf of Mexico shoreline, even though one had not been identified as yet.

Fundamental to interpretations of the significance of empirical data or the reality of geophysical model are assumptions that bear on the meltwater-controlled eustatic component of sea-level change during the middle Holocene period. For example, PELTIER (1998) assumes meltwater discharge until ca. 5 ka, but negligible additions after that based on the work of Fairbanks (1989), whereas FLEMING *et al*. (1998) infer 3-5 m of meltwater-driven sea-level rise since 7 ka. These assumptions deserve scrutiny in light of recent work in Antarctica, the most significant source for middle to late Holocene meltwater discharge to the ocean basins. GOODWIN (1998), for example, argues that minimum ice volumes characterised Antarctica during the middle Holocene, and ice expansion and thickening occurred after 4 ka (see also INGOLFSSON *et al*., 1998), a view supported most recently by PUDSEY and EVANS (2001). Moreover, work on Greenland ice cores suggests an inverse relationship between temperature and accumulation rates during the last 7 ka., and the ice sheet is therefore especially prone to volume reduction during periods of warm climate, such as the middle Holocene (CUFFEYand CLOW, 1997). FUNDER's (1989) summary of Greenland glacial records supports this view, noting that middle Holocene ice margins were considerably inland from present-day, and re-advanced after ca. 4 ka. GOODWIN (1998) suggested that volume changes of the magnitude envisioned for Antarctica would result in late Holocene eustatic sea-level lowering, and explain widespread observations of this kind.

If a middle Holocene highstand is verified by future investigations, the subject of causality is critical, as it remains difficult to determine the relative influence of local, regional, and global mechanisms. But the Gulf of Mexico shoreline, away from the subsiding Mississippi and Rio Grande depocenters, should provide a record of sea-level change with a strong globally-coherent signature, which suggests the data described herein may be more than locally and regionally significant. Regardless of causality, however, it now appears that much of the mainland coastal landscape along the non- to slowly-subsiding stretches of the northern Gulf of Mexico coast, at elevations of less than +3 m, bears the imprint of this middle Holocene highstand. This imprint is in the form of veneers of Holocene strata resting on erosionally truncated Pleistocene landforms, or fully-developed Holocene constructional landforms and their associated deposits. The data presented here represent but a small part of continuing efforts to address these issues, and revise models of sea-level change and coastal evolution in this area where so many classic early studies were undertaken.

ACKNOWLEDGEMENTS

This research was funded by the Geological Society of America and the Gulf Coast Association of Geologic Societies (student research grants to A. Carter), and the US National Science Foundation (grant to M. Blum). We thank the staff of Aransas National Wildlife Refuge, Refugio County, Texas, and Gulf State Park, Baldwin County, Alabama, for providing access, permission to obtain vibracores, and logistical support.

LITERATURE CITED

AITKEN, M.J., 1998, *Optical Dating*. Oxford University Press.

ANDERSON, J.B. and THOMAS, M.A., 1991, Marine ice sheet decoupling as a mechanism for rapid episodic sea level change: the record of such events and their influence on sedimentation. *Sedimentary Geology*, v. 70, pp. 87-104.

ANDERSON, J.B., SIRINGIN, F.B., SMYTH, W.C., and THOMAS, M.A., 1991, Episodic nature of Holocene sea level rise and the evolution of Galveston Bay. In: *Coastal Depositional Systems of the Gulf of Mexico*. GCSSEPM 12th Annual Research Conference, pp. 8-14.

ANDERSON, J.B., THOMAS, M.A., SIRINGIN, F.P., and SMYTH, W.C., 1992, Quaternary evolution of the Texas Coast and Shelf. In: FLETCHER, C.H. III and WEHMILLER, J.F. (eds.) *Quaternary Coasts of the United States: Marine and Lacustrine Systems.* SEPM Special Publication 48, pp. 253-265.

ANDERSON, J.B., ABDULAH, K., SARZALEJO, S., SIRINGIN, F., and THOMAS, M.A., 1996, Late Quaternary sedimentation and high-resolution sequence stratigraphy of the East Texas Shelf. In: DE BATIST, M. and JACOBS, P. (eds.) *Geology of Siliciclastic Shelf Seas.* Geologic Society of London Special Publication 117, pp. 95-124.

ASLAN, A. and BLUM, M.D., 1999, Contrasting styles of Holocene avulsion, Texas Gulf Coastal Plain. In: SMITH, N.D. and ROGERS, J.J. (eds.) *Fluvial Sedimentology VI*. International Association of Sedimentologists Special Publication 28, pp. 193-209.

BARD, E., HAMELIN, B., FAIRBANKS, R.G., and ZINDLER, A., 1990, Calibration of the ^{14}C timescale over the past 30,000 yrs using mass spectrometric U-Th ages from Barbados corals. *Nature*, v. 345, pp. 405-410.

BARD, E., HAMELIN, B., ARNOLD, M., MONTAGGIONI, L., CABIOCH, G., FAURE, G., and ROUGERIE, F., 1996, Deglacial sea-level record from Tahiti corals and the timing of global meltwater discharge. *Nature*, v. 382, pp. 241-244.

BEHRENS, E.W., 1966, Recent emerged beach in Eastern Mexico. *Science*, v. 152, pp. 642-643.

BERNARD, H.A., MAJOR, C.F., PARROTT, B.S., and LEBLANC, R.J. Sr, 1970, *Recent Sediments of Southeast Texas: Field Guide to the Brazos Alluvial-Deltaic Plain and the Galveston Barrier Island Complex*. Bureau of Economic Geology Guidebook 11, The University of Texas at Austin.

BLUM, M.D., and VALASTRO, S. Jr., 1994, Late Quaternary sedimentation, lower Colorado River, Gulf Coastal Plain of Texas. *Geological Society of America Bulletin*, v. 106, pp. 1002-1016.

BLUM, M.D. and CARTER, A.E., 2000, Middle Holocene evolution of the Central Texas Coast. *Transactions of the Gulf Coast Association of Geological Societies*. v. 50, pp. 331-341.

BLUM, M.D. and PRICE, D.M., 1998, Quaternary alluvial plain deposition in response to interacting glacio-eustatic and climatic controls, Gulf Coastal Plain of Texas. In: SHANLEY, K. W. and MCCABE, P. M. (eds.) *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks*. SEPM Special Publication No. 59, pp. 31-48.

BLUM, M. D. and STRAFFIN, E. C., 2001, Fluvial response to external forcing: examples from the Massif Central of France, the Texas Coastal Plain (USA), the Sahara of Tunisia, and the Lower Mississippi Valley (USA). In: MADDY, D. and MACKLIN, M. A. (eds.) *River Basin Sediment Systems: Archives of Environmental Change.* Balkema Press. pp. 195-228.

BLUM, M.D., MORTON, R.A., and DURBIN, J.M., 1995, "Deweyville" terraces and deposits of the Texas Gulf Coastal Plain. *Transactions of the Gulf Coast Association of Geological Societies*. v. 45, pp. 53-60.

BLUM, M.D., MISNER, T.J., COLLINS, E.S. SCOTT, D.B., MORTON, R.A., and ASLAN, A., 2001, Middle Holocene sea-level rise and highstand at +2m, Texas Gulf Coast. *Journal of Sedimentary Research*. v. 71, pp. 581-588.

CARTER, A.E., 2001, *Holocene evolution of the Central Texas Coast*. Unpublished MS Thesis, University of Nebraska-Lincoln.

CHAPPELL, J., OMURA, A., ESAT, T., MCCULLOCH, M., PANDOLFI, J., OTA, Y., and PILLANS, B., 1996, Reconciliation of late Quaternary sea levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. *Earth and Planetary Science Letters*, v. 141, pp. 227-236.

COLEMAN, J.M. and SMITH, W.G., 1964, Late Recent rise of sea level. *Geological Society of America Bulletin*, v. 79, pp. 833-840.

CUFFEY, K.M., and CLOW, G.D., 1997, Temperature, accumulation and ice sheet elevation in central Greenland through the last deglacial transition. *Journal of Geophysical Research*, v. 102, pp. 26,383-26,396

CURRAY, J.R., 1960, Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico. In: SHEPARD, F.P., PHLEGER, F.B. and VAN ANDEL, T.H. (eds.) *Recent Sediments Northwest Gulf of Mexico*: AAPG, pp. 221-226

DUBAR, J.R., EWING, T.E. LUNDELIUS, E.L. JR, OTVOS, E.G., and WINKER, C.D., 1991, *Quaternary Geology of the Gulf of Mexico Coastal Plain. In:* MORRISON, R.B. *(ed.) Quaternary Non-Glacial Geology of the Conterminous United States: v. K-2, The Geology of North America*. Geological Society of America, pp. 583-610.

DURBIN, J.M., BLUM, M.D., and PRICE, D.M., 1997, Late Pleistocene stratigraphy of the lower Nueces River, Corpus Christi, Texas: glacio-eustatic influences on valley-fill architecture. *Transactions of the Gulf Coast Association of Geological Societies*. v. 47, pp. 119-129.

FAIRBANKS, R.G., 1989, A 17,000 year glacio-eustatic sea-level record: influence of glacial melting rates on the Younger Dryas event and deep ocean circulation. *Nature*, v. 342, pp. 637-642.

FISK, H.N., 1959, Padre Island and Laguna Madre Flats, coastal south Texas. Proceedings of the Second Coastal Geography Conference, Louisiana State University, Baton Rouge, pp. 103-151.

FLEMING, K., JOHNSTON, P., ZWARTZ, D., YOKOYAMA, Y., LAMBECK, K., and CHAPPELL, J., 1998, Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth And Planetary Science Letters*, v. 163, pp. 327-342.

FRAZIER, D.E., 1974, *Depositional Episodes: Their Relationship to the Quaternary Framework in the Northwestern Portion of the Gulf Basin*. Geological Circular 74-1, Bureau of Economic Geology, The University of Texas at Austin.

FULTON, K.J., 1975, *Subsurface stratigraphy, depositional environments and aspects of reservoir continuity, Rio Grande delta, Texas*. Unpubl\ished Ph. D. Dissertation, University of Cincinnati, 314 p.

FUNDER, S., 1989, Quaternary geology of the ice-free areas of Greenland. In: FULTON, R.J. (ed.), *Quaternary Geology of Canada and Greenland: Volume K-1, The Geology of North America*. Geological Survey of Canada. pp. 741-791

GOODBRED, S.L., JR., WRIGHT, E.E., and HINE, A.C., 1998, Sea-level change and storm-surge deposition in a Late Holocene Florida salt marsh. *Journal of Sedimentary Research* v. 68, pp. 240-252.

GOODWIN, I., 1998, Did changes in Antarctic ice volume influence late Holocene sea level lowering? *Quaternary Science Reviews*, v. 17, pp. 319-332.

INGOLFSSON, O., HJORT, C., BERKMAN, P.A., BJORCK, S., COLHOUN, E., GOODWIN, I.D., HALL., B. HIRIKAWA, K., MELLES, M., MOLLER, P., and PRENTICE, M.L., 1998, Antarctic glacial history since the last glacial maximum: an overview of the record on land. *Antarctic Science*, v. 10, pp. 326-344.

LAMBECK, K. and CHAPELL, J. 2001, Sea Level Changes through the last glacial cycle. *Science*, v. 292, pp. 679-686.

LIU, K.-B., and FEARN, M.L., 1993, Lake-sediment records of late Holocene hurricane activities from coastal Alabama. *Geology*, v. 21, pp. 793-796.

MORTON, R.A., 1979, Temporal and spatial variations in shoreline changes and their implications, examples from the Texas coast. *Journal of Sedimentary Petrology*, v. 49, pp. 1101-1112.

MORTON, R.A., 1994, Texas barriers. In: DAVIS, R.A. (ed.) *Geology of Holocene Barrier Islands. Springer-Verlag*, pp. 75-114

MORTON, R.A., BLUM, M.D., and WHITE, W.A., 1996, Valley fills of incised coastal plain rivers, Southeastern Texas. *Transactions of the Gulf Coast Association of Geological Societies*, v. 46, pp. 321-331.

MORTON, R.A., J.G. PAINE, and M.D. BLUM, 2000, Responses of stable bay margins and barrier island systems to Holocene sea level changes, western Gulf of Mexico. *Journal of Sedimentary Research*, v. 70, pp. 478-490.

MURRAY, A.S. and WINTLE, A.G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. *Radiation Measurements*, v. 32, pp. 57-73.

NECK, R.W., 1985, Palaeoecological implications of a Holocene fossil assemblage, lower Rio Grande, Cameron County, Texas. Texas Memorial Museum Pearce-Sellards Series 41. The University of Texas at Austin, 20 p.

NELSON, H.F. and BRAY, E.E., 1970, Stratigraphy and history of the Holocene sediments in the Sabine-High Island area, Gulf of Mexico. In: MORGAN, J.P. and SHAVER, R.H. (eds.) *Deltaic Sedimentation, Modern and Ancient*: SEPM Special Publication No. 15, pp. 48-77.

OTVOS, E.G., 1995, Multiple Pliocene-Quaternary marine highstands, northeast Gulf Coastal Plain - fallacies and facts. *Journal of Coastal Research*, v. 11, pp. 984-1002.

OTVOS, E.G., 2001, Assumed Holocene highstands, Gulf of Mexico: basic issues of sedimentary and landform criteria-discussion. *Journal of Sedimentary Research*, v. 71, pp. 645-647.

OTVOS, E.G., and HOWAT, W.E., 1996, South Texas Ingleside barrier; coastal sediment cycles and vertebrate fauna. *Transactions of the Gulf Coast Association of Geological Societies*, v. 46, pp. 333-344.

PAINE, J.G., 1991, *Late Quaternary Depositional Units, Sea Level, and Vertical Movement Along the Central Texas Coast*. Unpublished Ph. D. Dissertation, The University of Texas at Austin.

PARKINSON, R.W., 1989, Decelerating Holocene sea-level rise and its influence on southwest Florida coastal evolution: a transgressive/regressive stratigraphy. *Journal of Sedimentary Petrology*, v. 59, pp. 960-972.

PELTIER, W.R., 1998, Post-glacial variations in the level of the sea: implications for climate dynamics and solid-earth geophysics. *Reviews of Geophysics*, v. 36, pp. 603-689.

PIRAZZOLI, P.A., 1991, *World Atlas of Holocene Sea-Level Changes*. Elsevier, Amsterdam, 300 p.

PIRAZZOLI, P.A., 1996, *Sea-Level Changes: The Last 20 000 Years*. John Wiley, 211 pp.

PUDSEY, C.J. and EVANS, J., 2001, First survey of Antarctic sub–ice shelf sediments reveals mid-Holocene ice shelf retreat. *Geology*, v. 29, pp. 787–790.

REHKEMPER, L.J., 1969, *Sedimentology of Holocene Estuarine Deposits, Galveston Bay, Texas*. Unpublished Ph.D. Dissertation, Rice University, 67 p.

RODRIGUEZ, A.B., 1999, *Sedimentary Facies and Evolution of Late Pleistocene to Recent Coastal Lithosomes on the East Texas Shelf*. Unpublished Ph.D. Dissertation, Rice University, 203 p.

RODRIGUEZ, A.B., ANDERSON, J.B., BANFIELD, L.A., TAVIANI, M., ABDULAH, K. and SNOW, J.N. 2000, Identification of a –15m middle Wisconsin shoreline on the Texas inner continental shelf. *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 158, pp. 25-43.

SCHOLL, D.W., CRAIGHEAD, F.C., and STUIVER, M., 1969, Florida submergence curve revisited: its relation to coastal sedimentation rate. *Science*, v. 163, pp. 562-564.

SCOTT, D.B., SUTER, J.R., and KOSTERS, E.C, 1991, Marsh foraminifera and arcellaceans of the lower Mississippi delta: controls on spatial distribution. *Micropaleontology*, v. 37, pp. 373-392.

SHEPARD, F.P., 1963, Thirty-five thousand years of sea level. In: *Essays in Marine Geology in Honor of K. O. Emory*. University of Southern California Press, pp. 1-10.

SHIDELER, G.R., 1986, *Stratigraphic Studies of a Late Quaternary Barrier-Type Coastal Complex, Mustang Island-Corpus Christi Bay Area, South Texas Gulf Coast*. United States Geological Survey Professional Paper 1328.

SIRINGIN, F.P. and ANDERSON, J.B., 1993, Seismic facies, architecture, and evolution of the Bolivar Roads tidal inlet / delta complex, east Texas Gulf Coast. *Journal of Sedimentary Petrology*, v. 63, pp. 794-808.

STAPOR, F.W., 1975, Holocene beach-ridge plain development in northwest Florida. *Zeitschrift fur Geomorphologie Supplament* 22, pp. 116-144.

STAPOR, F.W., MATHEWS, T.D., and LINDFORS-KEARNS, F.E., 1991, Barrier island progradation and Holocene sea-level history in southwest Florida. *Journal of Coastal Research*, v. 7, pp. 815-838.

TANNER, W.F., 1992, Late Holocene sea-level changes from grain-size data: evidence from the Gulf of Mexico. *The Holocene*, v. 2, pp. 249-254.

TANNER, W.F., DEMIRPOLAT, S., STAPOR, F.W., and ALVAREZ, L., 1989, The "Gulf of Mexico" late Holocene sea level curve. *Transactions of the Gulf Coast Association of Geological Societies*, v. 39, pp. 553-562.

THOMAS, M.A., 1990, *The Impact of Long-Term and Short-Term Sea-Level Changes on the Evolution of the Wisconsinan-Holocene Trinity/Sabine valley system, Texas Continental Shelf.* Unpublished Ph.D. Dissertation, Rice University, 247 p.

TOSCANO, M.A. and LUNDBERG, J., 1998, Early Holocene sea-level record from submerged fossil reefs on the southeast Florida margin. *Geology*, v. 26, pp. 255-258.

TUSHINGHAM, A.M. and PELTIER, W.R., 1992, Validation of the ICE-3G model of Wurm-Wisconsin deglaciation using a global data base of relative sea level histories. *Journal of Geophysical Research*, v. 97, pp. 3285-3304.

WILKINSON, B.H., 1975, Matagorda Island, Texas: the evolution of a Gulf Coast barrier complex. *Geological Society of America Bulletin*, v. 86, pp. 959-967.

WILKINSON, B.H., MCGOWEN, J.H. and LEWIS, C.R., 1975, Ingleside strandplain sand of the central Texas coast. *American Association of Petroleum Geologists Bulletin*, v. 59, pp. 347-352.

WILKINSON, B.H. and BASSE, R.A., 1978, Late Holocene history of the Central Texas coast from Galveston Island to Pass Cavallo. *Geological Society of America Bulletin*, v. 89, pp. 1592-1600.

WILLIAMS, H.F.L., 1994, Intertidal benthic foraminiferal biofacies on the central Gulf Coast of Texas: modern distribution and application to sea-level reconstruction. *Micropaleontology*, v. 40, pp. 169-183.

WRIGHT, S.S., 1980, *Seismic Stratigraphy and Depositional History of Holocene Sediments on the Central Texas Gulf Coast*. Unpublished MS Thesis, The University of Texas at Austin.