Offshore Sand Sources for Beach Replenishment: Potential Borrows on the Continental Shelf of the Eastern Gulf of Mexico

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Erosion of sandy beaches is a worldwide problem that elicits innovative geoengineering techniques to reduce adverse impacts of shoreline retreat. Beach replenishment has emerged as the "soft" shore-stabilization technique of choice for mitigating beach erosion. This method of shore protection involves the addition of sand to the littoral sediment budget for sacrificial purposes. Because inland sand sources are often uneconomical or impractical to use, and known nearshore sources are limited, finding adequate quantities of suitable sand on the inner continental shelf is often vital to beach replenishment projects. The technical studies of survey and materials analysis that identify and delineate usable sand sources are sometimes almost as expensive as small-project dredging, pumping, and placing the sand on the beach as fill. Inadequate quantity or substandard quality of shelf sand, as well as often-prohibitive overhead expenses, thus compel shoreline managers to seek suitable sand sources offshore.

In the study area off the central-west coast of Florida, offshore potential borrow areas (PBAs) were identified on the basis of studies conducted in reconnoitory and detailed phases. Sophisticated state-of-the-art equipment used in this investigation provided more detailed subbottom mapping information than is normally obtained with conventional seismic equipment. An example of sand exploration studies was incorporated in a 215-km^2 survey of offshore areas by conducting bathymetric surveys and subbottom seismic profiling, collecting jet probes, grab samples, and vibrocores, and analyzing sediment grading in subsamples from vibrocores. These combined analyses indicated that at least 8.8×10^6 m^3 of sand is available in potential borrow areas from 7.0 to 12 km offshore in water depths of 8.0 to 11.5 m. In the PBAs, mean grain size of sand falls into the range 0.13–0.53 mm, sorting averages 0.65–1.31ϕ, and the overall silt content varies from 3.9–8.5%. High silt contents (13–19%) mapped in some areas make these sedimentary deposits unsuitable as fill for artificial beach renourishment.

Keywords bathymetric survey, beach erosion, chirp sonar, geophysical exploration, geotechnical analysis, seismic survey, subsea borrow area, vibrocoring

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At the land–sea interface lies a vital and important natural buffer zone which is largely constituted by beaches and dunes. These constructional coastal landforms, which are comprised of mobile unconsolidated sands, protect many backshores from high-energy events (erosion, sedimentation, flooding) while at the same time providing much-needed recreational areas. Coastal erosion, often an incipient and pervasive process, is caused by many interrelated natural factors, the most prominent of which is relative sea-level rise (Dolan et al., 1983). Engineering works such as navigational entrances that are stabilized by jetties are also believed to cause shore erosion; Dean (1990), for example, estimates that perhaps 80–85% of the beach erosion problem in Florida is induced by inlets stabilized with jetties. Bruun (1995) recently confirmed the deduction after an exhaustive study of eroding beaches worldwide. Shoreline retreat, a common result of beach erosion, now locally threatens some human activities as well as buildings, roads, and other infrastructure. Beaches, dunes, marshes, and other coastal habitats are degraded or drowned because many natural barriers are adversely affected by storm waves and surge. Erosion is a problem along all U.S. Gulf coast shores but is especially problematic in subsiding areas such as the Mississippi River delta in south-central Louisiana, where rates of relative sea-level rise and coastal land loss (due to drowning) are higher than in other regions of the United States (Boesch et al., 1994) and, possibly, the world.

The artificial placement (nourishment or replenishment) of sand on the shore is one of several shore-protection techniques available to reduce erosion effects. Beach nourishment has global appeal as a common and effective measure to safeguard coastlines and hinterlands. Several prominent projects are reported, for example, from European countries (e.g., Germany, The Netherlands, Denmark, the United Kingdom) (Verhagen, 1990; Dette et al., 1994), and Australia (Bird, 1990), though beach nourishment also finds application in Japan (Kioke, 1990), New Zealand (Healy et al., 1991), South Africa (Zwamborn et al., 1970), and Brazil (Vera-Cruz, 1972).

Beach nourishment creates a "soft" (i.e., nonpermanent) structure by adding sand from an outside source to make a large sand reservoir, which pushes the shoreline seaward (National Research Council, 1995). Large volumes of sand fill may be required for projects that call for shore restoration and periodic renourishment. Thus, the availability of large volumes of sand from a nearby source area and the performance of the fill material on the nourished beach are key elements for a successful beach fill design (Meisburger, 1990). A crucial part of beach nourishment projects inevitably involves identification of potential offshore sand sources and the proving of reserves (Rowland, 1993). Exploration for sand deposits and evaluation of the resource in some areas may be almost as costly as placing sand on the shore, especially in cases where relatively small volumes of fill (e.g., $< 5 \times 10^5$ m^3) are required. Recently it has become very difficult to obtain suitable sand from lagoonal or inland sources in adequate quantities at an economical cost because of increased land values, depletion of previously used sources, increasing material handling, and transportation costs. Additionally, materials from lagoons, estuaries, and bays may not be suitable for long-term protection because of high silt-plus-clay contents and chemical contamination of sediments by heavy metals and other materials (Kennish, 1994). Ecological damage consequent to dredging in these ecologically sensitive areas further restricts their use as borrow sites. These are some of the main constraints which leave few options but to look for sand sources offshore. Thus, for the past three decades, the materials for most large beach nourishment projects in the United States have been obtained from offshore deposits (NRC, 1995). Most coastal states own the underwater sand resources from the beaches out to 4.8 km (3 miles) in the ocean. Due to reasons under which Florida entered the Union, the state controls offshore sand and gravel resources to about 3 marine leagues (10.2 miles, 16.3 km) out to sea in the Gulf of Mexico (Kitsos, 1996).

Sand Sources

The mode of delivery of sediment, its placement on the beach, and most important, the grain size are decisive factors in beach nourishment design projects (Dean, 1991). For these reasons, it is essential that project decision makers and designers have a basic understanding of sediment sources, transfer, and placement (NRC, 1995). The search for suitable material generally involves locating a deposit of sand and gravel of sufficient volume, appropriate grain size, and desired composition that it serves as a suitable source (Meisburger, 1990). Potential source areas (borrow sites) may be anywhere inland, through inlet throats, on ebb- and flood-tidal deltas, or offshore. Physical constraints of inland sand mining, the system of delivery to the coast (e.g., truck, rail, canal barge), accessibility of onshore unloading sites and sand distribution centers along urbanized shores (Finkl, 1993), and political forces have prompted the search for sand sources farther offshore than have been investigated historically (Walther, 1995). Prohibitive costs for mining and transportation, ecological considerations of onshore and inshore habitats (including coral reef systems), inadequate quantity and unsuitable quality often make upland and nearshore sand sources economically impractical to exploit. As a consequence, many sand searches now look farther offshore for suitable beach fill materials (Williams, 1986).

Purpose and Scope

The purpose of this investigation was to locate, map, and evaluate areas of offshore sand on the U.S. Gulf coast continental shelf that might be suitable as beach fill along the west-central Florida coast (Figure 1). The Longboat Key, Florida, beach restoration program is cited as an example of enhanced offshore exploration techniques that are used to advantage in the artificial renourishment of microtidal barrier island beaches. The study area occurs alongshore from New Pass to Longboat Pass and extends 13 km offshore (Figure 1). The evaluation of the seabed for sand and gravel resources features geological and geophysical surveys that define geographic locations and quantities of sediments which have potential for use in beach renourishment programs. Also relevant to studies of shelf sedimentary resources are investigations of bathymetry, seismic (subbottom) characteristics of the seabed, and analysis of jet probes and vibrocores. The data collected from these different kinds of surveys were analyzed in an effort to show new, state-of-the-art procedures for expediting selection of suitable seabed borrows. Large areas of potential interest were initially narrowed down by bathymetric and seismic surveys and subsequently investigated using jet probes and vibrocores to obtain more detailed information on sediment grain size and petrographic properties. Samples obtained by vibrocoring were analyzed for sand grain size by

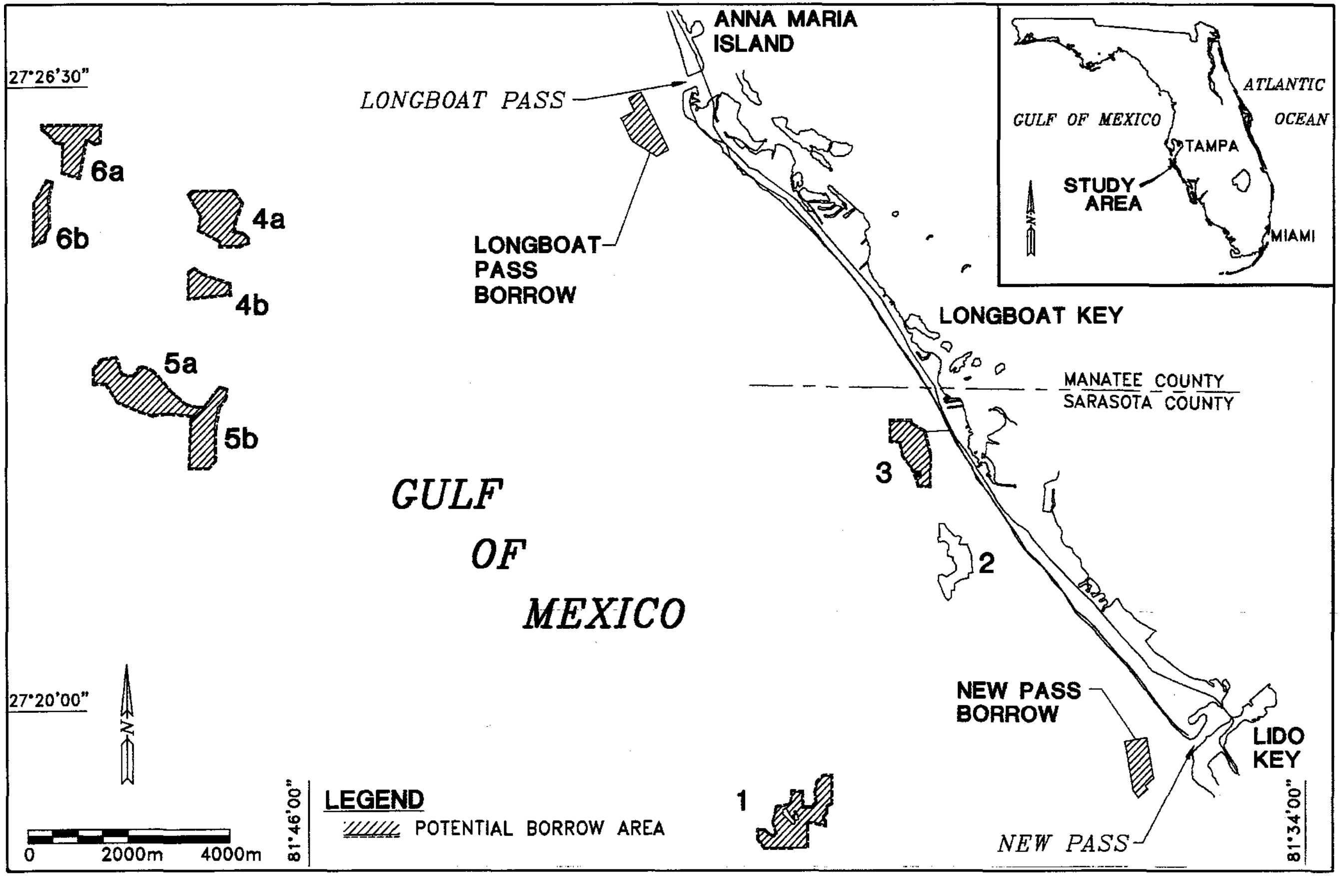

Figure 1. Location of study area on the continental shelf of the eastern Gulf of Mexico, offshore from the central-west coast of Florida. Potential borrow areas (PBAs) resulting from geophysical and geotechnical studies of the seafloor are indicated with lined polygons that are keyed to the text by location numbers.

sieving, and the silt-plus-clay fraction was determined by calculating the difference in weight between dry and washed samples.

Location of Study Area at Longboat Key, Florida

Located on the central west coast of the Florida peninsula, Longboat Key is a Gulf coast barrier island located on the border between Manatee and Sarasota Counties (Figure 1); the key lies 3–5 km off the mainland and is 16 km long by 1.5 km wide. Longboat Pass and New Pass separate the barrier island from Anna Maria Island and Lido Key, also in the barrier chain as described by Oertel (1985) and Evans et al. (1985).

Geophysical and Geotechnical Investigation of the Seabed

The equipment listed in Table 1 was used to conduct sequential geotechnical investigations of the seabed. In the initial phase of general study, rapid-reconnaissance off- and nearshore surveys were conducted on the basis of seafloor geomorphology that was inferred from navigational charts. Preliminary surveys involved about 125-line km of reconnoitary survey, 12 reconnoitary seismic cross-traverses, and the collection of numerous grab samples. The second phase was a detailed investigation that comprised composite bathymetric and seismic surveys, jet probing, and vibrocoring over an area of about 217 km^2. Six potential borrow zones (Figure 1) were delineated in water depths ranging from -6 m to -15 m (1929 National Geodetic Vertical Datum, NGVD).

Table 1
Geological and geophysical survey equipment used to study offshore sand sources in the Gulf of Mexico

Electronic navigational and positioning equipment	Bathymetric survey	Seismic survey	Jet probe	Vibrocoring
Trimble 4000 SE Land Surveyor II Global Positioning System interfaced with Coastal Oceanographic HYPACK Navigation Processing System	Fathometer[a]	Chirp sonar[b]	Jet pump[c]	Vessel[d]

[a] Innerspace 448 Digital Survey Fathometer.
[b] X-star full-spectrum digital subbottom profiler (EG & G).
[c] Briggs & Stratton 3.0-hp jet pump, capacity 8,460 gal/hr.
[d] Custom-rigged vessel equipped with a hydraulic-powered lift, a coring rig with barrel and frame assembly, vibrator, and a depth penetration recorder.

Electronic Navigation

A Trimble 4000 SE Land Surveyor II Global Positioning System (GPS), interfaced to a Coastal Oceanographic HYPACK Hydrographic Data Collection and Processing System, was programed for the line spacing and coverage required. The Trimble 4000 Pro-Beacon Differential GPS beacon receiver (which uses the U.S. Coast Guard Differential Correction Signal) was used to send accurate differential GPS signals to an onboard GPS receiver. The U.S. Coast Guard Egmont Key station was used during the survey as a reference station.

This GPS system is designed for moderate-precision static and dynamic positioning applications. It provides time and three-dimensional station coordinates and velocity measurements simultaneously every second. The 4000 SE receives the civilian signal from the Global Positioning System (GPS) NAVSTAR satellite. The system automatically acquires and simultaneously tracks GPS satellites and precisely measures code phase and Doppler phase shift, and computes positions and velocity. The system automatically determines time, latitude, longitude, and velocity every second.

The positional accuracy of the Trimble 4000 SE with a differential global positioning system (DGPS) is of the order of 1 m (in both x and y horizontal coordinates). Survey positioning data were simultaneously marked on the bathymetric and seismic records and recorded on the onboard computer for postsurvey trackline and anomaly plotting. The data were plotted to a grid, the Florida State Plane Transverse Mercator Projection Coordinate System, West Zone (NAD 27).

Bathymetric Survey

The Innerspace digital survey-grade fathometer (model 448) used in this survey is capable of operating in depth ranges from 0.5 to 155 m with a measuring accuracy of ± 0.03 m. The system was interfaced to the Coastal Oceanographic Hydrographic Navigation System to store depth and location data simultaneously. The transducer is mid-ship mounted, in line with the GPS antenna, at a depth of 0.6 m below the surface. End-of-day bar checks[1] were conducted to ensure against fathometer calibration drift. The fathometer and digitizer were calibrated daily by the bar check procedure at $\sim$ 1.5-m increments to the maximum depth of the project area.

The tide data were recorded at 15-min intervals during the entire survey using an offshore stand with tide staff and stilling well,[2] which sits seaward of the surf zone and is read manually by an optical level operation. The tide gauge was set south of the Sarasota County line near the center of the barrier island.

[1] Bar checks are obtained using a flat bar that is suspended by two precisely marked lines to a known depth below the transducer. The check is performed to correct for velocity variations and index errors in the echo sounding systems.

[2] A portable offshore stand (similar to a stilling well) developed by Coastal Planning & Engineering, Boca Raton, Florida, to measure water level accurately with the help of a tube (of varying length) depending on the tidal range. Tides, measured at an optimal location for the study area, are not estimated from a tide gauge at a remote station.

Seismic Survey

An X-STAR Full Spectrum Sub-Bottom Profiler, a wide-band FM high-resolution subbottom profiler, was used to generate cross-sectional images of the seabed and to estimate the thickness of the substratum, especially the unconsolidated sediments (e.g., sand horizon). This profiler collects digital normal incidence reflection data over a wide range of frequencies and transmits an FM pulse that is linearly swept over a full-spectrum frequency range (e.g., 2–16 kHz to over 20 ms). This frequency is known as a "chirp" pulse (Schock & LeBlanc, 1990) because of the chirplike sound emitted from the unit. Acoustic returns received by hydrophore are filtered and matched with the outgoing FM pulse. Combined in the XSTAR is a precision wide-band, low-noise, low-distortion analog sonar front end, a RISC workstation, and a Digital Signalling Processing (DSP) pipeline array coprocessor. The energy, amplitude, and phase characteristics of the acoustic pulses are precisely controlled because the FM pulse is generated by a digital analog converter with a wide dynamic range and a transmitter with linear components. This precision produces high repeatability and signal definition, which generates a high-resolution image of the subbottom stratigraphy. The X-STAR towfish (model SB-216S), which has an FM frequency band of 2–16 kHz, was used during the survey. Subbottom depth penetration is about 10 m in coarse calcareous sands and about 100 m in silt clays (Beaujean, 1995). The vertical resolution varies from 4 to 20 cm, depending on pulse frequency. The data are simultaneously displayed on video and recorded on an analog recorder giving a "hard copy" cross-sectional view of the seafloor subbottom.

The resulting data are processed to build maps of the horizontal and vertical distribution of the subbottom properties via acoustic impedance, acoustic attenuation, and band speed. The images resulting from the tapered waveform spectrum have virtually constant resolution with depth.

Detailed Investigation of the Seabed

Bathymetric and Seismic Survey

Seismic survey (subbottom profiling) was conducted simultaneously with detailed bathymetric mapping, using the equipment discussed previously (cf. Table 1) onboard a 9-m fiberglass vessel. About 348-line km were surveyed (Table 2). Draft isopach maps were computer-generated by AutoCAD using Eagle Point software. Isopachous maps for each potential borrow area were used to evaluate sand potentials of seabed sites and to select locations for jet probing. In the example shown here for PBA 4 (Figure 2), it is seen that sediment thickness is variable throughout the study area. Although sediment thickness is broadly ridged over the weathered limestone basement rock, there are distinct, 3-m-thick, N–S-trending sand waves that ornament the seabed sediment mounds (Figure 3).

The seafloor in the study area is gently sloping, with hummocks (sand waves) occurring haphazardly. The water depth ranges from 5 to 14 m NGVD. Bathymetry in the general region of PBA 4 (Figure 4) shows a gently undulating bottom that ranges in depth from 9.7 to 12.7 m. The isobaths shown in Figure 4 indicate small declivities on a generally smooth submarine topography. It should be noted that the subdued bottom topography is unrelated to irregularities (depressions) in the

Table 2
Survey statistics for seabed investigations

Area surveyed	215 km^2
Number of borrow sites identified	6
Surface grab samples	13
Vibrocore	61
Total core length	154 m
Sand sample analyses	196
Jet probes	80
Total jet probe length	179 m
Total line km surveyed (bathymetry and subbottom profiling)	348-line km

karstified limestone below and that sediment thickness cannot be derived from the bathymetry alone without additional subbottom information relating to depth of bedrock.

The weathered (karstified) paleosurface (Evans et al., 1985), over which the unconsolidated sediments lie, is clearly delineated by prominent acoustic reflection along with surface irregularities of the limestone (cf. Figure 3). The subbottom sediment layers here contain sand with shell hash, and rock fragments of varying texture and composition. These variations are depicted on the analog records by reflectors. If the unconsolidated sand layer is without much silt, clay, or coarser-than-sand material (e.g., > 2 mm), the analog is fairly clean, with little backscatter. The presence of silt and clay particle sizes causes acoustic impedance, which is recorded as noise on the analog record (Stoll, 1977). Because finer-textured sediments tend to form layers, their reflections form dark linear bands on the printout.

Irregularities of the karst erosional surface are at some places replicated in overlying sediments but at other places they smooth the microtopography in the form of channel fills. Mounds sometimes occur where blanket deposits fill irregularities in the erosion surface. One mound, with about 2 m local relief, was observed in PBA 1, whereas in PBA 5, sand waves reach 2.75 m above the adjacent seafloor. According to the isopachous map (Figure 2), the maximum thickness of unconsolidated sediments (i.e., sand layers) reaches 5.5 m in PBA 1. The average thickness varies, however, between 1.5 and 2.5 m in remaining areas.

Jet Probes for Geotechnical Study

Eighty jet probes were used to: (1) compare and evaluate the seismic data, (2) ascertain the thickness of the sediment layer, and (3) quickly appraise megascopic characteristics (visual estimation of sand size, and silt percentage of the sediment). Jet probes of seafloor sediments were made in all PBAs, and their locations, determined from evaluation of seismic records and isopach charts, were positioned to confirm the thickness of the unconsolidated sediment strata and to ascertain variations in thickness and sediment type or mineral composition (for locations of jet probes, see Figures 2 and 3). Positions in state plane coordinates for each probe

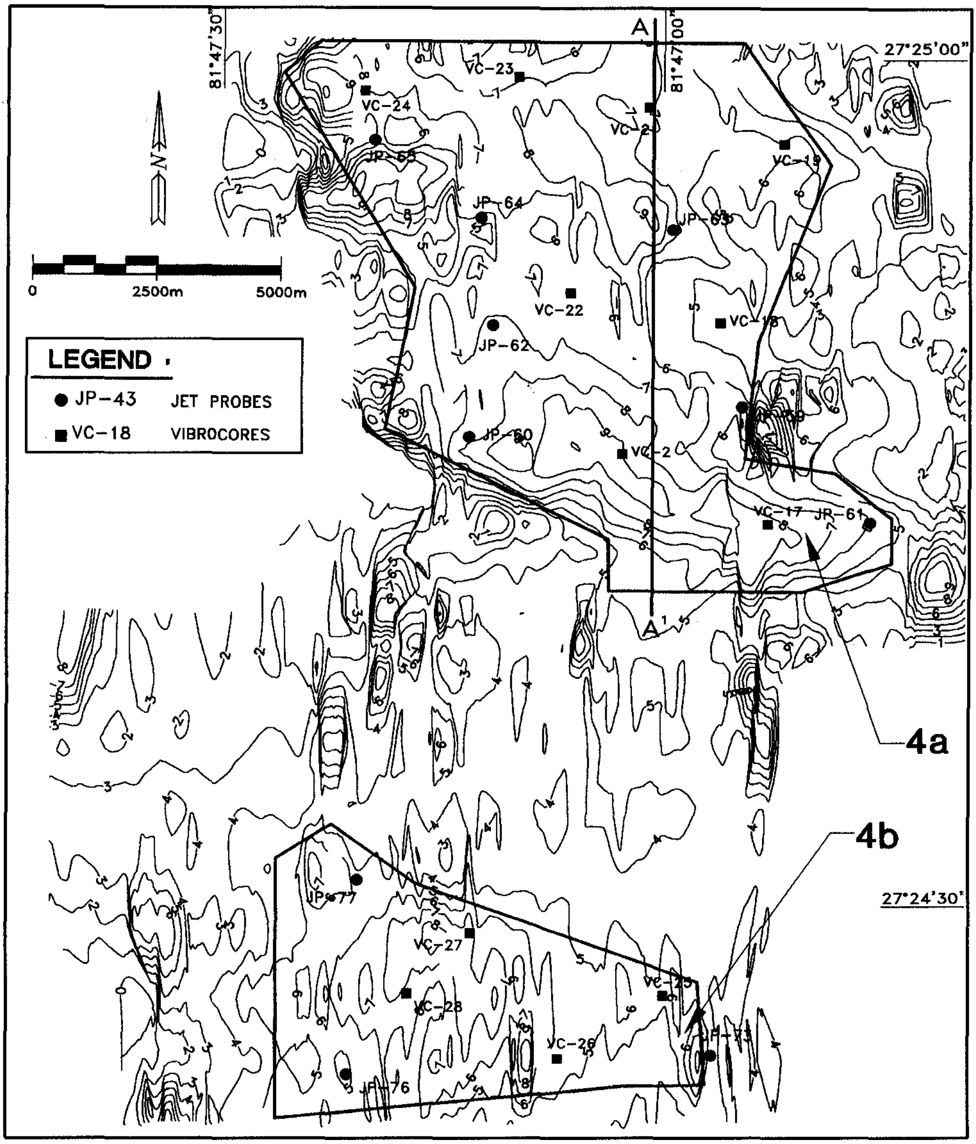

Figure 2. Isopachous (sediment thickness) map for PBA 4a, b resulting from seismic survey. The isopachs, numbered in customary units (feet below NGVD) as obtained in the seabed survey, show zones of sediment accumulation on the karstified limestone bedrock. Closely spaced isopachs mark zones of rapid change from sediment accumulations in sand waves to the weathered (now drowned) limestone on the seafloor. Locations of jet probes and vibrocores, used to verify the seismic survey and to obtain samples for geotechnical analysis, are shown by solid circles and squares, respectively. The A–A' transect through PBA 4a corresponds to the profile shown in Figure 5.

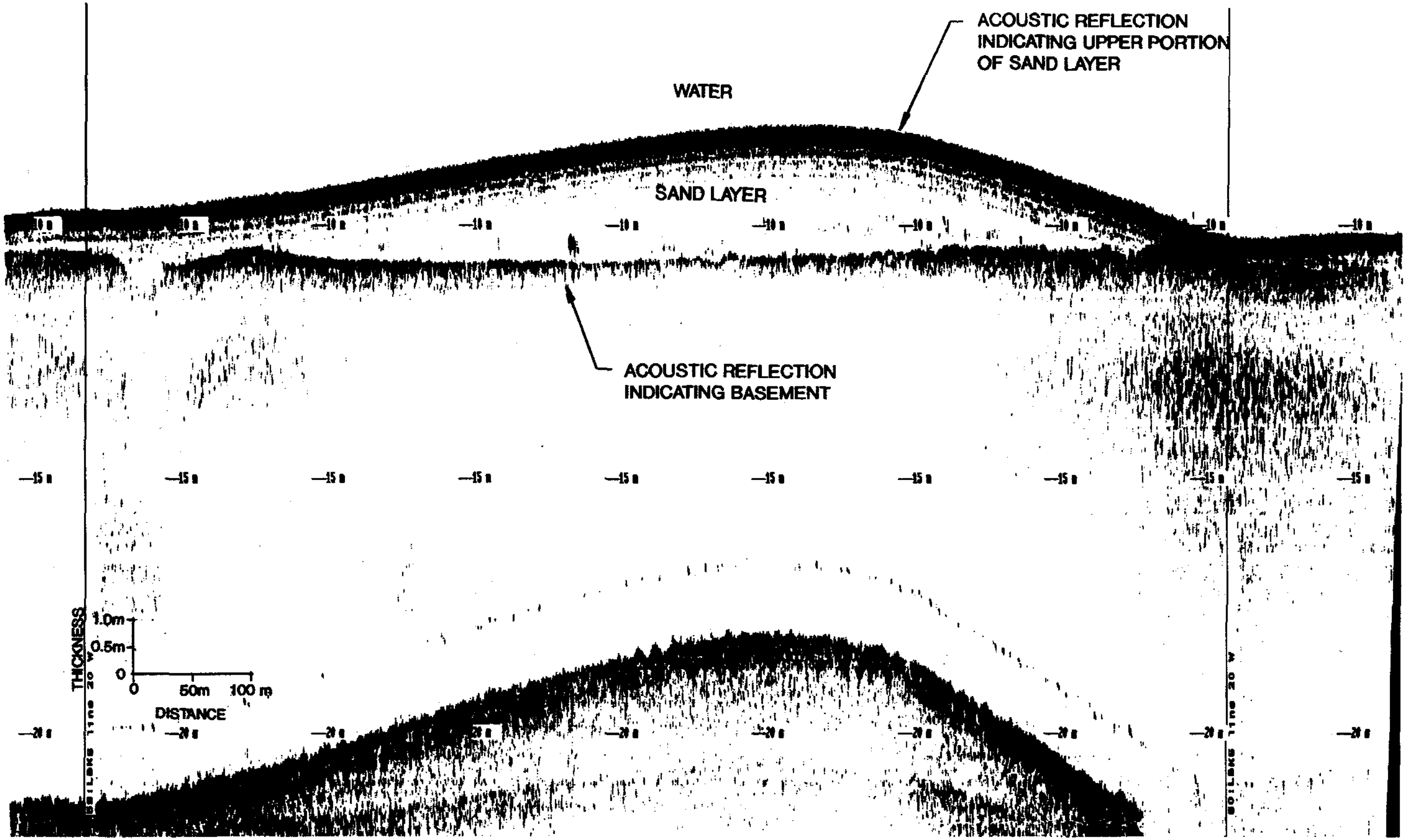

Figure 3. Cross-sectional image of the seafloor subbottom, along transect 20W in PBA 4a, obtained by the chirp sonar. Acoustic reflectors indicate various lithostratigraphic layers in the sedimentary cover on the seafloor.

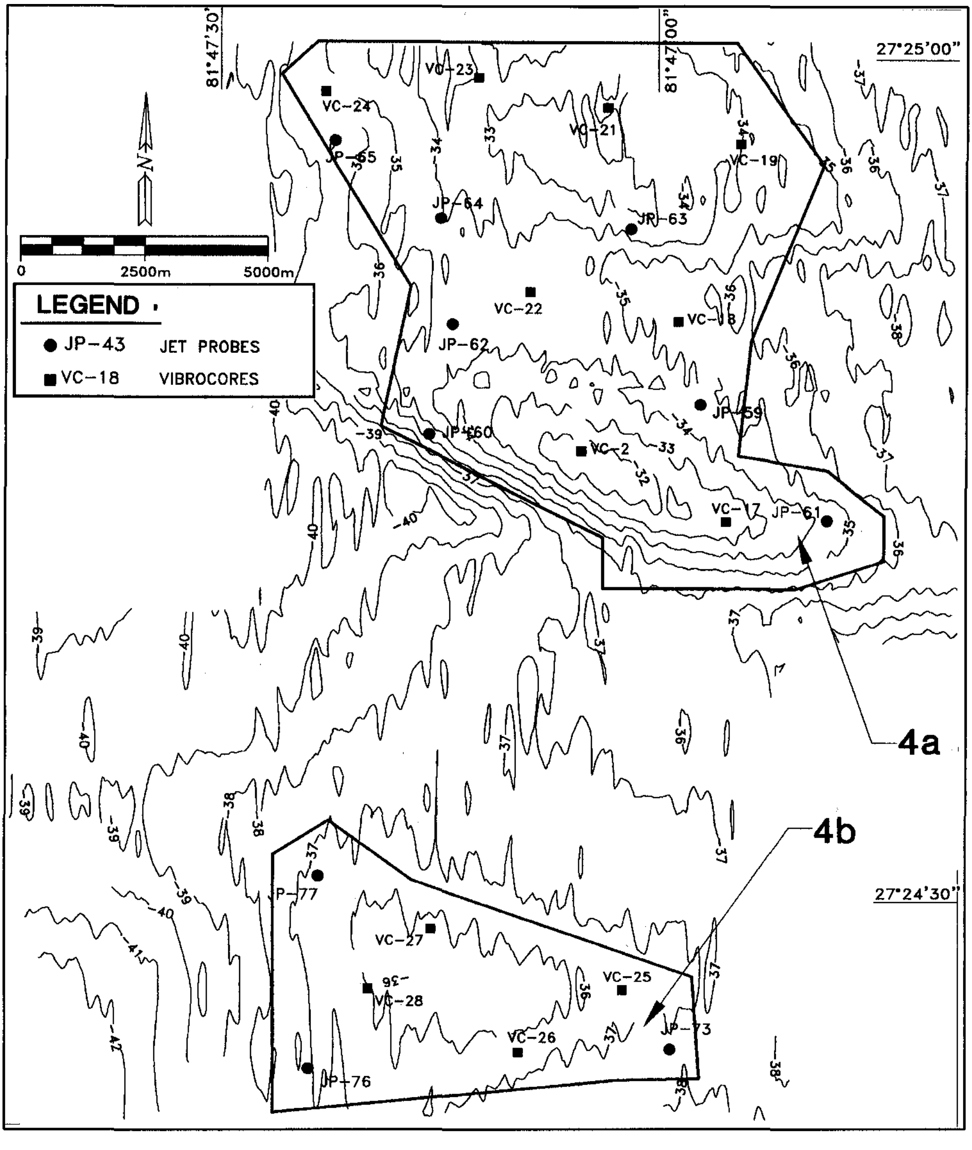

Figure 4. Bathymetric map for PBA 4a, b showing a gently undulating seabed surface marked by large sand waves. The general trend of the sand waves is north–south and the PBA lies across the axis of the wave. Locations of jet probes and vibrocores are the same as in Figure 2.

site were fixed using a Trimble DGPS and HYPACK Navigation System. Thirty-one jet probes in PBA 2 and PBA 3 confirmed the presence of fine to medium-grained calcareous sand with comparatively more siliciclastic silt-sized grains. Divers estimated subbottom conditions from penetration rates of the probe and the "feel" of the probe during penetration. Subsequently, logs for each probe were prepared for depths from 5 to 12 m.

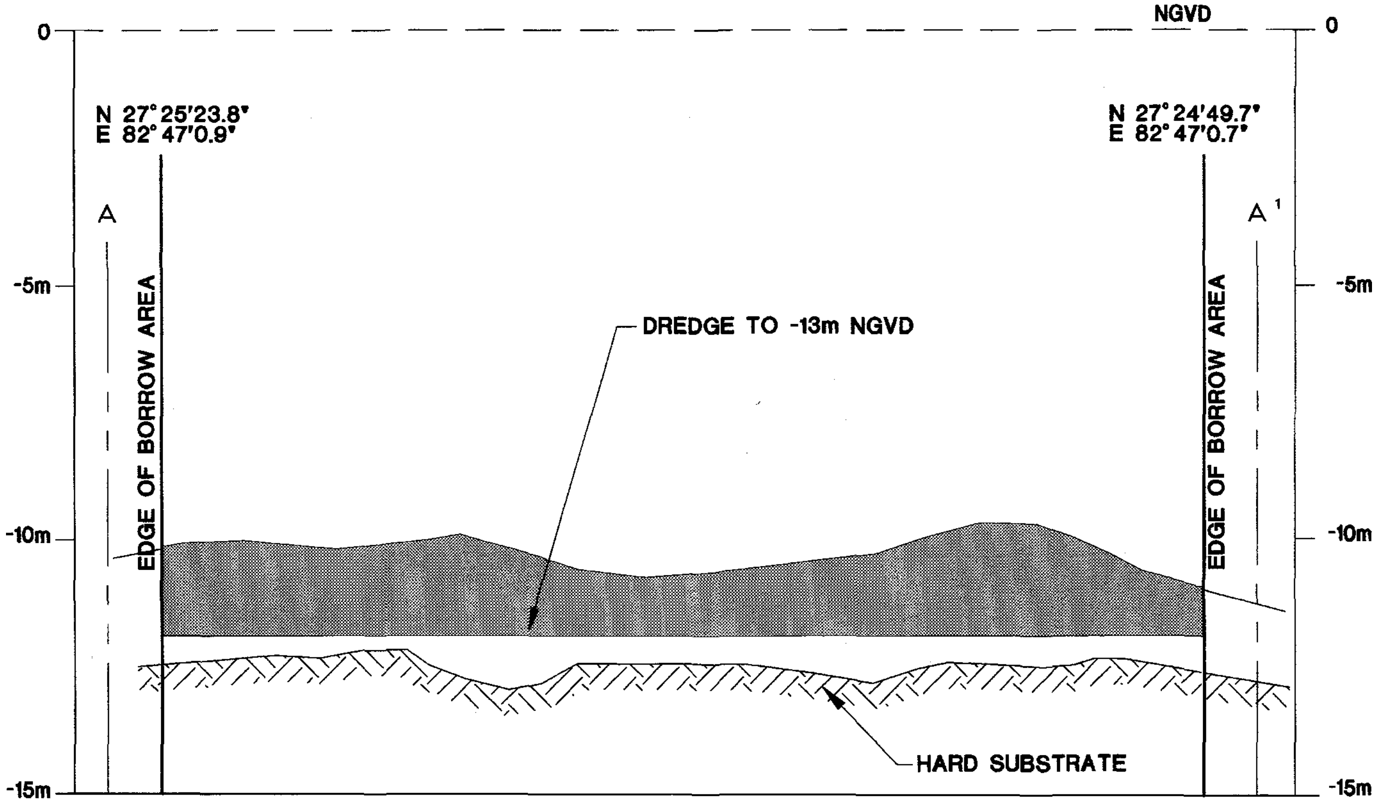

Figure 5. Cross-sectional view of the sand wave shown in Figure 2, along transect A–A′: The seafloor sediments fill irregularities in the weathered (karstified) limestone substrate to a thickness of about 10 m. The solid-colored area denotes dredgeable material to a depth of 13 m NGVD to ensure that the dredge's cutter head does not come in contact with the hard limestone substrate. Without further treatment, coarse gravels or limestone rock renders the fill unsuitable for beach nourishment.

SCUBA Dives on Nearshore Hardbottom

SCUBA dives were conducted at six sites ranging in water depth from 6 to 9 m in and around PBA 2 and PBA 3. This procedure was completed as a part of the ground-truthing operation to confirm the results of sonar surveys and to verify the "0"-isopach contour drawn on the basis of the completed seismic survey.

Vibrocoring of Sediments

In the final stages of investigation, after evaluation of all available bathymetric, seismic, and jet probe data, 61 vibrocores, spaced approximately 300 m apart were selected in the prospective borrow areas (cf. Figures 2 and 4). Each vibrocore was located so that its area of influence overlapped adjacent ones. The closely spaced vibrocores helped to minimize uncertainty factors related to sediment quantification and type, thereby maximizing confidence in selection of offshore borrows.

The vibrocoring was conducted in water depths ranging from 6 to 12 m. With full penetration, the length of the core normally obtained was about 3.5 m. Each vibrocore was split in halves: one half was kept for archival purposes after taking photographs of core sections; samples were drawn from the other half for particle-size analyses. Megascopic studies (e.g., color, texture, organic content, lithologic contact) and logging were conducted simultaneously.

Sediment Size Analyses

Visual descriptions, including an estimate of the effective length of each sample, were determined visually by color and textural change. The samples for analysis were taken from distinct layers within the core. Mechanical sieve analysis was carried out for 96 samples generated from 61 vibrocores obtained from six different borrow areas. The sieve analyses were conducted according to American Society for Testing and Materials (ASTM) Standard Materials Designation D422-63 for particle size analysis of soils (ASTM, 1987). This method covers the quantitative determination of the distribution of sand-size particles.

The sediment samples were oven dried, washed (in a solution containing sodium hexametaphosphate), and passed through a stack of 16 sieves (from sieve 5/8 to 230). The different fractions thus obtained were weighed by an electronic balance to the nearest hundredth gram. Quartile skewness (assymetry) and kurtosis (peakedness) were determined in an effort to characterize properties of grain size populations, as commonly shown in particle size–frequency distribution plots on log paper. Mean size and sorting were calculated using the moment method (Griffiths, 1967). Silt content was determined by calculating the percentage weight difference between dry and washed weights.

Results of Geophysical Surveys and Geotechnical Work

The overall results are based on analyses of data collected during the survey phases using the equipment listed in Table 1. From a total of six PBAs, three areas (PBAs 4, 5, and 6) were further split into two parts each (a and b) on the basis of geometry of the deposit, and the quality and quantity of sand.

Table 3
Characteristics and properties of seabed borrow sites

Borrow area	Distance from shore (km)	Area (km^2)	Water depth (NGVD) (m)	Average thickness of strata (m)	Volume of sand in PBA (m^3)	Total volume of sand (m^3)[a]	Average thickness of sand horizon[a] (m)
1	7.09	0.88	8.2–10	1.55	1,364,607	116,900	1.3
2	0.5	0.50	5.8–7.6	—	—	—	—
3	0.5	0.55	5.2–7.3	2.0	1,139,314	900,635	1.6
4	9.3	1.06	9.8–11.6	1.6	1,666,935	1,349,460	1.3
5	10.6	1.7	9.0–13	2.4	4,071,560	3,557,250	2.1
6	12.0	0.82	9.0–11.6	1.9	1,649,876	1,293,156	1.6

[a] Refers to amount of dredgeable sand.

Site Characteristics

Eight potential borrow sites lying offshore from Longboat Key, initially identified by a reconnaissance bathymetric survey, were further investigated by surficial sand samples (collected by petite-ponar grab) and reconnaissance seismic transects. From these, six PBAs (1, 2, 3, 4, 5, and 6) were selected for detailed investigations (Figure 1). PBA 3 is the nearest to the shore, about 0.5 km offshore, and lies at 5–9 m depth. PBA 7 is about 10 km offshore and lies at 9–12 m depth. PBAs 4, 5, and 6 form a cluster in the northwestern part of the study area and are farthest from shore. PBA 1 is located near the south end of Longboat Key about 7 km offshore.

The surface area of individual borrow sites ranges from 0.82 to 1.7 km^2. The volume of sand available from these PBAs varies from 0.34×10^6 m^3 to 2.36×10^6 m^3 (Table 3). Visual inspection showed that the cores contained layers of fine- to medium-grained sand with varying amounts of silt with shell hash.

The sediment size analyses showed that the mean grain size of sand varies from 0.13 mm (PBA 5b) to 0.53 mm, whereas the sorting value ranges from 1.02ϕ to 1.88ϕ. Silt contents ranged from 4.14% to 19.58% (Table 4).

Value of New Methods for Conducting Offshore Sand Searches

Conventional Techniques versus New Technologies

The equipment used during these geological and geophysical surveys are state of the art. The Trimble 4000 SE Land Surveyor II Global Positioning System (GPS), interfaced to the Coastal Oceanographic HYPACK Hydrographic Data Collection and Processing System, has a definite edge over previously used trisponders or other systems such as Loran C because horizontal positional accuracy is of the order of ± 1 m, whereas previous systems were of the order of ± 250 m as observed in the field. Added to this, the system automatically determines time, latitude, longitude, and velocity every second. The Innerspace Digital Survey Grade Fathometer (model 448) has a measuring accuracy of ± 0.03 m and operates accu-

Table 4
Results of grain-size analyses of sediments obtained from vibrocore sampling of the seabed

Borrow area	Number of vibrocores	Number of samples	Mean grain size (mm/ϕ)[a]	Sorting (ϕ)[b]	Silt content (%)[c]
1	10	15	0.23/2.16	1.36	8.52
2	3	9	0.17/2.54	1.54	19.58
3	9	38	0.23/2.11	1.87	13.84
4	12	37	0.51/0.98	1.24	4.18
4a	8	0	0.53/0.91	1.27	4.14
4b	4	0	0.46/1.12	1.17	4.26
5	14	44	0.28/1.84	1.31	4.92
5a	9	0	0.43/1.23	1.18	3.92
5b	5	0	0.13/2.96	0.65	7.85
6	13	43	0.21/2.23	1.11	5.67
6a	3	0	−.23/2.10	1.25	8.29
6b	6	0	0.20/2.30	1.02	4.36

[a] mm = mean diameter d_{50}.
[b] $\phi_{sort} = (\phi_{84} - \phi_{16})/2$.
[c] Silt content by weight percent.

rately within the water-depth range 0.5–155 m. Moreover, the fathometer and digitizer were calibrated daily by a bar check procedure at ~ 1.5-m increments to the maximum depth of the project area.

The X-Star Full Spectrum Sub-Bottom Profiler is one of the most sophisticated subbottom profilers presently available for commercial purposes. The X-Star towfish model SB-216S has an FM frequency band of 2–16 kHz. The penetration ranges from 10 to 100 m depending on the substratum. The vertical resolution varies from 4 to 20 cm, depending on pulse frequency. The main advantage of full-spectrum technology over a conventional system is increased penetration with high resolution through the use of matched filter correlation and waveform weighting techniques.

Chirp sonar is distinguished from conventional short-pulse sonars on the basis of the following unique features (Schock & LeBlanc, 1990):

1. It is a wide-band sonar which transmits computer-generated FM pulses that sweep over the frequency range 200–30 kHz (depending on the transducer configuration). The wide bandwidth ensures that sediment layers as close as 5 cm part can be resolved.
2. Excitation voltage for transducers is controlled digitally to prevent source ringing (decaying oscillations in the transmitted acoustic pulse). This is a common problem which reduces resolution of short-pulse systems. Source ringing is particularly undesirable when trying to detect layering within the upper 2 m of the seabed.
3. The energy of the transmitted FM pulses can be varied within the range 1–500 J by adjusting the power amplifier level and/or by selecting the pulse lengths from 5 to 200 ms.

4. Matched filter processing (which compresses the long FM pulses in time) and digital shading of transmitted pulses are used to produce practically noise-free images of the seabed to about 100 m beneath the seafloor with high spatial resolution and without any significant loss in vertical resolution.
5. The subbottom images also have a wide dynamic range, allowing detection of a seafloor or reflection that is 1,000 times smaller in amplitude than an adjacent reflection.
6. The system can generate images of seafloor in water depths as shallow as 30 cm to full ocean depth.

Ground truthing by jet probes adds to the accuracy of the survey. This is the fastest and one of the most reliable tools to check and confirm the data obtained during seismic survey and vibrocoring.

Discussion

Location of potentially compatible sand deposits is important to beach nourishment projects because supply and quality determine cost and influence design. In the case of Long Boat Key, an offshore sand search was necessary because sand from two adjoining nearshore regimes lacked required volume or was unsuitable as beach fill. An offshore investigation was thus performed to locate fill that was compatible with native beach sand.

The most suitable sand on the seabed was found in PBAs 4a and 54a (Figure 1). PBA 5 (a and b) contains 4.07×10^6 m^3 of 0.13- to 0.43-mm sand with a silt content of 3.9–7.9% (by volume). The deposit is a light gray-colored sand containing very small pieces of broken shell. The poorly sorted (1.27ϕ) sand deposit in PBA 4a is among the coarsest sediments (0.53 mm) in the study area. The next coarser sand (0.46 mm) occurs in PBA 4b. However, the maximum quantity (3.56×10^6 m^3) of dredgeable sand is available in PBA 5. Thus, the clustering of PBAs 4, 5, and 6 provides a suitable quality and adequate quantity of sand for beach nourishment.

Closer to shore in the central part of the study area, fine-grained sands were abundant but the silt contents of shelf sediments were found to be excessively high for beach renourishment. Although some areas contained moderate volumes of fine-grained sand (about 0.17 mm mean diameter) that is marginally suitable for beach renourishment sand, silt contents ranged up to 15.8%.

Conclusions

By adding sand to the shore reservoir, artificial beach nourishment creates a soft, nonpermanent (expendable) fill structure which relocates the shoreline seaward. A crucial part of the beach nourishment process is the identification of potential sand sources. Because of increased land value, depletion of previously used sources, enhanced transportation cost, and environmental considerations, it is often difficult to obtain suitable quality sand in adequate quantity from alongshore or inland sources. Therefore, offshore mining for sand from the inner continental shelf is the primary source of beach-fill material.

The delineation of PBAs was conducted using state-of-the-art equipment for multiphased offshore geological and geophysical surveys at reconnoitary and detailed levels. Application of advanced technologies increased the efficacy and accuracy of the survey. Although sufficient data were generated from bathymetric and seismic surveys to visualize surface and subsurface geomorphological features on the nearshore seafloor, the veracity of these data were confirmed by collecting vibrocores and groundtruthing using jet probes. Subsamples from the vibrocores were analyzed to determine mean grain size, sorting, skewness, kurtosis, and silt content. Synthesis of the survey and laboratory data indicates that approximately 8.8×10^6 m^3 of offshore sand is potentially available in water depths ranging from 8 to 12 m NGVD. This volume of sand is sufficient to replenish beaches on the Longboat Key barrier island. The mean sand grain size ranges from 0.13 to 0.53 mm and the sorting from 0.65ϕ to 1.31ϕ. Silt contents range from a low of 3.92% to a high of 8.52%. Sediments closest to the shore generally were not suitable for use as beach fill because of high silt contents (13.84–19.58%).

References and Bibliography

Applied Technology and Management, Inc. 1989. Geotechnical and sand source investigation, Longboat Key. Report prepared for Town of Longboat Key, FL.

ASTM. 1987. Standard method for particle-size analysis of soils, designation D422-63. *1987 annual book of ASTM standards, volume 04.08 soil and rock; building stones; geotextiles.* Philadelphia: American Society for Testing Materials.

Beaujean, P.-P. J. 1995. Sediment classification of the sea floor using the chirp sonar and Biot model. M.S. thesis, Florida Atlantic University, Boca Raton, FL.

Bird, E. C. F. 1990. Artificial beach nourishment on the shores of Port Phillip Bay. *Journal of Coastal Research, Special Issue No.* 6:55–68.

Boesch, D. F., M. N. Josselyn, A. H. Mehta, J. T. Morris, W. K. Nuttle, C. A. Simenstad, J. P. Swift. 1994. Scientific assessment of the coastal wetland loss, restoration, and management in Louisiana. *Journal of Coastal Research, Special Issue No.* 20.

Bruun, P. 1995. The development of downdrift erosion. *Journal of Coastal Research* 11(4):1242–1257.

Chen, C. S. 1965. The regional lithostratigraphic analysis of Paleocene and Eocene rocks of Florida. *Florida Geological Survey, Geological Bulletin No. 45.*

Davis, R. A., Jr., and B. J. Kuhn. 1985. Origin and development of Anclote Key, West-peninsular Florida. *Marine Geology* 63:153–171.

Dean, R. G. 1990. Channel entrances: impacts on coastal erosion. *Proc. 53rd Meeting of the Coastal Engineering Research Board (5–7 June 1990, Fort Lauderdale/Dania, Florida).* Vicksburg, Mississippi, CERC Final Report, pp. 51–53.

Dean, R. G. 1991. Equilibrium beach profiles: characteristics and applications. *Journal of Coastal Research* 7(1):53–84.

Dette, H., A. Fuhrboter, and A. Randkiv. 1994. Interdependence of beach fill volumes and repetition intervals. *Journal of Waterways, Port, Coastal and Ocean Engineering* 120(4):580–593.

Dolan, R., B. Hayden, and S. May. 1983. Erosion of the U.S. shorelines. In: P. D. Komar (ed.), *CRC handbook of coastal processes and erosion*, pp. 285–299. Boca Raton, FL: CRC Press.

Evans, M. W., A. C. Hine, D. F. Belknap, and R. A. Davis, Jr. 1985. Bedrock control on barrier island development: west-central Florida coast. *Marine Geology* 63:263–283.

Finkl, C. W., Jr. 1993. Pre-emptive strategies for enhanced sand bypassing and beach replenishment activities in southeast Florida: a geological perspective. *Journal of Coastal Research*, Special Issue No. 18:59–89.

Finkl, C. W., Jr. 1994. Management strategies for enhanced sand bypassing and beach replenishment in the southeast Florida coastal zone: potentials for application of new technologies. *MTS'94 Conf. Proc.* (Marine Technology Society Annual Meeting, Washington, DC), pp. 107–114.

Finkl, C. W., Jr. 1996. What might happen to America's shorelines if artificial beach replenishment is curtailed: a prognosis for southeastern Florida and other sandy regions along regressive coasts. *Journal of Coastal Research* 12(1):ii–ix.

Friedman, G. M., and K. G. Johnson. 1982. *Exercises in sedimentology.* New York: John Wiley.

Griffiths, J. C. 1967. *Scientific method in analysis of sediments.* New York: McGraw-Hill.

Harvey, J. 1982. An assessment of beach erosion and outline of management alternatives, Longboat Key, Florida. Report prepared for the Town Council, Town of Longboat Key, FL.

Hayes, M. O. 1979. Barrier island morphology as a function of tidal and wave regime. In: S. P. Leatherman (ed.), *Barrier islands*, pp. 1–28. New York: Academic Press.

Healy, T., C. Harms and W. de Lange. 1991. Dredge spoil and inner shelf investigations off Tauranga Harbour, Bay of Plenty, New Zealand. *Proc. Coastal Sediments '91* (American Society of Civil Engineers), pp. 2037–2051.

Kennish, M. J. 1994. Pollution in estuaries and coastal marine waters. *Journal of Coastal Research*, Special Issue No. 12:27–49.

Kioke, K. 1990. Artificial beach construction on the shore of Tokyo Bay, Japan. *Journal of Coastal Research*, Special Issue No. 6:45–54.

Kitsos, T. R. 1996. New requirements for obtaining beach sand from federal waters. In: L. S. Tait (ed.), *Proc. 9th Natl. Conf. on Beach Preservation Technology*, pp. 329–338. Tallahassee: Florida Shore & Beach Preservation Association.

McKinney, M. L. 1984. Suwanee channel of the Paleogene coastal plain: support for the carbonate suppression model of basin formation. *Geology* 12:343–345.

Meisburger, E. 1990. Exploration and sampling methods for borrow areas. CER C-90-18. Vicksburg, Mississippi: U.S. Army Corps of Engineers.

National Research Council (NRC). 1995. *Beach nourishment and protection.* Marine Board, Commission on Engineering and Technical Systems. Washington, DC: National Academy Press.

Oertel, G. F. 1985. The barrier island system. *Marine Geology* 63:1–18.

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* 59(6):960–972.

Pinet, P. R., and P. Popenoe. 1985. A scenario of Mesozoic-Cenozoic ocean circulation over the Blake Plateau and its environs. *Geological Society of America Bulletin* 96:618–626.

Rowland, T. J. 1993. Assessment of offshore sand bodies for coastal projects. *Proc. 6th Natl. Conf. on Beach Preservation Technology*, pp. 519–526. Tallahassee: Florida Shore & Beach Preservation Association.

Schock, S. G., and L. R. LeBlanc. 1990. Chirp sonar: new technology for sub-bottom profiling. *Sea Technology* 31:35–43.

Spackman, W., S. W. Scholl, and W. H. Taft. 1964. *Field guidebook to environment of coal formation in southern Florida.* Printed for the Geological Society of America, pre-convention field trip.

Stoll, R. D. 1977. Acoustic waves in ocean sediments. *Geophysics* 42:715–725.

Tanner, W. F. 1960. Florida coastal classification. *Gulf Coast Association Geological Societies Transactions* 10:259–266.

U.S. Army Corps of Engineers, 1991. General design memorandum, shore protection project, Sarasota County, Florida. U.S. Army Corps of Engineers, Jacksonville District, Florida.

Vera-Cruz, D. 1972. Artificial nourishment of Copacabana beach. *Proc. 13th Coastal Engineering Conf.* (American Society of Civil Engineers), pp. 1451–1463.

Verhagen, H. J. 1990. Coastal protection and dune management in the Netherlands. *Journal of Coastal Research* 6:169–179.

Walther, M. P. 1995. Looking for sand sources further offshore case study: Venice Phase II. In: *Sand wars, sand shortages and sand-holding structures*. Proc. 1995 Natl. Conf. on Beach Preservation Technology, pp. 1–16.

White, W. A. 1970. The geomorphology of the Florida peninsula. *Florida Bureau of Geology, Geological Bulletin No. 51.*

Williams, S. J. 1986. Sand and gravel deposits within the United States exclusive economic zone: resource assessment and uses. *Proc. 18th Offshore Technology Conference*. Richardson, Texas, Offshore Technology Conference, pp. 377–386.

Zwamborn, J. A., A. W. Fromme, and J. B. Fitzpatrick. 1970. Underwater mound for protection of Durban's beaches. *Proc. 12th Coastal Engineering Conf.* (American Society of Civil Engineers), pp. 975–994.