This manuscript may be cited as: Finkl, C. W., Andrews, J. L., Campbell, T. J., Benedet, L., & Waters, J. P. (2004). Coupling Geological Concepts with Historical Data Sets in a MIS Framework to Prospect for Beach-Compatible Sands on the Inner Continental Shelf: Experience on the Eastern Texas Gulf Coast. *Journal of Coastal Research, 20*(2), 533-549.

Journal of Coastal Research	20	2	533–549	West Palm Beach, Florida	Spring 2004

Coupling Geological Concepts with Historical Data Sets in a MIS Framework to Prospect for Beach-Compatible Sands on the Inner Continental Shelf: Experience on the Eastern Texas Gulf Coast[1]

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ABSTRACT

FINKL, C.W.; ANDREWS, J.L.; CAMPBELL, T.J.; BENEDET, L., and WATERS, J.P., 2004. Coupling geological concepts with historical data sets in a MIS framework to prospect for beach-compatible sands on the inner continental shelf: Experience on the eastern Texas Gulf Coast. *Journal of Coastal Research,* 20(2), 533–549. West Palm Beach (Florida), ISSN 0749-0208.

Chronic erosion of beaches along the eastern Texas barrier island coast is increasingly mitigated by renourishment efforts that periodically place large volumes of sand onshore. Location of beach-quality sands on the inner continental shelf is challenged in an environment where terrestrial rivers deposit fluvial sediments in back bays and lagoons instead of offshore and by shelf areas that are dominated by muds. The search for beach-quality sands thus requires understanding of the coastal geological framework and morphodynamic processes that accompanied late Quaternary evolution in the northern Gulf of Mexico. The occurrence of surficial sand deposits as positive bathymetric features on the seafloor (ridges, shoals, banks) and presence of sands buried in paleovalley (drowned channels) infill sequences makes for complicated search procedures that must accurately differentiate a range of sedimentary settings by geophysical and geotechnical surveys. Compilation of vast amounts of data from historical core logs and newly acquired information in a marine information system (MIS) permits spatial analyses in a format that is compatible with development of a sand search model. The resulting differentiated investigative sand-search methods, that comprise part of the Texas Sand Search Model (TSSM), are able to target potential borrow areas in ebb-tidal shoals, low-relief ridge deposits, high-relief banks, and in mud-covered paleovalley sequences.

ADITIONAL INDEX WORDS: *Beach erosion, coastal erosion, barrier island, sea-level rise, coastal sediments, paleovalley, vibracore, marine information system, sand resources.*

INTRODUCTION

Because many Texas Gulf coast beaches are in a chronic state of erosion (*e.g.* Morton, 1977; Morton and Paine, 1985; Morton *et al.,* 1995a) (as in the case of Florida sector Gulf beaches, *e.g.* Clark, 1993; Esteves and Finkl, 2000), new sand sources are required for periodic replenishment, which in turn stabilizes beaches for multiple use in coastal protection, recreation, or as natural habitat. Terrestrial sources of beach-quality sand pose logistical problems for delivery to the coast and costs associated with placement along the shore can be prohibitive. Advanced technological efforts to locate new sand sources therefore focus on submarine accumulations that can be dredged from offshore (*e.g.* Anderson *et al.*, 1994; Finkl, Khalil, and Andrews, 1997; Morton and Gibeaut, 1998; Anderson and Wellner, 2002; Dellepena, Allison and Seitz, 2002; Finkl *et al.*, 2002; Finkl, Andrews and Benedet, 2003). Sandy seafloor deposits vary in terms of composition, size, thickness, horizontal continuity, and admixture with other materials such as organics, silt plus clay, and rock reef rubble. Beach-quality sands have very specific parametric ranges in properties that are acceptable for placement on beaches and it is thus necessary to identify locations with potentially usable sand reserves and to eliminate others from further consideration. Traditionally, initial attempts to locate offshore sand sources were based on directed reconnaissance-level (*e.g.* Williams, Prins and Meisburger, 1979) or more or less random geophysical and geotechnical surveys over large expanses of seabed. Although random search methods are still commonly practiced in some locations, sand searches on the inner continental shelf have become increasingly sophisticated over the last two decades.

Seabed morphology and coastal sedimentary covers do not

03777C submitted 19 September 2003; accepted in revision 15 April 2004.

[1] Funding for this study was provided by Galveston County and Jefferson County (Texas), and the U.S. Army Corps of Engineers, Galveston District, Galveston, Texas.

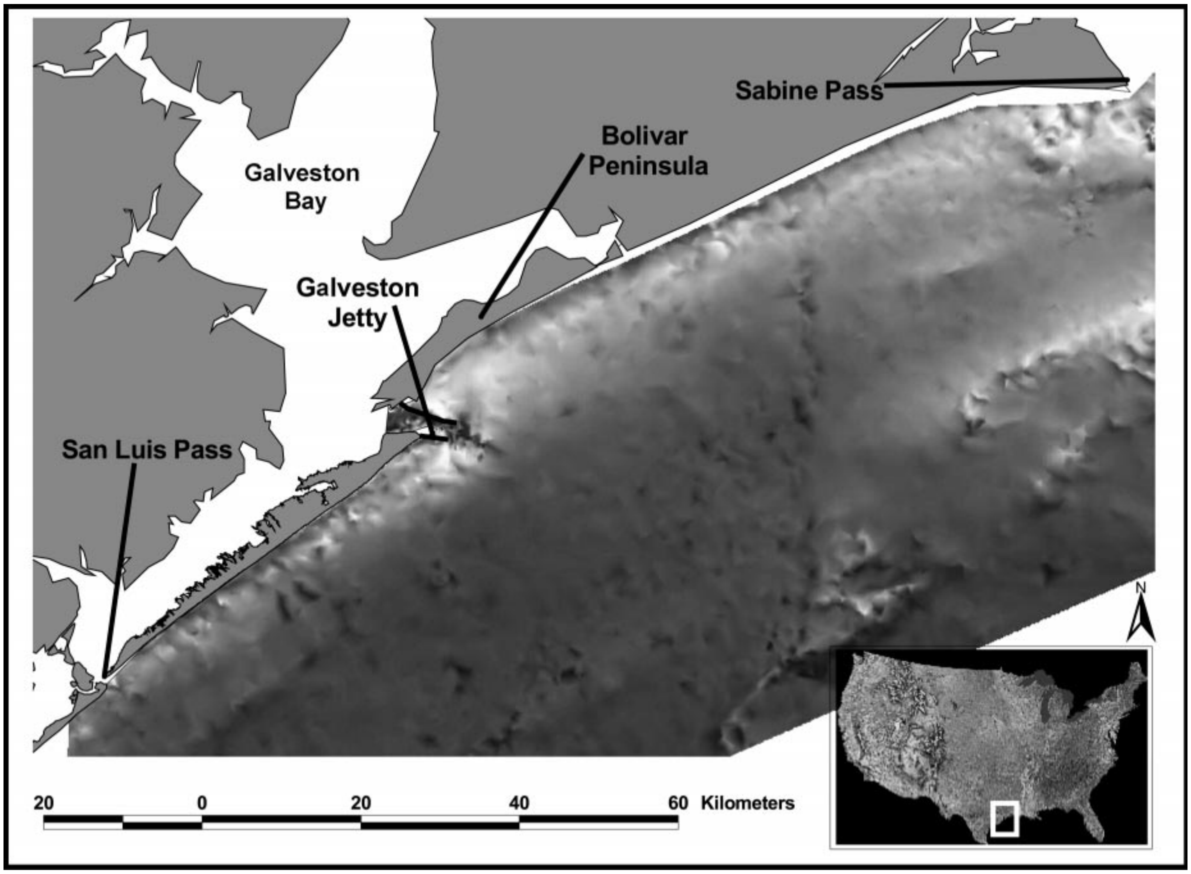

Figure 1. Location map of the general study area off Galveston Bay and along the eastern coast of Texas, extending from San Luis Pass to Sabine Pass.

occur in haphazard distribution patterns, but rather are highly organized in space and time (*e.g.* MORTON and MCGOWEN, 1980; THOMAS and ANDERSON, 1989; ANDERSON, SIRIGAN and THOMAS, 1990; ANDERSON *et al.*, 1994; MORTON and SUTER, 1996; EDGE and HUTCHINSON, 2001). Mapping and understanding the nearshore seabed in terms of morphologic units, such as morphostructures and landform elements (*e.g.* DUANE and MEISBURGER, 1969; KHALIL, 1999; WARNER, 1999; BENEDET, 2002; FINKL and WARNER, 2004), and analysis of existing geotechnical and geophysical data (FINKL *et al.*, 2003) provides a basis for recognizing geomorphic settings that favor the accumulation of beach-compatible sands. The combination of seabed morphology, existing data and an understanding of local Quaternary coastal evolution (viz. fluctuations in relative sea level, exposure and drowning of terrestrial landscapes on the continental shelf) integrates parameters that are essential to the conceptualization of a rational sand search methodology. Preliminary sand search investigations often focus on the presence of enclosed positive bathymetric features (ridges, shoals) that rise above an otherwise generally featureless seabed and which are highlighted in the analysis of local bathymetry and by sidescan sonar imagery. The recognition of valley fills that plug paleo-river channels cut into the inner continental shelf is also initially based on the analysis of seismic reflection sub-bottom records. The logistical sequencing of differentiated surveys thereby increases the cost-effectiveness and success of locating potential sand resources. This study summarizes recent research efforts that identify some geological conditions that lead to accumulation of beach-compatible sediments on the eastern Texas inner shelf. The integration of seafloor geology, geotechnical-geophysical surveys, and other historical data within a MIS analysis ring broadens the scope of investigation and increases perceptual recognition of previously unseen relationships. Application of these principles and concepts to the Texas inner continental shelf provides opportunity to demonstrate the effectiveness of this multidimensional approach.

GEOLOGY AND GEOMORPHOLOGY OF THE EASTERN TEXAS COAST

Geographic coordinates of the study area range from 28°9′ to 29°7′ North Latitude and by 93°8′ to 95°1′ West Longitude, extending for 146 km parallel to the Texas Barrier Island Coast (Figure 1). Planimetrically, the research area, which is limited by Sabine Pass to the northeast and by San Luis Pass in the southwest, extends about 48 km offshore.

In order to better appreciate the genesis and distribution of sedimentary deposits on the inner continental shelf, it is necessary to discuss the geological framework of the Texas coast. The eastern Texas shore is sediment-starved because rivers, instead of debouching directly into the Gulf of Mexico, discharge sediments to inner bay systems and estuaries where sand-sized sediments are deposited in bay head deltas (RODRIGUEZ *et al.*, 1998). Most of the Texas coast from the Sabine River (at the Louisiana border) south to the Rio Grande (marking the border with Mexico), is composed of long sandy barrier islands. Tidal inlets connect lagoons and estuaries between the barrier islands and the mainland with the Gulf of Mexico. These low-relief islands are generally attached to mainland areas by peninsulas on their wide northeastern extensions with the unattached ends tapering southwest (BULLARD, 1942). Morphometric properties and geological character of the seafloor and coastal plain along eastern Texas are directly related to geologic evolutionary sequences that include erosional and depositional processes, uplift and subsidence, sources and quantities of sediment supply, and eustatic sea-level changes (WILLIAMS *et al.,* 1979; MORTON and MCGOWEN, 1980). Antecedent topography and character of the substrate control barrier island thickness, slope and thickness of the shoreface, shoreline erosion rates, and ultimately the location of offshore sand deposits (MORTON and GIBEAUT, 1993).

Late Quaternary Geologic History

Holocene sediments on the Texas shelf unconformably overlie the Pleistocene Beaumont Formation (Fm.), which in Louisiana is also referred to as the Prairie Fm. The Beaumont Fm. (Sangamonian, approx. 130,000–115,000 YBP in age), which overlies the Montgomery Fm., is prevalent in subaerial and submarine exposures in this area. It contains abruptly changing facies within fluvial and deltaic sediments that are mixed with lagoonal and shallow marine deposits and sandy barrier island deposits (PETTIT and WINSLOW, 1957). These basal deposits are characterized in their uppermost units by highly oxidized stiff clays. Deweyville sediments (BERNARD *et al.,* 1962), which unconformably overlie and are inset within the Beaumont Fm., are clayey silts and silty fine sands with occurrences of sand and gravel. They are younger (*i.e.* early to late Wisconsin, ~100,000 to 30,000 YBP) and grade into Holocene sediments. Deweyville terraces fringing incised paleo-river channels occur on a portion of the shelf that represents a paleo-flood plain surface (PEARSON *et al.,* 1986). A prominent seismic reflector in the area marks the contact between the Pleistocene erosion surface (top of the Beaumont Fm.) and overlying Holocene sediments. This Pleistocene erosion surface underlies Galveston Island at about −12 m depth and has a gentle seaward slope across the shelf.

During the Holocene, many pre-existing fluvial terraces and incised river channels on the continental shelf were drowned during the most recent post-glacial sea-level rise (Flandrian Transgression, ~15,000 YBP to present). Deposits on the Texas shelf are divided among three major system tracts according to ANDERSON *et al.* (1990, 1994): Highstand (~125,000 to 40,000 YBP), Lowstand (~40,000 to 16,000 YBP), and Transgressive (~15,000 YBP to present). Deposits laid down in Flandrian times are represented by the Transgressive Systems Tract (~15,000 YBP to present), which was characterized by diminished sediment supply when deltas were backstepped and incised valleys were flooded and infilled with Holocene sediments. Major sand bodies were deposited during eustatic stillstands within the transgressive phase along the eastern Texas coast, for example on Sabine Bank and Heald Bank. The transgression was episodic and irregular rather than a continuous or uninterrupted rise of sea level (*e.g.* FAIRBRIDGE, 1961; RODRIGUEZ *et al.,* 1998) (Figure 2), which permitted deposition during relatively brief stillstands between transgressional phases. Remnants of barriers, for example, are reportedly preserved as linear sand bodies on the continental shelf off Texas (*e.g.* Sabine and Heald banks) and Louisiana (*e.g.* Ship Shoal) (PENLAND *et al.*, 1988). These coastal barriers probably formed during one of the brief still stands, or possibly during minor reversals in the overall increasing sea level trend (MORTON and GIBEAUT, 1993).

The width of the modern continental shelf varies from 232 km off the Texas-Louisiana border to about 177 km off Matagorda Bay (between Galveston and Corpus Christi) where a re-entrant of the Gulf of Mexico narrows the shelf width. Considerable change in seafloor slope occurs between High Island and Freeport, as demonstrated in the vicinity of High Island where the inner shelf is extremely flat and featureless with a slope of 0.3 m km^{-1} while at Freeport the shelf has a slope of 3 m km^{-1} (WILLIAMS *et al.,* 1979, WHITE *et al.,* 1985). The shelf slope shows marked cross-shore variation, where the nearshore is relatively steep to about 1.6 km offshore where it flattens out; approximately 16 km offshore, the slope decreases to about 0.4 m km^{-1} (WHITE *et al.,* 1985).

Barrier Island Morphology

Microtidal, wave-dominated nearshore processes control barrier island formation and are the dominant geomorphological dynamics in the region. Galveston Island, a well-known example of barrier island morphology, prograded seaward from about 5300 to at least 800 YBP (BERNARD *et al.,* 1962; LANKFORD and REKHEMPER, 1969; RODRIGUEZ *et al.,* 2004). Elongated, relatively narrow barrier islands, composed mainly of abandoned beach ridges separated by low swales parallel to the present shoreline (typical ridge-and-swale topography), characterize both Galveston Island and Bolivar Peninsula.

Texas beaches generally contain fine- to very fine-grained sands. Mean grain size of native beach sand decreases from High Island to Surfside, but all of the beach sand occurs in the very fine to fine grain sizes (that is, from 0.063 to 0.25 mm). Grain size also decreases cross-shore towards submerged areas (MORTON *et al.,* 1995b). The fine sands found on Texas beaches are transported along the coast by longshore currents and carried landward by overwash processes where they are deposited in bordering marshes.

Tidal exchange between marine and estuarine systems occurs mainly at Bolivar Roads, a tidal inlet between Galveston

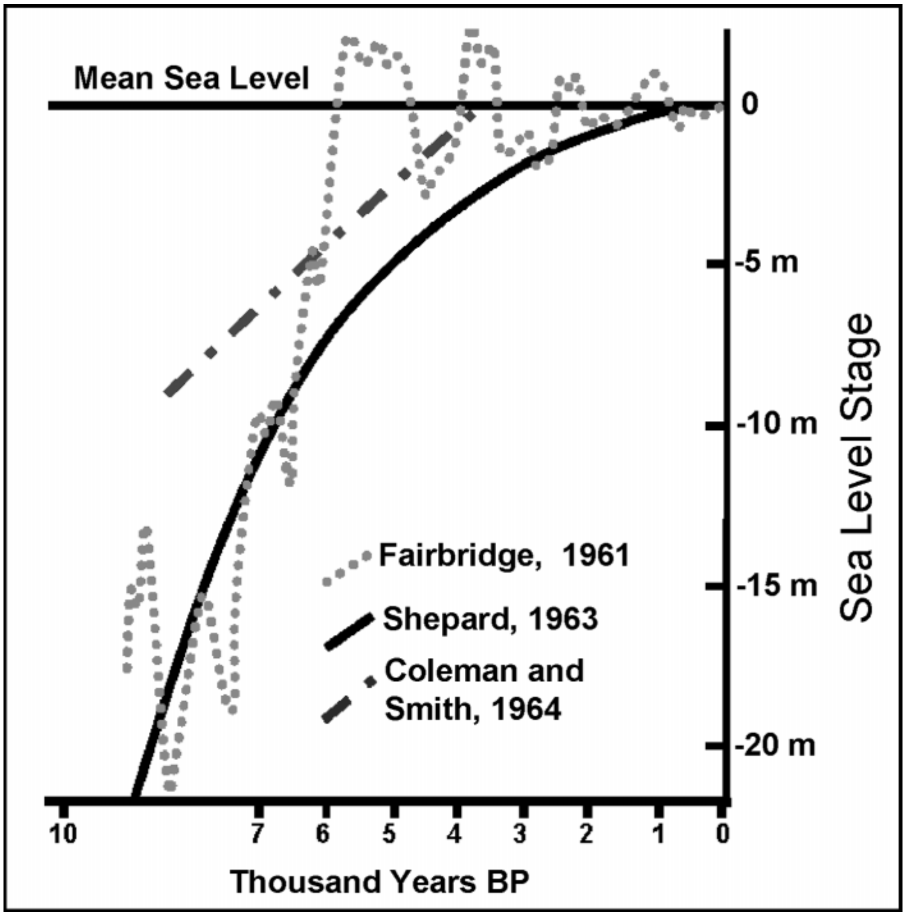

Figure 2. Proposed sea-level curves for the Gulf of Mexico. Stillstands or reversals (drops in sea level) shown in the Fairbridge curve most likely represent periods of shoal formation or valley cutting and alluviation (formation of river terraces) on the inner continental shelf. Valley cutting cycles and alluvial infilling sequences were interrupted by ravinement; valley infilling was often associated with periods of sea-level rise.

Island and Bolivar Peninsula; at San Luis Pass, a tidal inlet between Galveston and Follets islands; and at Rollover Pass, a man-made inlet through Bolivar Peninsula that connects the Gulf of Mexico with East Bay. The Trinity and San Jacinto rivers discharge into estuarine waters within the bay system.

San Luis Pass, a microtidal inlet that connects the Gulf of Mexico with Bastrop, Christmas, and West bays, is located at the southwestern end of West Bay in Galveston and Brazoria counties. The inlet, which separates Galveston Island from Follets and San Luis islands, supports an ebb-tide delta between the 1.8 and 9 m isobaths. San Luis Pass is the only major inlet on the Texas coast that is not stabilized by jetties (ISRAEL *et al.,* 1987; MORTON *et al.,* 1995a).

The Bolivar Roads tidal inlet is 2.8 km wide, making it the largest inlet on the Texas coast. Bolivar Peninsula, a long, narrow barrier beach that extends northeastward from the Bolivar Roads tidal inlet, is about 39 km long by 0.5 to 4.8 km wide; it is bounded by Bolivar Roads inlet to the southwest and Rollover Pass, a minor inlet about 30.5 km to the east. The general elevation of the peninsula is about 1.6 m, except for isolated hills (*e.g.* High Island salt dome).

Coastal Morphodynamics

The east Texas coast is characterized by astronomical tides that range from 0.3 to 0.6 m and relatively low amplitude waves with periods between 4 to 6 s (MORTON and MCGOWEN, 1980). Wave energy in the northwestern Gulf of Mexico is generally low to moderate with most significant wave heights being less than 0.6 m. Shallow waves greater than 1 m occur less than 1% of the time and storm waves are typically less than 1.8 m high (COE, 1971). These parameters fall into the mixed energy wave dominated field of DAVIS and HAYES (1984). Most waves approach the coast from the southeast, resulting in littoral drift to the southwest; however, shoreline orientation and seasonal wind patterns cause littoral drift direction to reverse periodically (MORTON *et al.,* 1995a). The average annual frequency of tropical cyclones crossing the Texas coast is about two storms every three years (HAYES, 1967). These low-latitude storms, moving generally from south to north, rapidly elevate Gulf water levels that in turn cause beach erosion and barrier overwash (MORTON and PAINE, 1985). Mid-latitude frontal systems, generally moving from the northwest to the southeast, are associated with the passage of cold fronts; on average, about 47 of these cold fronts affect the Texas coast every year (HENRY, 1979) by inducing erosion of barrier islands.

On the eastern Texas Gulf coast, the shoreface commonly contains three long and continuous break point bars (MORTON *et al.,* 1995a). The first inner (shoreward) bar forms at the toe of the low tide beach whereas the outer (seaward) bar is located in 3 m water depth. Beach cusps and other low amplitude morphological shoreline features are generally absent on fine-grained Texas beaches (MORTON *et al.,* 1995a). Falling into the dissipative domain of WRIGHT and SHORT (1984), these beaches are characterized by multiple breaker zones, fine-grained sediments, and gentle slopes on a beachface that dissipates wave energy. Profile (cross-shore) and shoreline (alongshore planforms) are relatively subdued. Using an extreme wave height of 2 m and a period of 9.4 s. WILLIAMS *et al.* (1979) estimated the closure depth for the Galveston coastal segment to be about 4.5 m.

The rate of increase in relative sea level (RSL) rise at Galveston Island between 1908 and 1986 was 0.63 cm a^{-1} (PENLAND and RAMSEY, 1990), which included land subsidence as a critical component in calculation of RSL. Historical subsidence rates around the Galveston area, calculated from tide gauge records, range from 0.12 to 0.18 cm a^{-1}. Due to combined effects of $>$ RSL and sediment deficits, the Texas coast is displaced landward by shoreline retreat over the long term (PAINE and MORTON, 1988; SIRINGAN and ANDERSON, 1993). The damming of rivers, stabilization of tidal inlets with jetties, and other disruptions of natural coastal sediment budgets further reduce sediment supply and cause localized high erosional rates along the Texas east coast. According to EDGE and HUTCHINSON (2001), the area off west Galveston Island, between the Galveston Seawall and San Luis Pass, has an average erosion rate of 2.8 to 4.6 m a^{-1} with a projected land loss of about 4.6 km^2 over the next 60 years. Galveston has a long history of coastal erosion, which is documented as early as 1838 (WASHINGTON, 1938). At the time the Galveston Seawall was constructed (1902–1904), there was a wide beach (100–200 m berm width) seaward of the seawall.

PREVIOUS SAND SOURCE ASSESSMENTS ON THE TEXAS SHELF

A number of sand searches have been conducted along the Texas continental shelf since the 1950's (see summary in LOHSE, 1955). These investigations of seafloor deposits focused on obvious sedimentary accumulations such as bars, banks, shoals, and deltas viz. nearshore parallel sand deposits and ebb-tide shoal deposits (WILLIAMS *et al.,* 1979; MORTON *et al.,* 1995b; CPE, 1994; SIRINGAN and ANDERSON, 1994), surface shelf sediments (WHITE *et al.,* 1985, 1987), and Sabine Bank and Heald Bank (PAINE *et al.,* 1988; MORTON and GIBEAUT, 1993, 1998). Exorheic rivers that transited terrestrial coastal plain but what is now submerged shelf area, cut into underlying sediments during eustatic lowstands but were subsequently infilled prior to and during relative sea-level rise (*e.g.* SMYTH *et al.,* 1988; RODRIGUEZ *et al.,* 1998, WELLNER *et al.,* 1986). Regional evaluations of sand resources on the Texas shelf, conducted recently by EDGE (2001) and ANDERSON and WELLNER (2002), provide summarized background information that is related to the main types of investigations and interpretations of sedimentary environments that refer to potential beach-compatible sediments, as presented in the following section.

Surface Sedimentary Cover

Sediment supply to the Texas inner shelf during the Quaternary was governed by fluvial deposition, shoreline and shoreface erosion (ravinement), redistribution of modern shelf and bay lagoon sediments, and re-working of exposed relict sediments (WHITE *et al.,* 1985). Influence of fluvial-deltaic sedimentation was mostly restricted to bay head delta formation. The nearest major river that discharges directly to the coast is the Brazos River. The Sabin/Neches and Trinity/San Jacinto rivers represent minor sources of suspended sediments that pass through Sabine Pass and Bolivar Roads respectively, reaching the inner shelf (WHITE *et al.,* 1985).

The surface sedimentary cover of the Texas shelf was extensively investigated in a comprehensive assessment termed the "Submerged Lands of Texas" project (WHITE *et al.,* 1985, 1987) where approximately 6700 bottom samples were collected at regular intervals across the submerged lands of Texas. A sandy shoreface, about 2.7 km wide, extends from the subaerial beach to 9 m depth off Galveston Island (WHITE *et al.,* 1985, 1987); the shoreface and inner shelf offshore Bolivar Peninsula is, on the other hand, dominated by mud. The largest extent of surficial sand was reported by WHITE *et al.* (1985, 1987) on the northeast end of Galveston and Bolivar islands where relatively clean sand extends at least 5 km seaward and merges with modern ebb-tidal deltas. Anomalous patches of coarser relict sediments occur in isolated inner shelf areas (Figure 3). Where relict deposits are absent, grain size changes tend to be uniform, but becoming progressively finer offshore (MORTON *et al.,* 1995).

The inner shelf is thus an important sink for eroded beach sands, deposited principally as storm beds, which accumulate slowly in water depths of 10 m or more (MORTON *et al.,* 1995b). In isolated areas where the Holocene sediment package is thicker (such as in infilled channels and where there are relict beach deposits), the percent sand is generally greatest whereas in shelf areas with thin sediment cover, mud (unconsolidated silt plus clay) tends to predominate (WHITE *et al.,* 1987).

Nearshore Deposits

Nearshore deposits along the Texas coast occur as shoreface sands and ebb-tidal shoals. Analysis of thirty-four (34) vibracores and interpretation of seismic reflection profiles on the shelf off Galveston County and Brazoria County (Surfside Beach) indicates a sandy shoreface and a muddy inner shelf offshore Galveston Island (WILLIAMS *et al.,* 1979). Clean sands (*i.e.* containing $< 5\%$ silt-plus-clay) are moderately to well sorted and found in shoals adjacent to the Galveston south

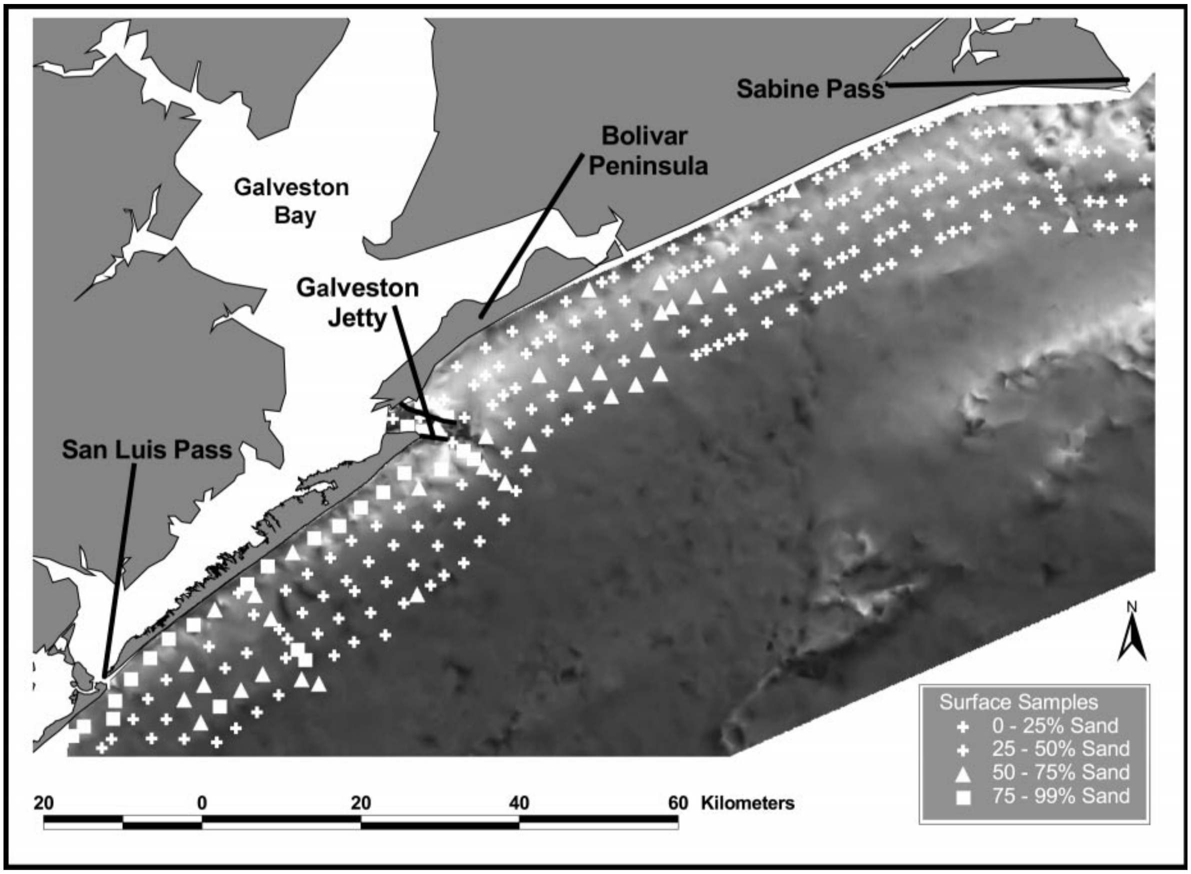

Figure 3. Surface sedimentary cover extracted from legacy provided by White *et al.* (1985, 1987) and imported to a geotechnical GIS. Symbols for the surface samples represent categories of percent sand.

jetty, seaward of San Luis Pass, and in limited areas on the shoreface offshore Bolivar Peninsula and Galveston Island (western part) to about 1 km off Surfside Beach. Potential shoreface and nearshore sand deposits (that may total about 102×10^6 m^3 of beach-compatible sand) occur in five disjunctive areas as deltaic or shoal accumulations (WILLIAMS *et al.,* 1979).

By way of a contra opinion, SIRINGAN and ANDERSON (1994) report that despite the abundance of storms along this coast and the presence of storm channels on the shoreface, there is no indication of large sand volumes lying on the inner shelf as storm deposits. Most sand occurs on the shoreface at less than 10 m depth but there are patchy sand concentrations farther offshore on the inner shelf (MORTON *et al.,* 1995b).

Holocene tidal deltas in the Trinity Incised Valley were evaluated by RODRIGUEZ *et al.* (1998) in an attempt to estimate their potential for exploration. The Bolivar Roads ebb-tidal delta, which formed during the last 3000 years after the rate of post-glacial sea-level rise slowed down, contains two sedimentary facies: a proximal facies located closer to the inlet and a distal facies located seaward. As a general trend, proximal ebb-tidal delta sands are coarser than distal ebb-tidal delta sands because sedimentation is controlled by the velocity of tidal currents that decrease farther away from the tidal inlet (RODRIGUEZ *et al.,* 1998). The proximal facies, composed of laminated to massive, well sorted sands (mean grain size 0.l5 mm), is about 3 m thick. The distal facies is composed of interlaminated sand and mud couplets; the sand layers are 0.5–2.0 m thick and well sorted with a mean grain size of 0.11 mm.

The eastern part of Bolivar Roads contains marine muds that have centimeter-thick shelly sand beds lying directly on top of the Pleistocene Beamount clay (SIRINGAN and ANDERSON (1993). Sediment distribution is sand-dominated southwest of the south jetty and mud-dominated northeast of the north jetty. This asymmetry in grain-size distribution is attributed to differences in wave energy and to different provenance. The lack of ebb-tidal delta deposits on the eastern side of the north jetty may be related to accelerated erosion following jetty construction (RODRIGUEZ *et al.,* 1998).

Amalgamated beach ridge deposits, located southwest of the study area in the modern Brazos River delta (RODRIGUEZ *et al.,* 2000), are massive upper shoreface sand deposits that grade into lower shoreface laminated sands that are interbedded with offshore mud and muddy sand layers. These deltaic deposits may constitute a major source of beach sand for a shoreline sector southwest of San Luis Pass.

Geophysical and geotechnical information from immediate-

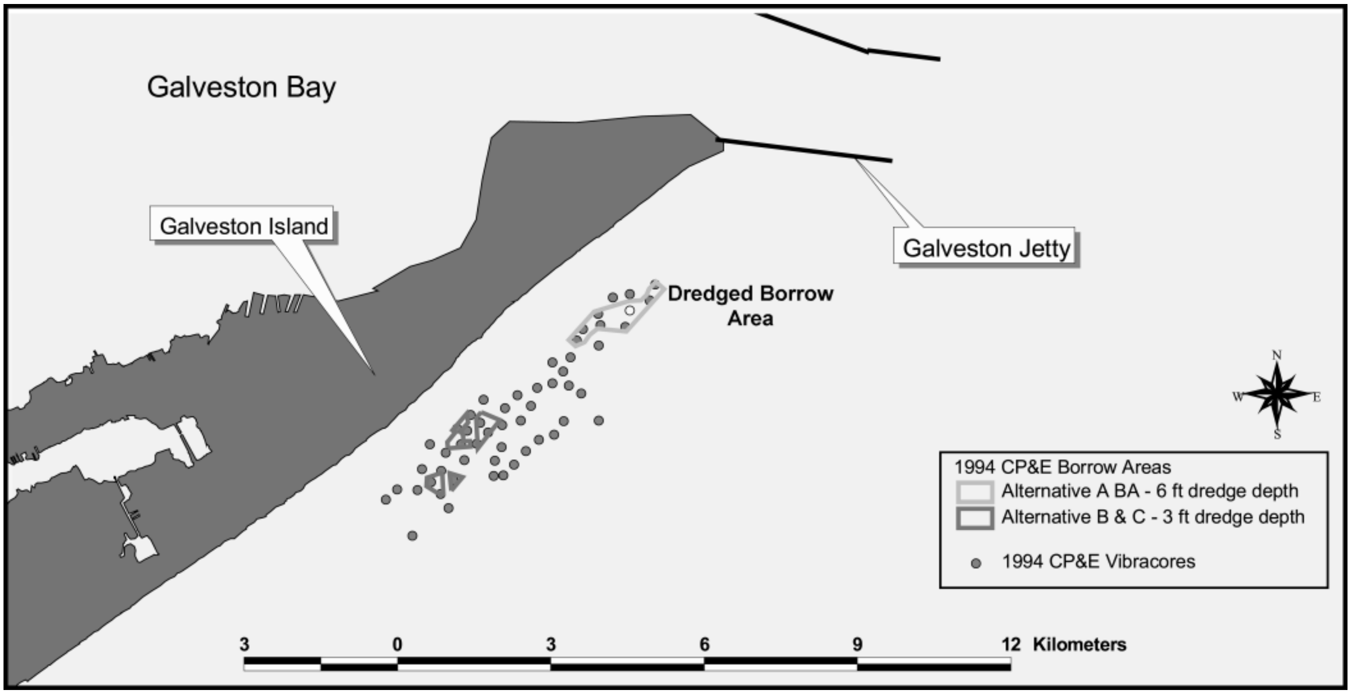

Figure 4. Borrow areas (BA) and vibracore locations in shoreface sands offshore Galveston Island (1994). Alternative A has not obstructions to dredging and is the thickest deposit (up to 4 m); half a million m^3 were previous dredged from this area in 1995. BAs B and C were a single borrow but they had to be separated because of pipelines.

ly offshore Galveston Island were re-visited (CPE, 1994) as part of on-going efforts to locate potential borrow areas for beach nourishment. Exploratory surveys that focused on the inner continental shelf offshore from Galveston Island identified low-relief shoreface sands in three potential borrow areas (Figure 4). Layer thickness varies from 1 to 4 m in these potential borrows with sediments that are slightly finer-grained than native beach sands. Thin interlaminated layers of muddy sand, silty sand, and mud also occur in the same area. About 542,000 m^3 of beach quality sand was dredged (in 1995) from the easternmost borrow area (Alternative A) and placed on the adjacent beach; the two remaining borrow areas (Alternatives B and C) collectively contain approximately 350,000 m^3 of sand (Figure 4).

Sand sources on the continental shelf off western Louisiana (located adjacent to the Texas east coast) were studied in efforts to define potential borrow areas that could be used to rehabilitate Holly Beach, Louisiana (Figure 5) (CPE, 2000). Vibracores obtained offshore from Peveto Beach, for example, indicate the presence of beach-compatible sands but they are buried beneath soft Holocene muds and stiff Pleistocene clays of the Prairie Fm. In the Peveto Channel, the Prairie Fm. covers approximately 3,500,000 m^3 of beach-compatible sediments. Potential borrows, located 7 to 13 km from shore, had an average grain size of 0.15 mm, about 15% silt content, and a muddy overburden averaging about 1.2 m thick. Exploitation of these buried sands, which required removal of about 1 to 2 m of surficial mud (silt plus clay) uncovered around 1.5×10^6 m^3 of clean white sand that was dredged to nourish Holly Beach in 2003 (Figure 5).

Multibeam high-resolution bathymetry, sidescan sonar, and chirp sub-bottom seismic profiler surveys in the near-shore area off Galveston Island (Dellapenna *et al.,* 2002) and in the Galveston Bay system indicate the presence of a thin Holocene sequence, with the Beaumont Fm. marking the boundary between a sandy mid-shoreface and a muddy lower-shoreface on the inner shelf. These kinds of bathymetric and geophysical surveys facilitate the location of buried channels in other Galveston offshore sections, including the area adjacent to San Luis Pass.

Valley Fill Deposits in Paleo-Rivers

Rivers on the Texas shelf were incised during periods of depressed sea level (*e.g.* Last Glacial Maximum, LGM, about 18,000 years ago) in the last Wisconsin glaciation when meandering rivers became entrenched on broad coastal plains. As sea level rose during the Holocene transgression, valleys were drowned, base levels of the streams were raised, and sediments infilled the incised valleys (Nelson and Bray, 1970; Pearson *et al.,* 1986; Thomas and Anderson, 1994). Along the river valleys, periods of slow sea-level rise, or still-stands, were signaled by the presence of tidal delta deposits within the incised river channels (Rodriguez *et al.,* 1998). Three discontinuous tidal delta complexes within the Trinity-Sabine incised river valley were mapped, for example, by Rodriguez *et al.* (1998) (Figure 7).

Figure 5. Holly Beach breakwater field, looking west from Louisiana towards Texas. The subaerial beach in this aerial photograph was constructed using sands buried in an offshore channel located about 3.5 miles offshore. Note the prominent salients forming in the lee of the emergent segmented breakwaters.

The Trinity Valley thalweg, which lies about 55 m below present sea level on the offshore shelf, is cut 30 to 38 m below the sea floor (THOMAS and ANDERSON, 1989). Although the valley was backfilled during the Holocene transgression, only about one-third of the valley fill seaward of Bolivar Roads contains fluvial sands (THOMAS and ANDERSON, 1989). The Sabine River valley thalweg, which also cuts into the Beaumont Fm., is located approximately 36 m below the sea surface. The river valley deposits generally exhibit a fining upwards sequence that is typical of a marine transgression and drowned incised valleys where coarse fluvial sands are preserved in the bottom of a transgressive sequence and are successively overlain by coastal sediments and fine-grained estuarine and lagoonal silts and muds (paralic facies). This transgressive sequence is overlain by up to 20-m thick deposits of modern marine muds. Other sizeable channels that incise the Pleistocene surface, are located west of High Island, immediately east and offshore of Crystal Beach on Bolivar Peninsula, and west of Freeport Harbor (the ancestral Brazos channel).

Valley fill deposits on the Texas shelf may contain significant sand resources for beach restoration. SMYTH *et al.,* (1988), for example, used detailed seismic data (mini-sparker and uniboom lines) to study relationships between lithofacies in the infilled river valley beneath Galveston Bay. Good correlations between sedimentary facies and seismic reflection signals were verified on the basis of detailed descriptions of reflectors.

Vibracores obtained from an archaeological study site along the relict Sabine River valley (PEARSON *et al.,* 1986), show that mud thickness is greater than 12 m in the center of the incised valley and that sands occurring on channel margins are closer to the surface with a thinner overburden (often < 9 m). Sediments bordering the channel (*e.g.* the Deweyville Terraces) are composed of gray silty to sandy clay or gray sand, and are cut by sectionalized paleo-river meanders and/or paleo-oxbow lakes (PEARSON *et al.,* 1986). The thick mud overburden of the Trinity-Sabine River Valley is an obstacle to economical exploration of the majority of these deposits (PAINE *et al.,* 1988). In order for these deposits to be economically viable, suitable sand and gravel deposits must occur within the inner continental shelf portion of the valley fills where shallow water combined with thinner overburden and proximity to the shore contributes to lower exploration costs.

Although backsteepened paleo ebb-tidal deltas are also present along the Trinity-Sabine Incised River Valley complex (Figure 6), they resemble mostly distal delta facies with very fine sands and muds (RODRIGUEZ *et al.,* 1998). The absence of clean sands (*i.e.* low levels of organic matter and silt-plus-clay contents less than 5%) from proximal facies along the valley fill is attributed to erosion during the continuous and rapid transgression from 18,000 to 4000 YBP (RODRIGUEZ *et al.,* 1998) when shoreface erosion and tidal ravinement removed deposits that previously occurred in upper portions of the valley fill.

Mid Shelf Deposits—Sabine and Heald Banks

Sabine and Heald banks, located 32 to 50 km offshore eastern Texas and western Louisiana (Figure 7), represent paleo-shoreline or paleo nearshore parallel sand deposits drowned

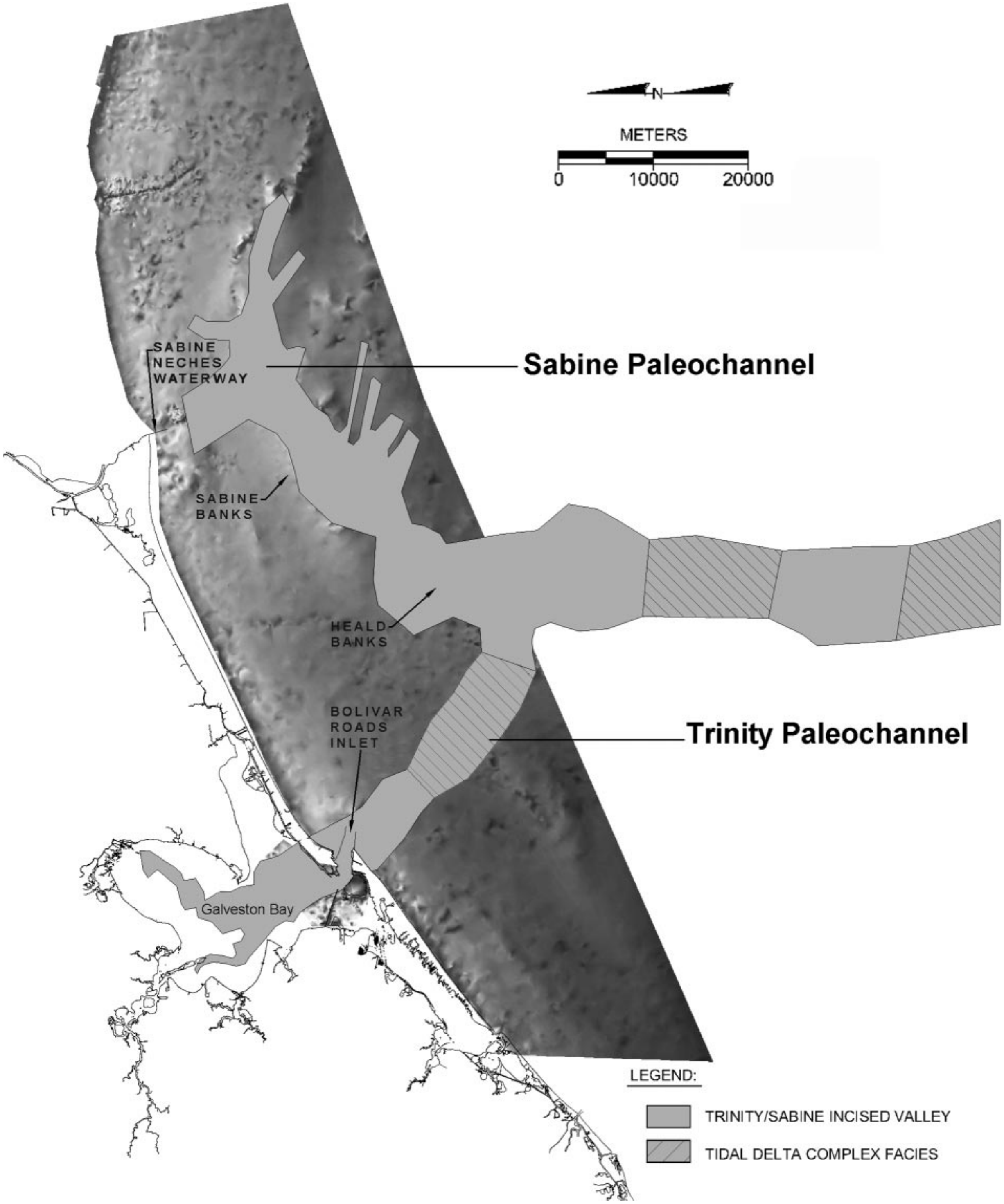

Figure 6. Approximate location of the Trinity and Sabine incised river valley and paleo tidal/delta complexes.

by the last Holocene transgression and reworked superficially by modern marine processes (Morton and Gibeaut, 1993). These banks contain potential sand sources that are suitable for restoration of Texas beaches (Paine *et al.,* 1988). Reassessment of potential sand sources on the banks by Morton and Gibeaut (1993), who employed seismic and vibracore surveys to estimate sand volumes, found $> 5 \times 10^9$ m^3 of beach-compatible sands.

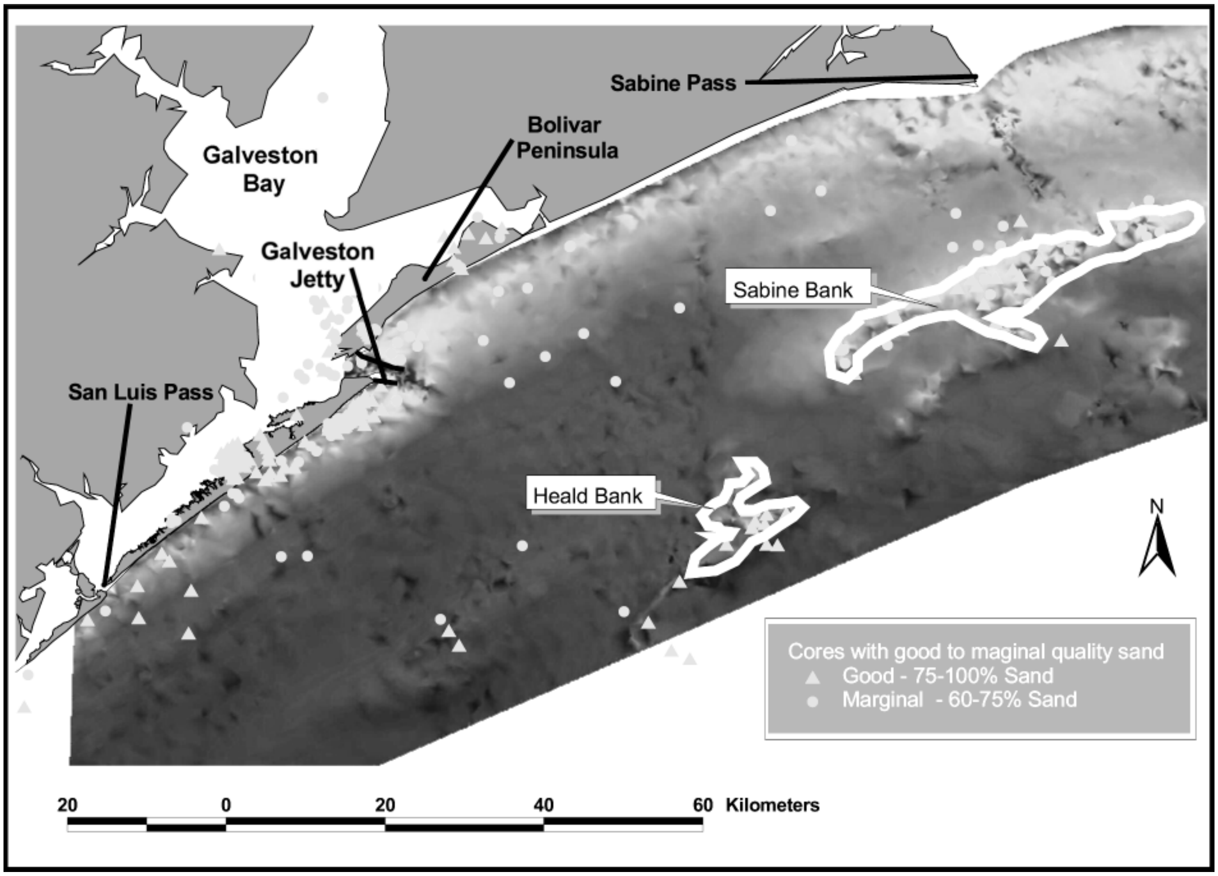

Figure 7. GIS query view illustrating the location of vibracores that contained beach quality sand. Sabine Bank and Heald Bank, respectively lying off Galveston Bay and Sabine Pass, both contain 75–100% clean sands.

Bank thickness is on the order of 3 m, based on geophysical and geotechnical surveys, and mostly comprised by fine to very fine sands that are similar to native Texas beach sediments. Six lithofacies were identified by Morton and Gibeaut (1993) as: (1) fine sand; (2) shelly sand and gravel, (3) slightly muddy sand, (4) muddy sand, (5) sandy mud and (6) organic clay. The first three sandy facies contain less than 15% mud and have mean grain sizes ranging from 0.13 to 0.59 mm. A follow-up study (Morton and Gibeaut, 1998) described the upper 2 m of sediment on the Sabine Bank as containing 91% sand; high shell concentrations occur on crests and seaward flanks of the banks. The upper 2 m of sediments on Heald Bank contain about 95% sand. Revised volume estimates (Morton and Gibeaut, 1998) indicate more than 1.79×10^9 m^3 of beach-compatible sediments. Compared to Sabine Bank, Heald Bank is located in deeper water, but is favored by less shell material and closer proximity to Galveston Island.

Based on vibracore and seismic data, the Sabine Banks were estimated to contain about 22×10^6 m^3 of beach-quality sand (CPE, 1994). The Sabine Bank borrow areas, located 11 to 37 km from shore, contain olive gray sand (average grain size of 0.24 mm) with varying amounts of shell hash and less than 5% silt. Paine *et al.,* (1988) emphasized potential use of the bank for nourishment of Texas beaches based on its predominantly sandy nature and estimated that more than 5×10^9 m^3 of beach compatible sands are available in the banks.

PREVIOUS REGIONAL SAND RESOURCE ASSESSMENTS

Reviewing salient advances in research related to major sedimentary deposits along the eastern Texas Gulf Coast, Edge and Hutchinson (2001) summarized a wide range of data in terms of sub-summaries for: (1) sediments in the incised valleys of the Trinity and Sabine rivers (Anderson *et al.,* 1990, 1994), (2) nearshore deposits and offshore shoals (Williams *et al.,* 1979), and (3) sand deposits of the Sabine and Heald banks (Morton and Gibeaut, 1998, 1995). Dredge spoil from Galveston Harbor, Sabine and Neches Waterway was investigated as alternative sand sources, but these marginal sands could only be used as storm protection materials along eroded shores that were not developed of commercial or urban use.

Sand resources along the Texas shelf include short-term bayside borrow areas and long-term borrows on mid to outer sections of the eastern Texas shelf (Anderson and Wellner, 2002). Short-term potential borrow areas also occur at the entrance of Galveston Bay, in the Bolivar Roads channel, and adjacent to Pelican Island (bayside area west of the modern Bolivar Roads flood-tidal delta). The Pelican Island deposit is "highly variable" because the tidal deposits contain alternating layers of intercalated sand, mud, and shell hash. The volume of the quality sand is about 860,000 m^3 whereas marginal and high quality sands combined may only amount to 6,800 m^3 (ANDERSON and WELLNER, 2002). A second potential borrow site occurs in the flood-tidal delta of the ancestral Bolivar Roads; associated channel deposits occur farther upstream in the Bolivar Roads channel. This clean body of sand is 8 m thick but of limited areal extent. Valley infills, such as occur in the incised Sabine and Trinity paleovalleys, have potential use for beach restoration (ANDERSON and WELLNER, 2002).

MATERIALS AND METHODS

This sand search investigation is based on a geomorphological analysis of geotechnical and geophysical data that were used in the construction of a geographical information system (MIS) database. These separate but interrelated disciplines and procedures were combined in a MIS analysis ring in an effort to locate seafloor sand deposits that can be targeted in subsequent phases of sand search investigations to determine their potential for beach nourishment. An auxiliary purpose of this effort is to relate spatio-temporal distributions of these deposits with local geology, geomorphology and late Quaternary land- and seascape evolution for the purpose of better understanding the various sediment distribution patterns.

The analysis of historical data was incorporated into a comprehensive MIS database for the eastern Texas offshore and bay areas. Spatial coordinates were compiled for 833 cores (vibracores, core borings, platform borings, and other geotechnical perforations) of the inner-middle and outer shelves. These data were then converted to a single coordinate system and geo-referenced to a single datum (State Plane, South Central NAD83) and input into the MIS database. The data was collected from five main sources: surface sample information was obtained from the Submerged Lands of Texas Projects (6700 samples), Rice University Website and requests, BEG (Bureau of Economic Geology) website and requests, Coastal Planning and Engineering, and Rice University Sand Search Surveys, WILLIAMS *et al.* (1979), and from the U.S. Army Corps of Engineers (Galveston District). Use of a data aggregation engine facilitated population queries from the core logs. Formulation of object-oriented queries that focused on indicators or proxies for sand bodies was used to advantage. By generating query results in this way, it was found that of the 833 cores entered into the MIS, 462 core logs contained sufficient textural and sedimentological data for use in evaluation of sand resources. The remaining 371 cores, which had insufficient data or contained errors that could not be resolved or restored, were discarded from the dataset. Sedimentological and textural data from the 462 usable cores were divided into subclasses for posterior data querying and analysis. The main classification parameters were the percentage of fine and very fine sand, thickness of sandy layers, and the thickness of muddy overburden (surficial sedimentary beds containing admixtures of silts, clays, and organic material). Sedimentary layers that contained 60% to 75% sand (generally fine to very fine sand) were classified as "marginal sands"; layers containing 75% to 100% sand were classified as "good sands". Sediments with high silt and clay contents (*i.e.* less than 60% sand) were arbitrarily termed "mud" for purposes of this investigation. Thickness of muddy overburden is a critical parameter for sand prospecting because it normally must be removed (*e.g.* sidecast) to access underlying sands. Layer thicknesses were measured and entered in the MIS database.

Bathymetric data from NOAA-NOS (1996) was represented by color ramps in a three dimensional (3D) topological structure using the Triangular Irregular Network Model (TIN) procedure. The resulting view of seabed morphology, shown here in grayscale representation, permits rapid identification of shelf surface geomorphology, especially positive bathymetric features such as nearshore and offshore sand ridges, banks, and shoals (Figure 7).

ANALYSIS AND DISPLAY OF HISTORICAL DATA USING THE MIS DATABASE

Vibracore data, especially those that assisted with the location of beach-quality sands (Figure 7), were integrated into the development of geologic models of coastal frameworks. Seabed geomorphology, visualized from the 3D model of bathymetric data, was interpreted in terms of relative local relief to identify boundaries of banks and shoals, in particular Sabine Bank, Heald Bank and shoal areas west of Galveston Bay entrance and east of San Luis Pass. An additional positive linear feature was noted about 12 km from the shoreline and shoreward of Sabine Bank.

The spatial distribution of cores containing good or marginal quality sands is summarized in Figure 7, as shown superimposed on the bathymetric model. Toggling the overview bathymetry permits rapid identification of core data clusters as well as perception of dispersed patterns for good and marginal quality sands. Layer-imposition on top of the bathymetry has the additional advantage of immediately showing spatial core-log data in relation to seafloor geomorphological features. Greater concentration of good quality sands, for example, are seen to occur on Sabine and Heald banks, west of the Galveston Harbor entrance, in the vicinity of a prior borrow area (CPE, 1994), and scattered on the shoreface sand body off Galveston Island and near San Luis Pass. Most cores containing marginal quality sands occur off Bolivar Peninsula (1.6 to 22 km offshore), in the Bolivar Roads channel, and inside the Galveston Bay system.

Cores with good to marginal sands were queried in the MIS database using deposit and mud overburden isopachs as additional selection criteria. Results of the query process are summarized in Figure 8 that shows cores where there is less than 1.5 m of mud overburden and more than 1.2 m of good and marginal sand and cores where there is a minimum of 1.2 m of quality sand (good and marginal) and no mud overburden. Cores meeting these selection criteria were found on Sabine Bank and Heald Bank, west of Galveston Harbor en-

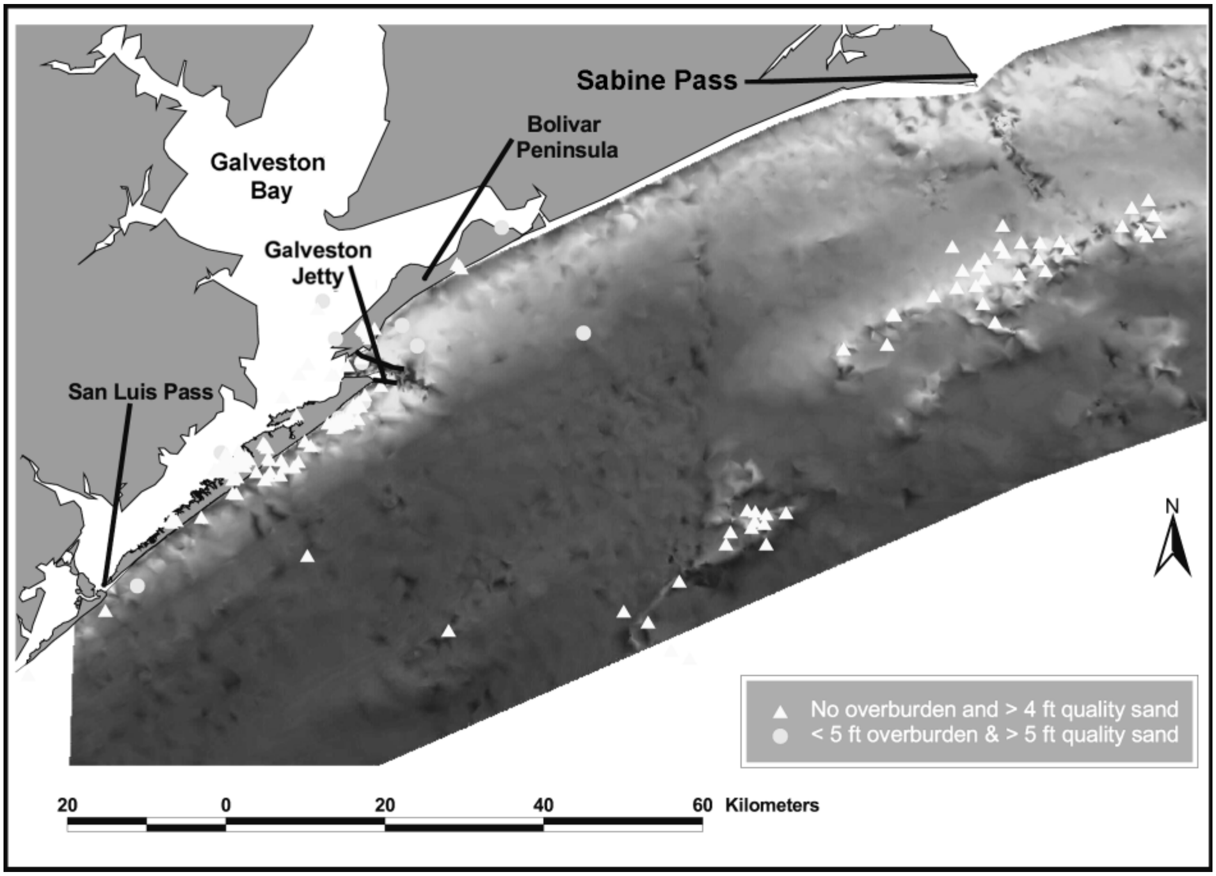

Figure 8. GIS query view showing the location of vibracores that contained beach quality sand. The circle shows vibracore locations with less than 5 ft (1.5 m) 'mud' (silt plus clay) overburden and more than 5 ft (1.5 m) of sandy sediments. Core locations with no muddy overburden and more than 4 ft (1.2 m) of sand are identified by the triangle symbol.

trance near the Bolivar Roads Inlet to central Galveston Island, and adjacent to San Luis Pass (Figure 8). Cores located east of the Galveston Harbor entrance and in the nearshore area off Bolivar Peninsula contain quality sands covered by muddy overburden. This observation is attributed to deposition of modern muds (CURRAY, 1960; WILLIAMS *et al.,* 1979; PEARSON *et al.,* 1986) and to the lack of cores in some key locations.

Historical cores lacking good quality sand or those with insufficient sedimentological or textural data are scattered across the study area. The distribution of fine-grained sediment facies verifies the sand starved nature of the study area and modern mud-dominated sedimentation. Unfortunately, some cores that lack textural information are located in key locations (*e.g.* eastern area of San Luis Pass, parts of the Trinity River Valley, and near the shore-parallel shoal that is landward of the Sabine Banks) (Figure 9).

West of Bolivar Roads Ebb-tidal Shoal and Central Galveston Island

A continuous nearshore sandy area off Galveston Island (Figure 9, Area 1) is narrower and thinner in the central portion of Galveston Island, but it widens towards Bolivar Roads Inlet and east of San Luis Pass (SIRINGAN and ANDERSON, 1994; WHITE *et al.,* 1985). This sandy zone contains subdued low-relief ridges associated with ebb-shoal and storm deposits (MORTON *et al.,* 1995a). The literature and core data analyzed here (Figure 9) suggests that these deposits extend towards Bolivar Roads Inlet (and offshore of the 1995 Galveston borrow areas) where sand deposits gradually become finer and thinner. Based on converging lines of evidence that point to the presence of beach compatible sand deposits (*e.g.* WILLIAMS *et al.,* 1979; RODRIGUEZ *et al.,* 1998; CPE 1994; Figure 9), these seafloor features seem to represent potential beach-compatible sediment sources. Further geotechnical and geophysical surveys (employing reconnaissance hydrographic and jet probing surveys) of the nearshore sand body west of Bolivar Roads (Figure 9, Area 1) and on the nearshore sandy body (Figure 9, Area 4) are required to spatially define these deposits.

Bathymetric Features Offshore Galveston Island

Bathymetric features offshore central Galveston Island suggest the possible occurrence of paleo-channels (Figure 9,

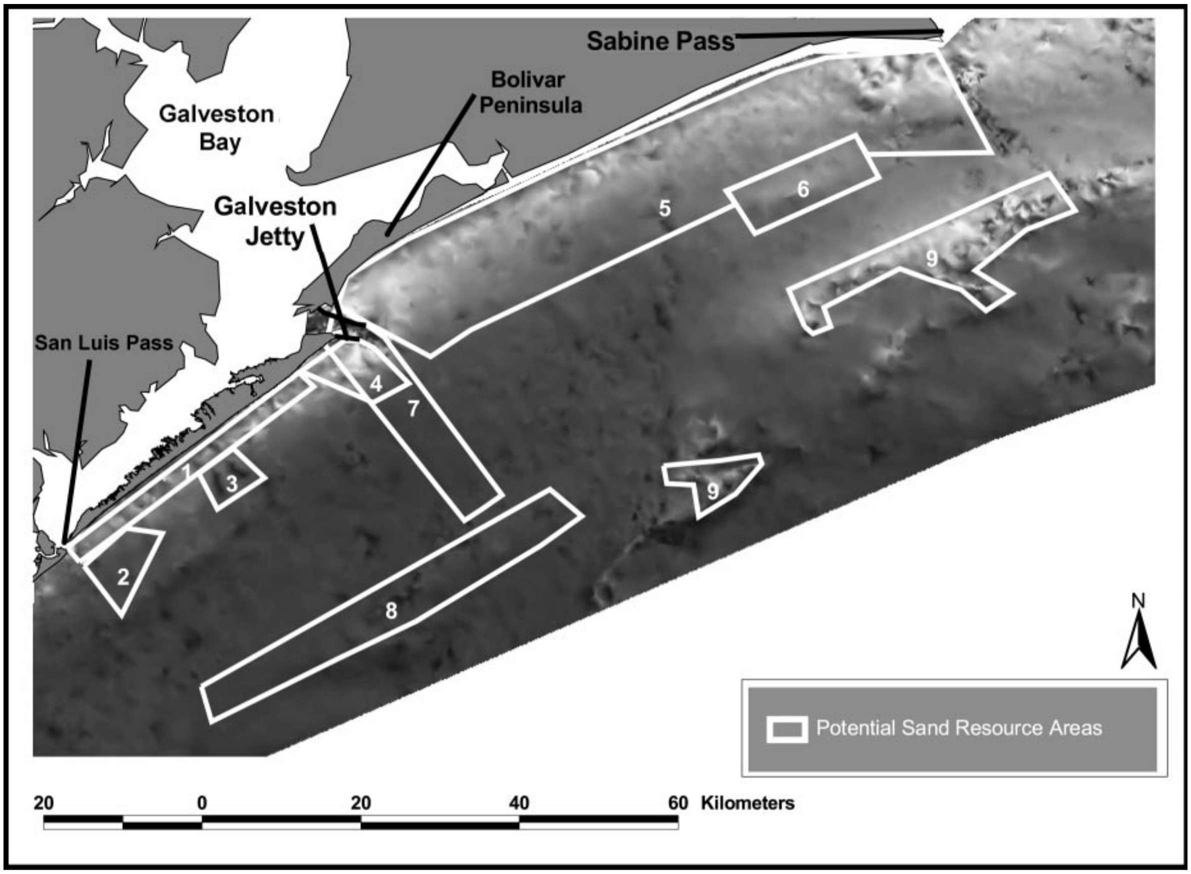

Figure 9. Potential sand resource areas that require further study. Numbers inside the boxes are linked to descriptions of the deposits in Table 1 viz. nearshore sand body, Galveston Island (1), San Luis Pass ebb-tidal delta and paleo channels (2) ridges and channels, west end of Galveston seawall (3), west of Bolivar Roads ebb-tidal inlet (4), east of Bolivar Roads tidal inlet and shoreface sands (5), low relief ridges east of High Island (6), Trinity and Sabine incised river valleys (7), Galveston Bank (8) and Sabine and Heald banks (9).

Area 3). Vibracores with quality sands in the vicinity of these paleo-channels (Figure 7) further indicate that these features might constitute potential sand deposits, but detailed hydrographic, geophyisical (seismic) and geotechnical investigations (jet probes and vibracoring) are required.

San Luis Pass Ebb-Tidal Delta and San Luis Paleo-Channels

After surveying the nearshore area from Sabine Pass to Freeport, WILLIAMS *et al.* (1979) reported that: "San Luis Pass contains the best quality sand as well as the largest estimated sand volume in the area". A large and continuous area of sand was mapped between 3.5 and 10 m isobaths. Although a limited number of vibracores was used by WILLIAMS *et al.,* (1979) to delimit the borrow area, their extensive seismic surveys indicate considerable quantities of beach-compatible sands, including an eastward extension of this shoal. Recent work identifies a paleo-river channel in the area offshore San Luis Pass ebb-tide shoal (*e.g.* DELLAPENA *et al.,* 2002), which may be infilled with beach quality sands. The San Luis ebb-shoal area (Figure 9, Areas 1 and 2) is a promising site for the location of beach-compatible sand deposits but additional reconnaissance bathymetry, jet probing and vibracoring is required to accurately survey and map these deposits.

Low Relief Ridges—High Island to Sabine Pass

A prominent bathymetric high similar to a ridge deposit (Figure 9, Area 6), was identified shoreward of Sabine Banks about 6.8 km offshore Bolivar Peninsula in our MIS analysis. This bathymetric high coincides with the occurrence of surface sands on the seaward boundary of WHITE *et al.,* (1985) study area (Figure 3) and is identified as a promising deposit for the Bolivar Peninsula region.

Infilled Paleo-Channels—Galveston Entrance to Sabine Pass

Paleo-channel deposits in this region surround High Island and are identified as a shore transverse borrow area with fine sands infilling a channel located 10 km offshore (WILLIAMS *et al.,* 1979). Seismic records show numerous other infilled channels in this area, but they are either too small to contain significant sand repositories or they were filled with mud.

Non-surveyed channels in this area may contain sand sources, but they need to be identified in reconnaissance seismic surveys (Figure 9, Area 5) and cored to ascertain volumes of beach-compatible sediments.

Trinity and Sabine Incised River Valley

Although there are limited numbers of cores in the incised Trinity-Sabine River valley system, there may be fluvial and marine sediments within the valley fill sequence (RODRIGUEZ *et al.,* 1998; RICE, 2002). These deposits are often covered by a thick mud layer, as recorded in descriptions of valley fill stratigraphy that indicates sand with thinning mud overburden closer to shore, in channel margin deposits (PEARSON *et al,* 1986) (mud thickness increases towards the thalweg), and in paleo-deltaic facies (RODRIGUEZ *et al.,* 1998) associated with stillstands in MSL. Detailed geophysical and geotechnical surveys are needed to delimit economically feasible sand bodies (Figure 9, Area 7).

Low Relief Ridges Offshore from Galveston Island

A prominent bathymetric high, indicating a low-relief linear sand body (Figure 14, Area 8) occurs about 27 km offshore of Galveston Island where there is good quality sand (Rice University, 2002) (Figure 9). This large sand deposit represents an alternative to large-scale and long-term projects where sufficient sedimentary volumes are not located closer to shore.

Sabine and Heald Banks

The potential of Sabine and Heald banks for containing exploitable sand deposits was widely discussed in the last decade (*e.g.* MORTON *et al.,* 1988; MORTON and GIBEAUT (1993–1998); ANDERSON and WELLNER, 2002) and our MIS study confirms that abundant good quality sand exists on the banks (Figure 9). Geotechnical data indicate that sand deposits are distributed in elongated lenses and that the banks are not composed exclusively of "clean" beach sands because several areas contain large quantities of shell hash and interlaminated silt-clay beds. Because of its long distance from the shore (30 to 45 km), obstructions to dredging (oil platforms, pipelines and navigation aids) and ecological considerations, exploration of these banks was contested (ANDERSON and WELNER, 2002). However, on the Louisiana side of the Sabine Banks, only a few kilometers to the east, there are sand sources that can be permitted and economically explored for beach restoration purposes as demonstrated by CPE (2000).

CHARACTERIZATION OF POTENTIAL BEACH COMPATIBLE DEPOSITS

The comprehensive review and analysis of geotechnical, geophysical, and geospatial data provides new insight into sand search methodologies for offshore sand resources. Using the Texas coast as an example, benefits of the review and analysis of historical data become manifest. When a large amount of data is processed, analyzed, spatially converted and entered into a MIS database (see Figure 9, Table 1), it constitutes a key source of information that can be used for future sand prospecting on the inner continental shelf of Texas. A salient observation resulting from this MIS analysis is that the Texas shore is "sand starved" and that the offshore seafloor is "mud dominated". Sand deposits are seen to occur in modern and relict shore-parallel sand bodies, modern ebb-tidal shoals and paleo-shoals, paleo-deltaic systems (shelf edge), and infilled river channels. Subaerial mud or exposures of the Beaumont clays are dispersed among these sand deposits. The compacted Beaumont clay is the basal sedimentary package over much of the study area, and in many places there is no sand accumulation overlying the Beaumont. Incised transverse erosion surfaces on the Beaumont clay (*e.g.* paleo–channels) are, however, capable of retaining sand deposits. Beaumont clays can be identified in seismic records as can coarse-grained valley fills, which indicate potentially usable deposits in reconnaissance surveys where geotechnical data is not available. In the MIS, these observations are synthesized from previous investigations that identified potential sand deposits and targets for future sand search surveys.

Based on the elucidation of geological and geomorphological frameworks using MIS tools, several depositional areas were identified for potential for sand prospecting. Each area occurs in a distinct geomorphological setting and is suitable for differentiated investigative methods (Figure 9). Target areas located on the innershelf are shown in Figure 9 and summarized in Table 1. These areas require additional investigation in order to accurately define the presence of long-term sand sources for beach nourishment along the eastern Texas shore.

CONCLUSIONS

Several potential sand deposits on the Texas continental shelf were identified as a result of this investigation. Nearshore deposits (*e.g.* San Luis and Galveston ebb-tidal shoals, parabathic ridges, and nearshore channel fill deposits) represent the most cost effective options to restore eroded beaches. Deposits described on the inner to middle shelf (*e.g.* Sabine Bank and Heald Bank, ridges offshore Galveston, Trinity and Sabine Valley System) contain large quantities of suitable sands, but they are not as cost-effective as nearshore deposits.

The innovative methodology applied here is an efficient tool for preliminary assessment of sand resources. Historical data displayed and analyzed in a MIS framework provides unique opportunities to summarize knowledge of geology and shelf geomorphology with existing geotechnical and geophysical data that facilitate identification of sand resources. This kind of understanding abbreviates the need to conduct random geophysical and geotechnical surveys over large expanses of the seabed and is more efficient and economical because only potential deposits are targeted.

Continued development of sand search methodologies along Gulf coasts (*i.e.* Florida, Louisiana and Texas) will contribute to the development of a generic Texas Coast Sand Search Model (TSSM). The model will be deployed in efforts that show beach-quality sands can be anticipated in distinct morphodynamic settings. The conceptualization of contem-

Table 1. *Summary of potential beach compatible deposits on the eastern Texas shelf indicating main previous literature sources for each deposit.*

Source Area	Site #(2)	Distance from Shoreline (km)	Water Depth (m)	Estimated Volume (m^3)	Sand Percentage	Mud Overburden
Nearshore Sand Body, Galveston Island (1, 2, 3, 5)	1	0.8 to 4.8	1.5–9	Non-estimated	Varying	Less than 5 feet
San Luis Pass Tidal delta and paleo channels (1, 5, 6)	2	0.6 to 3	3.5–9	17,500,000	80–100%	None to less than ??
Ridges and channels West end of Seawall (6)	3	3 to 6.5	9–12	Non-estimated	Not known	Not known
West of Bolivar Road Tidal Inlet (1, 2, 3)	4	0.5 to 5	4.5–9	15,300,000 (1)	60–100%	None to less than ??
East of Bolivar Roads Tidal Inlet (1, 2)	5	2.5 to 5	4.5–9	7,000,000 (1)	40–80%	Less than 4 feet
Low Relief Ridges East of High Island (1, 5, 6)	6	13 to 16	4.5–9	Non-estimated	60–100% (surface)	Not Present
Trinity and Sabine Incised River Valleys (2)	7	Varying	1.5–15	Non-estimated	20–100%	More than 10 feet
'Galveston Bank' (2, 6)	8	27 to 35	16–19	Non-estimated	75–100%	None
Sabine and Heald Banks (2, 4, 6)	9	32 to 75	4.5–12	840,000,000 (4)	70–100%	None

(1) Williams, S.J.; Prins, D.A, and Meisburger, E.P., 1979. *Sediment Distribution, Sand Resources, and Geologic Character off Galveston County, Texas.* Fort Belvoir, Virginia: U.S. Army Corps of Engineers, Report No. 79-4. **(2)** Rice University, Gulf of Mexico Research Group, 2002. http://gulf.rice.edu/ various links. **(3)** Coastal Planning & Engineering, Inc., 1994. *Galveston Island Beach Nourishment Project Coring and Sediment Analysis.* Boca Raton, Florida: CPE. Rice University, Coastal Marine Geology Research Group. **(4)** Morton, R.A. and Gibeaut, J.C., 1998. *Physical and Environmental Assessment of Sand Resources: Texas Continental Shelf, Second Phase, 1994–1995,* Austin, Texas: Bureau of Economic Geology. **(5)** Dellapenna, T.M., 2002. *Personal Communication*—Previous results of research conducted under GLO-CMP cycle 6 research grant. **(6)** This paper.

porary and relict environmental frameworks and boundary conditions, provide an operational basis for conducting sand searches using geoindicators to suggest appropriate oceanographic and geologic tools that elucidate understanding of transgressive low energy shelves.

The model objective is to provide a rational basis for exploration of the seabed to locate potential borrows that must be proved by geophysical and geotechnical surveys that are specific to distinct geological settings. The logistical sequencing of differentiated surveys thereby increases the cost-effectives of sand searches. Because the TSSM is open-ended and based on morphologic principles, it has the capacity to incorporate additional coastal morphodynamic frameworks. Such a model will facilitate the comprehension of the sets of circumstances under which beach-quality sands are likely to be found. That is, the geomorphologic conditions that represent geoindicators of sand bodies with desirable characteristics. Because beach-quality sands occur on the inner shelf in highly organized and restricted distribution patterns, these patterns require comprehension before going to the field.

ACKNOWLEDGEMENTS

The authors would like to thank Elizabeth Henrie, Melany Larenas, Johnny "Osku" Backstrom, Angela Belden, Matthew Andrews, Anthony Larenas, and all the other investigators from Coastal Planning and Engineering (Boca Raton, Florida) that contributed graphics and assisted with compilation of MIS databases and other information necessary in the development of this work. To Raquel Rosa we have a special debt of gratitude becasue she painstakingly made many format conversions for the figures, moving from ArcView to high quality TIFF files. Of particular note are her effors to improve quality of the graphics by digitizing, font replacement, etc. Robert Morton (U.S. Geological Survey, Center for Coastal and Watershed Studies, St. Petersburg, Florida) reviewed the manuscript and provided useful comments and insight for an area of the Texas coast that he is most familiar with. We acknowledge and appreciate Bob's comments for improvement of this paper.

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