GEOLOGICAL SURVEY OF ALABAMA

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SAND-QUALITY CHARACTERISTICS OF ALABAMA BEACH SEDIMENT, ENVIRONMENTAL CONDITIONS, AND COMPARISON TO OFFSHORE SAND RESOURCES: ANNUAL REPORT 2

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by

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CONTENTS

ILLUSTRATIONS

TABLES

ABSTRACT

This report is the second annual report for a five-year project on Alabama beach sand quality and potential offshore sources for replacement of lost beach sand. In the first year, particle-size analysis was performed on samples from Alabama beaches and the results were compared to previous work on offshore sand sources. In the second year, previously collected vibracores from the continental shelf off Baldwin County were reexamined and sampled for more detailed particle-size analysis than had been done in earlier studies. Recent digital bathymetric data allowed more detailed analysis of offshore geomorphology than was previously possible.

Much of the Baldwin County shelf is underlain by the Graded Shelly Sand and Shelly Sand lithofacies. The Graded Shelly Sand lithofacies is slightly coarser than the Shelly Sand lithofacies and contains thin layers of sandy shell gravel as well as sand. This offshore sand is slightly finer than Baldwin County beach sand but resembles Baldwin County beach sand in sorting, skewness, and kurtosis. Mud forms an insignificant portion of the two lithofacies and of beach sand. Shell fragments coarser than associated sand in the two lithofacies account for 5 to 6 percent of the sediment. Both lithofacies are suitable sources of sand for beach nourishment.

The offshore sand resource has been more clearly defined in terms of sand quality and distribution. The resource consists mainly of fields of oblique sand ridges, sourced ultimately from Florida, and subdivided into three zones that roughly parallel the shore. High-quality sand underlying the ridges (Graded Shelly Sand and Shelly Sand lithofacies) is much thicker than similar sand in intervening swales. Sand is transported southwestward as the ridges migrate, chiefly during storms, and is also transported into deeper water to the southeast. Sand from the inner and middle zones of oblique ridges closely matches Baldwin County beach sand in particle size, color, and other economically important characteristics. Sand from the outer zone has been winnowed and is relatively fine-grained; it is less suitable for beach nourishment.

INTRODUCTION

The Minerals Management Service (MMS) and the Geological Survey of Alabama (GSA) have long cooperated in the study of Alabama's coastal area (published results cited in this report). The MMS and GSA are now in the second year of a five-year study of Alabama beach sand quality and possible sources of sand for beach nourishment from Federal waters off the Alabama coast. In the first year of the study, natural Alabama beach sand was characterized in greater detail than ever before for comparison with offshore sand. In the second year, the goal was to reexamine MMS Study Areas 1 and 2 and the adjacent shelf (fig. 1; pl. 1) as potential sand sources to replenish beaches in Baldwin County, Alabama. This report presents results of the second year of the five-year study.

The chief accomplishments of this year's work were the acquisition and analysis of quantitative particle-size data from vibracores that had only been studied semi-quantitatively, more accurate assessment of bioturbation in the same vibracores, the correlation of sedimentary patterns with offshore landforms, and the preliminary development of a more realistic assessment of total volume of beach-quality sand available in and near Study Areas 1 and 2.

Sedimentary structures of GSA archival cores from Study Areas 1 and 2 and vicinity were described and documented (pl. 1). New data on shell size and orientation and burrow types and distribution yielded useful information on the depositional environments of the sand units for their assessment as beach-nourishment sand sources (appendix A). Previously published descriptions of the cores focused on basic information about particle size, boundaries between sedimentation units, and the unconformity overlying pre-Holocene strata (Parker and others, 1997; Hummell, 1990, 1999). Parker and others (1997) defined generalized lithofacies; this year the GSA used new and preexisting particle-size data and new information about sedimentary structures to refine characterizations of the Graded Shelly Sand (GSS), Shelly Sand (SHS), and Sand with Mud Burrows (SMB) lithofacies. The GSS and SHS are the most suitable sources of beach-nourishment sand in Study Areas 1 and 2 and vicinity, whereas the SMB is less desirable for this purpose (Kopaska-Merkel and Rindsberg, 2005; this report).

The GSA performed particle-size analyses of 44 additional samples from MMS Study Areas 1 and 2 and vicinity, in vibracores archived at the GSA. Samples from some of these cores were analyzed previously by less precise microscopic methods (Hummell, 1999). Particle-size analysis has led to better understanding of the characteristics of the

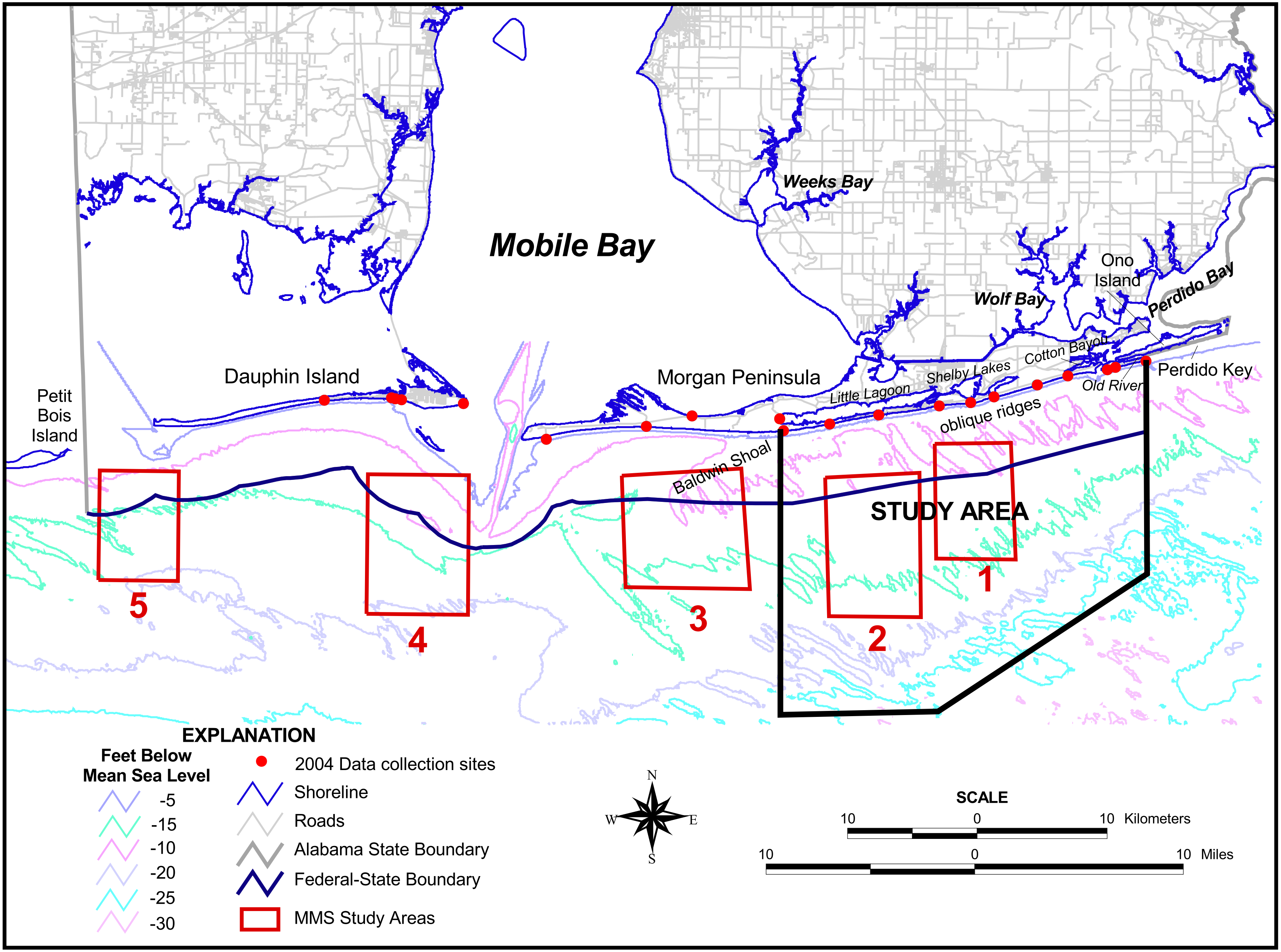


Figure 1. Location of study area.

Graded Shelly Sand and Shelly Sand lithofacies of Parker and others (1997) (as modified by Hummell, 1999). This permits more accurate assessment of their utility for beach nourishment.

Particle-size analyses of selected winter beach samples collected by GSA staff were used to test the hypothesis that particle size on the beach changes seasonally. This further refined understanding of Alabama beach-sand quality and dynamics.

New and existing particle-size data from Alabama beaches and the continental shelf (including Areas 1 and 2) were incorporated in an expanded database. The database was used for the purposes outlined in the preceding two paragraphs and to establish a baseline dataset for future nourishment projects on the Alabama coast. The results of all particle-size analyses were included in the existing Geographic Information Systems (GIS) project that was originally developed under previous cooperative efforts.

The GSA described and documented the geometry of offshore sand bodies based on bathymetry with emphasis on Areas 1 and 2 (fig. 1). This permitted refinement of information available on existing lithofacies maps. The results were compared to published sedimentologic data and to the results of particle-size analysis. The purpose of this task was to refine estimates of sand volume and to test hypotheses about sediment movement and deposition on the shelf.

In this report, “Previous work” summarizes the relevant published literature, and detailed procedures are covered in “Methods.” The “Coastal and offshore setting” is briefly described based largely on previous literature, focusing on coastal processes that affect the deposition and erosion of beaches in Alabama. The subsequent sections under “Results” summarize our findings with regard to particle sizes in and around Study Areas 1 and 2, the major geomorphic features in the area, and refinements in facies classification of Holocene sediment in the area of study. The resources available for beach nourishment in and near Study Areas 1 and 2 are evaluated in the section entitled “Resource evaluation.” The text continues with a brief discussion of research opportunities that could lead to an improved understanding of the distribution of sand and other sediment types south of Baldwin County, followed by a summary and conclusions.

New data collected for this report are given in the appendices. Appendix A consists of vibracore descriptions supplementary to previously published descriptions of the same vibracores. Appendix B contains raw particle-size data collected this year, again supplementing previous work. Appendix C includes the results of two-sample t-tests comparing the particle size of beaches and offshore sediment. Appendices D and E contain raw particle-size data collected from vibracores in previous years.

ACKNOWLEDGMENTS

We would like to thank Albert E. Browder (Olsen Associates, Inc.) and John Rowland (MMS) for lending their expertise. Ruth T. Collier drafted illustrations.

PREVIOUS WORK

MMS Study Areas 1 through 5 were delineated by GSA researchers in the 1990s (Parker and others, 1997; Hummell and Smith, 1995, 1996). The study areas are numbered from east to west; Areas 1 and 2 are south of the urban Baldwin County coast and so are the focus of the present study (pl. 1).

The physical and biologic oceanography of coastal and offshore Alabama has been studied many times, as shown by extensive bibliographies (Lipp and Chermock, 1975; O'Neil and others, 1982). Chermock and others' (1974) *The Environment of Offshore and Coastal Alabama* is outdated, but still a good overview of all aspects of coastal Alabama. The surficial geology and physical environment of the Alabama continental shelf were studied, among others, by Gould and Stewart (1955), Parker (1968), Boone (1973), Kent and others (1976), Schroeder (1976), Alexander and others (1977), Wanless (1977), Doyle and Sparks (1980), Chuang and others (1982), U.S. Army Corps of Engineers (1984), Exxon Company U.S.A. (1986), Otvos (1986), Kindinger (1988), Donoghue (1989), Kindinger and others (1989, 1991, 1994), Rezak and others (1989), Gittings and others (1990), Howard (1990), Hummell (1990, 1996, 1997, 1998, 1999), Shultz and others (1990), Brooks and Giammona (1991), Parker and others (1992, 1993, 1997), Sager and others (1992), GSA (1993), Hummell and Smith (1995, 1996), Kennicutt and others (1995), McBride and others (1995, 1996, 1997), Parker and others (1997), U.S. Minerals Management Service (1997), Davis and others (1998), and Gardner and others (2001). Information on the oblique sand ridges that comprise the chief offshore sand resource can be found in articles and reports by Parker and others (1997), Hummell (1999), Byrnes and others (2004), and references cited therein.

General environmental and biologic studies of the Alabama continental shelf, some of them funded by the MMS, include those of Parker (1960), van Wyk (1973), Williams (1974), Defenbaugh (1976), Kent and others (1976), Dames & Moore (1979), TechCon (1980), Shaw and others (1982), Vittor & Associates (1982, 1985, 1988), Exxon Company U.S.A. (1986), Darnell and Kleypas (1987), Continental Shelf Associates (1989, 1998), Continental Shelf Associates and Vittor & Associates (1989), Harper (1991), Laswell and others (1992), Byrnes and others (1999, 2004), Hammer and others (2000), Browder and others (2003), Olsen Associates (2001), and Olsen and Browder (2004).

Alabama beach and offshore sand has been studied primarily for heavy-mineral content (van Andel and Poole, 1960; Foxworth and others, 1962; Upshaw and others, 1966; Parker, 1990). Olsen Associates (2001), Kopaska-Merkel and Rindsberg (2002, 2005), and Kopaska-Merkel (2005) described Alabama beach sand as nearly white coarse-medium to fine-coarse quartz-dominated sand with less than 2 percent mud. Offshore sand resources, to be useful for beach nourishment, must match Alabama beach sand closely in mineralogy, color, and particle-size distribution.

Based on 160 vibracores, Browder and others (2003) mapped nearshore oblique sand ridges off Baldwin County from Perdido Key westward to Gulf Shores, where three borrow sites were identified (fig. 2). Olsen Associates mined sand to replenish beaches for the Cities of Gulf Shores and Orange Beach north of Study Areas 1 and 2 in 2000-01 and 2005 (Olsen Associates, 2001; Browder and others, 2003; Olsen and Browder, 2004) (fig. 2).

METHODS

CORE DESCRIPTION

Vibracores for this study were recovered and processed in the 1990s by GSA personnel (Hummell, 1990, 1999; Parker and others, 1997). The cores were split longitudinally into working and archive halves; for each vibracore, the working half was sampled and discarded, and the archive half was stored in a plastic sheath at room temperature for later use. Digital photographs of each core were taken of the investigated cores. Archive halves were thoroughly oxidized and mostly desiccated by 2005, but otherwise were largely undisturbed.

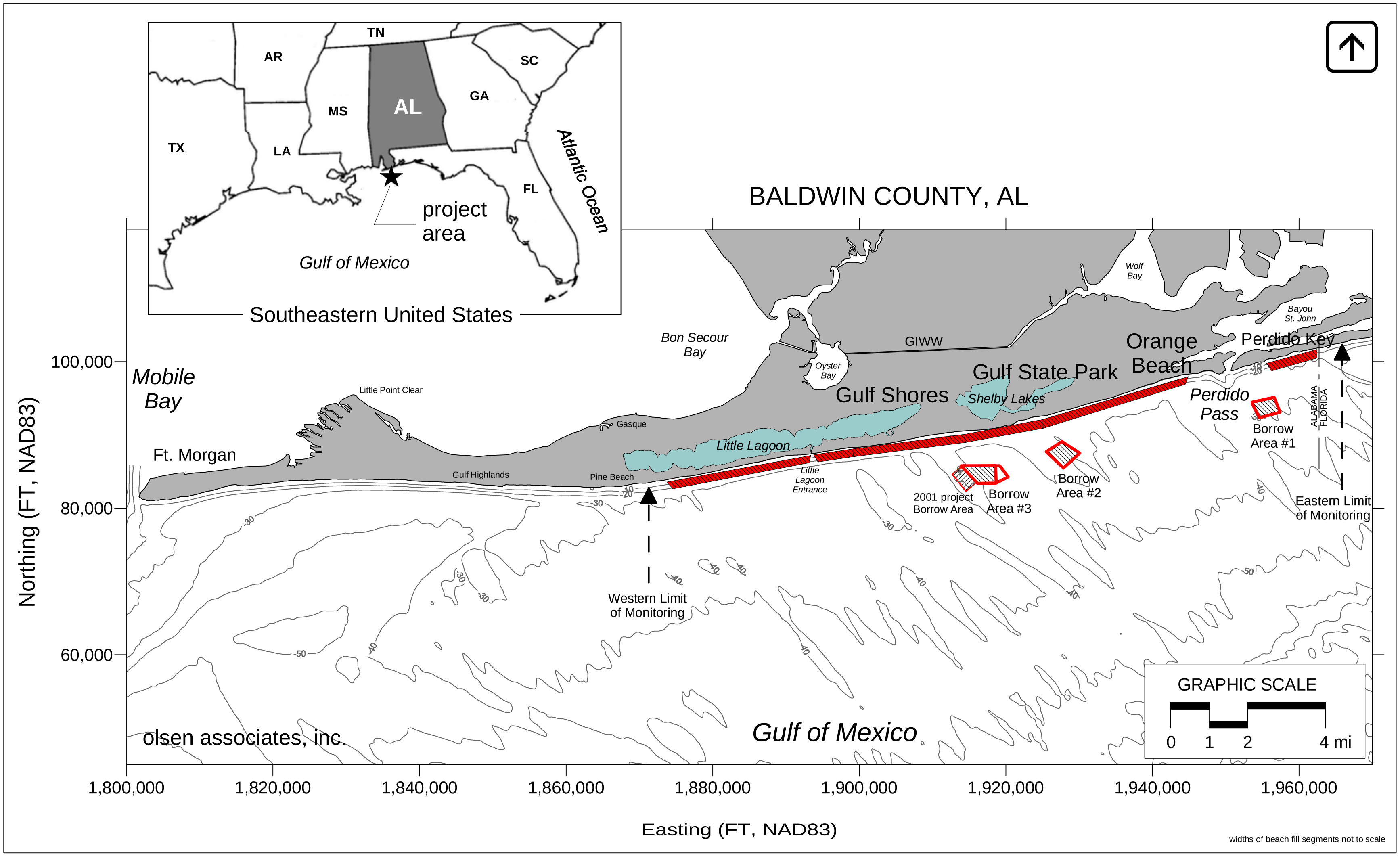


Figure 2. Map showing locations of borrow sites and nourished beach, 2005 Baldwin County Beach Nourishment Project (reproduced with permission from Browder and others, 2003).

Cores from the two study areas and vicinity were reexamined visually and compared to original laboratory notes and published descriptions. Additional data were noted with particular attention to contacts and sedimentary structures.

PARTICLE-SIZE ANALYSIS

Because offshore sand is commonly muddy, the procedure for particle-size analysis was more complex than that used previously for beach sand (Kopaska-Merkel and Rindsberg, 2005). The method followed that of previous GSA researchers (Parker and others, 1997, p. 17) and was based ultimately on that of Lewis (1984), as updated by Lewis and McConchie (1994) (fig. 3). All weights were measured on a Sartorius® top-pan balance accurate to 0.001 grams (g).

Sediment samples were collected at intervals of about 70 to 100 centimeters (cm) (2 to 3 feet [ft]) within the vibracores, with modifications as required by lithofacies and to avoid disturbed or chemically altered parts of the core. After the surface was cleaned by scraping, sediment samples were collected from the center of the core from an interval 10 cm in vertical extent, centered on the desired distance downcore. About 100 g was taken, the amount being tailored to yield a sufficient split of sand (40 to 60 g) for particle-size analysis, plus a duplicate split.

Each sediment sample was placed in a 1000-milliliter (mL) beaker and washed in deionized water to which a measured quantity of a dispersing agent, sodium hexametaphosphate (Calgon®) was added. The sample was stirred with a rod until the sediment was thoroughly suspended. This treatment dissolved water-soluble salts and disaggregated particles. Clay was allowed to settle overnight for at least 17 hours.

The excess fluid was drawn off to a graduated cylinder in which the suspension was stirred and its specific gravity was measured by hydrometer (Ertco® ASTM 152H Soil Hydrometer). A 200-mL sample of the fluid was withdrawn and placed in a preweighed beaker. The water was evaporated in an oven and the mud-containing beaker was weighed. This represented part of the clay fraction.

The remaining sediment in the 1000-mL beaker was wet-sieved through a 63-micrometer (μm) (U.S. Standard No. 230) stainless steel screen into a basin; mud (silt and clay) passed through the screen while sand was retained. The muddy water in the

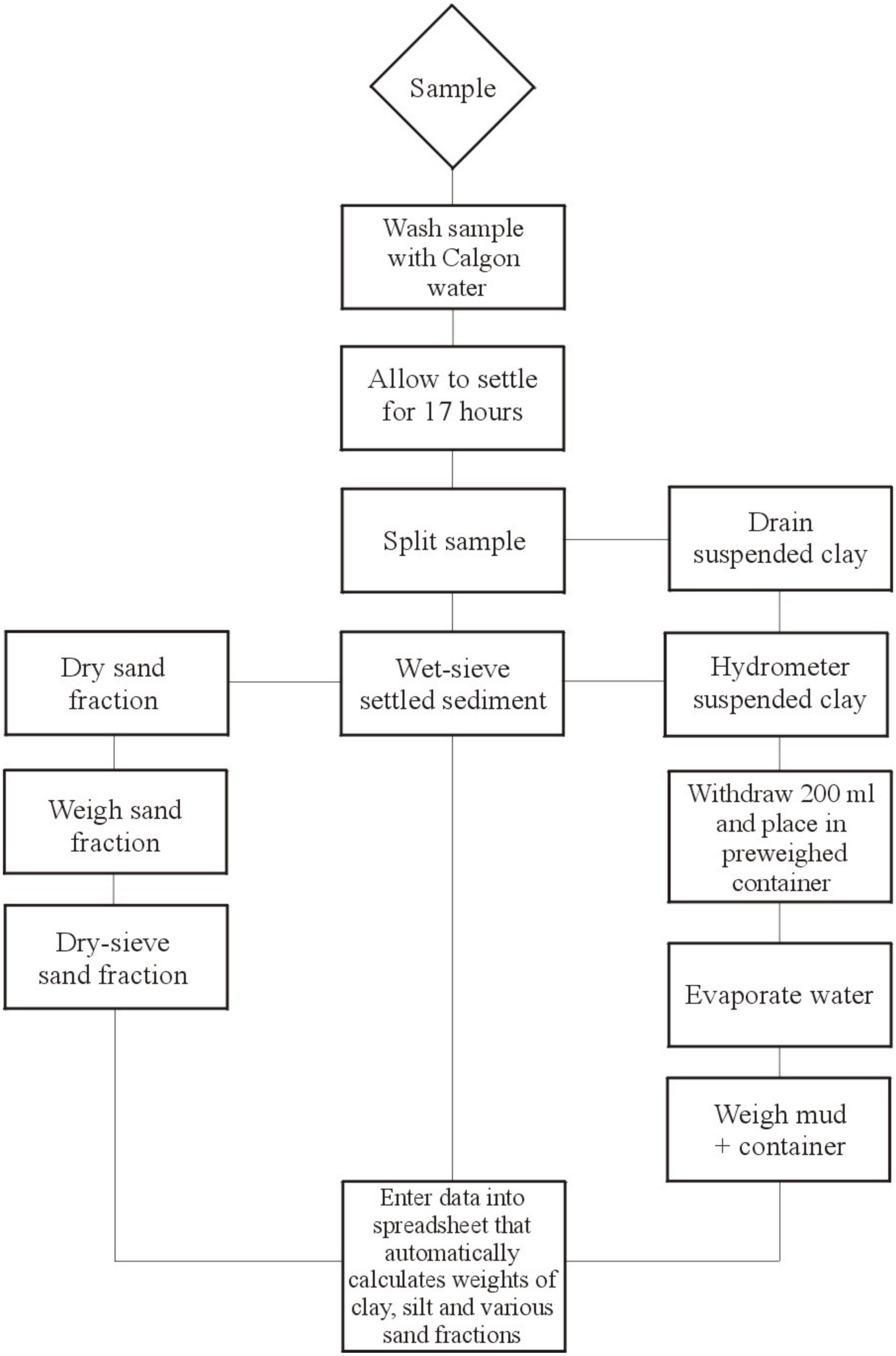


Figure 3. Flow chart for particle-size analysis.

basin was measured by hydrometer using the same technique as described in the previous paragraph.

The wet sand retained on the 63-µm screen was dried in an oven at 80º C (176º F) and the dry sand was weighed. The dry sand was sieved for 30 minutes at 0.5-φ intervals from -2 to 4 φ. The boundary between sand and silt is set at 4 φ, equivalent to 63 µm (Lewis and McConchie, 1994).

Data were entered into an Excel® spreadsheet to calculate the weights of mud and sand as well as the amounts lost during the laboratory procedure. Sand fractions were entered into a Gradistat® version 5 spreadsheet for more detailed analysis (Blott and Pye, 2001). The first four statistical moments (mean, sorting, skewness, and kurtosis) of the sand portion of each sample were calculated; histograms and other graphs were prepared for selected samples.

This procedure differed slightly from previous methods (Parker and others, 1997; Kopaska-Merkel and Rindsberg, 2005). The clay fraction was allowed to settle for at least 17 hours instead of 12. Following Parker and others (1997), sand fractions were sieved at 0.5-φ intervals rather than 0.25-φ intervals, a change that reduced precision from that of Kopaska-Merkel and Rindsberg (2005), but halved sieving time and allowed direct comparison with previous data measured by Parker and others (1997) from vibracores from MMS Study Areas 1 and 2.

Measurement of the weight of mud is estimated to be accurate to 0.01 g. Therefore, estimates of the weight of samples that include significant mud fractions are accurate to 0.01 rather than 0.001 g, which is the precision for weighing of sand samples. However, although we erred on the side of caution by emulating our predecessors' methods, measurement of mud fractions proved to be unnecessary because the amount of mud in the sand samples that were the focus of this study is trivial.

In presentation of statistical data in this report, we also refer to both moment measures and other statistical parameters of individual samples and of groups of samples, making clear from context or explicit notation to which we refer in any given instance. For example, we may illustrate, using a histogram, an example of the GSS (a single sieved sample), or we may refer to the average geometric mean particle size of all samples assigned to that lithofacies.

GEOMORPHOLOGY

A brief geomorphic analysis was conducted of the offshore sand ridges in the study area by visual examination and tracing of bathymetric charts, following a literature search. The GSA (2005) developed an improved bathymetric chart based on data archived in the National Ocean Survey Hydrographic Data Base. Data were extracted in ASCII format and converted to a grid; contours were built with ArcGIS 9.x Spatial Analyst using Inverse Distance Weighted interpolation (S. C. Jones, written communication, November 3, 2005). The result (pl. 1) was of particular value as it is far more detailed than charts available to previous GSA researchers (Parker and others, 1997; Hummell, 1999). A chart showing bathymetric changes over a 50-year period in the twentieth century (Byrnes and others, 2004, fig. 7) was also highly useful.

COASTAL AND OFFSHORE SETTING

This section, largely summarized from reports by Hummell and Smith (1995), Parker and others (1997), and Hummell (1999), is a brief review of conditions and processes that influence sand quality on Alabama beaches and offshore.

The Alabama continental shelf is part of a triangular area that includes parts of offshore Louisiana, Mississippi, Alabama, and northwest Florida (Boone, 1973; Parker, 1990). The triangle is bounded on the north by the Mississippi-Alabama-Florida coastline, to the west by the Mississippi Delta in Louisiana, and on the south by the continental slope (including the DeSoto Submarine Canyon) on the south.

The largest feature of the Alabama coastal region is Mobile Bay, which separates the area into western and eastern regions, respectively, in Mobile and Baldwin Counties. The western coastal region includes Dauphin Island, Pelican Island, and the eastern part of Mississippi Sound. The eastern coastal region includes the Morgan Peninsula, which forms the southern boundary of eastern Mobile Bay and merges eastward with a mainland containing small estuaries and lakes behind sand barriers.

West of Mobile Pass, the seafloor off Dauphin Island is relatively smooth and steep (pl. 1). It is bounded to the east by a broad topographic high, the ebb-tidal delta of Mobile Bay (pl. 1). The plume of muddy water leaving Mobile Bay through Mobile Pass, particularly during floods and after hurricanes, is deflected westward by the prevailing current (Hardin and others, 1976). This part of seafloor is thus relatively muddy compared to the shelf off Baldwin County.

East of Mobile Pass, the seafloor appears smooth to the diver, but has relatively high relief and several distinctive kinds of ridges and other landforms that reflect the area's complex geologic history. Relict coastal features survived reworking by marine transgression, followed by Holocene fluviodeltaic sedimentation and growth of shelf sand ridges and oblique bars (Vittor and Associates, 1985; Rindsberg, 1992; Parker and others, 1997). Larger bathymetric features off Baldwin County include the shelf sand sheet, the eastern part of the Mobile Bay ebb-tidal delta, and a large, relict landform: Baldwin Shoal (pl. 1). The eastern side of the ebb-tidal delta occupies a triangular area off Mobile Pass, flanked on the southeast by a large depression. Baldwin Shoal is anchored to the shoreline west of Pine Beach.

Oblique sand ridges, whose sediment is the main object of the present study, occupy much of the seafloor off Pine Beach eastward at least to Santa Rosa Island, Florida (pl. 1). The sand ridges are gently curved more or less in a north-northwest south-southeast orientation. Many of the ridges in shallow state waters are attached to the shoreface (pl. 1). The oblique ridges form chiefly during storms but are modified by fair-weather currents and bioturbation (Parker and others, 1997). Three sets of oblique ridges (pl. 1) have been recognized at depths of less than 12 meters (m), 12-17 m, and greater than 17 m, each with subtly different geometry and particle-size characteristics (see "Geomorphology" under "Results"). They contain much of the sandy Holocene sediment in and near Study Areas 1 and 2.

The sand on Alabama beaches comes from present marine environments because sand transported by rivers is deposited near the heads of estuaries such as Mobile, Perdido, and Pensacola Bays. Sand sources include Pleistocene barrier deposits near Destin, Florida, and reworked sediment on the Alabama shelf (Kwon, 1969; Parker and others, 1997).

Along the Gulf barriers, westward longshore currents appear to dominate the transport of sediment (Foxworth and others, 1962; Parker, 1990). Sustained northwesterly or westerly winds may cause temporary reversals in direction of local currents (Abston and others, 1987).

Westward longshore drift has been the predominant mode of sediment movement throughout the Holocene (Parker and others, 1997) as well as at present (Hardin and others, 1976). Holocene sediment at depth is generally much muddier west of Mobile Pass, suggesting that muddy plumes of water exiting Mobile Bay have long been deflected westward. Except for modern oblique sand ridges, the mode and degree of lateral variability in surface and subsurface lithofacies distribution are similar in both strike and dip directions.

Bulk quantities of sediment in Alabama's longshore drift system were summarized by Hummell (1999). Estimates of the volume of sand moving in the littoral system range widely (Cooper and Pilkey, 2004). Garcia (1977) calculated the total net littoral transport at Dauphin Island to be about 179,000 m^3 (196,000 cubic yards [yd^3]) per year. This is comparable to the U.S. Army Corps of Engineers' (1955, 1984) estimates of about 183,000 m^3 (200,000 yd^3) per year at Perdido Pass and 194,000 m^3 (212,000 yd^3) per year at Petit Bois Island, Mississippi, west of Dauphin Island, Alabama. In contrast, Byrnes and others (2004) estimated the flux of sediment between Perdido Pass and Mobile Pass as 106,000 m^3 (139,000 yd^3) per year. The amount of sand estimated by Garcia (1977) and the U.S. Army Corps of Engineers (1955, 1984) would be enough to cover a strip of beach about 30 m (100 ft) wide and 5 kilometers (km) (3 miles) long to a depth of about 0.3 m (1 ft).

Bioturbation is an important factor in defining offshore lithofacies (see "Lithofacies"). Using boxcores and a geologic point of view, Kent and others (1976) briefly described benthic communities in coastal Alabama and adjacent Florida typical of dunes, backshore, foreshore, "shoreface" (including our "inner zone" of oblique sand ridges), "inshore" (equivalent to our "middle zone"), and "offshore" (equivalent to our "outer zone"). Using grab samples and biological statistics, Vittor & Associates (1985) described four depth-related benthic communities in the northeastern Gulf of Mexico: shallow beach, inner shelf, intermediate shelf, and outer shelf, each subdivided by sediment texture (mud, sandy mud, muddy sand, sand). All of the shelf near MMS Study Areas 1 and 2 lies within Vittor & Associates' (1985) inner shelf-sand infaunal assemblage. They found that the infauna vary seasonally, with densities of individuals generally being lowest in winter (Shaw and others, 1982; Vittor & Associates, 1985; Harper, 1991).

RESULTS

Particle-size characteristics of specific offshore environments are discussed first, followed by a section on "Bioturbation." Offshore lithofacies are described in "Facies Composition and Stratigraphy," with emphasis on particle-size characteristics. Submarine landforms are described in "Geomorphology." The "Depositional Model" shows how geomorphology, lithofacies, and particle size are interrelated.

PARTICLE-SIZE ANALYSIS

This section is divided into two parts. First, particle-size characteristics among Alabama beaches, sediment underlying state waters, and sediment underlying federal waters are compared. Particle size of sediment varies with water depth, which is roughly comparable to distance from shore. Seasonal effects on particle-size distribution on beaches are examined using the newly acquired winter-beach data and other beach data presented by Kopaska-Merkel and Rindsberg (2005). Particle size of sediment off Baldwin County also is strongly related to lithofacies and geomorphology, which are discussed in following sections.

During this project year, 44 samples were sieved (appendices A, B). Of the new samples, 38 were newly collected from vibracores in and near Study Areas 1 and 2, and 6 were collected on winter beaches in Baldwin County during 2002 and 2003 (Kopaska-Merkel and Rindsberg, 2002, 2005). In addition, samples sieved by Parker and others (1997) have been included in some of our analyses (appendix D).

COMPARISON OF BEACH AND OFFSHORE SAND

Beach nourishment ideally should draw on a source of sand closely resembling native Alabama beach sand. In this section, we summarize particle-size similarities and differences between beach sand and potential offshore sources of sand, referring to the samples as "sediment" because a few contain a significant proportion of mud. Except for samples taken at Gulf Shores, samples were collected before the latest round of beach nourishment began and so approximate natural beach conditions insofar as is possible.

Figure 4 represents the distributions of geometric mean particle sizes of samples from Alabama beaches and the GSS and SHS in offshore state waters and offshore federal waters. The beach dataset includes samples from both Baldwin and Mobile Counties, but most beaches in the two counties are strikingly similar (Kopaska-Merkel and Rindsberg, 2005). On the average, sand on Alabama beaches (geometric mean particle size 330 ± 73 µm) (Kopaska-Merkel and Rindsberg, 2005) is coarser than that in offshore state waters (geometric mean 290.8 ± 50.7 µm), which is in turn coarser than that in federal waters (geometric mean 284.5 ± 176.9 µm), although all three distributions overlap considerably (fig. 4). This distribution of particle sizes is consistent with offshore winnowing (see "Depositional Model").

Because the mean values in figure 4 are averages of geometric mean values from individual sieved samples, these "means of means" represent the average particle sizes over large areas, for example, sand in state waters. The standard deviation values correspond to the variation over large areas of the average particle size as measured at single points. Where the standard deviation is small, the sand is homogeneous across the area in question. Thus, sand from the GSS and SHS in state waters is far more homogeneous with regard to mean particle size than sediment farther offshore in federal waters, and it is even more homogeneous than sand on the beach. This accurately reflects the quality of the offshore sand resource, because our samples of the offshore sand were chosen from the high-quality sand units that are considered to be potential sources of sand for beach nourishment. If muddy lithofacies that are associated with the GSS and SHS were included in the calculations, then the standard deviations of particle size in the offshore would be much greater.

Histograms of representative examples of beach sand and potential state and federal source sand appear in figure 5. Sorting also varies systematically among these three regions, with beach sand the best sorted and federal source sediment the most poorly sorted (fig. 4). In addition, beach sand is about equally well sorted everywhere on the Alabama coast, whereas sorting of offshore sand is more variable (and increasingly so farther offshore), probably because mechanisms of deposition are more diverse there (for example, ridge versus swale depositional settings). Beach sand is the least skewed, but federal sediment is on the average slightly less skewed than state sand (fig. 4).

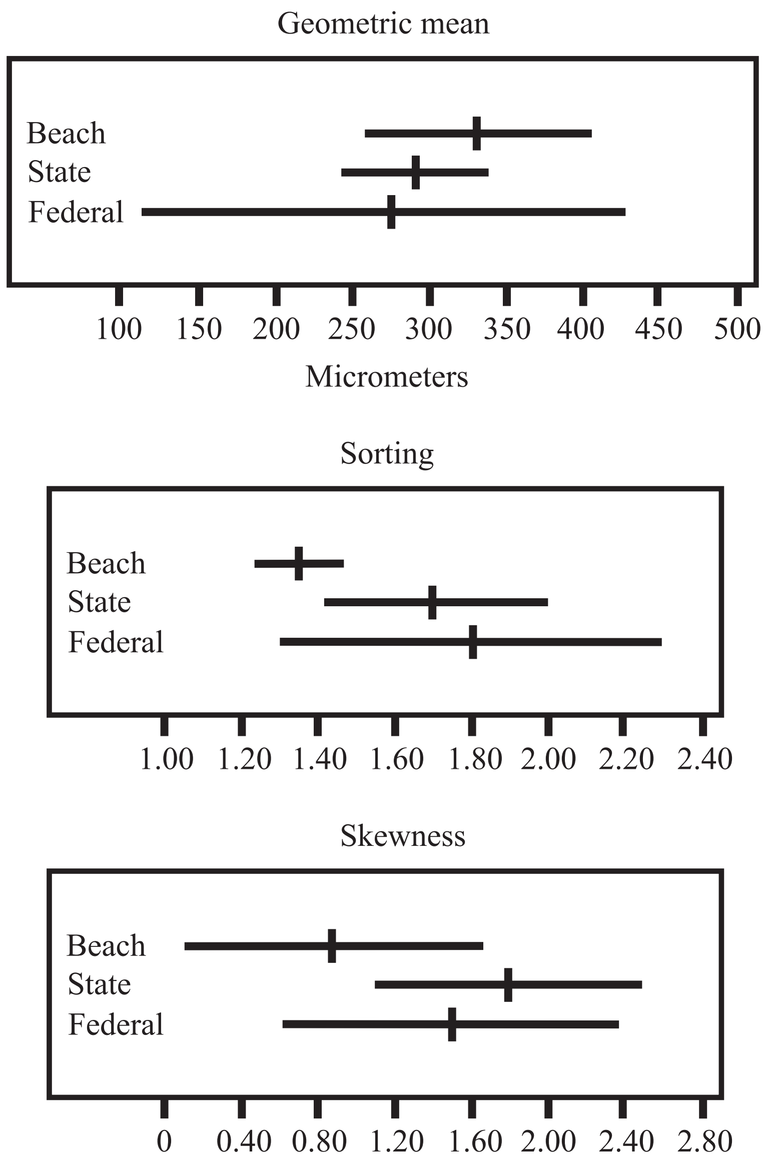


Figure 4. Means and standard deviations of three moment measures of Alabama beach sand, sand in state waters, and sand in federal waters.

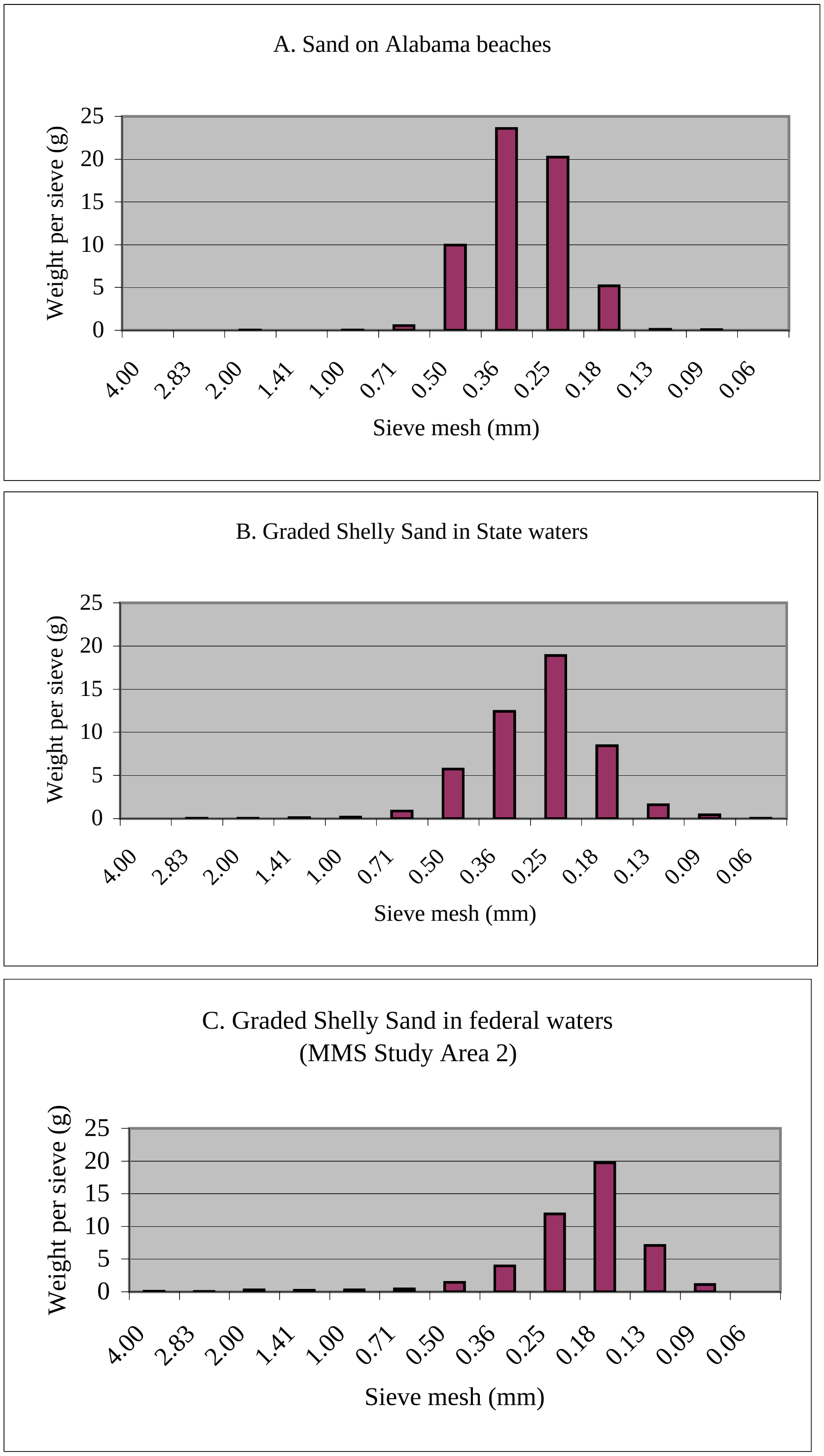


Figure 5. Histograms comparing particle-size distributions of representative samples of (A) Alabama beach sand, sample 021203-6-1a; (B) Graded Shelly Sand lithofacies in State waters, SR-109A -100; and (C) Graded Shelly Sand lithofacies in federal waters (MMS Study Area 2), SR-101A-15.

Overall, sand in state waters is more similar to beach sand (coarser and better sorted), although these moment measures show no great differences between sediment in state and federal waters. New data confirm conclusions drawn previously (Parker and others, 1997; Olsen Associates, 2001)—that a considerable amount of sand in both state and federal waters is sufficiently similar to Alabama beach sand in particle size to be used for beach nourishment. Previous studies have shown that lithofacies and seafloor topography are closely related to sand quality and quantity (for example, Parker and others, 1997; Olsen Associates, 2001); these relationships are explored in following sections.

In the study area (fig. 1), offshore sand is compositionally more complex than beach sand, which is very strongly dominated by quartz and hence is nearly white. Offshore sand is richer in heavy minerals and thus is somewhat darker than Baldwin County beach sand, even with silt, clay, and organic matter removed (Parker and others, 1997). It is thus comparable to beach sand on the Gulf side of Dauphin Island (Hummell and Smith, 1996). The major components obvious to the naked eye are shells and shell fragments, quartz, and dark minerals; muscovite occurs in some samples.

Qualitative observations suggest the following analysis of relationship between sand composition and particle size. The shells and shell fragments are relatively coarse and dominate the coarsest fractions down to about 1 mm. Because whole shells are not necessarily transported but can grow in place, the coarsest particles can be arbitrarily large. Their sizes may bear no relationship to maximum water velocities. Also, the diameter of the sample limits the maximum size of shells that can be incorporated.

At about 1 mm, the exact size varying from one sample to another, the major component shifts rather abruptly from shell fragments to rounded quartz. Finer fractions are largely quartz, with varying amounts of muscovite, shell, and dark minerals. The finest sand fractions (typically very fine sand) are increasingly dark due to the higher proportion of dark minerals in successively finer sieves. Thus, the sand can be treated either as a single bell curve, or as a more complex curve composed of several functions that each act differently (whole shell, shell fragments, quartz, muscovite, dark minerals). Because quantitative data on the size distribution of various sand components are unavailable, and because most samples are approximately normally distributed (the occurrence of coarse tails notwithstanding), samples are treated as coming from single populations of particles.

SEASONAL CONSISTENCY

Winter beaches commonly differ from summer beaches on many coastlines because fair-weather wave energy is generally higher in the winter (Ingle, 1966). In last year's report (Kopaska-Merkel and Rindsberg, 2005), only general conclusions could be made on seasonal trends in beach particle-size distribution, because few samples collected in the winter months were analyzed. A tentative conclusion was made that ". . . the exposed parts of Gulf beaches become steeper and particle size becomes coarser during winter . . . sieve data measured so far are too limited to show seasonal trends," and that "average geometric mean particle size on Alabama beaches is about 330 micrometers (µm) (medium sand; standard deviation 73 µm)." This average included only three winter samples out of a total of 35 fair-weather windrow samples. Nonwinter samples (n = 32) averaged 327.5 µm in particle size, with a standard deviation of 79.1 µm.

Additional winter samples were sieved this year (pl. 1; fig. 6; table 1). A total of seven winter beach samples can be used to calculate a geometric mean. The winter samples average 324.3 µm; standard deviation 48.3 µm (fig. 7). The winter and nonwinter distributions are thus nearly identical in geometric mean and standard deviation, suggesting that Alabama beaches do not change seasonally in particle size. Comparison of mean particle sizes of winter and nonwinter samples from the same sites yields the same result (table 2), although samples from any one site are too few to draw firm conclusions.

By contrast, Alabama winter beaches contain less material finer than 250 µm than do summer beaches, suggesting that a considerable amount of sediment that would be stable on summer beaches could erode in winter (table 3). Apparently, fine material eroded from the beach in winter has little effect on the overall particle-size distribution, for reasons not yet understood.

None of the calculations presented in the previous paragraphs include the six relatively coarse outliers that were described in a previous report (Kopaska-Merkel and Rindsberg, 2005). Two relatively coarse outliers measured this year are also excluded.

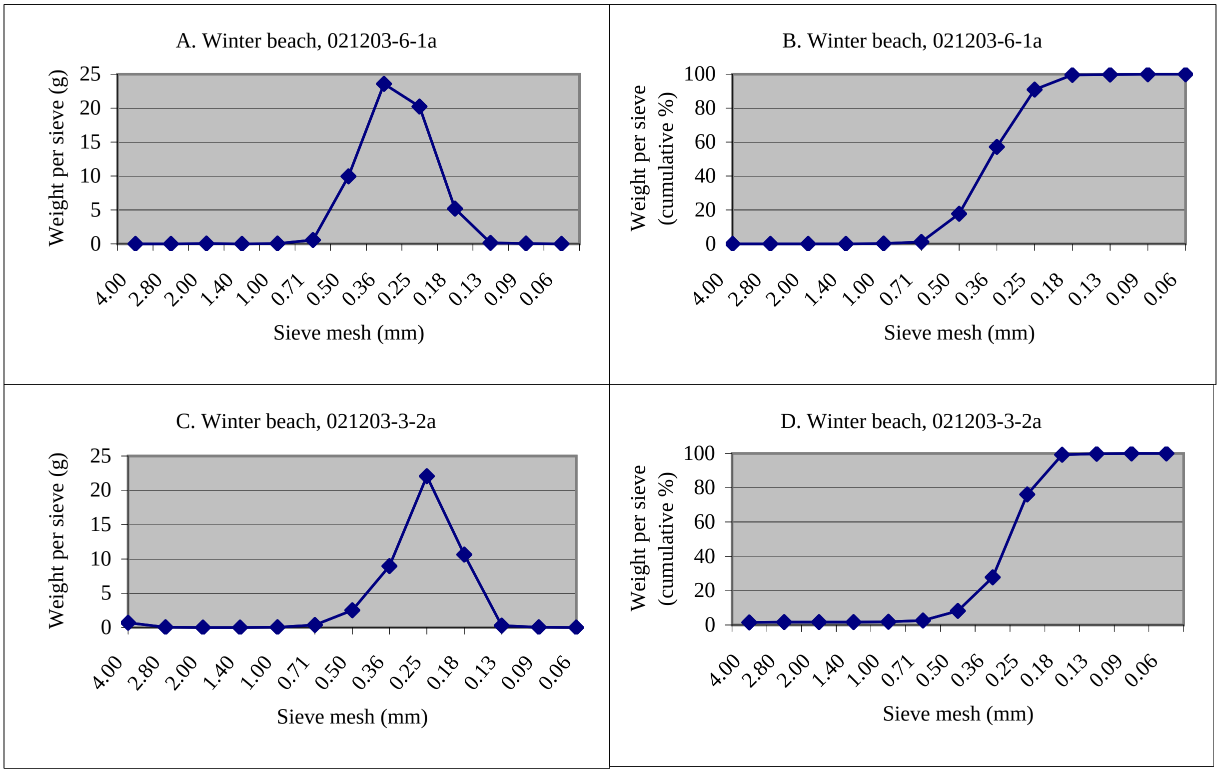


Figure 6. Frequency and cumulative frequency curves of winter beach sand samples. (A) 021203-06-1a, frequency curve; (B) 021203-6-1a, cumulative frequency curve; (C) 021203-3-2a, frequency curve; (D) 021203-3-2a, cumulative frequency curve.

Table 1. Locations of beach sediment stations.
GSP = Gulf State Park. Winter samples from stations in boldface.
(Modified from Kopaska-Merkel and Rindsberg, 2005.)

Station number	Station name	Latitude	Longitude	7.5-minute quadrangle
1	**Alabama-Florida state line**	**30.27970**	**-87.51818**	**Orange Beach**
2	Florida Point East (GSP)	30.27503	-87.54322	Orange Beach
3	**Florida Point West (GSP)**	**30.27326**	**-87.54987**	**Orange Beach**
4	Cotton Bayou (GSP)	30.26899	-87.58215	Orange Beach
5	Gulf Shores Public Beach (GSP)	30.24684	-87.68754	Gulf Shores
6	**Pine Beach**	**30.22865**	**-87.81492**	**Pine Beach**
6B	Little Lagoon	30.23699	-87.81815	Pine Beach
7	Fort Morgan East	30.22111	-88.00942	Fort Morgan
8	Little Lagoon Pass	30.24034	-87.73698	Gulf Shores
9	Pines public boat access	30.23864	-87.89011	St. Andrews Bay
10	Romar Beach	30.26214	-87.67070	Orange Beach
11	Gulf State Park Convention Center	30.24935	-87.66176	Gulf Shores
12	**Gulf State Park Pavilion**	**30.25359**	**-87.64273**	**Gulf Shores**
13	Cortez Street	30.23093	-87.92757	Pine Beach
14	Dauphin Island Sea Lab	30.24615	-88.07760	Fort Morgan
15	Dauphin Island Public Beach	30.24824	-88.12831	Fort Morgan NW
16	West End	30.24759	-88.19179	Fort Morgan NW
17	Alabama Highway 182 mile 2	30.23374	-87.77723	Pine Beach
18	Old pass East, Dauphin Island	30.24894	-88.13360	Fort Morgan NW
19	Old pass West, Dauphin Island	30.24959	-88.13674	Fort Morgan NW

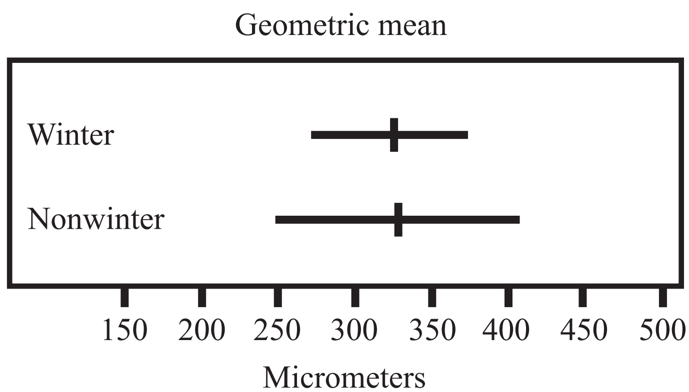


Figure 7. Means and standard deviations of geometric means of winter (n = 7) and nonwinter (n = 70) sieve data from Alabama beaches.

Table 2. Geometric mean particle sizes of winter and nonwinter beach samples from the same sites.[1, 2]

Station	Winter mean (µm)	n	Nonwinter mean (µm)	n
1 Alabama-Florida line	323.4	1	436.2	2
3 Florida Point West	361.6	2	341.9	2
6 Pine Beach	375.7	1	442.0	2
12 Gulf State Park Pavilion	296.8	1	306.3	1

[1] Excludes relatively coarse outliers.
[2] Fair-weather samples only.

Table 3. Proportions of samples having relatively coarse and fine sand in Baldwin County and offshore.

Category	**Decimal fraction of samples coarser than 500 µm**	**Decimal fraction of samples finer than 250 µm**
All offshore samples (n = 86)	0.10	0.57
Nonwinter beach samples (n = 39)	0.11	0.25
Winter beach samples (n = 6)[1]	0.09	0.19
Inner zone of oblique ridges (n = 64)	0.10	0.57
Middle zone of oblique ridges (n = 26)	0.10	0.58
Outer zone of oblique ridges (n = 6)	0.06	0.56
State waters (n = 22)	0.10	0.46
Federal waters (n = 64)	0.11	0.60
Graded Shelly Sand Lithofacies (n = 60)	0.13	0.48
Shelly Sand Lithofacies (n = 19)	0.07	0.59

[1] Excluding relatively coarse outliers.

One of those two samples was collected at neap tide, and one was collected a few days after neap tide (NOAA, 2004). Hence, seven out of eight coarse outliers were collected at or near neap tide, further supporting the inference that coarse samples correspond to windrows sampled low on the foreshores of neap-tide beaches (Kopaska-Merkel and Rindsberg, 2005).

BIOTURBATION

Bioturbation is the transport and mixing of sediment within the substrate by living organisms. In the vibracores, the burrows of animals were identified insofar as visual examination allowed, and the proportion of sediment that was bioturbated was estimated. This information is useful in interpreting environmental conditions on and beneath the seafloor.

Bioturbation is frequently studied in cores (Chamberlain, 1978). Because modern traces tend to have low visual contrast with surrounding sediment, X-radiography is the preferred method for studying them in cores (Howard, 1969a, b; Rindsberg, 1992). However, the sand resources project vibracores have desiccated and altered chemically too much since collection of for this method to be applied reliably.

Previous studies of bioturbation in Alabama waters were summarized by Rindsberg (1992), who examined cores from eastern Mississippi Sound. Of these studies, the most applicable to this study is that of Kent and others (1976), who studied the physical and biogenic sedimentary structures of environments from dunes offshore to a water depth of 43.3 m (142 ft) east of MMS Study Area 1. Parker and others (1997) and Hummell (1999) included brief notes on bioturbation in each vibracore used in the present study, but did not identify ichnotaxa and tended to underestimate the degree of bioturbation.

Vibracores and boxcores give different information on the sediment underlying the seafloor. Vibracores are long and narrow, and tend to disturb the uppermost sediment, whereas boxcores are short and wide, and thus sample only the uppermost sediment. Together, the two methods yield a more detailed image of the environment than either used alone. Fortunately, boxcores studied by Kent and others (1976) complement the vibracores studied by Parker and others (1997), Hummell (1990, 1999), and the authors.

Kent and others (1976) studied trench cuts and boxcores in four transects southward from Orange Beach, Alabama, and Perdido Key and Santa Rosa Island, Florida. In the inner sand ridge zone to a water depth of about 9-10 m (30-33 ft) (see "Geomorphology"), they noted that bioturbation was slight, but that several kinds of animals constructed burrows with distinct linings in the shifting sand. These include the ghost shrimp *Callianassa,* enteropneust *Balanoglossus,* and polychaetes *Onuphis* and *Diopatra,* which respectively construct burrows that might be termed as *Ophiomorpha*/*Thalassinoides, Arenicolites, Skolithos,* and *Diopatrichnus*. Farther offshore, in the oblique sand ridge field, Kent and others (1976) found that the uppermost sand was slightly to wholly bioturbated, with burrows dominated by those of the heart urchin *Moira atropos; Balanoglossus, Onuphis,* and *Diopatra* were also present, along with trails of sand dollars *Mellita* and nests of an unidentified burrowing wrasse ("miner fish"). The heart urchin burrows would be termed as *Subphyllochorda* in the fossil record.

Geological Survey of Alabama vibracores supplement the work of Kent and others (1976) in the oblique ridge field off Alabama. The uppermost layer of substrate is usually disturbed or absent in the vibracores, and fish nests are too large to recognize in the narrow cores. As shown by vibracores, the sand ridges consist largely of thick, fining-upward beds having high-angle crossbedding, commonly with basal shell lags (Parker and others, 1997). The burrows found in vibracores include *Ophiomorpha* and *Thalassinoides* as well as *Subphyllochorda* (a burrow attributable to heart urchins) and other traces that are incompletely understood (table 4). Only the crustacean and echinoid burrows are discussed in this report.

Ophiomorpha and *Thalassinoides* are similar and commonly occur at the same sites (fig. 8). *Ophiomorpha* is common in the Graded Shelly Sand lithofacies. The burrows are horizontal to oblique, usually 0.5 to 4.0 cm in internal diameter, and lined with distinct nodules of mud or muddy sand that are smoothed within the burrow but stick out into the host sand as knobs (fig. 8) (Rindsberg, 1992). *Thalassinoides* is similar to *Ophiomorpha* in size and orientation, but lacks the nodular lining; it can be identified positively only where the vibracore reveals one of the characteristic branch junctions. These junctions tend to be smoothly enlarged and may branch rather evenly at angles of about 120º. Thalassinidean burrows commonly penetrate modern substrates as deeply as several meters (Frey and others, 1978; Bromley, 1996).

Both *Ophiomorpha* and *Thalassinoides* occur in sand to muddy sand at all water depths and in all relevant environmental settings on the Alabama continental shelf, including MMS Study Areas 1 and 2 (table 4). Because the animals penetrate deeply in the substrate, they are easily preserved. Indeed, in some cases, modern burrows penetrate relict sediment, as in SR-31 (49-84.5 cm downcore), and they commonly obliterate the record of more shallowly penetrating burrows.

Echinoid burrows *Subphyllochorda* are recognizable in cross section as ovals of concentrically arranged sand and shelly debris, up to 7 cm wide (probable example, fig. 9) (Kent and others, 1976; compare Howard and others, 1974; Bromley and Asgaard,

Table 4. Traces in vibracores from the Alabama continental shelf.

Trace	Tracemaker	Environment	Zone and water depth	Vibracore, depth downcore (cm)
Ophiomorpha	thalassinidean shrimp including *Callianassa* spp.	oblique ridge stoss, lee, and deep end; swale; relict ridge	inner to outer (10.7-22.9 m; 35.0-75.1 ft)	SR-31, 49-84.5 SR-36B, 126 SR-100C, 393-403.5 SR-102, 0-22, 46-481 SR-103, 97-119, 207-210, 253-260, 271-273, 334-357 SR-110, 253-262, 277-283, 292-308 SR-111, 139-201
Thalassinoides?	thalassinidean shrimp including *Callianassa* spp.	oblique ridge crest, stoss, and lee; relict ridge; swale	inner to outer (10.7-22.9 m; 35.0-75.1 ft)	SR-33, 15-39 SR-36B, 138-159 SR-97C, 376-405 SR-98B, 345-358 SR-100C, 373-399 SR-102, 39-41 SR-111, 87-102 SR-114, 59-176 SR-115, 17-177
Subphyllochorda	irregular echinoids including *Moira atropos*	oblique ridge lee; relict ridge; swale	inner to middle (10.6-15.5 m; 34.1-51.0 ft)	SR-7B, 145-185 SR-22B, 161-167 SR-34A, 62.5-78.5 SR-111, 215-228
large, complex feeding trace	arthropods?	ridge stoss	inner (12.8 m; 41.9 ft)	SR-33, 41-44
narrow vertical burrows	polychaetes?	swale	middle (17.0 m; 55.9 ft)	SR-103, 290-304
narrow horizontal to oblique burrows	polychaetes or other worms?	ridge lee; swale	inner through middle (10.7-17.0 m; 35.0-55.9 ft)	SR-103, 368-403 SR-111, 61-87 many other examples
narrow, complex feeding trace	polychaetes or other worms?	ridge lee	middle (12.5 m; 41.1 ft)	SR-101, 197-214

A B

Figure 8. Photographs of vibracores including crustacean burrows *Ophiomorpha* and *Thalassinoides*. (A) Vibracore SR-100C, with 0 on scale equal to 367 cm downcore. Mud-lined, vertical *Ophiomorpha* at about 394-402 cm downcore (27-35 cm in photograph); collapsed vertical *Thalassinoides* at about 384-399 cm downcore (17-32 cm in photograph); (B) Close-up of *Ophiomorpha* and *Thalassinoides*.

A B

Figure 9. Photographs of vibracores including tentatively identified echinoid burrows *Subphyllochorda*. (A) Vibracore SR-102A with possible echinoid burrow at about 34.5-39 cm downcore. (B) Peel of vibracore SR-7B with probable but subtle echinoid burrows at about 162-167 cm downcore (corresponding to 17-22 cm in photograph).

1975). They are difficult to see without the aid of X-radiography, but Kent and others (1976) showed that they are very widespread in the uppermost few centimeters of sand on the Alabama shelf. *Moira atropos* is probably only one maker of *Subphyllochorda* off Alabama, as other heart urchins occur in the Gulf as well (Clark, 1954; Serafy, 1979). In the present study, echinoid burrows were found only within the inner and middle oblique sand-ridge zones (which are described in "Geomorphology"), but Kent and others (1976) found them in the uppermost part of the substrate in the outer zone to a water depth of 43.3 m (142 ft). At greater depths downcore in vibracores, the burrows are preserved only in the lee of sand ridges or in swales (table 4), that is, within the areas of most rapid deposition (Byrnes and others, 2004, fig. 7). All the other burrows not made by ghost shrimp are also shallow-tier traces and, like *Subphyllochorda,* are preserved only in these environments (table 4), indicating that they are preserved in the geologic record only where rapid burial removes them from the possibility of reworking by storms or ghost shrimp.

FACIES COMPOSITION AND STRATIGRAPHY

Lithofacies stratigraphy was described by Parker and others (1997) and summarized by Kopaska-Merkel and Rindsberg (2005). We retain the descriptive lithofacies terminology of Parker and others (1997), rather than using the newer classification based on depositional environment (Hummell, 1999), because the former classification is more applicable to the present study (table 5).

Table 5. Lithofacies of continental shelf sediments off Alabama (modified from Parker and others, 1997; Kopaska-Merkel and Rindsberg, 2005). The most suitable lithofacies for beach nourishment are italicized.

Facies associations	Lithofacies
Clean sand	*Graded shelly sand*
	Orthoquartzite
	Shelly sand
	Sand with mud burrows
Dirty sand	Muddy sand
	Muddy shelly sand
Biogenic sediments	Oyster biostrome
	Peat
Muddy sediment	Silty/clayey sand
	Sand-silt-clay
	Mud-sand interbeds
pre-Holocene	diverse

Following Hummell and Smith (1996) and Hummell (1999), we combine the Graded Shelly Sand and Echinoid Sand lithofacies (table 5). The Echinoid Sand lithofacies is neither widespread nor thick, and occurs almost exclusively at the surface on top of the GSS. The Echinoid Sand is probably part of the GSS; with transport and/or burial, the fragile echinoderm tests that are diagnostic of the Echinoid Sand degrade until they are no longer recognizable (Parker and others, 1997). This may result from physical or biogenic reworking, from chemical diagenesis, or from multiple factors. Further, we no longer distinguish between lithofacies and microfacies. Instead, all are referred to as lithofacies, and groups of similar lithofacies are facies associations (table 5).

In this report we focus on the GSS and SHS lithofacies because they are the best sources of sand for beach nourishment (Kopaska-Merkel and Rindsberg, 2005). The

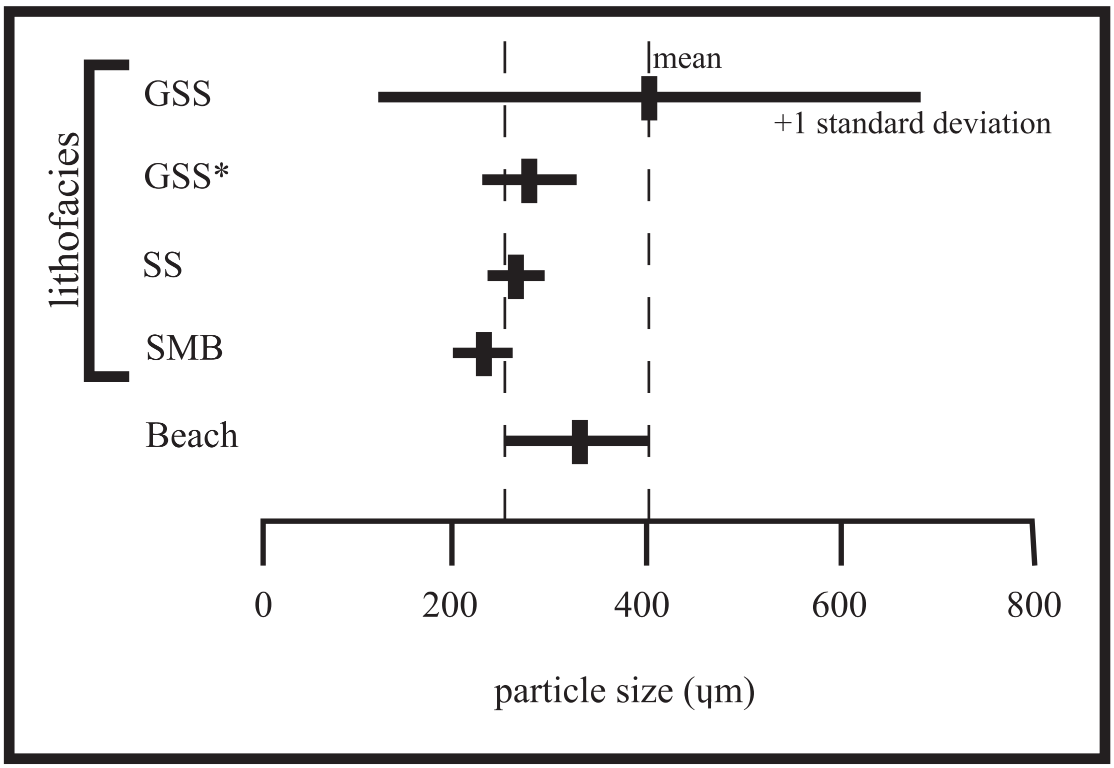
SMB lithofacies is similar in particle-size characteristics to the Shelly Sand lithofacies, but is noticeably finer (Parker and others, 1997) (fig. 10) and is uncommon in the area of study (fig. 11). Accordingly, this facies is not discussed at any great length in this report, but is briefly described in the section entitled “Sand with Mud Burrows Lithofacies” because it makes up part of the offshore sand resource.

GRADED SHELLY SAND LITHOFACIES

The Graded Shelly Sand lithofacies consists of normally graded shelly sand units that occur singly or stacked in successions up to at least 4.6 m (15 ft) in thickness. The thickness of individual graded layers may exceed 90 cm (3 ft), but averages about 30 cm (1 ft). Coarse lags are found at the base of some graded beds; others are amalgamated. The bases of graded beds that lack obvious coarse lags consist of sand that is slightly coarser than immediately overlying sand. The upper parts of upward fining units generally consist of thoroughly bioturbated shelly sand very similar to that found in the SHS, which is described in the next section.

Where present, the basal lag is a coarse, distinctly graded shelly sand consisting of medium to coarse sand together with whole shells and shell fragments. Relatively thick basal lags may grade upward from a sandless coquina with many whole mollusk valves, to sand-supported sandy shell composed largely of fragments, to sand-supported shelly sand with fragments and few whole valves. The shelly debris ranges widely in size from one station to another. Lags in some vibracores contain shells no larger than a few millimeters across, whereas others contain shells nearly as wide as the cores themselves (about 7.3 cm [2.875 inches]) (appendix A). Larger shells, which could not be sampled using vibracores, probably occur at some locations.

The graded units have sharp bounding surfaces that evidently result from widespread erosion during major storm events (Aigner, 1985). Parker and others (1997) realized that storm-event beds could be amalgamated, resulting in laminated to bioturbated sequences as thick as 4.6 m. We could document individual storm beds only as thick as 87 cm in the cores: still an impressive thickness for a depositional episode that lasted at most only days.



*Excluding relatively coarse shelly lags

Figure 10. Means and standard deviations of geometric mean particle sizes of Alabama beach sand and several offshore lithofacies. GSS, Graded Shelly Sand; GSS*, Graded Shelly Sand excluding relatively coarse shelly lags; SHS, Shelly Sand; SMB, Sand with Mud Burrows. (lithofacies defined by Parker and others, 1997).

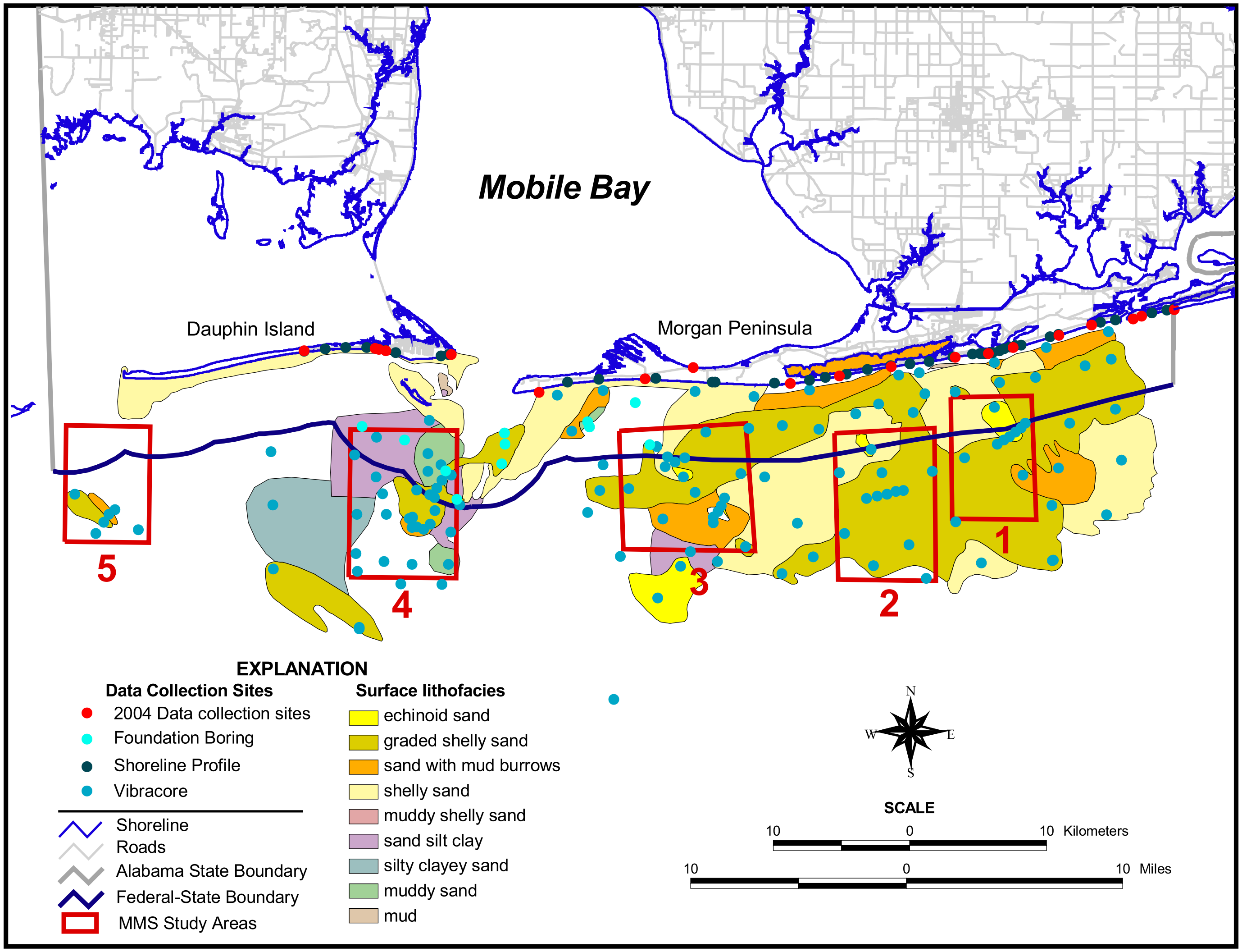


Figure 11. Map of surface sediment texture on the Alabama shelf (Kopaska-Merkel and Rindsberg, 2005; lithofacies defined by Parker and others, 1997).

The GSS is the coarsest lithofacies in offshore Alabama; it is similar to Alabama beach sand but includes a significant proportion of shells and shell debris, particularly at the bases of graded beds (Parker and others, 1997; Kopaska-Merkel and Rindsberg, 2005) (fig. 12; table 6). Indeed, grading is chiefly recognized in vibracores on the basis of sand- and gravel-sized shell fragments. Grading of quartz sand, where present, is subtle. The GSS is as coarse as Alabama beach sand (appendix C), but much more variable (table 6; fig. 12) because shelly lags in the GSS (fig. 13) are much coarser than beach sand or the bulk of the GSS. In fact, if shelly lags are excluded, then Alabama beach sand is significantly coarser than the GSS (appendix C). Exclusion of the shelly lags also reduces the variance of the GSS to a value comparable to that of Alabama beach sand.

Table 6. Moment measures of Alabama beach sand and selected offshore sediment lithofacies.[1]

Lithofacies	Geometric mean (µm)	Sorting	Skewness	Kurtosis
Beach sand[2] (n = 70)	327.50 ± 79.12	1.34 ± 0.12	0.74 ± 0.54	6.56 ± 3.14
Shelly Sand (n = 19)	250.51 ± 29.22	1.70 ± 0.18	1.70 ± 0.86	9.42 ± 4.42
Graded Shelly Sand (n = 57)	322.03 ± 181.89	1.81 ± 0.55	1.37 ± 0.72	7.79 ± 3.70
Graded Shelly Sand[3] (n = 53)	279.07 ± 50.95	1.69 ± 0.30	1.45 ± 0.66	8.21 ± 3.48

[1] ± indicates plus or minus 1 standard deviation.
[2] Nonwinter samples.
[3] Excluding the four coarsest samples.

The GSS, like Alabama beach sand, is unimodal. The mean particle size (excluding shelly lags) is 279 µm for GSS and 328 µm for Alabama beach sand, so on the average this offshore sand is considerably finer than beach sand. The mode for GSS is 405 µm but without the shelly lags it is 235 µm. The mode for Alabama beach sand is 318 µm, and the relationship between the modes is consistent with that of the means. The means for GSS and beach sand are greater than the modes, because the means have been pulled towards larger particle sizes by the coarse tails of shelly debris present in many samples. Sorting of GSS samples is 1.81 ± 0.55, whereas that of beach samples is 1.34 ± 0.12 (table 6). Excluding samples of shelly lags, sorting of GSS samples is 1.69 ± 0.30. Alabama beach sand is more homogeneous than sand in the GSS. If shells are screened out during dredging, as is done in some other states, then the relatively favorable sorting value of 1.69 should be used; if shells are pumped along with sand onto the beach, then the sorting value of 1.81 should be used.

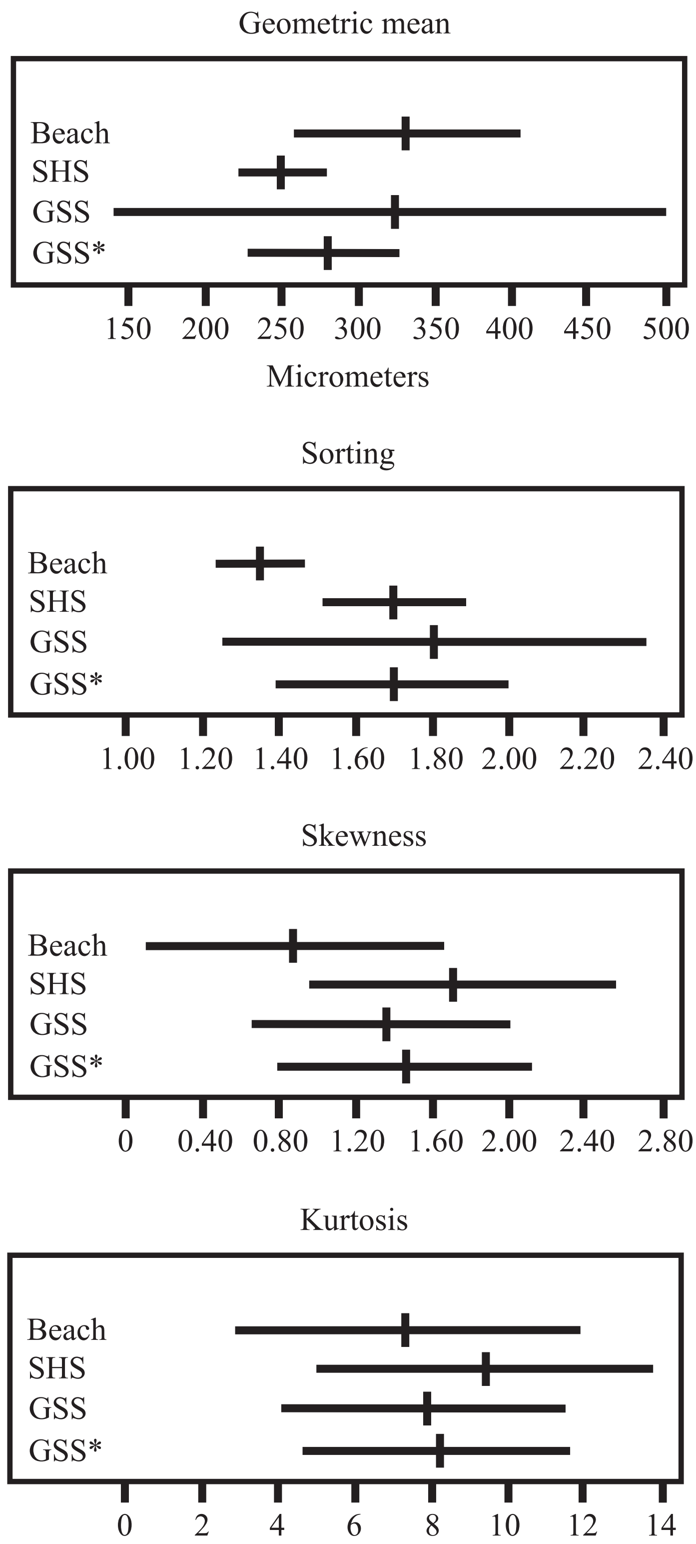


Figure 12. Means and standard deviations of four moment measures of Alabama beach sand, Shelly Sand (SHS), Graded Shelly Sand (GSS), and Graded Shelly Sand excluding four samples of basal shelly lags (GSS*).

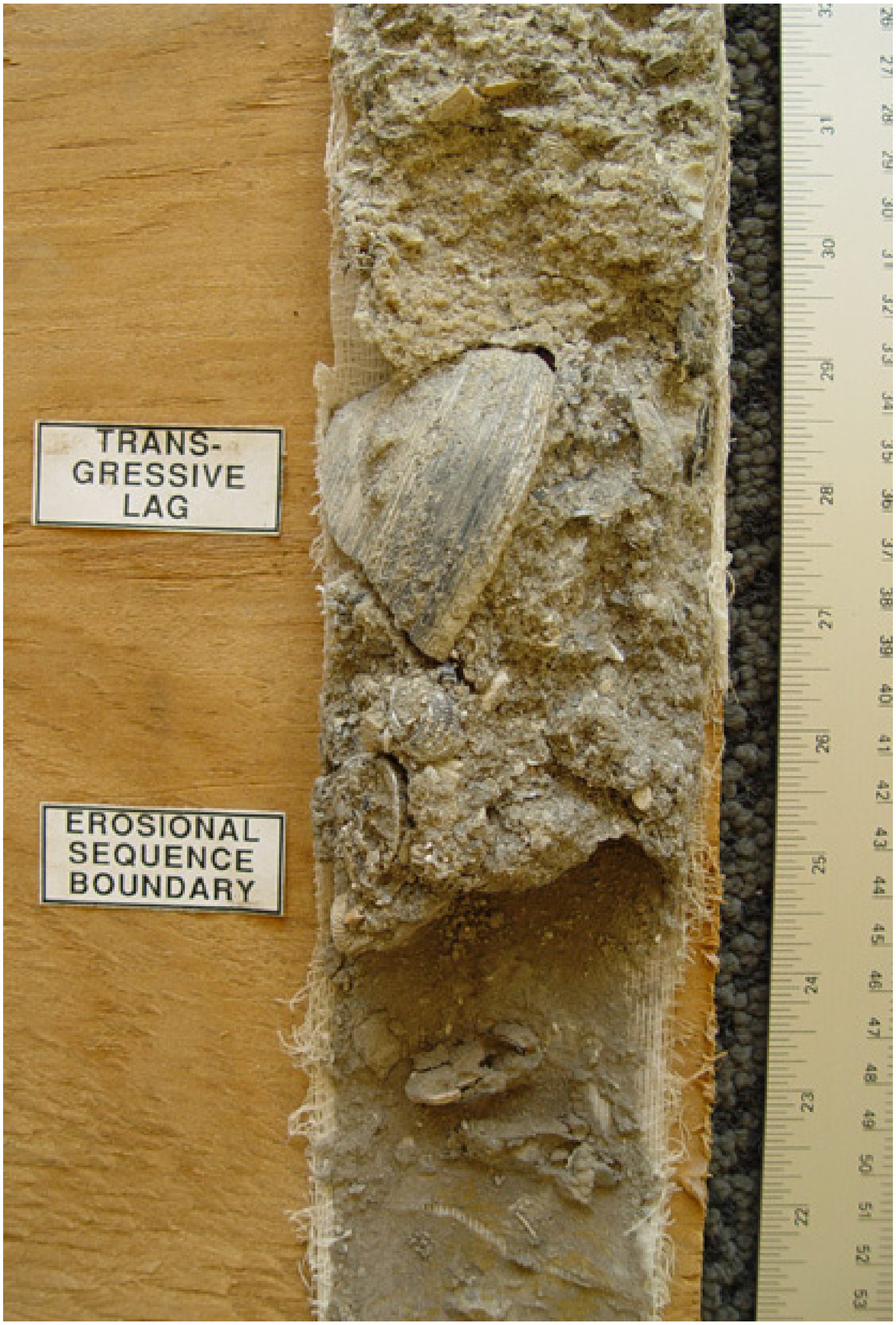


Figure 13. Coarse shell lag at base of graded layer in the Graded Shelly Sand lithofacies, vibracore SR-31. Centimeter scale (right) indicates depth downcore.

Regardless of where the GSS is mined for beach nourishment, some sand is likely to be finer and some shells coarser than the beach sand before nourishment. Skewness of GSS samples is 1.37 ± 0.72, whereas that of beach sand is 0.74 ± 0.54; in other words, GSS samples tend to have relatively prominent coarse tails that consist primarily of shelly debris (fig. 13). Beach sand kurtosis averages 6.56 ± 3.14, whereas GSS kurtosis averages 7.79 ± 3.70. These values are not greatly different, and most samples are leptokurtic, that is, much of the sample consists of a single narrow peak. The tails of the distribution (table 3) indicate that, exclusive of shelly lags, the GSS resembles Alabama beach sand at the coarse end of the distribution but on the average is considerably finer.

Samples collected from lags differ dramatically from samples collected higher in graded layers (figs. 14-17). Grading within basal lags is obvious (fig. 13), but grading above the basal strongly graded layers is subtle (fig. 18) (vibracores SR-20, 40, 112, 113) to nonexistent (for example, SR-34) (Parker and others, 1997; Hummell, 1999). Some suites of sieve data suggest a more complex history, for example, vibracore SR-109. Five samples from this core, spaced at 1-m (3.3-ft) intervals, are neither homogeneous in particle size nor smoothly graded. Coarsening and fining, accompanied by changes in sorting, suggest the presence of multiple graded layers.

Geometric mean particle sizes of samples from the GSS lithofacies form a positively skewed distribution (fig. 19) because strata assigned to this lithofacies consist of normally graded units ranging in thickness from a few centimeters to more than 4 m (13 ft) and having relatively coarse basal shell lags (fig. 13). Four samples of shell lags were sieved (the coarsest being SR-31, 30 cm; fig. 13), and these samples are largely responsible for the coarse tail in the distribution of GSS geometric mean particle sizes. Examination of vibracores and vibracore photographs suggests that relatively coarse shell lags account for substantially less than 5 percent of GSS sediment by volume.

Samples of the GSS lithofacies were evaluated for homogeneity of distribution of particle-size parameters. The GSS lithofacies can be divided on this basis into two sediment types that can be recognized throughout the area of study: shelly lag (n = 4; table 7) and (generally) bioturbated sand (n = 53; appendix B). Bivariate comparison of geometric mean, median, D10, and D90 particle-size parameters illustrates the

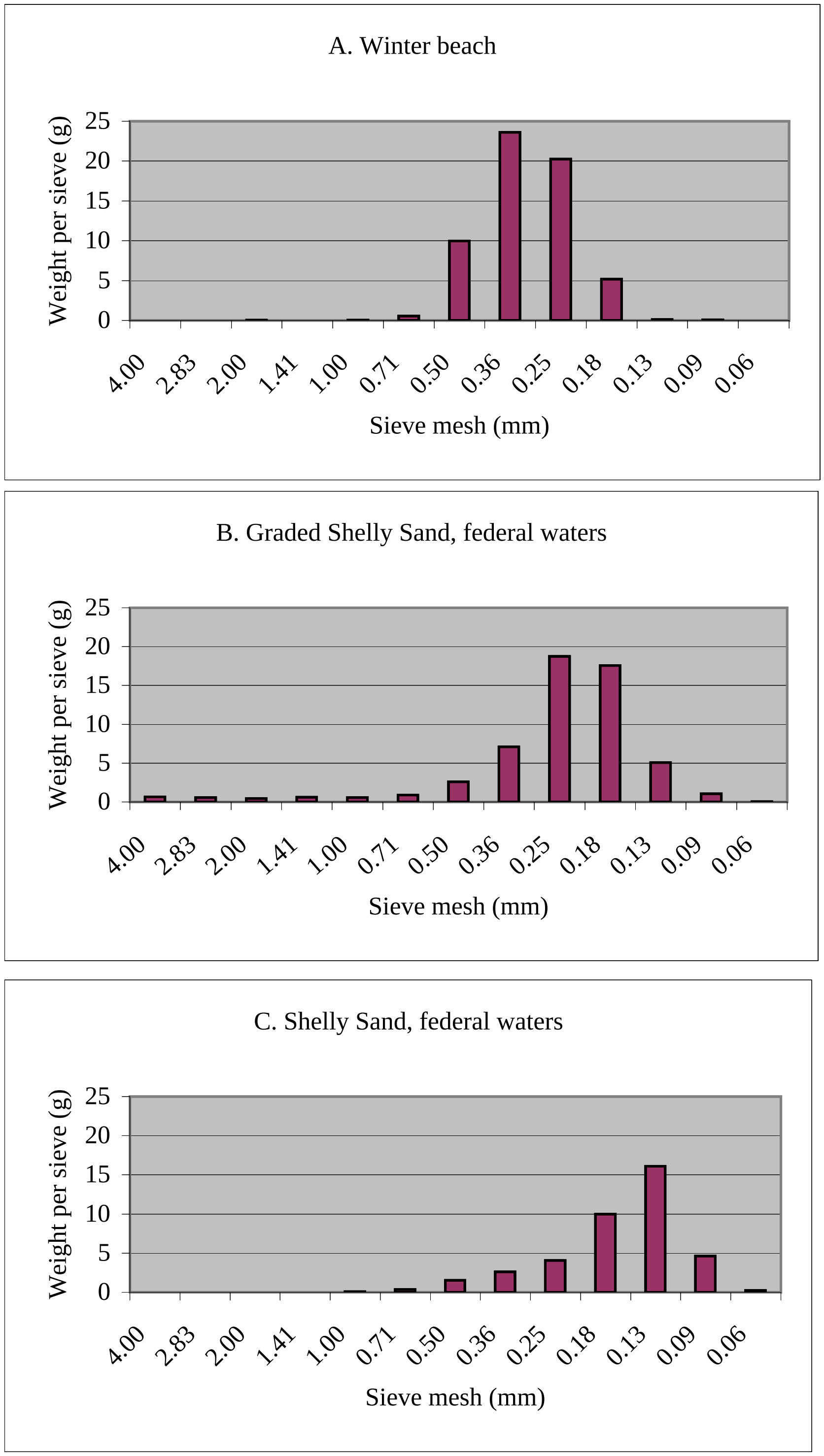


Figure 14. Histograms comparing particle-size distributions of representative samples of (A) Alabama winter beach sand, sample 021203-6-1a; (B) Graded Shelly Sand Lithofacies, SR-103A-15; and (C) Shelly Sand Lithofacies, SR-100B-200.

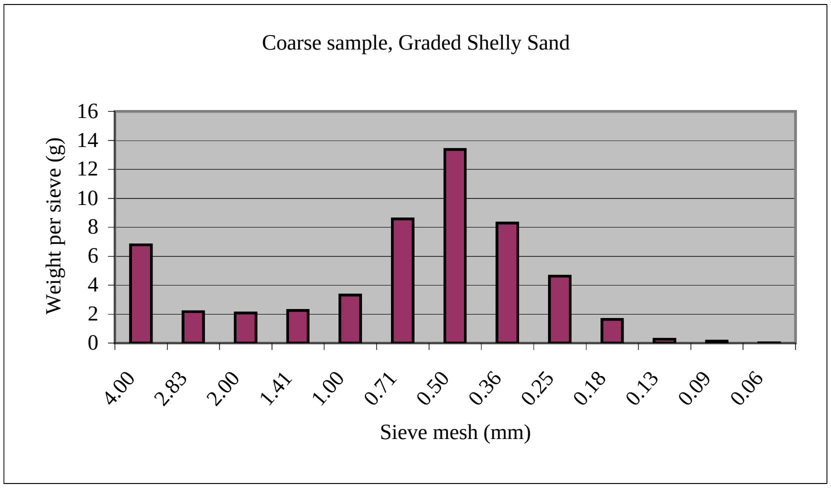


Figure 15. Histogram of relatively coarse sample from Graded Shelly Sand lithofacies, vibracore SR-23-bg.

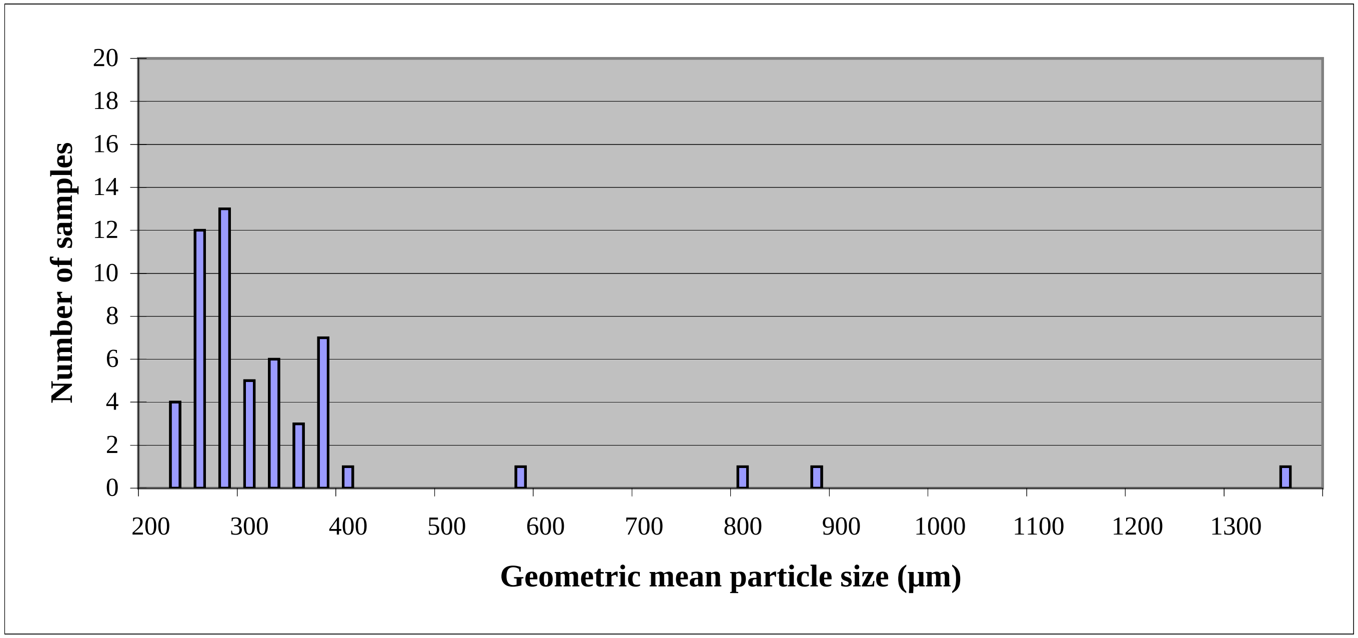


Figure 16. Histogram of geometric mean particle sizes of sieved samples from the Graded Shelly Sand lithofacies.

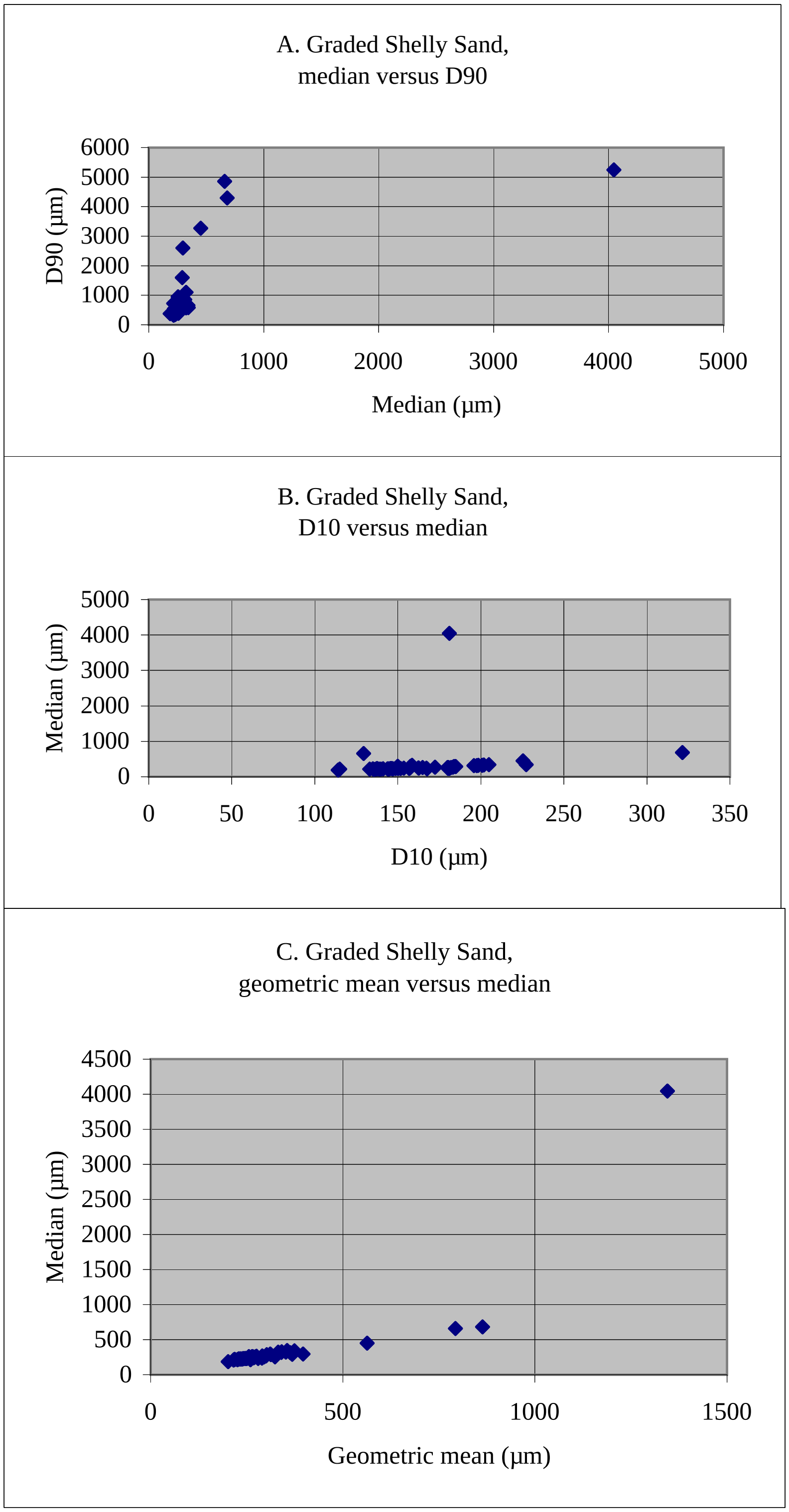


Figure 17. Bivariate comparisons of particle-size parameters for the Graded Shelly Sand lithofacies. (A) median particle size versus D90 (size greater than that of 90 percent of particles), (B) D10 versus median particle size, (C) geometric mean versus median particle size.

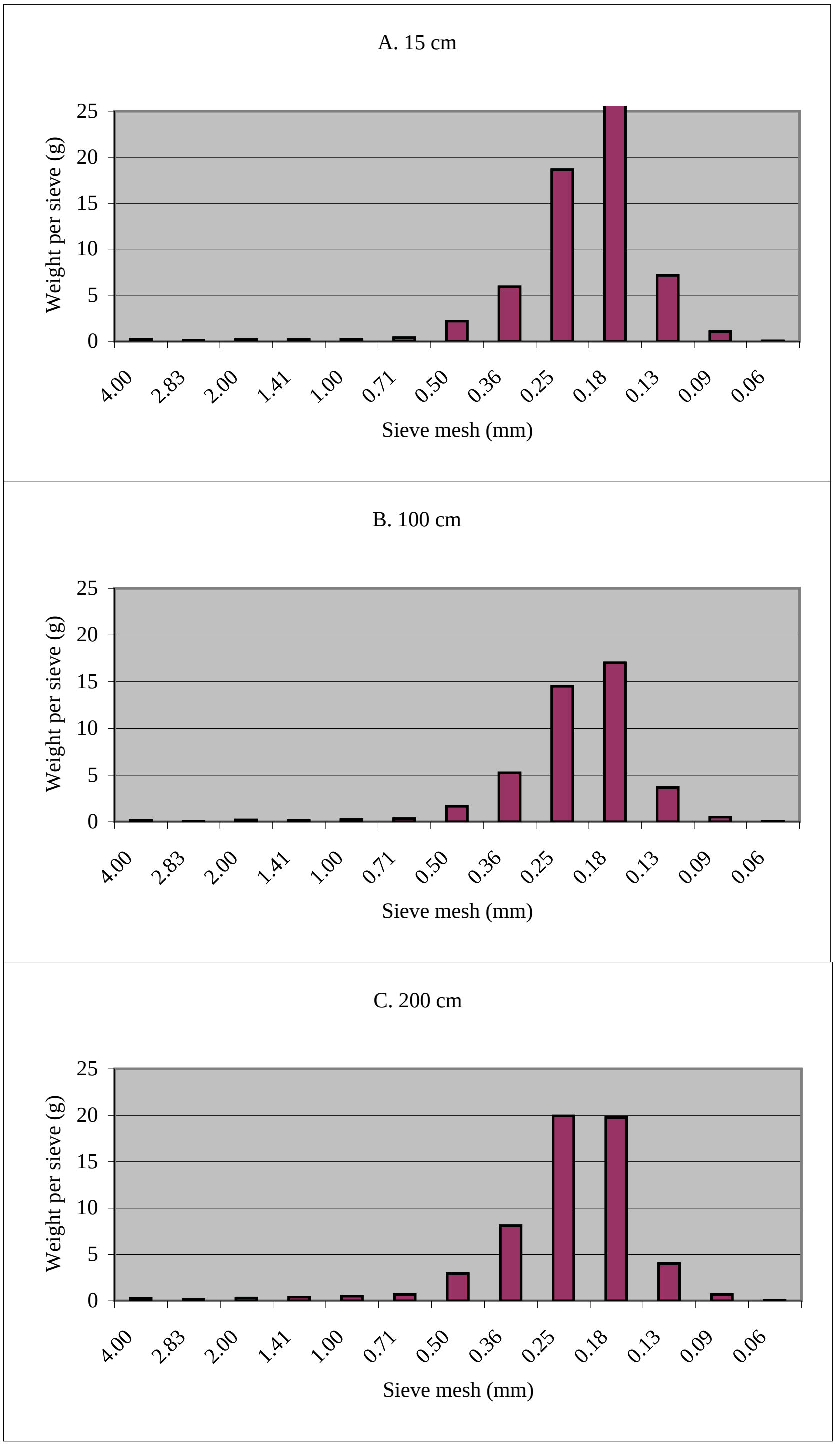


Figure 18. Subtle normal grading in sediment particle size within a graded layer (vibracore SR-113) at (A) 15 cm, (B) 100 cm, and (C) 200 cm downcore.

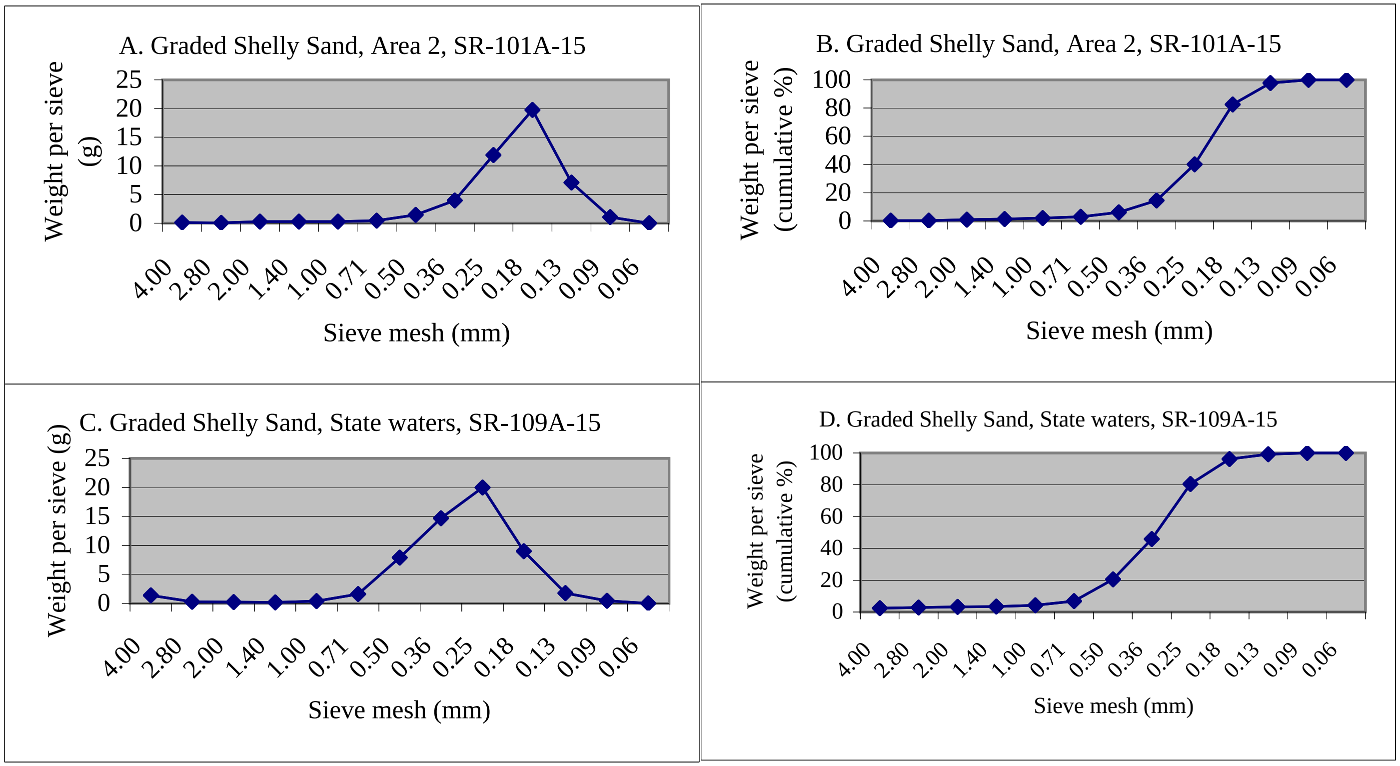


Figure 19. Frequency and cumulative frequency curves of Graded Shelly Sand samples. (A) Area 2, SR101A-15, frequency curve; (B) Area 2, SR101A-15, cumulative frequency curve; (C) State waters, SR109A-15, frequency curve; (D) State waters, SR109A-15, cumulative frequency curve.

Table 7. Sieved samples of shelly lags in the Graded Shelly Sand lithofacies.

Sample number	Vibracore	Sample depth (cm)	Geometric mean particle size (µm)
SR-31-30	SR-31	30	563.6
SR-34-350	SR-34	350	1,345.3
SR-23-bg	SR-23	Surface	863.3
SR-27-bg	SR-27	Surface	792.7

homogeneity of the structureless sand and its difference from the shelly lag sediment type (fig. 17). Relatively coarse samples of shelly lag stand out from samples of structureless sand, which form a coherent group in terms of particle-size distribution and grading. The difference between the two sediment types also can be seen in histograms (fig. 16) and by visual inspection of vibracores (figs. 13, 20, 21). Shelly lags in the GSS in the area of study are thin (60 cm or thinner; Parker and others, 1997), and where the GSS is relatively thick (several meters), it typically consists of stacked beds each of which fines upward from a shell lag to slightly shelly sand (for example, SR-6, 10, 110, 114) (Parker and others, 1997; Hummell, 1999). Because shell lags are thin and intercalated with thicker intervals of sand that are laminated-to-bioturbated upward, the two sediment types are not separately mappable and cannot usefully be identified as subfacies. Vibracore penetration is halted by stiff shell lags and several vibracores in our dataset end only a few centimeters into shell lags, so it is possible that thick shell lags exist but were not sampled.

SHELLY SAND LITHOFACIES

Following Parker and others (1997, p. 41), the SHS is defined as follows:

> clean sand with a variable component of molluscan shell material, at times including some echinoderm fragments. All units are sand supported, and most contain mud filled burrows. Unlike the Graded Shelly Sand Facies, this microfacies shows at most very minor grading. Units are often much thinner (less than one foot [0.3 m]) than those of the Graded Shelly Sand Facies, and bases may not be as sharp.

The SHS is dominated by quartz sand, but contains an average of 5.6 percent shell debris (Parker and others, 1997). This lithofacies is less common than the GSS and tends to be thinner, but is fairly widespread both on the seafloor (fig. 11) and beneath it (Parker and others, 1997; Hummell, 1999).

Figure 20. Photograph of peel of coarse shelly lag, Graded Shelly Sand lithofacies, vibracore SR-35, 345-369 cm downcore. Add 267 cm to scale to get true core depth. Interval 69-78 cm is typical of the upper portions of graded units that make up this lithofacies.

Figure 21. Photograph of Shelly Sand, vibracore SR-100A 93-106 cm downcore. Depth downcore is indicated in centimeters.

The SHS lithofacies is distinguished from the GSS lithofacies primarily because it lacks the relatively coarse, normally graded shell lags that give the GSS its name. In addition, the SHS is significantly finer (mean particle size 251 µm; appendix C), more strongly skewed, and more platykurtic than the GSS (fig. 12; table 6). Shell contents of the SHS and GSS are similar (Parker and others, 1997), and, if coarse tails are excluded, the sand particle-size distributions are similar (table 8). The SHS and GSS are equally well sorted (1.70 ± 0.18 and 1.69 ± 0.30) (table 6). The SHS is unimodal, with a mode of 221 µm, which is similar to that of the GSS (235 µm excluding shell lags) and indicates that the most abundant particles are not much smaller in the SHS (fig. 22). Although shelly sand assigned to this lithofacies is significantly finer than Alabama beach sand, the size distributions overlap extensively (table 6) and this sand could be used in beach replenishment.

Table 8. Average of geometric means of truncated size distributions for sand of preferred particle size for beaches (very fine to medium sand).

Data set	Average (µm)	Standard deviation (µm)
Alabama fair-weather summer beaches (n = 20)	319	40
Alabama fair-weather winter beaches (n = 7)	308	36
Alabama storm beaches[1] (n = 41)	296	30
Graded Shelly Sand (n = 53)	235	46
Shelly Sand (n = 19)	225	42

[1]These data may be biased toward finer particle sizes (Kopaska-Merkel and Rindsberg, 2005).

SAND WITH MUD BURROWS LITHOFACIES

The Sand with Mud Burrows lithofacies was not a focus of study this year, because it is finer than either the SHS or GSS, and is therefore less desirable as a source of sand for beach nourishment (Parker and others, 1997; Kopaska-Merkel and Rindsberg, 2005). Pooling data from both sources, the SMB averages 210 ± 94 µm in particle size. Most samples of the SMB are finer than most samples of Alabama beach sand (Kopaska-Merkel and Rindsberg, 2005, fig. 14), so the overfill ratio would be highly unfavorable if this material were used to replace sand lost from Alabama beaches. The SMB consists of

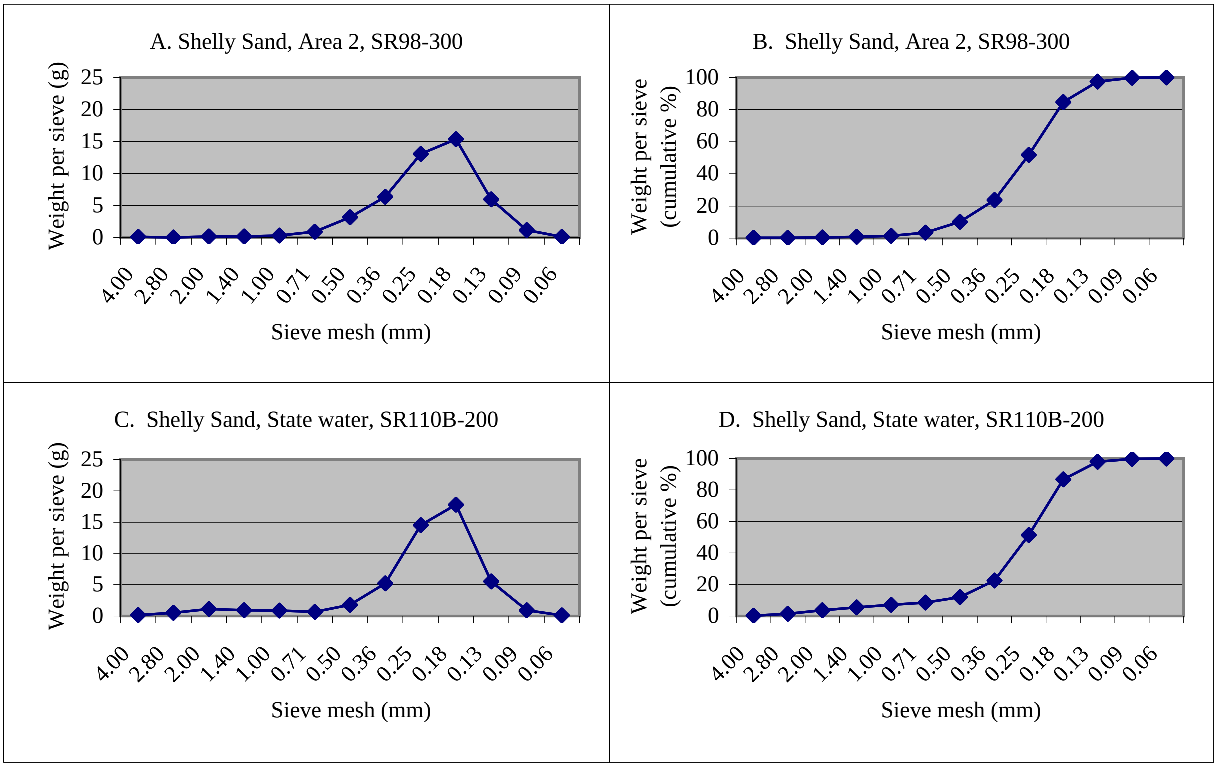


Figure 22. Frequency and cumulative frequency curves of Shelly Sand samples. (A) Area 2, SR-98-300, frequency curve; (B) Area 2, SR-98-300, cumulative frequency curve; (C) State waters, SR-110B-200, frequency curve; (D) State waters, SR-110B-200, cumulative

clean sand that commonly has less shell debris than the SHS or GSS. The lithofacies is characterized by common mud-lined burrows (*Ophiomorpha*) and these linings apparently account for most of the fine material in the SMB (Parker and others, 1997).

GEOMORPHOLOGY

The geomorphology of the eastern Alabama continental shelf, particularly of the oblique sand ridges, was investigated to achieve a better understanding of the target sand facies that they contain. Although many geomorphic studies of the Alabama coast have been published (Carlston, 1950; Hardin and others, 1976; Smith, 1996, 1998; and references therein), few have touched on the geomorphology of the shelf. When it was realized that the offshore sand ridges constitute an economic resource, interest in them increased (Brooks and others, 1989; Davies and others, 1993; Davies, 1994; Parker and others, 1997; Byrnes and others, 2004; Hayes and Nairn, 2004).

Most of the Alabama shelf is smoothly covered by siliciclastic sand to mud, but the edge of the continental slope is locally irregular and includes hardgrounds (Ludwick, 1964; Boone, 1973; Parker and others, 1997). The Alabama shelf has markedly different topography east and west of Mobile Pass at the mouth of Mobile Bay (Parker and others, 1997, p. 8-11) (pl. 1). West of Mobile Pass, the shelf is relatively steep and lacking in relief. East of Mobile Pass, the shelf as a whole has a relatively gentle seaward slope but is characterized by two sets of ridges (pl. 1), one consisting of large ridges oriented approximately ENE-WSW, and the other consisting of smaller, overlapping ridges oriented approximately SE-NW. Seaward of Mobile Pass itself, a roughly semicircular ebb-tidal delta is present, part of which (Sand Island) is intermittently emergent (pl. 1). Although the study area focuses on the oblique sand ridges, context is useful and so each of these features is discussed here.

MOBILE EBB-TIDAL DELTA

The mouth of Mobile Bay is characterized by a large ebb-tidal delta, that is, a delta formed by an excess of ebb-tidal currents (aided by flux from the Mobile and Tensaw Rivers) over flood-tidal currents (Boone, 1973; Hummell, 1990). The delta (pl. 1) consists of a flattish platform (the ebb ramp) with steeper sides (the ebb shield) (pl. 1). The Mobile ebb-tidal delta is thought to have been built up during the last 4,500 years based on comparison with a similar, radiocarbon-dated delta in South Carolina

(Hummell, 1990). In its natural state, the delta consisted of a large semicircular lobe with the western rim extending above sea level as a discontinuous series of islands, plus a smaller lobe in deeper water (Ryan, 1969; Ryan and Goodell, 1972; Hummell, 1990). The tides kept a channel (Mobile Pass) as deep as 16 m (54 ft) open, shallowing to north and south.

To allow shipping through the outer shoal, Mobile Pass was deepened and extended through the tidal bar at its southern tip during the latter half of the nineteenth century. This evidently diverted sand beyond the southern tip of the small lobe (Ryan, 1969; Ryan and Goodell, 1972). In recent years, the U.S. Army Corps of Engineers has dumped dredge spoil from Mobile Pass onto a disposal site south-southwest of the ebb-tidal delta, creating a ridge of minable sand in MMS Study Area 4 (Hummell, 1999). Westward currents evidently still supply the part of the delta west of the channel with sediment, as sediment-laden plumes of floodwater have been observed (Hardin and others, 1976; Abston and others, 1987). Water depths are relatively stable (Byrnes and others, 2004, fig. 7), so influx of new sediment evidently offsets erosion. However, erosion dominates the part of the delta east of the channel (Byrnes and others, 2004, fig. 7).

The ebb-tidal delta is a complex of diverse lithofacies (Hummell, 1990). In general, relatively coarse ebb-ramp strata consisting largely of cross-bedded, shelly, clayey sand overlie finer ebb-shield strata made up largely of partially bioturbated shelly clay with sand lenses. Tidal channel deposits, probably consisting mainly of cross-bedded sand, cut into ebb-shield and ebb-ramp strata alike.

BALDWIN SHOAL

The largest ridges on the eastern Alabama-Florida shelf trend west-southwestward, unlike the smaller ridges of the oblique ridge field. These include the North Perdido Shoal in federal waters south of Perdido Key (Browder and others, 2003), and Baldwin Shoal in state and federal waters south of the Morgan Peninsula (Browder and others, 2003) (pl. 1).

Baldwin Shoal is the largest linear ridge on the eastern Alabama shelf (pl. 1). The ridge is connected to the Morgan Peninsula shoreface at Pine Beach. It slopes gently and irregularly to the southeast, with surficial oblique sand ridges that continue downslope.

However, the northwestern slope is linear and (relatively) steep, and the adjacent depression has a closed contour.

Beneath a thin modern sand sheet (including oblique ridges), Baldwin Shoal is underlain by ebb-tidal deposits (Parker and others, 1997, p. 11). These authors noted that the ridge is located south of a channel of the ancestral Mobile River that was active during a Pleistocene lowstand. The river valley would presumably have been drowned during the Holocene transgression to become the large depression between the Mobile ebb-tidal delta and Baldwin Shoal. Parker and others (1997) speculated that the ridge might be a relict feature made up of deposits from a Pleistocene ebb-tidal delta, or alternatively from an early Holocene barrier spit that was overtaken by rising sea level during transgression. The two explanations are not mutually exclusive; the eastern tip of Dauphin Island, for example, is currently part of a barrier island that may have originated as a Pleistocene marine or coastal terrace deposit (Otvos, 1979; compare Smith, 1997). Four of the seven vibracores in Baldwin Shoal penetrated the surficial sand sheet into older deposits compatible with deposition on an ebb-tidal delta (SR-1, 4, 5, 10). However, the linear form of the ridge, with as much as 6 m (20 feet) of relief to the northwest, and its narrowing westward, both suggest a barrier or interfluve role, possibly with an episode of channeling on the northwestern side before final submergence.

Minor features of Baldwin Shoal can be related to ancient and ongoing processes. The northwestern slope of the ridge is relatively steep, straight, and well defined, but the southeastern slope is gentle and highly irregular. The shape of the northwestern slope may be inherited from the eastern valley wall of the ancient Mobile River; if sand were transported over the ridge into the large depression to the west, that would have smoothed the form of the valley wall. Oblique sand ridges are clearly superficial, as shown by vibracores. In sum, the shape of the shoal may be that of the ebb-tidal delta as modified by fluvial erosion and later by migration of oblique sand ridges. However, further subsurface investigations are needed to test this speculation.

Oblique sand ridges are superimposed on Baldwin Shoal; these are smaller ridges and swales of shape, dimensions, and orientation similar to those characterizing most of the eastern Alabama shelf. Their relief is up to about 3 m (9 ft), and seven vibracores (SR-1 to 5, 9, 10) show that they are composed of about 1.2 to 4.7 m (4 to 15.4 ft) of one or more fining-upward beds of clean, shelly sand (GSS lithofacies). The base of the surficial sand sheet is at 13 to 18 m (44 to 60 ft) below MSL in these vibracores, with the greatest depths being at SR-1 on the northwestern slope and at SR-10 near the southwestern tip of the ridge. The vibracores on the main part of the ridge have the disconformity at 13 to 14 m (44 to 46 ft), a depth similar to that of the disconformity farther east on the shelf.

As shown by Byrnes and others (2004, fig. 7), Baldwin Shoal was dominantly erosional between 1917-20 and 1982-93, with some areas being eroded by as much as 2.0 m (6.6 ft). This further indicates that Baldwin Shoal is a relict feature.

OBLIQUE SAND RIDGES

Most of the eastern Alabama continental shelf is covered by topography with a linear pattern characterized by curved ridges and swales oriented more or less northwest-southeast, markedly oblique to the shoreline (pl. 1). Smaller fields of oblique ridges are present on the western Alabama shelf as well (pl. 1). Continental shelves having similar fields of ridges oblique to shore include parts of the North Sea (Houbolt, 1968; Caston, 1972; David and Balson, 1992), Georges Bank (Stewart and Jordan, 1964), New Jersey (Stubblefield and Swift, 1976; Stubblefield and others, 1984), Maryland and Delaware (Hayes and Nairn, 2004), and the Gulf shelf off parts of central Florida (Hyne and Goodell, 1967; Harrison and others, 2003).

Many different interpretations have been proposed for the origin of these ridge fields. When improved nautical charts revealed the ridge fields' existence, Shepard (1960) considered them to be relict features: beach or dune ridges, or even interfluves, drowned as the sea rose during the past ten thousand years or so. He gave the ridge field off Baldwin County as one example. Although Emery (1968) noted that the ridges to a depth of about 18 m (60 ft) were composed of movable sand and drew a careful distinction between modern and relict ridges on continental shelves, including the Alabama shelf, some subsequent researchers thought that the Alabama ridges were relict. Hayes (1967), working on the central Texas coast, noted that water returning to the sea from lagoons after hurricanes could transport sediment onto the shelf. Another explanation was put forth by Houbolt (1968) when he interpreted the North Sea ridges as tidal, and this concept was broadly applied in the petroleum industry (Stride and others, 1982). However, the Alabama ridges, being in a microtidal regime, did not fit this model, and further study showed that the North Sea ridges themselves are relict (David and Balson, 1992). Swift and others (1971, 1983) reconsidered the concept of relict shelf sediments, and Morton (1981) offered a reinterpretation of the Gulf and North Sea ridges as storm deposits.

Davies and others (1993) and Parker and others (1997) sampled the Alabama ridge field in detail, and they determined that most of the parallel, oblique ridges are composed of thick-bedded sand overlying the basal Holocene transgressive unconformity. Because only winds of hurricane force could generate waves sufficient to stir the seafloor to such depths, Parker and others (1997) concluded that hurricanes had created the ridge field, though the direction of sand transport remained speculative. Byrnes and others (2004) agreed, and further discovered that the oblique, parallel ridges closest to shore have been moving generally southwestward since the 1920s, while irregular shelf ridges farthest from shore (pl. 1) are eroding. Thus, the oblique ridges are forming today but the irregular ridges of the outer shelf are relict.

Based on new bathymetric data (pl. 1), the oblique ridges and swales are arranged in three zones that broaden westward and end abruptly south of Mobile Pass, west and south of Baldwin Shoal (pl. 1). The three zones are distinguished by breaks in shelf slope at 12 and 17 m (respectively, 39 and 56 ft) below mean sea level. The base of the shoreface, marked by another break in slope, ranges from about 5 m (16 ft) below sea level at Perdido Key to about 9 m (30 ft) on the barrier separating Little Lagoon from the Gulf.

Each zone has its own characteristic geomorphology, although some ridges are continuous across the zones and ridges of the inner and middle zones are similar. The general pattern is of approximately parallel, anastomosing ridges oriented approximately NW-SE near the shore to WNW-ESE farther offshore (pl. 1). Ridges are nearly straight to curved, bowing outward to the southwest; they have narrow crests and are asymmetric, with relatively gentle slopes on the northeast and steeper slopes on the southwest. The gentler slopes are identified as stoss slopes, and the steeper slopes as lee slopes, based on bathymetric changes over time as documented by Byrnes and others (2004, fig. 7). The ridges in deeper water are short and somewhat irregular, with relatively steep lee slopes.

The innermost ridges are welded onto the shoreface (pl. 1). These ridges tend to curve in a more northerly direction close to shore.

The intervening swales are relatively narrow and sloping in the inner zone, but broader and flatter in the middle zone. Vibracores show that swales in the middle zone are underlain by pre-Holocene strata with only a thin veneer of recent sediment.

The stoss-lee asymmetry of the ridges suggests southwestward transport of sediment on the Alabama shelf (Byrnes and others, 2004, fig. 7). The southwestward bowing of ridges is consistent with this interpretation. More subtly, ridges overlap most in the inner zone where swales are narrow; indeed, the longest ridges tend to have the greatest relief and to branch into smaller ridges on the lee side, suggesting that relatively fast-moving ridges are overtaking and covering other ridges as they travel southwestward. The proximate sediment source for the Alabama shelf is thus the Santa Rosa Island shore and shelf in Florida. The ridges become more distinct and more separated by broad, sediment-poor swales away from this source, suggesting that sediment eroded from the Alabama shelf does not contribute greatly to the oblique sand ridges. If this is so, then much of the sand entering the Baldwin County shelf from the east probably ends up in relatively deep federal waters south of Baldwin Shoal.

Sediment transport from shallow to deep water is also indicated by net deposition in the outer zone of oblique ridges (Byrnes and others, 2004, fig. 7). Even farther offshore, on the shelf characterized by irregular relict landforms, erosion is localized on irregular ridges and deposition in irregular swales, showing that the shelf is in a process of becoming smoothed out there.

Comparative evidence comes from the western Alabama continental shelf, which includes relatively small and poorly developed fields of oblique sand ridges in and near MMS Study Areas 4 and 5 (pl. 1). One such field is associated with Petit Bois Pass and Petit Bois Island, and another with the U.S. Army Corps of Engineers dredge-spoil dumping ground south of Dauphin Island. These ridges have approximately the same orientation as those off Baldwin County. The Petit Bois field has a similar pattern of sediment transport as the eastern Alabama shelf, with southwestward movement across ridges and southeastward movement downslope to the southeast. The Dauphin field, which has been enriched with a vast quantity of added material, shows only accretion and may well have formed in response to dumping of dredge spoil. (It is curious that the Mobile ebb-tidal delta, a major sand body, is not associated with additional oblique ridges, but most of the surrounding seafloor seems to be in equilibrium [Byrnes et al., 2004, fig. 7].) On both eastern and western shelves, the evidence suggests that oblique sand ridges form only where sand has been added to the Alabama shelf from the coast, not from erosion of the shelf itself.

INNER ZONE

The inner zone of the oblique sand-ridge field extends from the shelf off Santa Rosa Island, Florida, west to Baldwin Shoal off the Morgan Peninsula, between the shoreface and middle zone (pl. 1). The zone includes the sand veneer of Baldwin Shoal, but not the large swale north of it; the inner zone becomes detached from the shoreface at Pine Beach. The inner zone broadens westward from about 7 km (4 miles) off Pensacola Pass to about 11 km (7 miles) on Baldwin Shoal and vicinity. The base of the shoreface lies at about 5 to 9 m (16 to 30 ft) below mean sea level, deepening westward, but this applies mainly to the swales between ridges. Where ridges are welded onto the shoreface, both have nearly the same water depth. The line between inner and middle zones follows a subtle break in slope on the shelf, as seen in swales. Where ridges cross the boundary, particularly on the shelf south of Little Lagoon, the boundary is blurred.

Off Perdido Key, Alabama and Florida, the inner zone crosses a discontinuous submarine scarp that trends northwest-southeast (pl. 1). The bathymetric features on the continental shelf northeast of this scarp are elevated by about 3 m (10 ft) compared to that on the southwest.

All sand so far mined from sources off the Baldwin County shore has been from inner-zone oblique ridges close to the shore. The seafloor off Gulf Shores has a ridge-and-swale bathymetry, with ridges and swales tapering to the southeast (pl. 1; compare Hammer and others, 2000, unnumbered figure on p. 6).

The seafloor north of Study Area 1 was mined for the beach nourishment project of 2000 (Hammer and others, 2000). A ridge south of the western boundary of Gulf State Park was selected as the sand source; sand was mined to a depth of about 13 m (43 ft) below MLLW, as much as 5 m (16 ft) beneath the seafloor. The northern edge of the mined area is about 1,500 m (5,000 ft) south of the Gulf Shores shoreline (Hammer and others, 2000). Subsequent borrow pits have been situated similarly (fig. 2).

MIDDLE ZONE

The middle zone of the oblique sand-ridge field is bounded by breaks in slope that separate it from the inner and outer sand-ridge zones. The middle zone, like the inner zone, is recognizable off Pensacola Pass, but with a discontinuity across the aforementioned scarp (pl. 1). In most respects, the middle zone is similar to the outer part of the inner zone, and some ridges cross the boundary. MMS Study Areas 1 and 2 are largely situated within the middle zone (pl. 1). During the 1990s, the Geological Survey of Alabama recovered ten vibracores from Area 1 (SR-34, 35, 39 to 45, and 102) and 13 vibracores from Area 2 (SR-24 to 33, 97, 98, and 101) (Parker and others, 1997; Hummell, 1999).

In May and December 1997, Byrnes and others (1999) collected 16 Smith-McIntyre grab samples within Area 1 and four more nearby. They collected 16 grab samples within Area 2, with additional trawls and water-column samples. Infauna and sediment texture were identified based on these samples. Also, the bottom was trawled twice along two transects and water-column properties were measured at four stations (Hammer and others, 2000, fig. 4-2). Water-column parameters included temperature, conductivity, dissolved oxygen, and water depth. Salinity was calculated from conductivity and temperature.

Results for Areas 1 and 2 were similar. Numerically, the most abundant infaunal taxa in the May 1997 grab samples were the gastropods *Caecum pulchellum* and *Caecum cooperi,* followed by undifferentiated bivalves, the polychaete *Spiophanes bombyx,* and bivalves *Tellina* spp. (Hammer and others, 2000, table 4-1). In December 1997, the total numbers were about two-thirds of those for May; the most abundant taxa were *Caecum pulchellum, Caecum cooperi, Polygordius* spp., *Euvenopus honduranus,* and *Scoletoma verrilli*. Cluster analysis suggested that seasonal factors are a major source of variation in infaunal assemblages in Study Areas 1 and 2. Hammer and others (2000, p. 59) suggested that *Caecum* spp., which were not abundant in samples from an earlier study, may be opportunistic.

OUTER ZONE

The outer zone is separated from the middle zone by a slope break, and from the outer shelf by a marked difference in landforms. The outer zone is characterized by relatively short oblique ridges that trend WNW-ESE, more easterly than in the middle and inner zones. Farther offshore, shelf topography (pl. 1) is dominated by irregular, nonparallel ridges and valleys that may represent relict fluvial topography.

Only four vibracores were taken in the outer zone in the study area by GSA researchers in our area (SR-25, 36, 37, 98). Kent and others (1976) collected a few boxcores there as well. In most vibracores, the sediment includes relatively thick but fine sand deposits.

SUMMARY

Based on the preceding treatment, a depositional model can be presented for the study area (fig. 1; table 9), followed by a discussion of the role of major storms.

DEPOSITIONAL MODEL

The eastern Alabama continental shelf includes diverse pre-Holocene deposits overlain unconformably by a more homogeneous Holocene sand, most of which is contained in oblique ridges (table 10). The unconformity is highly irregular but generally slopes seaward; relict topography is exposed and evidently eroded during major storms throughout the study area (fig. 1) (Byrnes and others, 2004, fig. 7).

Major storms drive erosion and deposition in the sand-ridge field at water depths from 5 to 24 m (16 to 79 ft), resulting in a deposit of sand similar to that of adjacent beaches though of lower quality (table 9). The dominant mineral is quartz; calcium carbonate, heavy minerals, and muscovite are present in varying amounts.

With increasing water depth, the mean particle size decreases somewhat from 279 µm to 252 µm, which is somewhat less than that of beach sand (330 µm) (table 6). Sorting is high (well to very well sorted), slightly higher offshore (1.5-1.8) than on the beach (1.3), though it too decreases as water depth increases. Skewness and kurtosis show similar offshore trends (table 9). Mud content is very low and increases slightly offshore.

Table 9. Depositional model of Holocene topographic features in the eastern Alabama shelf.

	Beach	Inner zone	Middle zone	Outer zone
Water depth (m)	~0	5-12	12-17	17-24
Shell gravel content[1] (weight %)	1.44 ± 2.73	3.27 ± 8.32	2.31 ± 4.69	0.26 ± 0.25
Mean particle size (μm)	330 ± 73	279 ± 165	278 ± 138	252 ± 14
Sorting	1.3	1.8	1.7	1.5
Skewness	0.7	1.7	1.5	1.2
Kurtosis	6.6	9.6	8.1	7.5
Physical sedimentary structures	low-angle lamination ripples	high-angle crossbedding megaripples ripples		
Graded bed thickness (cm) (to amalgamated thickness)	none	11-87 (to 393)	27-43.5 (to >470)	none (to 171.5)
Bioturbation	slight	complete except in shelly lags		complete
Biogenic sedimentary structures	*Psilonichnus*	*Ophiomorpha, Thalassinoides Skolithos, Arenicolites, Diopatrichnus, Subphyllochorda*		
Shells	common bivalves, sand dollars, gastropods			few bivalves, sand dollars, barnacles
Surficial lithofacies	beach	GSS, SHS	GSS, SHS, SMB	GSS, SHS

[1] Sand-dominated lithofacies only.

Sorting, skewness, and kurtosis all decrease from the inner zone to the outer zone (table 9), suggesting a winnowing process. Winnowing implies seaward movement of sand and fines, while the ridges themselves were moving southwestward. The outer ridges, therefore, are contemporary features, not relict ones. Winnowing of sediment on the shelf couples with winnowing on winter beaches (see "Seasonal Consistency") to move sediment offshore as part of a dynamic system. Episodic sediment transport from Florida to the Alabama beaches and shelf, and winnowing, both controlled by major storms and seasonal changes in water energy, selectively move finer sediment offshore from the entire beach-shelf system to the outer shelf.

Table 10. Summary of modern environments and lithofacies at vibracore stations off Baldwin County, Alabama.

Vibracore	Water depth (m)	Water depth (ft)[1]	Zone	Environment	Surface lithofacies[2,3]	Area[4]
SR-7	10.4	34.1	inner	lee	GSS (thin)	MMS 3[5]
SR-20	11.3	37.1	inner	lee	GSS	MMS 3[5]
SR-23	14.7	48.1	middle	lee	GSS (thin)	federal
SR-24	14.7	48.1	middle	stoss	GSS (thin)	MMS 2
SR-25	17.3	56.9	outer	lee	SHS	MMS 2
SR-26	15.5	51.0	inner	swale	GSS	MMS 2
SR-27	13.4	43.9	inner	stoss	GSS (thin)	MMS 2
SR-28	11.6	38.0	middle	stoss	GSS	MMS 2
SR-29	13.1	42.9	middle	lee	GSS (thin)	MMS 2
SR-30	14.1	46.2	middle	lee	GSS (thin)	MMS 2
SR-31	13.7	44.9	middle	swale	GSS (thin)	MMS 2
SR-32	11.9	39.0	inner	lee	GSS (thin)	MMS 2
SR-33	12.8	41.9	inner	stoss	GSS (thin)	MMS 2
SR-34	11.6	38.0	inner	lee	GSS	MMS 1
SR-35	13.7	44.9	middle	stoss	GSS	MMS 1
SR-36	22.9	75.1	outer	stoss	GSS	federal
SR-37	18.3	60.1	outer	lee	SHS	federal
SR-38	15.5	51.0	middle	stoss	SMB	federal
SR-39	12.5	41.0	inner	swale	GSS (thin)	MMS 1
SR-40	12.2	40.0	inner	stoss	GSS	MMS 1
SR-41	10.4	34.1	inner	stoss	SHS	MMS 1
SR-42	13.7	44.9	inner	lee	SHS (thin)	MMS 1
SR-43	11.6	38.0	inner	stoss	GSS	MMS 1
SR-44	11.6	38.0	inner	lee	GSS	MMS 1
SR-45	9.4	30.9	inner	lee	GSS	MMS 1 (state)
SR-97	14.9	48.8	middle	swale	SMB (thin)	MMS 2
SR-98	16.7	54.7	outer	stoss	SHS	MMS 2
SR-99	16.5	54.0	middle	lee	SHS	federal
SR-100	15.3	50.1	middle	swale?	SMB	federal
SR-101	12.5	41.1	inner	lee	GSS (thin)	MMS 2
SR-102	14.6	48.0	middle	stoss	GSS (thin)	MMS 1
SR-103	17.0	55.9	middle	swale?	GSS	federal
SR-104	16.1	52.8	middle	lee	SHS (thin)	federal
SR-105	14.0	45.8	inner	swale	GSS (thin)	federal
SR-106	14.2	46.7	inner	swale	GSS	federal
SR-107	8.1	26.7	inner	crest	SHS	state
SR-108	11.6	38.2	inner	lee	GSS (thin)	state
SR-109	14.6	34.1	inner	crest	GSS	state
SR-110	10.7	35.0	inner	lee	GSS (thin)	state
SR-111	10.7	35.0	inner	lee	GSS (thin)	state
SR-112	9.1	29.9	inner	lee	GSS	state
SR-113	10.0	32.9	inner	crest	GSS	state
SR-114	11.5	37.8	inner	swale	GSS	state
SR-115	11.9	38.9	inner	stoss	GSS (thin)	state
SR-116	12.2	39.9	inner	swale	GSS (thin)	state
SR-117	14.9 [?]	48.8 [?]	inner	crest	GSS	state

[1] After Parker and others (1997) and Hummell (1999). The depth for SR-117 should be about 9.5 m (31 ft) according to bathymetric charts.
[2] Abbreviations: GGS = Graded Shelly Sand; SHS = Shelly Sand; SMB = Shell with Mud Burrows.
[3] "Thin" indicates modern deposits less than about 3 m (10 ft) thick over Pleistocene(?) deposits.
[4] All stations in MMS Study Areas 1 and 2 are in federal waters except for SR-45.
[5] Peels of two vibracores from Baldwin Shoal (MMS Study Area 3) were examined but not included in statistics.

Sand is coarsest on ridge crests and finest in swales (table 11), a pattern consistent with the observation elsewhere that crests of oblique ridges tend to be more reworked by waves than swales, especially in deeper water (Hayes and Nairn, 2004). Particle size is more variable on stoss and lee slopes of ridges. Such a distribution is consistent with enhanced winnowing of ridge crests and relative stability of swales. This is also consistent with movement of fine sediment seaward parallel to ridges as an explanation for observed fining and apparent winnowing from inner to outer zones of oblique ridges (table 12).

Table 11. Moment measures of particle size in oblique sand ridge environments off Baldwin County.

Geomorphic position	Geometric mean (µm)	Sorting	Skewness	Kurtosis
Stoss (n = 38)	299.3 ± 207.6	1.9 ± 0.6	1.6 ± 0.8	8.8 ± 4.6
Crest (n = 8)	314.7 ± 41.9	1.6 ± 0.2	1.5 ± 0.7	8.9 ± 2.7
Lee (n = 22)	263.3 ± 132.7	1.8 ± 0.6	1.7 ± 0.9	9.1 ± 4.8
Swale (n = 16)	261.5 ± 97.4	1.7 ± 0.3	1.6 ± 0.8	8.4 ± 4.5

Table 12. Moment measures of particle size of three zones of oblique ridges off Baldwin County.

Zone	Geometric mean (µm)	Sorting	Skewness	Kurtosis
Inner zone (n = 64)	279.4 ± 164.7	1.8 ± 0.6	1.7 ± 0.9	9.6 ± 4.6
Middle zone (n = 26)	278.4 ± 138.2	1.7 ± 0.3	1.5 ± 0.7	8.1 ± 3.5
Outer zone (n = 6)	251.5 ± 13.5	1.5 ± 0.1	1.2 ± 0.7	7.5 ± 4.3

Shells are relatively common at shallower depths and least common in the outer ridge zone. Coarse shelly debris does not exceed about 5 percent of the material.

Sedimentary structures of offshore sand ridges are compatible with storm deposition as well. Vibracores typically penetrate graded beds with shelly lags at depth within the substrate, but the surficial sediment is thoroughly bioturbated in most cases (table 10; appendix A). The result is that storm-graded beds generally only 10 to 30 cm thick, and probably up to 90 cm or thicker, are usually amalgamated biogenically into graded beds 1 to 4.5 m thick. Physically graded beds are thickest in the inner and middle ridge zones and not present at all in the outer zone, where all such beds are amalgamated by bioturbation.

Both physical and biogenic sedimentary structures are preserved. Physical sedimentary structures include ripples, megaripples, and high-angle crossbedding. Biogenic sedimentary structures are incompletely understood, but seem to be dominated by large crustacean burrows (*Ophiomorpha, Thalassinoides*), which penetrate the substrate more deeply than any others and therefore tend to bioturbate the sediment for the last time before burial. Heart urchin burrows (*Subphyllochorda*) dominate the shallower tier of substrate but are preserved only in cases of rapid burial by thick sand deposits. It may be significant that the vibracores were collected during the 1990s, after a gap of a dozen years or more since the last major hurricane to affect the area directly (Frederic in 1979). This would have given animals more than ten years to obliterate physical sedimentary structures before collection of vibracores. Vibracores collected soon after a major storm would probably show more physical structures, including a widespread graded bed made by the storm.

The internal architecture of sand ridges is complex (Parker and others, 1997; Hummell, 1999). During storms, sediment is evidently transported both southwestward across the shelf, and southeastward away from shore; the details of sediment transport are poorly understood.

The surficial lithofacies show intriguing trends with regard to their position in the oblique sand-ridge field (tables 13, 14). The GSS is strongly associated with the inner zone, decreasing in frequency offshore (table 13), whereas the SMB lithofacies occurs at the surface only in the middle zone. The SHS lithofacies is most characteristic of the outer zone, a result of the biogenic amalgamation of graded beds.

Surficial lithofacies also show trends with regard to position on ridges and swales (table 14). The GSS lithofacies occurs in all such environments and is notably frequent on ridge crests, which must have relatively high wave energy, especially during storms. The bioturbated SMB lithofacies is uncommon but is particularly associated with swales. The SHS is especially common on the lee sides of ridges. A detailed study of offshore ridges would be helpful in deciphering these patterns.

Table 13. Relationship of surficial lithofacies and zones of oblique ridges.

Zone	Graded Shelly Sand	Sand with Mud Burrows	Shelly Sand	Total number of sites
Inner	23	0	3	26
Middle	9	3	2	14
Outer	1	0	3	4
Total number of sites	33	3	8	44

Table 14. Relationship of surficial lithofacies and ridge-related environments.

Environment	Graded Shelly Sand	Sand with Mud Burrows	Shelly Sand	Total number of sites
Swale	8	2	0	10
Stoss	10	1	2	13
Crest	3	0	1	4
Lee	12	0	5	17
Total number of sites	33	3	8	44

In sum, the offshore sand deposits of the eastern Alabama continental shelf are mostly tempestites (storm deposits). Offshore ridges are amalgamated into a continuous sheet near the Florida border, but are nearly separate landforms toward the west, like starved ripples (pl. 1).

ROLE OF MAJOR STORMS

As shown by researchers including Parker and others (1997), hurricanes and tropical storms probably control the morphology of the Alabama oblique ridges, although the mechanisms are still poorly understood. What is known is that oblique ridges generally develop with crests parallel to the dominant storm-wind direction (Hayes and Nairn, 2004). On Alabama’s shoreline, hurricanes usually approach from the southern quadrant, commonly from the southeast (Chermock, 1976; Chermock and others, 1974, fig. 16). As a hurricane crosses the shoreline, its winds lose energy over land and regain it over water, so the winds on the eastern flank of the storm, blowing from southwest, south, and southeast, are the strongest regardless of the eye’s track. Prolonged or intense southerly to southeasterly wind-driven waves would account for the ridges’ lineation. The reasons for southwestward transport of sand are not easily explained, but fining-upward beds a meter thick must be related to storms rather than fair-weather waves and currents.

Coastal sediments contain a stratigraphically and chronologically distinct record of hurricane strikes during late Holocene time. In Alabama, the depositional signature of major storms has been recognized so far in the Shelby Lakes (Liu and Fearn, 1993, 2000), Weeks Bay (Haywick and others, 1994), and offshore (Parker and others, 1997). Little Lagoon should also contain a record of storm layers. The same methods have been used to read the storm history of other coasts as well, for example, in South Carolina (Scott and others, 2003).

Significant erosion also takes place during hurricanes. The floor of Mobile Bay was scoured during Hurricane Frederic in 1979 to an average depth of 0.5 m (1.5 ft) (Isphording and others, 1987; Isphording and Isphording, 1991). The central bay floor was coarsened from patchily distributed clay and silty clay to uniform silty clay.

Frederic—a strong category 3 hurricane that struck the Alabama coast in 1979—left a distinct sand layer in the nearshore sediments of Middle Shelby Lake as a result of storm-tide overwash of beaches and dunes. Sediment cores taken from the center of Middle Shelby Lake contain multiple sand layers, suggesting that five major hurricanes (category 4 or 5) directly struck the Alabama coast during the past 3.2 thousand years, based on radiocarbon (Liu and Fearn, 1993, 2000; compare Otvos, 1999).

The stratigraphic record of major hurricanes suggests how often the seafloor off Alabama is reworked to substantial depth. Graded shelly sand layers (the deposits of single storms) as thick as 90 cm (3 ft) underlie sand ridges offshore (for example, SR-40 in Study Area 1). Major storms appear to exert primary control over the distribution of high-quality sand at the top of the sediment pile on the Alabama shelf by winnowing sediment and depositing it on oblique ridges. Because storm effects lessen as water depth increases, in the deepest zone the crests of oblique ridges should be more strongly affected by storms than swales (Hayes and Nairn, 2004). The frequency and effects of major storms on coastal and offshore Alabama set bounds on input to models of sand movement, accumulation, and redistribution.

RESOURCE EVALUATION

In this section, a regional survey of factors critical to sand-resource evaluation is presented, based on currently available data and practices (Michel, 2004, and references cited therein). Original contributions are added to previous work on the eastern Alabama continental shelf (Parker and others, 1997; Hummell, 1999). Such a survey is essential to identify the most likely targets, but detailed resource evaluation such as that of Olsen Associates, Inc. (2001) is required to prove suitability of a particular deposit for mining. For example, in 1999, Olsen Associates, conducted an offshore seismic survey off Gulf Shores, which allowed two nearshore sand ridges to be targeted for vibracoring. They collected forty-seven vibracores and analyzed the sand for particle size and color for comparison with natural beach sand (Olsen Associates, 2001).

ECONOMIC FACTORS

Particle size, color, thickness, water depth, and distance from shore of submarine sand deposits are some of the most important specifications used to evaluate potential source sand for beach nourishment (Olsen Associates, 2001; A. E. Browder, written communication to DCKM, May 6, 2005) (table 15). Sand mined to replace natural beach sand should match it as closely as possible in order to minimize waste by erosion and to maximize aesthetic value. If the restored beach is too fine-grained, it will erode too quickly. If it has the wrong color or contains mud or too much shelly debris, beachgoers will be disturbed (Pilkey and others, 2004; Kopaska-Merkel and Rindsberg, 2002). Each of these factors is discussed below.

Table 15. Engineering specifications for replacement sand on Baldwin County beaches.

Characteristic	Value	References
Sand sorting	Well sorted	Kopaska-Merkel & Rindsberg, 2005
Particle size mode	All beach environments 0.31-0.32 mm; high tide level 0.334 mm	Olsen Associates, 2001; Kopaska-Merkel & Rindsberg, 2005
Sand color (Munsell standard)	White to very pale brown (after oxidation)	Olsen Associates, 2001
Deposit thickness	≥ 2.5-3 m (8-10 ft) to ≥ 13 m (43 ft)	Browder, written communication, May 6, 2005
Water depth	~20-25 m (~70-80 ft)	Browder, written communication, May 6, 2005
Distance from shore	Minimal	Olsen Associates, 2001

PARTICLE SIZE 1: MUD AND FINE SAND

The ideal particle size range for Gulf beaches in Baldwin County is remarkably constant, due to similar wave climate and a relatively constant natural sand source. Beach sand is well sorted to very well sorted, with a mode averaging about 320 µm and a geometric mean about 330 µm (Olsen Associates, 2001, table 3.1; Kopaska-Merkel and Rindsberg, 2005). Shelly debris is relatively fine, uncommon (typically less than 1 percent), and well worn. To determine the economic viability of an offshore sand deposit, particle-size analysis of closely spaced cores is necessary.

Inevitably, most offshore sand is not as well sorted as beach sand (table 6; fig. 10), because wave action is the main process that sorts sand and this is maximal on the beach in storms as well as fair weather. Samples of sandy offshore lithofacies range from moderately to well sorted, and the GSS and SHS generally contain very little mud (Parker and others, 1997). When emplaced on the beach, the finer fraction of the borrowed sand is more easily transported than the coarser natural sand, and tends to be carried offshore within a few years. The SMB is a component of some offshore sand ridges, and contains more mud than the GSS and SHS, but, with an average mud content of 4 percent (Parker and others, 1997), this lithofacies also is strongly dominated by sand.

The fraction of beach fill that is too fine to remain on the beach under normal wave conditions is called “overfill” (U.S. Army Corps of Engineers, 1984; Dean, 2000). Overfill is essentially wasted sand and must be discounted in forecasts of performance. Alabama beach sand averages 330 µm in size, with a standard deviation of 73 µm (table 6) (Kopaska-Merkel and Rindsberg, 2005). This means that most Alabama beach sand is 184 µm or coarser (2 standard deviations below the mean).

Because a 0.5 φ sieve interval was used, the percentage of sediment coarser than 250 µm could be estimated as a conservative approximation to 184 µm. Seventy-two percent by weight of the beach sand that was sampled for this study was caught by the 250 µm and coarser sieves (medium sand or coarser). By contrast, offshore samples contain only 43 percent medium sand or coarser. Of the coarsest lithofacies, the GSS, only 52 percent of the sediment is medium sand or coarser, compared to 40 percent of samples of the SHS lithofacies (table 3). Samples from state waters average 54 percent sediment coarser than 250 µm, whereas federal samples average 40 percent. Of the three bands of oblique ridges, the nearshore band (currently mined for beach nourishment in 2001 and 2005; fig. 2) averages 43 percent medium sand or coarser, the middle band 42 percent, and the outer band 44 percent (table 3). Thus, overfill will be considerable for any deposits in the area studied, but GSS is by far the most economic lithofacies for beach nourishment. Mining of sand closer to shore will reduce overfill ratios.

PARTICLE SIZE 2: SHELL GRAVEL

Sediment that is too coarse is no more desirable for beach replenishment than sediment that is too fine, though a certain proportion can be tolerated. A shell content of 5 percent by weight is noticeable, and one of about 10 percent is excessive for Alabama sand (A. E. Browder, written communication to DCKM, August 30, 2005). A small proportion of whole shells is not only acceptable but attractive to beach-going tourists if shells are not broken into sharp fragments by dredging (Rindsberg, 2005).

Relatively coarse shelly debris is common only in sandy shell lags (described in "Graded Shelly Sand Lithofacies") that form the bases of graded layers in the GSS. Two standard deviations above the mean particle size on Alabama beaches is 514 µm, which can be estimated using our data as 500 µm (the boundary between medium and coarse sand). GSS samples average 13 percent (by weight) coarser than medium sand, and beach samples average 11 percent. Four GSS samples are more than one-third coarse sand or coarser, and all are strongly bimodal mixtures of fine to medium sand and shell gravel (SR-31-30, SR-34-350, SR-23-bg, and SR-27-bg; appendices B, D). These four samples of shell lags show up as relatively coarse outliers on bivariate plots of particle-size parameters (fig. 17). These considerations indicate that most GSS samples contain no more relatively coarse material than is acceptable on Alabama beaches. As overfill is washed away, the proportion of gravel-sized material should increase, which should be considered in future calculations.

The question of how much of the resource might be too coarse to put on beaches can be investigated using a more stringent criterion: the amount of a deposit coarser than 1 mm. This is approximately the boundary between size fractions dominated by quartz sand and those dominated by shelly debris for offshore samples analyzed this year. Less than 1 percent of Alabama beach sand, excluding windrows, is coarser than 1 mm. The equivalent percentage for the GSS (excluding shelly lags) is 3 percent, but in practice the lags probably cannot be avoided during mining. Including shelly lags, this number is 6 percent, and for the SHS it is 2 percent. The maximum amount of material coarser than 1 mm measured in any sample of shelly lag is 59 percent. By this criterion as well, the key question is how much of the deposit consists of shelly lags.

The GSS lithofacies includes amalgamated, fining-upward beds about a meter thick, whose bases commonly consist of several centimeters of sandy shell. These sandy shell lags are undesirable for beach replenishment, but can be used if the total shell content is not too great. It would be impractical to mine the graded beds without their basal lags, because the total thickness of these deposits is commonly less than 4 m (13 ft) (table 9) (Parker and others, 1997; Hummell, 1999). Also, where graded beds are stacked, sandy shell lags occur within the sand deposits as well as at their bases.

Sandy shell lags account for less than 5 percent of the total thickness of the GSS as estimated from vibracore photographs, although graphic vibracore logs published by Parker and others (1997) suggest that lags account for 7 percent or more of the GSS. The shell content of the lags has not been measured accurately, but appears to be considerably less than half (see "Color and mineralogy" and appendix B). A shell content of more than 5 percent renders a deposit questionable as a source of sand for beach nourishment (A. E. Browder, verbal communication, 2005) and both the GSS and SHS appear to contain less than 5 percent coarse shell material on average. The GSS may contain local concentrations of shelly lags that reduce its value as a sand source for beach nourishment.

COLOR AND MINERALOGY

The natural beach sand of Baldwin County is nearly white—technically, a very pale brown exceeding Munsell Soil Color 10YR 8.0/2.0, and probably closer to 10YR 9.0/1.5 (Olsen Associates, 2001, p. 8). This color, which is unusually white for American beaches, results from the nearly pure quartz composition of the sand (Parker and others, 1997; Olsen Associates, 2001; this study). There is only a small amount of admixed calcitic and aragonitic shell debris, much of which is also nearly white, and heavy minerals, which are largely black and opaque. The "snow-white" beaches of Baldwin County are attractive to tourists (Kelley and Wade, 1999), so there is a powerful economic incentive to match the color of the natural beach sand (Olsen Associates, 2001).

Only a small proportion of offshore sand consists of nearly pure quartz. At most stations, offshore sand contains additional mud, stable and unstable dark minerals, and shell debris. Mud (silt and clay) is unattractive and easily eroded from beaches, contributing to water turbidity. The GSS and SHS contain, on the average, no more than 1.5 percent mud (Parker and others, 1997). Mud is therefore not a serious issue when these two lithofacies are considered as potential sand sources for beach nourishment. By contrast, the SMB contains, on the average, about 4 percent mud (Parker and others, 1997). This is still a modest burden of fine sediment, but is enough to make the sand of marginal quality for beach nourishment in Alabama.

Shells in offshore deposits range from nearly white to very dark gray due to the precipitation of iron sulfide (Pilkey and others, 2004). Iron sulfide may oxidize to yellow, orange, red, or brown iron oxides and hydroxides under similar conditions, but the process is little studied (Pilkey and others, 2004).

Only a small proportion of shells retains original pigments and these are lost within a matter of days on exposure to sunlight.

The heavy mineral content of offshore sand deposits is typically less than 0.5 percent east of Mobile Pass, increasing up to 4 percent near Dauphin Island (Goldstein, 1942; Hsü, 1960; van Andel and Poole, 1960; Stow and others, 1975; Kent and others, 1976; Drummond and Stow, 1979; Doyle and Sparks, 1980; Woolsey, 1984; Parker and others, 1997). These minerals are mostly dark and include large proportions of ilmenite and magnetite as well as other oxides that are very stable in marine conditions. At the higher proportions, these impart a distinctly dark chroma to the beach, especially where heavy minerals are sorted naturally into distinct, dark laminae by wave action, as occurs naturally on Dauphin Island.

WATER DEPTH AND DISTANCE FROM SHORE

From an economic standpoint, the best place for a borrow pit is as close as possible to the project location where the sand will be used. The cost is also lower for mining in shallow water than in deeper water. Because water depth generally increases with distance from shore, the two factors are interdependent. The sand cannot be taken from the shoreface, which is integral with the beach itself. The Baldwin County shoreface has a relatively steep slope compared to that of most of the continental shelf (pl. 1) and extends up to about 0.8 km (0.6 mile) offshore.

In 2001, Olsen Associates mined the crest of a sand ridge at a depth of 7.9 to 8.9 m (26 to 29 ft) about 1.6 km (1 mi) off Gulf Shores (Olsen Associates, 2001, fig. 2.3). More of this ridge, as well as the crest of another ridge at a similar distance offshore, is being mined in 2005 for beach restoration after Hurricane Ivan (fig. 2) (Browder and others, 2003). Federal waters begin 4.8 km (3 mi) offshore; federal sand is likely to become desirable as beach replenishment source material only after economic resources in state waters have been exploited.

DEPOSIT THICKNESS

The typical offshore ridge east of Mobile Point consists of an elongate body of sand having a lenticular cross section and overlying thick, muddy pre-Holocene deposits (Parker and others, 1997). Ridges are flanked by swales that are generally floored by less than 1 m (3 ft) of sand. A minimum thickness of 2.5-3 m (8-10 ft) is needed for mining offshore sand (A. E. Browder, written communication, 2005), and the deposit mined in 2001 was about 4.5 m (15 ft) thick (Olsen Associates, 2001, p. 14). Therefore, only the crest of a ridge can be mined economically; ridge flanks generally have too thin a veneer of sand. Detailed data from closely spaced seismic profiles or cores are needed to determine the amount of sand that can be mined from any one ridge (Olsen Associates, 2001).

As shown by Parker and others (1997), the sand ridge deposits are not vertically or laterally uniform, but consist of lenses or wedges of GSS, SHS, SMB, and other lithofacies that Hummell (1999) lumped together as his “surficial sand sheet.” Hummell (1999, table 5) accordingly estimated that the eastern Alabama continental shelf contains a total of about 1.35 billion cubic meters (1.75 billion cubic yards) of material in the “sand sheet,” about a third of which is in state waters. However, his estimates were based on too sparse a sampling pattern for seafloor characterized by ridges that were poorly defined by the bathymetric data then available. Moreover, Hummell (1999, fig. 43) included within his estimate large tracts of sand too thin or of poor quality to be mined economically. The result was an estimate that Browder and others (2003, p. 17) qualified as “unlikely” for economic purposes. Indeed, they emphasized that economic sand resources are quite limited on the Alabama shelf and urged authorities to conserve beach-quality sand whenever possible.

Although it is not possible to provide an accurate estimate of the offshore sand resource given the sparsity of data, we did reappraise the thickness of available sand with regard to more accurate bathymetry (pl. 1) and in the light of the storm-ridge interpretation. If a sand deposit must be at least 2.5-3 m (8-10 ft) to be mined economically (table 15), then such deposits are very limited in area, and as Browder and Olsen (2004) have emphasized, the best match for the beach sand is located on ridge crests.

The most extensive deposits are in the inner and outer ridge zones; the ridges are relatively thin and sparse in the middle zone. Vibracores SR-107, 109, and 112 each penetrated at least 3 m (10 ft) of sand in state waters within the inner zone, all on ridge crests that were mined by Olsen Associates in 2000-05 (table 10; fig. 2; pl. 1). Each of these deposits contains a considerable, but limited, quantity of sand. In federal waters within the inner zone, vibracores SR-8, 34, and 40 (the latter two of which are in MMS Study Area 1) penetrated at least 3 m (10 ft) of surficial sand. Considering the number of cores taken in the inner zone and particularly in federal waters, useful sand deposits probably cover only a small proportion of the area.

The middle zone is relatively sparse in offshore sand. Only two cores, SR-23 and 35 (the latter being in MMS Study Area 1), of the several taken penetrated the required thickness of sand.

In contrast, the outer zone does show promise as a sand source, though the area is distant from shore and the amount of overfill would be relatively high because the sand is relatively fine. Of the few cores taken, most penetrated an adequate thickness of sand, including SR-25, 37, 98, and 99. Vibracores SR-25 and 98 were collected in MMS Study Area 2.

POTENTIAL ADVERSE EFFECTS

Acting for the MMS, Drucker and others (2004) and Nairn and others (2004) summarized the potential adverse effects of dredging offshore sand. The Minerals Management Service is particularly concerned about risks to marine life, especially long-term effects on fisheries, and about changes in the physical environment that may affect wave climate onshore (Drucker and others, 2004; Nairn and others, 2004). In other MMS-supported work, Byrnes and others (2004) and Hayes and Nairn (2004) discussed these risks with regard to sand mining off Alabama and Delmarva.

Sport and commercial fisheries are important to the culture and economy of coastal Alabama (Kelley and Wade, 1999). Hayes and Nairn (2004) pointed out that little is known of the ecology of any offshore ridge-and-swale system, particularly their role in the migration of fish. Based on available evidence, including benthic samples, Byrnes and others (2004) estimated that biologic communities off Baldwin County would recover within one to three years of mining, provided that standard practices are followed. This is consistent with the proposal put forth by Olsen Associates (2001) for sand mining off Gulf Shores.

Offshore sand mining could increase or decrease wave energy on particular strands of shoreline, and such changes in wave climate can be modeled (Hayes and Nairn, 2004). In general, the effect should be reduced with distance from shore of the borrow site. Byrnes and others (2004) performed models of changed wave energy under "normal" (fair-weather) and storm conditions, but only presented data for fair-weather conditions. As they emphasized, under fair-weather conditions, wave height would be increased by only up to about 0.2 m (0.7 ft) on particular stretches of Alabama coastline, an amount that they considered negligible. However, as demonstrated by Hayes and Nairn (2004), the change of wave climate during storms can be far more significant than the change under fair-weather conditions. Given the vulnerability of the Alabama coastline to major hurricanes, post-mining wave models under storm conditions should be given more attention.

OPPORTUNITIES FOR FUTURE RESEARCH

Further research on Alabama's coastal sand resources could focus on refining our understanding of the resources or on using our understanding of the resources in other ways; for example, prediction of the effects of tropical cyclones. Possibilities include:

- testing the hypothesis that offshore swales coincide with sites of repeated temporary inlet formation by tropical cyclones,
- refinement of estimates of sand resource volume via a program of vibracoring guided by detailed bathymetry, and

- study of offshore sedimentary effects of recent hurricanes and short-term fair-weather processes by collecting new vibracores at sites where vibracores were collected in the 1990s.

These three opportunities are described briefly below.

Perhaps the most urgent need for new information about offshore Alabama is to improve our ability to predict the effects of major hurricanes on Alabama's coastal region. This may now be possible where oblique ridges and swales lie just offshore. The results of a preliminary survey, based largely on historical maps and on two sets of annual aerial photographs one decade apart (Kopaska-Merkel and Rindsberg, 2005), suggest that storm-induced breaches preferentially form at the landward ends of swales in the inner zone of oblique ridges on the seafloor.

A wealth of information is available to test ideas about inlet formation in Alabama. Aerial photographs of coastal Alabama and the nearshore marine environment to the south are available for many years dating back to the 1960s. Only a few historical maps and aerial photographs for 1991 and 2001 have been examined (Kopaska-Merkel and Rindsberg, 2005). Nautical charts and maps can be used to extend the analysis before the years for which suitable aerial photographs are available. Written records of past storm breaches may add to the scope of the database. Regardless of the merits of the swale hypothesis, this study would result in the discovery and documentation of patterns that are likely to be of practical use in coastal management.

More detailed bathymetry than was available to Parker and others (1997) or Hummell (1999) could be used to take vibracores, boxcores, and bottom photographs on the crests and slopes of selected ridges to determine how the quality and thickness of sand deposits are related in detail to subsea topography. The centers of intervening swales would be vibracored for comparison. Most existing vibracores were not placed directly on crests or in swales, partly because the bathymetric data available in the 1990s were inadequate to the task. More detailed knowledge of a few selected ridges would help to refine estimates of the sand resource. This study would require funding for ship time and personnel, as well as for laboratory analysis of vibracores.

The sedimentary effects of Hurricanes Ivan (2004) and Katrina (2005) could be investigated by taking offshore vibracores at the same stations as studied by previous

GSA researchers (Parker and others, 1997; Hummell, 1990, 1999). The oblique sand ridges constituting the main offshore sand resource are affected by major storms, which have deposited beds as thick as 1 m (3 ft) (Parker and others, 1997). This study would require funding for ship time as well as personnel to handle and process cores at sea and in the laboratory.

CONCLUSIONS

The coast of Baldwin County, Alabama, faces a large field of oblique sand ridges stretching from Pine Beach eastward into Florida. Sand ridges migrate southwestward during hurricanes, and sand is also transported southeastward parallel to the ridges. Sand ridges and intervening swales form three curved zones roughly parallel to the shore. Each zone has different amounts and quality of sand, and the outer zone is relict and is currently undergoing erosion.

Oblique sand ridges off Baldwin County are underlain by the GSS, SHS, and SMB lithofacies. The GSS and SHS lithofacies are the coarsest identified on the Baldwin County shelf and are the most similar to Alabama beach sand. The GSS consists of upward fining units that each range in thickness from a few tens of centimeters (about 1 ft) to more than 3 m (10 ft). Each graded unit consists of variably shelly sand, commonly with a basal coarse shelly lag. The shelly sand units resemble Alabama beach sand in particle-size characteristics (mode 235 µm; sorting 1.7; skewness 1.4; kurtosis 7.8; 5.1 percent shell). The SHS is similar to the GSS (mode 221 µm; 5.6 percent shell), but lacks the coarse shelly lags. The GSS is up to 4.6 m (15 ft) thick; the SHS is up to 2 m (6.6 ft) thick.

The oblique sand-ridge field is probably sourced proximately from the adjacent Florida coast and shelf. As sediment is transported southeastward into relatively deep water, sand is winnowed and mud added. Winter winnowing of beach sand may also contribute to this process. Mollusks living on the shelf add a considerable quantity (up to a few percent of the sediment by volume) of shells to the sand. The concentration of shell gravel falls within the acceptable range for beach nourishment and the presence of large whole shells in the sand will make nourished beaches attractive to beachcombers. Thus, the sand ridges closest to shore contain relatively coarse sediment that is well suited for beach restoration, whereas the ridges in deepest water contain relatively fine sediment that is less desirable, but still serviceable for this purpose.

The sand-ridge field can be subdivided into three geomorphic zones: inner, outer, and middle (pl. 1; table 9). The inner zone, at water depths of about 5 to 12 m (16 to 39 ft) in Alabama state waters and immediately adjacent federal waters, contains sand very similar to that on Baldwin County beaches. Olsen Associates, Inc., mined sand from these ridges in 2000 and again in 2004-05 to nourish beaches at Gulf Shores and Orange Beach, with few complaints other than the sharpness of the shells. The risk of adverse change to the fair-weather- and storm-wave climate onshore by removal of ridges close to shore should be further modeled and monitored.

The middle zone, at water depths of about 12 to 17 m (39 to 56 ft) in federal waters, contains sand ridges of suitable quality for beach replenishment. However, these deposits are relatively thin and sparse compared to those of the inner zone, and their sand is finer grained.

The outer zone, at water depths of 17 m (56 ft) and deeper in federal waters, was not sampled this year, although vibracores collected in this zone were analyzed by previous researchers at the GSA. This zone contains sand that may be suitable for beach nourishment.

Economic sand deposits as thick as 4.6 m (15 ft) underlie the oblique sand ridges, as shown by particle-size characteristics, aerial extent of ridges, and thickness of beach-quality sand. We concur with Browder and Olsen (2003) that the total volume of economically accessible, beach-quality sand in oblique ridges is far less than previously estimated. Much of the most accessible beach-quality sand has already been mined for beach restoration following Hurricane Ivan. We agree with Browder and Olsen (2003) that steps should be taken immediately to conserve beach-quality sand on this coast. The possibility of utilizing relatively fine, but thick sand deposits in the outer zone within federal waters should be considered.

Oblique ridges atop relict ridges, for example, atop Baldwin Shoal in MMS Study Area 3, contain only thin deposits of usable sand. These deposits may be subeconomic.

Overfill will be considerable for any deposits in the area studied. Mining of sand closer to shore will entail lower overfill ratios. GSS is by far the most economic lithofacies for beach nourishment. Areas where the GSS lithofacies is thick are ideal for sand mining.

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APPENDIX A

SUPPLEMENTARY DESCRIPTIONS OF VIBRACORES

As part of Task 1, sedimentary structures in cores from Study Areas 1 and 2 and vicinity were described and documented to supplement previous core logs by Parker and others (1997) and Hummell (1999). Cores and peels were photographed and samples were taken and sieved for particle-size analysis. Visual examination and x-radiography are the standard methods for studying sedimentary structures in vibracores, but the cores are so altered chemically and desiccated after years of storage at room temperature that x-radiography would be fruitless.

Visual examination of sedimentary structures depends largely on recognition of patterns based on color and texture, in which shells are considered physically as sedimentary particles that give clues to the depositional environment. Shell size is an important observation. Grading of beds is recognized largely by shell size, which is measured as the longest visible dimension, and in unbioturbated beds the maximum shell size is probably related to the maximum current velocity during deposition.

Shell orientation is also significant. Where shells (whole or fragmented) are oriented subhorizontally, the sediment is probably laminated even in the absence of visible laminae. Where shell debris is oriented at an angle to the core wall, the sediment is probably crossbedded. Where shell debris is oriented at all angles with no apparent preferred direction, the sediment is probably wholly bioturbated even in the absence of visible burrow structures. Generally, it is impossible to distinguish among different kinds of crossbedding and burrows without x-radiography, but distinctive sedimentary structures can be discerned in some cores, such as intertidal couplets of laminae in vibracore SR-33 and the crustacean burrow *Ophiomorpha* in SR-100 (see “Bioturbation” under “Results”). Fortunately, erosional contacts and grading are readily visible in many cores, which is especially useful for evaluating the origin and thickness of the economic sand resource.

Shell color is included as a crude indicator of the time elapsed since deposition; buried shells that are white or with original color are presumably younger than those that have become chemically reduced (gray) or oxidized (brown, yellow, red). Shell color is also one measure of esthetic quality of the sand for beach nourishment.

Bioturbation was estimated in previous GSA reports by the area covered by visible burrows rather than by reference to absence of lamination or shell orientation, and thus the estimates of bioturbation are much higher in the current report. Thoroughly bioturbated sediment commonly looks featureless. Unless otherwise stated, the dimension given for burrows is the minimum internal diameter, which is most likely to represent the true diameter in oblique sections (Chamberlain, 1978).

The new observations of contacts and sedimentary structures supplement the older work of Parker and others (1997) and Hummell (1999), which should be consulted for additional information on sedimentary properties. For locations of vibracores, see pl. 1; for coordinates, see the GIS project on this CD or the aforementioned reports.

VIBRACORE SR-7

Description based on a peel from section B of the interval from 145 to 248 cm downcore (Parker and others, 1997, p. 117; Hummell, 1999, p. 133).

Depth downcore (cm)	Description
145-195	VERY SHELLY TO SHELLY SAND, sand-supported. Shells oriented in all directions, white to dark gray, increasingly dark downcore, consisting of angular to rounded fragments up to 8 mm in great dimension; bivalves and echinoids (sand dollars) common. Bioturbation thorough, dominated by concentric bundles of sand (heart urchin burrows *Subphyllochorda*) up to about 3 cm wide. Lower contact sharp, bioturbated.
195-214/217	SANDY SHELL, sand-supported above to probably shell-supported below, unbioturbated. Shells oriented horizontally, whitish to dark gray, especially light gray; whole valves to debris; fragments subangular to subrounded; mostly bivalve with minor sand dollar and gastropod (including some with original color). Bivalves include *Anomia simplex,* arcids, *Chione cancellata, C. intapurpurea, Divaricella quadrisulcata, Venericardia tridentata*; gastropods include naticids. Lower contact sharp, inclined from 214 to 217 cm.
214/217-243	SHELL with virtually no sand, shell-supported. Shells oriented subhorizontally or at low angle (probably crossbedded). Bioturbation absent. Shells include whole valves to coarse sand-sized debris; maximum size more than 20 mm; predominantly light to dark gray, some with original color, some white; shells abraded; fragments subangular to subrounded. Bivalves: arcids, *Chione cancellata,* corbulids(?), *Divaricella quadrisulcata,* pectinids, *Venericardia tridentata*. Gastropods *?Oliva sayana, ?Strombus alata*. Echinoid *?Mellita quinquiesperforata*. Lower contact sharp (core disturbed).
243-~248	SHELL with many whole, relatively large shells; no sand. Shells mainly whole valves, maximum size more than 40 mm; some gastropods; color and abrasion as above. Bivalves: *Anomia simplex, Chione cancellata, C. intapurpurea, Dinocardium robustum* (original color), *Macrocallista nimbosa* (grayed original color), *Noetia ponderosa, Ostrea equestris*. Gastropod: *Oliva sayana* (original color). Polychaete: polydorid boring.

VIBRACORE SR-20

Description based on a peel, now in poor condition, from section D of the interval from ~470 to ~520 cm downcore (Parker and others, 1997, p. 126; Hummell, 1999, p. 145).

Depth downcore (cm)	Description
~470-~510	MUDDY SAND consisting of relatively clean sand with burrows filled with muddy sand; sediment slightly shelly though with one large (~45 cm) fragment of bivalve *Mercenaria* at 1-5 cm downcore; other shell debris only up to 12 mm long. Shells mostly bivalve, with few whole, tiny gastropods and one scaphopod *Dentalium;* subangular fragments, mostly white but some light to dark gray (including *Mercenaria*). Lower contact very badly preserved in peel.
~510-~520	Interval very badly preserved, but including both SAND and MUD.

VIBRACORE SR-22

Description based on a peel from section B of the interval from 130 to 187.5 cm downcore (Parker and others, 1997, p. 127; Hummell, 1999, p. 147). The units from 130 to 187.5 cm may constitute a single graded bed or amalgamated beds.

Depth downcore (cm)	Description
130-153	SHELLY SAND with shells oriented at all angles but largely subhorizontally. Bioturbation indeterminate. Shells mostly fragments to sand-sized debris, some with original color, some dark gray; mollusk debris angular to subangular; sand dollar debris rounded; maximum size 8 mm. Mostly bivalves (including *Venericardia tridentata*), plus gastropods and scaphopods. Lower contact gradational.
153-161	SANDY SHELL, disturbed by coring; sediment sand-supported. Shells white to dark gray, some with original color; maximum size 27 mm. Bivalves *Chione cancellata* (juvenile, light gray, abraded), *Dinocardium robustum* (original color), pectinids (original color), *Venericardia tridentata* (dark gray), others. Balanid (dark gray). Sand dollar (white, rounded fragment). Contact gradational or disturbed.
161-173.5	SHELLY SAND similar to 130-153 cm interval, with probable echinoid bioturbation to 167 cm downcore, and subhorizontal (probably crossbedded) shell orientation below. Shells include bivalve debris, scaphopod. Lower contact sharp.
173.5-179	MUDDY SHELLY SAND, disturbed by coring, with finer sand than above. Bioturbation: mud-filled crustacean(?) burrows ~12 mm across. Shells white to dark gray, angular fragments to whole valves; maximum size 35 mm. Bivalves arcid, *Dinocardium robustum*.
179-187.5	MUDDY SANDY SHELL, apparently shell-supported, disturbed by coring. Shells with original color, white, light to dark gray, whole to debris; many whole valves; mainly bivalves, also gastropods, echinoid, balanid; fragments angular; maximum size 66 mm. Bivalves *Anomia simplex* (white), arcid, *Chione grus* (whitish), *Chione intapurpurea* (to dark gray), *Divaricella quadrisulcata* (light gray), *Mercenaria campechiensis* (66 cm across, white to dark gray), *Ostrea equestris* (dark gray), others. Gastropod *Oliva sayana* (original color), fragments. Sand dollar (light brown fragment). Balanid (one dark gray plate). Clionaid borings.

VIBRACORE SR-24

Description based on a peel from section B of the interval from 137 to 240 cm downcore (Parker and others, 1997, p. 128; Hummell, 1999, p. 149).

Depth downcore (cm)	Description
137-195.5	SAND, increasingly shelly downcore, with shell fragments fining upward; shells oriented subhorizontally (up to ~30º off horizontal, suggestive of crossbedding). Shells nearly all debris less than 4 mm, plus some whole valves up to 5 mm; white to very light gray, some dark gray, a few fragments oxidized to orangish or reddish hues; shell debris mostly angular, especially larger fragments. Bioturbation obscure, including indistinct circular outlines. Lower contact gradational.
195.5-206.5	SHELLY SAND, sand-supported, with coarser sand than above and shells oriented horizontally. Shells consisting of valves to angular fragments, mostly white to light gray, some oxidized yellowish to reddish, some dark gray; maximum size 7 mm. Bioturbation nil. Lower contact gradational.
206.5-211.5	SANDY SHELL, shell-supported, with shells oriented horizontally, either concave-upward or convex-upward. Shells consisting of valves to fragments, many whole, many angular; maximum size 10 mm. Bioturbation nil.
211.5-221	SANDY SHELL, coarser than above. Shells white to dark gray, a few with original color (especially olivids); bivalves and gastropods whole valves to sand-sized debris, angular; maximum size 19 mm. Bioturbation nil.
221-230	MUDDY SANDY SHELL, shell-supported, with muddy sand clinging to shell interiors (which are apparently somewhat washed out). Shells consisting of whole valves to angular fragments, mostly white to light gray, few with original color or dark gray; maximum size 37 mm. Bivalves: arcid, *Chione cancellata, C. intapurpurea* (several), corbulid, cf. *Dinocardium,* lucinid, *Macrocallista nimbosa* (with drillhole *Oichnus paraboloides*). Gastropods *Oliva sayana* (2), others. Echinoids *Mellita* (fragments). Bioturbation nil.

VIBRACORE SR-26

Description based on a peel from section C of the interval from 279 to 308 cm downcore (Parker and others, 1997, p. 130; Hummell, 1999, p. 151).

Depth downcore (cm)	Description
279-308	SAND with "muddy sand-filled burrows" of Hummell (1999), which comprise about half the area of the section. Shells consisting of minor debris, mostly white, one fragment gray. Bioturbation thorough.

VIBRACORE SR-31

Description based on a peel of the interval from 0 to 101 cm downcore (Parker and others, 1997, p. 132; Hummell, 1999, p. 156).

Depth downcore (cm)	Description
0-~18.5	SAND to SHELLY SAND, fining upward, oxidized. Shell fragments largely white, subangular to subrounded, more abundant and coarser below (as is sand); maximum size 5 mm. Bivalve and serpulid(?) fragments. Bioturbation apparently thorough. Lower contact gradational.
~18.5-31/32.5	SHELLY SAND to SANDY SHELL, sand-supported, oxidized, with shelliest part in middle; shell orientation subhorizontal in center of core, disturbed near wall. Shells consisting of bivalve fragments, largely white, some with original color, some oxidized, some light to dark gray. Bioturbation nil. Lower contact sharp, angular.
31/32.5-41/43.5	VERY SANDY SHELL, with shell orientation disturbed by coring. Shells consisting of bivalves, fragmented, white to dark gray, some with original color; maximum size 66 mm (*Mercenaria*). Bivalves *Chione cancellata* (abraded), *C. intapurpurea* (original color), *Mercenaria* (fragmented). Bioturbation indeterminate but probably nil. Lower contact sharp (interpreted as erosional sequence boundary).
41/43.5-49	SILT to VERY FINE SAND, light brownish-gray, with minor shells apparently in burrow fill. Shells bivalves, whole to fragmented, white to dark gray, subrounded. Bivalves *Chione intapurpurea,* ostreids. Bioturbation probably thorough; burrow 27 mm wide containing shells. Lower contact bioturbated, gradational.
49-84.5	SANDY CLAY (host sediment) to CLAYEY SAND (burrow fills); peaty, especially below; plant matter common, black, fragmented; sediment medium-dark brownish-gray, light brownish-gray, and very light yellowish-gray, with superposed orange hues due to oxidation. Shells absent. Bioturbation thorough, with at least four generations of overlapping burrows; some relatively young burrows subhorizontal with subcircular lumen, pellet-lined, 11-17 mm in least internal diameter; others oblique, 21-~30 mm internal diameter, lined smoothly or with muddy sand pellets. Lower contact sharp.
84.5-101	PEATY SANDY MUD, stiff, darker than above and darkening downcore but accompanied throughout by oxidized sediment.

VIBRACORE SR-33

Description based on a peel of the interval from 0 to 66 cm downcore (Parker and others, 1997, p. 133; Hummell, 1999, p. 158).

Depth downcore (cm)	Description
0-4.5	SHELLY to SLIGHTLY SHELLY SAND, shelliest at 3-4.5 cm, bioturbated in top 1-3 cm; shell debris oriented at all angles in top 1-3 cm and largely subhorizontally in 3-4.5 cm. Shells fragmented, white; maximum size 7 mm. Lower contact apparently sharp.
4.5-12	SANDY PEBBLY SHELL, probably shell-supported; shell orientation disturbed by coring but probably originally subhorizontal; pebble limonitic, more than 50 mm across. Shells consisting of bivalves, whole to fragmented, mostly whitish, some with original color, some light to dark gray. Bivalves including *Chione grus, Chione* sp., *Dinocardium robustum* (original color). Unit probably includes damaged interval at 12-15 cm below.
12-15	SAND, coarse? (peel incomplete).
15-39	SANDY CLAY with SAND- and SANDY CLAY-filled burrows. Shells absent. Bioturbation of overlapping burrows of several generations, up to about 25 mm across, especially large toward base of unit. Lower contact gradational.
39-53	SANDY CLAY, oxidized, partly laminated and partly bioturbated. Shells absent. Bioturbation: complex burrow system at 41-44 cm downcore.
53-60.5	SANDY CLAY, oxidized, laminated in couplets (interpreted as intertidal lamination). Shells absent. Bioturbation nil. Unit may represent lower, unbioturbated part of overlying one.
60.5-66	SANDY CLAY, variegated, bioturbated(?). Shells absent. Unit poorly preserved.

VIBRACORE SR-34

Description based on a peel from section A of the interval from 223 to 368 cm downcore (Parker and others, 1997, p. 134; Hummell, 1999, p. 159).

Depth downcore (cm)	Description
223-272	SHELLY SAND, with shells largely vertically oriented to 255 cm (due to core disturbance?) and at all orientations farther downcore. Shells consisting of bivalves, small gastropods, minor sand dollar, fragments angular, mostly sand-sized, white to light gray; maximum size 3 mm. Bioturbation thorough at least from 255 cm downcore. Lower contact gradational; oxidized zone at 271-271 cm.
272-285.5	SHELLY SAND, much shellier than above. Shells fragmented, angular, white to light gray; maximum size 8 mm. Bioturbation thorough. Lower contact gradational.
285.5-301.5	SANDY SHELL, slightly lighter and much shellier than above, sand-supported; shell orientation subhorizontal to swirled (as in echinoid bioturbation). Shells fragmented, angular, mostly white (to dark gray), consisting of bivalves and serpulids(?); maximum size 8 mm. Bioturbation partial? Lower contact gradational.
301.5-342.5	SANDY SHELL, shell-supported; shell fragments fining upward, subhorizontally oriented; probably crossbedded near base. Shells whole to fragmented, angular, white to dark gray (largely light gray), consisting of bivalves (including whole, convex-upward or concave-downward valves), balanid plates, scaphopods, lunulitid bryozoan; maximum size 20 mm. Lower contact sharp.
342.5-347	VERY SHELLY SAND to SANDY SHELL, only partly preserved in peel. Shell fragments much smaller than above; maximum size 7 mm. Lower contact sharp.
347-373	SANDY SHELL, only partly preserved in peel below 361 cm. Shell orientation above 361 cm subhorizontal, largely concave-upward, probably crossbedded. Shells fragmented, angular, predominantly light gray (white to dark gray), consisting largely of bivalves (including few whole valves of *Anomia simplex;* unidentified bivalves with attached serpulids), olivid at ~363 cm. Bioturbation probably nil.

VIBRACORE SR-35

Description based on a peel from section C of the interval from 267 to 378 cm downcore (Parker and others, 1997, p. 134; Hummell, 1999, p. 160).

Depth downcore (cm)	Description
267-349	SHELLY to SLIGHTY SHELLY SAND, brownish, mottled, with some horizons relatively shelly; shells at all orientations. Shells consisting mostly of bivalves ranging from small whole valves to sand-sized bioclasts, mainly light gray (white to dark gray overall); fragments angular to subrounded; small subcylindrical gastropods also present. Bioturbation presumably thorough. Bivalves *Anadara transversa?, Anomia simplex, Chione intapurpurea* (common, some with original color), lucinid, *?Ostrea equestris,* others. Lower contact sharp.
349-372	VERY SANDY SHELL, sand-supported, brownish; shell orientation disturbed by coring, several valves concave-upward. Shells relatively large (maximum size 36 mm), all bivalves, including many whole valves to sand-sized fragments; color predominantly white to light gray, also original and dark gray. Bioturbation: possible burrows near top of unit, oblique, filled with dark muddy sand, 4 mm across; penetration to ~17 mm.
372-378	Lithology uncertain due to poor peel preservation.

VIBRACORE SR-36

Description based on a peel from section B of the interval from 71 to 181 cm downcore (Parker and others, 1997, p. 135; Hummell, 1999, p. 161).

Depth downcore (cm)	Description
71-138	SLIGHTLY MUDDY SAND, including much bioclastic sand and some coarse muscovite. Shells consisting of bioclasts, whitish, with no obvious orientation. Bioturbation thorough; relatively large burrow with sand lining and lumen 4 mm wide at 26 cm downcore; *Ophiomorpha* with mud fill, light-colored, nodose sand lining, and lumen 5 mm across at 55 cm downcore. Lower contact bioturbated, gradational.
138-155	SLIGHTLY MUDDY SAND, slightly shelly (more so than above). Shells whitish to dark gray, molluscan and serpulid debris, oriented subhorizontally outside burrows and without obvious orientation within them; debris angular. Bioturbation partial, overall ~50 percent, with ill-defined oblique burrows about 2 cm across. Lower contact bioturbated, gradational.
155-171.5	SANDY SHELL to SHELLY SAND, fining upward, crossbedded. Bioturbation less than 10 percent; possible burrow about 12 mm across. Lower contact sharp.
171.5-181	SANDY SHELL. Shells consisting of valves to debris, angular, white to dark gray, one with original color; maximum size 31 mm. Bivalves *Anomia simplex,* arcids, *Ostrea equestris,* pectinid. Gastropod *Crepidula fornicata* (with original color). Echinoids probably *Mellita quinquiesperforata*. Serpulids on bivalve fragment.

VIBRACORE SR-41

Description based on a peel from section A of the interval from 0 to 152 cm downcore (Parker and others, 1997, p. 139; Hummell, 1999, p. 166).

Depth downcore (cm)	Description
0-22	SHELLY SAND with shells oriented at all angles. Shells consisting of bivalves and sand dollars, fragmented, white to dark gray, angular; maximum size 11 mm. Bioturbation subtle, evidently thorough, consisting of overlapping burrows ~2 cm across. Lower contact sharp, curved, irregular.
22-152	SHELLY SAND, lighter than above and with somewhat smaller shells at all angles. Shells consisting of bivalves and minor echinoid and balanid debris, including fragments up to 9 mm across and a few whole valves (*Anomia simplex*). Bioturbation not visible, but probably thorough as lamination and preferred shell orientation are absent.

VIBRACORE SR-43

Description based on a peel from section B of the interval from 150 to 282 cm downcore (Parker and others, 1997, p. 140; Hummell, 1999, p. 168).

Depth downcore (cm)	Description
150-237.5	SAND, coarsening upward, with shells oriented at all angles. Shells consisting of whole valves (*Chione* sp.), angular fragments, and sand-sized debris, white to dark gray (chiefly white); maximum size 2.2 cm. Lower contact sharp.
237.5-282	MUDDY SAND, slightly shelly at top and with a few shelly layers, especially lower in the unit; shells oriented at all angles. Shelly layer with sharp, articulated, white *Chione cancellata* at 128-132 cm. Shells consisting of bivalves (whole and fragmented), balanid plates, gastropods (whole and fragmented), and possible echinoid or bryozoan debris, mostly white, some light gray, angular. Bioturbation thorough, consisting largely of burrows about 1 cm across with possible concentric fill and vertical spreites.

VIBRACORE SR-44

Description based on a peel from section B of the interval from 140 to 181.5 cm downcore (Parker and others, 1997, p. 140; Hummell, 1999, p. 169).

Depth downcore (cm)	Description
140-157	SHELLY SAND, sand-supported. Shells mostly fragmented, including much sand-sized debris; few whole gastropods; molluscan debris white to dark gray; maximum size 5 mm. Bioturbation obscure. Lower contact gradational.
157-165	SANDY SHELL, shell-supported. Shells mostly bivalves, with gastropods and scaphopod, few with original color, others mostly white, some light to dark gray; few whole valves, most fragmented; maximum size 17 mm. Bivalve *Chione cancellata;* scaphopod *Dentalium* sp. Lower contact gradational.
165-181.5	SANDY SHELL, shell-supported. Shells including many whole valves (*Chione cancellata, C. intapurpurea,* lucinid, *Mercenaria* sp.) as well as fragments to sand-sized debris (including *Chione cancellata, ?Crassostrea virginica, ?Mellita quinquiesperforata,* olivid, other gastropods); color preserved in *Chione intapurpurea,* otherwise white to dark gray; maximum size 56 mm.

VIBRACORE SR-45

Description based on core sections A through C (Parker and others, 1997, p. 141; Hummell, 1999, p. 170). Section A is 0-121 cm; section B is 121-280 cm; section C is 280-432 cm. Section D was not examined.

Depth downcore (cm)	Description
0-~197	SAND, very slightly shelly, including much bioclastic material, especially sand dollar, bivalve, and gastropod fragments; similar to beach sand in appearance. Shells fragmented; sand dollar fragments white, maximum size 10 mm; bivalve fragments white to dark gray, maximum size 12 mm. Bivalve *Pandora* sp. (122 cm); smooth, subcylindrical gastropods up to 3 mm long. Bioturbation probably thorough; some horizontal burrows filled with muddy sand, 2-3 mm across; sand-filled burrows visible for a short time after moistening. Core incompletely preserved from 0 to 90 cm. Lower contact gradational.
~197-~214	SAND, slightly shelly, shellier downcore. Shells fragmented, white to dark gray, including balanid plate; maximum size 4 mm. Bioturbation thorough; some burrows filled with finer sand than host sediment. Lower contact gradational.
~214-273	SHELLY SAND, shells fining upward and also less abundant upward. Possible base of graded bed indicated by relatively large shells and fragments (up to 12 mm) at 231 cm downcore. Shells consisting of bivalves (*Anomia* sp., *Chione cancellata* juvenile), small, smooth, ovoid gastropods; white to dark gray; maximum size 35 mm. Core extensively altered during storage.
273-280	SANDY SHELL with many diverse, whole shells. Shells whole to fragmented, including *Chione cancellata,* mostly white to light gray; maximum size 32 mm. Bioturbation nil?
280-334	SAND, slightly shelly, with sandy shell bed ~1 cm thick at 315 cm and shelly lamina at 328 cm. Shells consisting of bivalves and sand dollars; whole valves (up to 76 mm) to sand-sized debris, color original (*Macrocallista nimbosa*), white to dark gray, mostly dark gray. Bioturbation nearly thorough; burrows mostly subhorizontal, filled with muddy sand, 2 to ~40 mm across.
334-379	Core disturbed from 350 to 380 cm; interval from 334 to 379 cm may belong to unit above.
379-405?	SAND, slightly shelly. Shells light-colored, some with original color (small subcylindrical gastropod). Bioturbation thorough; muddy sand-filled burrows up to 10 mm across. Lower contact disturbed but apparently sharp.

405?-432	MUDDY SAND, disturbed (core largely void between 410 and 420 cm). Shells include a few whole valves. Bioturbation thorough; burrows subhorizontal, lighter than host sediment, 1.5-4 mm across.

VIBRACORE SR-97

Description based on core sections A through C (Hummell, 1999, p. 207). Section A is 0-178 cm; section B is 178-362 cm; section C is 362-472 cm.

Depth downcore (cm)	Description
0-27	SAND, slightly shelly. Shells fragmented, angular. Bioturbation thorough. Lower contact bioturbated.
27-77	MUDDY SAND, somewhat shelly; shells oriented at all angles. Shells including many whole valves (*Chione?, Divaricella quadrisulcata, Mellita,* others). Shells largely with original color. Bioturbation thorough; larger burrows oblique, mud-filled, 12-14 mm across; most burrows oblique to subhorizontal, 2-3 mm across. Lower contact sharp.
77-94.5	VERY MUDDY SAND to MUDDY SAND, rooted (paleosol). Shells sand-sized bioclasts, white. Bioturbation: burrows horizontal to vertical, mostly 2-3 mm across; some apparently ~1 cm. Lower contact sharp.
94.5-159	SANDY MUD with roots, mostly tiny but up to 7 mm across. Shells absent. Bioturbation: burrows oblique, filled with muddy sand, 9-12 mm across, especially to 111 cm; also one isolated burrow above root at 134-136 cm.
159-182	VERY MUDDY SAND. Bioturbation thorough; burrows filled with muddy sand, most subhorizontal to oblique, ~0.5-2 mm across; larger burrows 10-15 mm across with secondary burrows. Lower contact apparently sharp.
182-246	MUDDY SAND, partly laminated and partly with "spiderewb" variegation (therefore secondarily laminated?). Bioturbation thorough. Lower contact gradational. Much of unit distorted by coring.
246-472	VERY MUDDY SAND similar to 159-182 cm, rooted, darker downcore, grading to SANDY MUD. Shells absent. Bioturbation thorough; burrows mainly subvertical, 9-15 mm across, largely vertical at 246-292 cm, 320-330 cm, and 376-405 cm, horizontal at 292-320 cm and >330 cm; subhorizontal root ~1 cm across at 408-410 cm.

VIBRACORE SR-98

Description based on core sections A through C (Hummell, 1999, p. 208). Section A is 0-177.5 cm; section B is 177.5-361 cm; section C is 361-443 cm. Samples for particle-size analysis were taken at 15 ± 5 cm, 100 ± 5 cm, 200 ± 5 cm, and 300 ± 5 cm downcore.

Depth downcore (cm)	Description
0-340	SAND with very little shell (hence suitable for beach nourishment); shelly patch at 320 cm. Shells fragmented, including bivalves and gastropods, white to dark gray, chiefly dark gray. Bioturbation probably thorough; burrows horizontal to oblique, filled with darker finer sand, 2-4 mm across. Post-collection alteration near core wall. Lower contact smooth, sharp (pre-Holocene unconformity).
340-434	MUD, stiff, colors ranging from dark gray to greenish-bluish gray to orange and dark brown, less oxidized downcore to 406 cm, variegated with spiderweb texture (paleosol). Shells absent except in burrows, white, including scaphopod. Bioturbation partial; branched burrows 17-30 mm across, filled with orange-brown, muddy sand including shells, with walls sharply defined without lining (*Thalassinoides* or *Spongeliomorpha*); other burrows subhorizontal, 3-5 mm across. Mud largely oxidized at interval 352-406 cm and reduced at 340-352 and more than 406 cm downcore.
434-443	PEATY CLAY, very dark brown.

VIBRACORE SR-99

Description based on core sections A and B (Hummell, 1999, p. 209). Section A is 0-167 cm; section B is 167-296 cm. Samples for particle-size analysis were taken at 30 ± 5 cm, 100 ± 5 cm, and 200 ± 5 cm downcore.

Depth downcore (cm)	Description
0-296	SAND, slightly shelly; relatively shelly bed with whole bivalves at 85-89 cm (including *Chione intapurpurea* with original color). Shells small valves to fragments, most white to light gray, some dark gray, angular to subangular, including bivalves, scaphopods, gastropods, echinoids; sand dollar fragments common at 0-53 cm downcore. Bioturbation obscure, probably thorough; moistening core suggests pervasive burrows about 1-2 cm wide. Section A disturbed for much of its length, especially 0-92 cm.

VIBRACORE SR-100

Description based on core sections A through C (Hummell, 1999, p. 210). Section A is 0-183 cm; section B is 183-367 cm; section C is 367-417 cm. Samples for particle-size analysis were taken at 15 ± 5 cm, 100 ± 5 cm, 120 ± 5 cm, and 200 ± 5 cm downcore.

Depth downcore (cm)	Description
0-367	Top of core probably missing. Sections A and B badly oxidized after collection and not studied in detail. SAND, slightly shelly; shelly horizon at 188-192 cm with *Chione intapurpurea* having original color. Shells few, whole to fragmented, largely white or with original color. Bioturbation thorough; burrows mud-filled, about 1.5-2 cm across, with angular (partial?) mud fills.
367-405.5	SAND, partly bioturbated. Collapsed *Thalassinoides* shaft at 373-399 cm, up to 18 mm wide. *Ophiomorpha* at 393-403.5 cm, mud-lined, sand-filled, inner diameter 12 mm, nodules up to 4 mm.
405.5-406.5	PEAT interlaminated with SAND, with sand-filled burrow about 1 cm across.
406.5-417	PEATY SAND, laminated, apparently partly bioturbated; MUDDY SAND at 407-409 cm.

VIBRACORE SR-101

Description based only on core section A (Hummell, 1999, p. 211). Section A is 0-176 cm. Sample for particle-size analysis were taken at 15 ± 5 cm downcore.

Depth downcore (cm)	Description
0-101	SHELLY SAND. Shells fragmented, about the same size throughout, subangular to angular; maximum size 11 mm. Bioturbation: mud-filled burrow about 2.5 mm across at 15 cm. Lower contact gradational.
101-133	SANDY SHELL. Shells fragmented, fining upward; maximum size 45 cm, some with original color, others white to dark gray. Bivalve *Argopecten gibbus* (fragment with original color). Lower contact sharp.
133-145	MUDDY SAND, bioturbated with sandy shell-filled burrows.
145-154.5	MUD, variegated, with shelly sand-filled vertical burrows about 1 cm across.
154.5-160.5	MUDDY SAND, partly laminated and partly bioturbated with horizontal burrows filled with muddy shelly sand to sand, about 0.5 cm across.
160.5-176	MUD, similar to 145-154.5 cm, but with oblique burrows.

VIBRACORE SR-102

Description based on core sections A through C (Hummell, 1999, p. 212). Section A is 0-180.5 cm; section B is 180.5-364 cm; section C is 364-481 cm.

Depth downcore (cm)	Description
0-32	PEATY SAND. Bioturbation thorough, including oblique *Ophiomorpha* up to 22 mm across, but with rather indistinct nodules. Lower contact sharp, bioturbated.
32-39	SAND, slightly shelly with sand-sized molluscan debris. thickly laminated. Bioturbation less than 10 percent. Lower contact sharp.
39-41	MUD, bioturbated with oblique, sand-filled burrows up to 15 mm across. Lower contact sharp.
41-46	PEATY SAND with mud-filled irregularities (probably burrows). Lower contact sharp, bioturbated.
46-~346	PEATY MUDDY SAND, with darkest and muddiest part above, lightening gradually with depth (chemical wave front?); mud horizon at 104-105 cm with mud downdrawn into burrows below to 149 cm. Only one shell fragment seen (*Dinocardium?,* may be out of place). Bioturbation thorough, including mud-lined, horizontal to oblique *Ophiomorpha* up to 22 mm across.
~346-481	SAND. Bioturbation thorough, including horizontal to oblique, thickly mud-lined *Ophiomorpha* with internal diameter up to 23 mm.

VIBRACORE SR-103

Description based on core sections A through C (Hummell, 1999, p. 213). Section A is 0-175 cm; section B is 175-357 cm; section C is 357-403 cm. Samples for particle-size analysis were taken at 15 ± 5 cm, 100 ± 5 cm, 300 ± 5 cm, and 395 cm downcore. Samples for particle-size analysis were taken at 15 ± 5 cm, 100 ± 5 cm, 300 ± 5 cm, and 395 ± 5 cm downcore.

Depth downcore (cm)	Description
0-92	SHELLY SAND, fining upward. Shells mostly fragmented, consisting of mollusks, subangular, white to dark gray; whole valves at 83-92 cm. Bioturbation thorough. Lower contact apparently sharp.
92-148	SAND, slightly muddy due to mud-lined burrows. Bioturbation thorough, including mud-lined *Ophiomorpha* (subvertical, internal diameter at least 12 mm, nodules up to 8 mm thick) at 97-119 cm downcore; other burrows indistinct.
148-162	No core.
162-175	SAND similar to 92-148 cm.
175-207	No core.
207-334	SAND similar to 92-148 cm, partly laminated below to bioturbated above, with bioturbation complete above 286 cm. Bioturbation including *Ophiomorpha* at 207-210 cm, 253-260 cm, and 271-273 cm; also vertical burrow 3 mm wide at 209-304 cm. Lower contact sharp, irregularly bioturbated.
334-403	SAND. Bioturbation thorough, including subhorizontal, mud-lined *Ophiomorpha* at 334-357 cm, and subhorizontal to oblique, mud-filled burrows 2-3 mm across at 368-403 cm.

VIBRACORE SR-109

Description based on core sections A through C (Hummell, 1999, p. 219). Section A is 0-181 cm; section B is 181-364 cm; section C is 364-416 cm. Samples for particle-size analysis were taken at 15 ± 5 cm, 100 ± 5 cm, 200 ± 5 cm, 300 ± 5 cm, and 400 ± 5 cm downcore.

Depth downcore (cm)	Description
0-38	SAND, slightly shelly. Shells fragmented, consisting of sparse sand dollars (up to 37 mm across) and very sparse mollusks (white, angular, up to 4 mm across). Bioturbation thorough; visible burrows mud-filled, horizontal, 2-4 mm across. Top of core probably missing. Lower contact gradational, distinguished by presence of sand dollar fragments above.
38-380	SAND, slightly shelly. Bioturbation thorough; visible burrows mud-filled, horizontal, 2-8 mm across, at 38-63 cm downcore (probably related to modern surface conditions).
380-393	SANDY SHELL. Shells consisting of bivalves, many whole valves (including *Chione cancellata*), also large angular fragments (including *?Macrocallista nimbosa*). Whole valves white; up to 19 mm across; fragments, white to dark gray, up to 40 mm across.
393-412	SAND. Bioturbation thorough.
412-416	SANDY SHELL?, disturbed by coring. Shells include possible whole bivalve.

VIBRACORE SR-110

Description based on core sections A and B (Hummell, 1999, p. 220). Section A is 0-176 cm; section B is 176-345 cm. Samples for particle-size analysis were taken at 25 ± 5 cm, 100 ± 5 cm, and 200 ± 5 cm downcore.

Depth downcore (cm)	Description
0-11	SANDY SHELL. Shells consisting almost entirely of sand dollar fragments, thin, rounded to angular, up to 23 mm across. Bioturbation thorough. Lower contact sharp.
11-~144	SAND, slightly shelly. Shells consisting of sand dollar and mollusk fragments, subangular, white to dark gray, up to 8 mm across. Bioturbation thorough, including a few distinct mud-filled burrows up to 5 mm across. Lower contact gradational.
~144-181	SHELLY SAND. Shells consisting of bivalves (valves and fragments) and whole small gastropods, largely dark gray, some white or reddish; fragments angular, up to 12 mm across; whole valves at base up to 30 mm. Bioturbation thorough. Lower contact probably sharp.
181-248	MUDDY SANDY SHELL; sparse woody fragments present. Shells consisting largely of sand dollar fragments up to 15 mm across; common molluscan fragments, white to dark gray. Bioturbation thorough, with indistinct burrows up to 13 mm across. Lower contact bioturbated.
248-345	SAND, very slightly shelly. Bioturbation thorough, including mud-lined *Ophiomorpha* of 5-17 mm internal diameter, concentrated at 253-262 cm, 272-283 cm, and 292-308 cm.

VIBRACORE SR-111

Description based on core sections A and B (Hummell, 1999, p. 221). Section A is 0-173 cm; section B is 173-329.5 cm. Samples for particle-size analysis were taken at 15 ± 5 cm, 100 ± 5 cm, and 200 ± 5 cm downcore.

Depth downcore (cm)	Description
0-61	SHELLY SAND. Shells fragmented, angular, up to 7 mm across, white to dark gray or with original color. Bioturbation thorough. Lower contact gradational.
61-87	MUDDY SHELLY SAND. Shells consisting of bivalves and sand dollars, fragmented, some probably whole, white to dark gray, angular, up to 26 mm across. Bioturbation thorough, with mud-filled, horizontal burrows up to 4 mm across. Lower contact sharp.
87-~102	MUDDY SAND. Shells absent. Bioturbation thorough, with oblique to horizontal burrows up to 9 mm across. Lower contact bioturbated, gradational.
~102-139	MUDDY SHELLY SAND. Shell fragments mostly white, angular, up to 8 mm across. Bioturbation thorough. Lower contact irregular (bioturbated?).
139-~201	MUDDY SAND, slightly shelly. Bioturbation thorough, including mud-rimmed *Ophiomorpha* with internal diameter about 10 mm. Lower contact gradational, bioturbated.
~201-221	VERY MUDDY SAND, slightly shelly. Shells chalky. Bioturbation thorough; concentrically filled horizontal burrows 10-13 mm across at 215-228 cm downcore. Lower contact bioturbated.
221-329.5	MUD, slightly sandy. Bioturbation thorough; large concentric burrows at 221-228 cm.

VIBRACORE SR-112

Description based only on core section A and upper part of section B (Hummell, 1999, p. 222). Section A is 0-183 cm; section B is 183-366 cm.

Depth downcore (cm)	Description
0-260	SAND, slightly shelly. Shells fragmented, angular, white to dark gray, up to 4 mm across. Bioturbation apparently thorough.
260-266	MUD with sandy laminae and SAND-filled burrows. Bioturbation about 60 percent, consisting of horizontal to oblique, sand-filled burrows up to 9 mm across; one burrow filled with shelly debris.

VIBRACORE SR-113

Description based on core sections A and B (Hummell, 1999, p. 223). Section A is 0-183 cm; section B is 183-270 cm.

Depth downcore (cm)	Description
0-~9	SHELLY SAND. Shells consisting of mollusk and sand dollar fragments; mollusk fragments white to dark gray; sand dollar fragments light brown. Bioturbation thorough. Lower contact gradational.
~9-270	SHELLY SAND, fining upward from 243 to 9 cm. Shells consisting of mollusk fragments with only sparse sand dollar debris; colors as above. Bioturbation thorough.

VIBRACORE SR-114

Description based only on core section A (Hummell, 1999, p. 224). Section A is 0-176 cm.

Depth downcore (cm)	Description
0-31	SAND, slightly shelly, now oxidized. Shell fragments either dark gray, dispersed, and up to 8 mm across, or white and concentrated in burrow fills at 7-8 cm and 21-22 cm downcore. Bioturbation thorough. Lower contact rather sharp (bioturbated?).
31-59	SHELLY SAND to SANDY SHELL, fining upward. Shells consisting of sand dollar and bivalve fragments, angular to subangular. Bioturbation thorough. Lower contact sharp, irregular.
59-176(+)	SHELLY MUDDY SAND, with shelly interval at 33-43 cm. Shells consisting of mollusks, mostly fragmented; color mostly original to white. Gastropod *Oliva sayana* at 56-57 cm. Bioturbation nearly thorough (about 80-90 percent), including smoothly mud-lined burrows with internal diameter up to 21 mm.

VIBRACORE SR-115

Description based only on core section A (Hummell, 1999, p. 225). Section A is 0-177 cm.

Depth downcore (cm)	Description
0-7	SAND, slightly shelly. Top disturbed. Bioturbation thorough. Shell fragments dark gray. Lower contact gradational.
7-17	SHELLY SAND. Shells consisting of sand dollar and bivalve fragments; sand dollars brown, bivalves light to dark gray, subangular. Bioturbation thorough. Lower contact sharp.
17-177	MUDDY SAND, slightly shelly, thickly laminated; thin, partly bioturbated mud beds at 55-64 cm, 84-87 cm, 98-104 cm, ~125-~135 cm, and 155.5-157 cm. Bioturbation apparently about 50 percent, including subhorizontal to oblique burrows up to ~20 mm across, filled with sand or mud (*Thalassinoides?*).

APPENDIX B

RAW PARTICLE-SIZE DATA OF SELECTED SAMPLES FROM OFFSHORE BALDWIN COUNTY AND ALABAMA WINTER BEACHES*

				Phi units of sieves							
Sample	Description	Lithofacies	Initial weight (g)	-2	-1.5	-1	-0.5	0	0.5	1	1.5
021203-1-1a	winter beach sand	NA	54.651	0	0	0	0.019	0.103	2.174	36.582	13.259
021203-3-2a	winter beach sand	NA	45.716	0.709	0.058	0.013	0.015	0.065	0.376	2.53	8.952
021203-6-1a	winter beach sand	NA	59.834	0	0	0.025	0.003	0.05	0.561	9.97	23.607
031106-1c	winter beach sand	NA	63.735	1.212	0.956	0.402	0.14	0.473	4.423	23.42	22.652
031106-3c	winter beach sand	NA	59.067	0	0.065	0.017	0.007	0.109	0.509	10.427	29.141
031106-12c	winter beach sand	NA	52.625	0	0	0.008	0	0.002	0.01	0.424	9.351
SR98A 15 ± 5 cm	MMS Study Area 2 sand	SHS	55.489	0	0	0.058	0.084	0.196	0.719	2.565	5.444
SR98A 100 ± 5 cm	MMS Study Area 2 sand	SHS	67.347	0	0	0.015	0.031	0.141	0.464	2.538	7.389
SR98B 200 ± 5 cm	MMS Study Area 2 sand	SHS	49.536	0.25	0	0.056	0.07	0.178	0.51	2.676	6.065
SR98B 300 ± 5 cm	MMS Study Area 2 sand	SHS	46.716	0.092	0	0.134	0.15	0.281	0.895	3.171	6.361
SR99A 30 ± 5 cm	Federal offshore sand	SHS	63.698	0.889	0.164	0.167	0.144	0.289	0.513	1.374	3.309
SR99A 100 ± 5 cm	Federal offshore sand	SHS	33.357	0	0.103	0.154	0.151	0.155	0.253	0.875	1.832
SR99B 200 ± 5 cm	Federal offshore sand	SHS	47.687	0.125	0.056	0.125	0.139	0.204	0.383	0.927	1.992
SR100A 15 ± 5 cm	Federal offshore sand	SHS	42.348	0.327	0.046	0.058	0.119	0.153	0.346	1.348	3.178
SR100A 100 ± 5 cm	Federal offshore sand	SHS	39.293	0.324	0.124	0.157	0.071	0.117	0.316	1.269	3.044
SR100B 120 ± 5 cm	Federal offshore sand	SHS	46.305	2.082	0.071	0.202	0.197	0.239	0.561	2.025	3.922
SR100B 200 ± 5 cm	Federal offshore sand	SHS	39.79	0	0.008	0	0.008	0.071	0.354	1.548	2.601
SR101A 15 ± 5 cm	MMS Study Area 2 sand	GSS	46.829	0.091	0.05	0.276	0.254	0.296	0.441	1.438	3.964
SR103A 15 ± 5 cm	Federal offshore sand	GSS	55.96	0.644	0.558	0.434	0.603	0.587	0.885	2.615	7.106
SR103A 100 ± 5 cm	Federal offshore sand	S	44.466	0	0	0	0.016	0.04	0.139	1.108	5.815
SR103B 300 ± 5 cm	Federal offshore sand	S	38.358	0	0	0	0.041	0.082	0.431	1.871	3.235
SR103C 395 ± 5 cm	Federal offshore sand	S	44.451	0	0	0	0	0.033	0.141	0.717	2.248
SR109A 15 ± 5 cm	State offshore sand	GSS	57.863	1.375	0.281	0.216	0.139	0.385	1.595	7.874	14.689
SR109A 100 ± 5 cm	State offshore sand	GSS	48.721	0	0.035	0.032	0.1	0.169	0.888	5.744	12.429
SR109B 200 ± 5 cm	State offshore sand	GSS	61.571	0.145	0.063	0.191	0.131	0.335	1.401	7.668	15.698
SR109B 300 ± 5 cm	State offshore sand	GSS	50.361	0.15	0.534	1.137	0.909	0.862	0.668	1.795	5.208
SR109C 400 ± 5 cm	State offshore sand	GSS	53.414	0.1	0.028	0.047	0.028	0.157	1.034	6.803	16.481
SR110A 25 ± 5 cm	State offshore sand	GSS	60.028	0.379	0.337	0.529	0.415	0.524	1.041	5.71	13.727
SR110A 100 ± 5 cm	State offshore sand	GSS	54.235	0.646	0.451	0.361	0.417	0.491	1.012	5.573	12.644
SR110B 200 ± 5 cm	State offshore sand	SHS	50.361	0.15	0.534	1.137	0.909	0.862	0.668	1.795	5.208
SR111A 15 ± 5 cm	State offshore sand	GSS	56.318	0	0.014	0.037	0.082	0.134	0.193	0.693	5.841
SR111A 100 ± 5 cm	State offshore sand	SHS	49.957	0	0.028	0.131	0.11	0.117	0.188	0.639	2.628
SR111B 200 ± 5 cm	State offshore sand	SHS	45.401	0.243	0.028	0.088	0.092	0.13	0.281	1.51	5.317

* Analyst: Andrew K. Rindsberg

APPENDIX B
RAW PARTICLE-SIZE DATA OF SELECTED SAMPLES FROM
OFFSHORE BALDWIN COUNTY AND ALABAMA WINTER BEACHES* - continued

Sample	2	2.5	3	3.5	4	Pan
021203-1-1a	2.17	2.226	0.018	0.027	0.004	0.003
021203-3-2a	22.084	10.629	0.275	0.051	0.003	0.004
021203-6-1a	20.24	5.187	0.127	0.066	0.005	0.005
031106-1c	9.318	0.771	0.012	0.012	0.002	0.003
031106-3c	16.936	1.838	0.046	0.03	0.003	0.004
031106-12c	33.01	10.375	0.246	0.059	0.005	0.005
SR98A 15 ± 5 cm	14.695	21.201	8.691	1.494	0.078	0.018
SR98A 100 ± 5 cm	19.117	25.31	10.137	1.94	0.08	0.076
SR98B 200 ± 5 cm	13.568	17.731	6.7	1.436	0.071	0.044
SR98B 300 ± 5 cm	13.064	15.372	5.944	1.152	0.081	0.014
SR99A 30 ± 5 cm	11.175	30.386	12.692	2.222	0.156	0.058
SR99A 100 ± 5 cm	5.853	16.032	6.532	1.254	0.065	0.026
SR99B 200 ± 5 cm	6.669	22.907	11.224	2.49	0.099	0.129
SR100A 15 ± 5 cm	7.115	14.357	12.457	2.56	0.144	0.082
SR100A 100 ± 5 cm	7.069	13.641	10.581	2.301	0.144	0.064
SR100B 120 ± 5 cm	7.841	14.191	11.884	2.724	0.182	0.066
SR100B 200 ± 5 cm	4.046	9.972	16.088	4.624	0.256	0.206
SR101A 15 ± 5 cm	11.906	19.759	7.078	1.087	0.02	0.018
SR103A 15 ± 5 cm	18.746	17.581	5.093	1.062	0.05	0.027
SR103A 100 ± 5 cm	17.085	16.284	3.405	0.519	0.06	0.023
SR103B 300 ± 5 cm	6.608	14.119	9.646	2.214	0.113	0.062
SR103C 395 ± 5 cm	4.933	12.245	17.42	6.033	0.198	0.395
SR109A 15 ± 5 cm	19.992	9.008	1.782	0.423	0.026	0.016
SR109A 100 ± 5 cm	18.887	8.433	1.621	0.423	0.025	0.007
SR109B 200 ± 5 cm	22.974	10.348	1.97	0.539	0.035	0.011
SR109B 300 ± 5 cm	14.498	17.811	5.541	0.928	0.107	0.151
SR109C 400 ± 5 cm	21.513	6.277	0.641	0.217	0.022	0.015
SR110A 25 ± 5 cm	22.455	11.81	2.406	0.496	0.039	0.014
SR110A 100 ± 5 cm	19.989	10.159	1.815	0.539	0.031	0.015
SR110B 200 ± 5 cm	14.498	17.811	5.541	0.928	0.107	0.151
SR111A 15 ± 5 cm	22.98	19.163	6.302	0.806	0.03	0.01
SR111A 100 ± 5 cm	10.357	18.154	15.097	2.423	0.09	0.05
SR111B 200 ± 5 cm	14.62	17.637	4.733	0.655	0.032	0.01

APPENDIX C

TWO SAMPLE T-TESTS COMPARING WINTER BEACHES, GRADED SHELLY SAND AND SHELLY SAND LITHOFACIES

t-Test: Winter beach versus GSS

	Winter beach	*GSS*
Mean	368.068812	326.0472397
Variance	9303.57803	33863.19979
Observations	9	55
Hypothesized Mean Difference	0	
df	19	
t Stat	1.03467976	
P(T<=t) one-tail	0.15690454	
t Critical one-tail	1.72913133	
P(T<=t) two-tail	0.31380909	
t Critical two-tail	2.0930247	

The means are not significantly different.

t-Test: Winter beach versus GSS excluding shell lags

	GSS	*Winter beach*
Mean	283.289332	368.068812
Variance	2611.36284	9303.578029
Observations	52	9
Hypothesized Mean Difference	0	
df	9	
t Stat	-2.57505343	
P(T<=t) one-tail	0.01496929	
t Critical one-tail	1.83311292	
P(T<=t) two-tail	0.02993857	
t Critical two-tail	2.26215716	

The means are significantly different.

t-Test: GSS versus SHS

	SHS	*GSS*
Mean	250.511259	326.7151629
Variance	853.859464	33272.48805
Observations	19	56
Hypothesized Mean Difference	0	
df	63	
t Stat	-3.01436395	
P(T<=t) one-tail	0.00185386	
t Critical one-tail	1.66940222	
P(T<=t) two-tail	0.00370772	
t Critical two-tail	1.99834052	

The means are significantly different.

APPENDIX C
TWO SAMPLE T-TESTS COMPARING WINTER BEACHES,
GRADED SHELLY SAND AND SHELLY SAND LITHOFACIES--continued

t-Test: GSS excluding shell lags versus SHS

	GSS	*SHS*
Mean	283.289332	250.5112587
Variance	2611.36284	853.8594644
Observations	52	19
Hypothesized Mean Difference	0	
df	56	
t Stat	3.36015762	
P(T<=t) one-tail	0.00070392	
t Critical one-tail	1.6725223	
P(T<=t) two-tail	0.00140785	
t Critical two-tail	2.0032407	

The means are significantly different.

All tests assume unequal variances.

APPENDIX D
SELECTED PARTICLE-SIZE DATA FROM SAMPLES COLLECTED IN FEDERAL WATERS OFF ALABAMA

Sample Identity[1]	**SR-20-100**	**SR-20-200**	**SR-20-300**	**SR-20-400**	**SR-27-40**	**SR-28-100**	**SR-28-200**	**SR-29-100**	**SR-29-180**	**SR-30-60**	**SR-31-30**
Initial Sample Weight (g)	50.71	51.361	54.729	49.12	51.499	52.233	54.598	54.901	52.454	49.365	52.725
Lithofacies[2]	GSS	GSS	GSS	SMB	SMI	GSS	GSS	GSS	GSS	GSS	GSS
Sieve size (µm)	**Weights3**										
4000	0.020	0.315	0.804		0.831	0.045	0.158	0.046	1.415		4.426
2800	0.064	0.421	0.416		0.490	0.031	0.257		0.497		1.489
2000	0.069	0.349	0.285	0.038	0.342	0.049	0.464	0.042	0.474	0.014	1.286
1400	0.116	0.317	0.348	0.067	0.298	0.072	0.651	0.268	0.535	0.029	1.358
1000	0.169	0.306	0.216	0.055	0.274	0.197	0.906	0.355	0.494	0.115	1.238
710	0.246	0.407	0.420	0.062	0.247	0.361	1.160	0.528	0.543	0.220	2.790
500	0.972	1.475	1.655	0.339	0.439	1.686	3.542	1.630	1.595	1.099	9.957
355	3.298	4.305	5.119	1.891	0.921	6.078	8.801	3.751	3.382	4.137	12.663
250	12.341	13.335	14.979	10.356	3.013	19.297	18.821	10.635	9.725	11.935	10.605
180	23.482	21.319	22.062	24.495	8.061	19.164	15.536	22.059	19.915	20.033	5.109
125	7.979	6.964	6.694	9.616	16.549	4.326	3.538	12.115	10.828	9.197	1.230
90	1.834	1.726	1.621	2.033	13.266	0.860	0.708	3.164	2.788	2.334	0.519
63	0.076	0.092	0.070	0.126	4.924	0.047	0.031	0.225	0.186	0.177	0.025

[1]Core numbers plus depths in core (cm)
[2]GSS, Graded Shelly Sand; SMB, Sand with Mud Burrows; SMI, Sand Mud Interbeds; SM, Muddy Sand; OB, Oyster Biostrome; SCS, Silty/Clayey Sand; SHS, Shelly Sand; S, Sand
[3]Weights (g) of sample sieve size fractions
Data were summarized by Parker and others (1993).
Site locations are presented in the ArcView project.
(modified from Kopaska-Merkel and Rindsberg, 2005)

APPENDIX D
SELECTED PARTICLE-SIZE DATA FROM SAMPLES COLLECTED IN FEDERAL WATERS OFF ALABAMA

Sample Identity*	**SR-32-100**	**SR-32-175**	**SR-32-195**	**SR-32-215**	**SR-32-250**	**SR-32-350**	**SR-32-450**	**SR-34-150**	**SR-34-250**	**SR-34-300**
Initial Sample Weight (g)	54.101	51.784	50.301	38.273	51.269	49.66	50.068	53.284	52.267	51.462
Lithofacies	GSS	GSS	SM	OB	SCS	SCS	SCS	GSS	GSS	GSS
Sieve size (µm)										
4000	0.182	3.582	1.355	2.122			0.336			0.206
2800	0.189	0.771	0.374	1.728	0.064		0.509	0.031	0.153	0.336
2000	0.235	0.594	0.363	1.176	0.169	0.030	0.314	0.008	0.106	0.921
1400	0.415	0.363	0.367	1.174	0.140	0.013	0.187	0.021	0.214	1.736
1000	0.550	0.462	0.456	1.445	0.150	0.020	0.141	0.084	0.681	2.733
710	0.767	0.659	0.428	1.330	0.144	0.025	0.102	0.174	1.768	3.697
500	3.207	2.499	1.222	0.949	0.338	0.059	0.133	1.031	7.411	5.969
355	8.917	7.085	3.319	0.603	0.853	0.142	0.246	5.680	9.898	7.682
250	20.267	17.095	10.142	1.139	3.390	1.088	1.083	14.043	11.612	9.640
180	15.194	14.351	17.803	3.692	9.349	8.815	8.415	20.187	12.956	11.352
125	3.209	3.317	9.241	6.408	11.745	14.971	17.309	9.980	6.115	5.817
90	0.889	0.918	3.687	9.546	12.386	12.945	11.623	1.932	1.282	1.295
63	0.047	0.052	1.118	5.573	8.973	8.359	7.265	0.078	0.044	0.055

APPENDIX D

SELECTED PARTICLE-SIZE DATA FROM SAMPLES COLLECTED IN FEDERAL WATERS OFF ALABAMA - continued

Sample Identity*	SR-34-350	SR-39-100	SR-39-180	SR-39-230	SR-39-330	SR-40-100	SR-40-200	SR-40-300	SR-40-395	SR-40-460
Initial Sample Weight (g)	47.081	50.072	52.994	50.347	49.992	51.628	52.821	49.694	48.138	48.342
Lithofacies	GSS	GSS	GSS	SMB	SM	GSS	GSS	GSS	SMB	SM
Sieve size (µm)										
4000	24.304		0.044	0.338	0.104			0.032	0.763	
2800	1.426	0.071	0.350	0.271	0.101			0.122	0.257	0.043
2000	0.907	0.082	0.777	0.118	0.123	0.020	0.012	0.176	0.156	0.060
1400	0.601	0.042	1.009	0.117	0.255	0.014	0.071	0.187	0.142	0.115
1000	0.531	0.079	1.489	0.138	0.245	0.035	0.106	0.202	0.138	0.097
710	0.568	0.103	3.625	0.176	0.283	0.100	0.257	0.567	0.166	0.103
500	1.257	0.515	5.287	1.288	0.335	0.526	0.985	1.529	0.271	0.171
355	2.154	3.320	7.159	5.993	0.422	1.833	2.368	2.831	1.204	0.596
250	4.184	14.628	18.557	23.890	1.077	11.367	12.430	10.862	7.533	2.492
180	6.459	20.128	13.094	16.628	2.542	27.003	26.445	23.513	18.628	4.927
125	3.627	9.073	0.987	0.698	9.250	9.184	8.717	8.351	10.654	9.425
90	0.907	1.910	0.502	0.528	20.330	1.355	1.277	1.137	5.950	15.141
63	0.055	0.088	0.083	0.130	12.398	0.138	0.123	0.132	1.702	11.497

APPENDIX D
SELECTED PARTICLE-SIZE DATA FROM SAMPLES COLLECTED IN FEDERAL WATERS OFF ALABAMA

Sample Identity*	**SR-41-100**	**SR-41-200**	**SR-41-250**	**SR-42-75**	**SR-43-100**	**SR-43-175**	**SR-43-250**	**SR-44-100**	**SR-44-150**	**SR-45-100**
Initial Sample Weight (g)	52.824	52.819	47.726	54.047	53.045	51.725	51.59	50.893	51.56	53.168
Lithofacies	SHS	SHS	SMI	SHS	GSS	SMB	SM	GSS	GSS	GSS
Sieve size (µm)										
4000		0.771	0.109		1.264	0.264	1.386		0.169	0.095
2800	0.071	0.322	0.236	0.059	0.896	0.100	0.090	0.056	0.393	0.117
2000	0.128	0.199	0.227	0.192	0.815	0.149	0.075	0.218	0.470	0.240
1400	0.138	0.240	0.254	0.375	0.475	0.173	0.166	0.344	0.771	0.348
1000	0.239	0.227	0.281	0.376	0.667	0.198	0.200	0.361	1.148	0.360
710	0.497	0.394	0.342	0.939	1.112	0.209	0.169	0.545	2.333	0.726
500	1.991	1.300	0.608	5.134	3.015	0.248	0.188	1.371	4.830	2.460
355	6.928	4.071	1.158	11.173	4.907	0.362	0.479	2.745	4.744	5.639
250	20.651	16.688	3.388	17.158	10.287	1.490	2.143	6.339	5.874	15.455
180	18.470	22.812	8.505	12.150	16.614	12.997	4.501	15.171	10.948	21.273
125	2.965	4.843	19.817	5.014	10.326	26.576	14.517	16.737	13.003	5.518
90	0.681	0.906	11.062	1.395	2.460	7.979	20.980	6.350	6.131	0.879
63	0.045	0.031	1.314	0.053	0.161	0.761	5.835	0.507	0.557	0.035

APPENDIX D

SELECTED PARTICLE-SIZE DATA FROM SAMPLES COLLECTED IN FEDERAL WATERS OFF ALABAMA - continued

Sample Identity*	SR-45-200	SR-45-300	SR-45-400	sr-46-100	SR-47-100	SR-47-300	SR-48-130	SR-54-250	SR-55-100	SR-56-55
Initial Sample Weight (g)	53.211	48.564	48.566	48.045	51.01	46.454	52.46	52.919	50.223	52.738
Lithofacies	GSS	SMB	SM	SM	SM	SMI	SCS	SM	SM	SHS
Sieve size (µm)										
4000	0.921	0.409	0.394	0.377	1.997			3.974		
2800	1.009	0.151	0.245	0.226	0.210			1.014		
2000	1.216	0.325	0.373	0.351	0.155	0.015	0.054	0.976	0.019	0.013
1400	1.108	0.239	0.215	0.256	0.278	0.003	0.107	0.846	0.010	0.074
1000	0.813	0.209	0.297	0.336	0.398	0.021	0.146	1.032	0.157	0.272
710	1.621	0.343	0.241	0.627	0.528	0.059	0.293	1.621	1.004	0.879
500	3.386	0.946	0.586	1.484	0.940	0.644	1.020	3.463	4.390	4.323
355	5.216	2.555	1.531	2.979	1.856	4.835	3.499	4.029	7.377	10.715
250	12.027	8.489	5.507	7.502	5.515	22.900	11.716	7.196	8.208	12.922
180	18.272	20.583	16.097	11.021	10.853	11.406	18.523	9.549	9.380	13.778
125	6.196	12.113	14.658	9.889	11.542	1.700	11.951	7.609	8.007	6.454
90	1.336	2.048	6.557	9.532	12.045	1.060	3.983	8.518	8.133	2.680
63	0.062	0.114	1.494	2.844	3.771	2.454	0.795	2.476	2.898	0.464

APPENDIX D

SELECTED PARTICLE-SIZE DATA FROM SAMPLES COLLECTED IN FEDERAL WATERS OFF ALABAMA - continued

Sample Identity*	**SR-56-125**	**SR-56-170**	**SR-57-100**	**SR-58-100**	**SR-58-250**	**SR-59-100**	**SR-59-200**	**SR-1-60**	**SR-1-120**	**SR-2-60**
Initial Sample Weight (g)	50.984	54.803	53.345	50.093	51.481	53.241	51.379	47.129	49.292	54.315
Lithofacies	SM	SM	GSS	SMB	SMB	GSS	GSS	SM	SCS	S
Sieve size (µm)										
4000	1.539	0.072		0.472	0.104		0.030	0.364	0.767	0.249
2800	1.504	0.540	0.087	0.311	0.230		0.039	0.620	0.869	0.161
2000	1.076	1.469	0.632	0.229	0.211	0.002	0.106	0.680	1.118	0.229
1400	1.165	2.898	2.007	0.314	0.236	0.025	0.383	0.574	0.750	0.210
1000	1.412	3.543	2.834	0.602	0.338	0.194	0.728	0.726	0.702	0.402
710	2.086	4.372	3.691	1.287	1.219	0.338	1.339	0.548	0.369	0.446
500	5.698	10.390	7.927	3.000	3.739	1.898	4.602	0.529	0.571	1.025
355	7.028	9.773	8.652	3.498	6.424	7.283	10.395	1.036	0.535	3.258
250	8.527	7.831	8.474	7.223	12.803	21.003	19.389	4.224	1.377	11.121
180	11.496	8.194	10.198	13.512	17.168	17.432	11.769	10.243	3.399	21.086
125	5.811	3.623	6.615	7.477	6.198	2.808	1.537	14.884	10.364	12.766
90	2.815	1.661	1.950	8.631	1.808	2.082	0.872	10.267	16.698	3.100
63	0.573	0.290	0.197	2.989	0.765	0.138	0.151	1.959	8.612	0.189

APPENDIX D
SELECTED PARTICLE-SIZE DATA FROM SAMPLES COLLECTED
IN FEDERAL WATERS OFF ALABAMA - continued

Sample Identity*	**SR-2-120**	**SR-2-160**	**SR-3-15**	**SR-3-60**
Initial Sample Weight (g)	48.404	50.911	49.208	52.636
Lithofacies	SM	S	SMB	GSS
Sieve size (µm)				
4000	0.280	0.237		
2800	0.298	0.157	0.074	
2000	0.172	0.335	0.145	0.015
1400	0.191	0.531	0.149	0.050
1000	0.282	0.718	0.233	0.089
710	0.314	0.777	0.234	0.141
500	0.623	0.919	0.226	0.408
355	1.824	2.051	0.310	2.552
250	6.492	9.373	2.843	13.498
180	16.437	20.262	19.625	22.081
125	15.815	11.627	20.589	11.270
90	5.204	3.577	4.552	2.394
63	0.383	0.259	0.156	0.093

APPENDIX E															
SIEVE ANALYSES OF GULF OF MEXICO BOTTOM GRAB SAMPLES															
SCREEN	**SR-1-BG[2]**	**SR-2-BG**	**SR-3-BG**	**SR-4-BG**	**SR-5-BG**	**SR-6-BG**	**SR-7-BG**	**SR-8-BG**	**SR-9-BG**	**SR-10-BG**	**SR-11-BG**	**SR-12-BG**	**SR-13-BG**	**SR-14-BG**	**SR-15-BG**
OPENING	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**
(phi units)															
-2	0.015	0	0	0	0	0.418	0.118	0.036	0	0	10.562	0.146	1.075	0.486	0.095
-1.5	0.058	0	0	0	0	0.471	0.171	0.024	0	0.027	1.08	0.047	0.142	0.494	0.076
-1	0.129	0	0.005	0.089	0.054	0.994	0.189	0.044	0	0.066	0.914	0.078	0.251	0.739	0.1
-0.5	0.139	0.03	0.036	0.107	0.049	1.012	0.261	0.065	0.011	0.149	0.779	0.145	0.314	0.561	0.153
0	0.177	0.056	0.041	0.175	0.112	1.107	0.398	0.108	0.022	0.156	0.533	0.139	0.414	0.828	0.211
0.5	0.228	0.086	0.057	0.225	0.197	1.613	0.56	0.131	0.063	0.324	1.065	0.287	0.495	1.501	0.323
1	0.284	0.332	0.267	0.953	0.887	6.138	2.058	0.532	0.512	2.006	4.188	1.459	0.536	6.913	0.812
1.5	0.639	1.984	1.465	4.878	4.236	13.019	8.356	2.125	4.057	7.628	8.046	5.335	0.852	14.981	1.895
2	3.234	9.434	6.64	16.102	14.554	15.945	20.347	8.308	16.52	19.855	12.519	16.011	4.131	16.506	4.476
2.5	11.868	21.171	17.079	23.324	21	8.247	14.496	20.958	21.55	15.971	11.453	20.308	12.163	8.298	8.964
3	17.262	12.009	16.387	6.333	5.076	1.76	2.639	16.132	8.828	4.274	2.368	5.07	14.589	1.99	16.321
3.5	13.011	2.297	4.129	0.787	0.74	0.395	0.377	2.578	2.66	0.809	0.582	0.848	12.175	0.471	12.456
4	3.492	0.079	0.144	0.022	0.016	0.027	0.019	0.145	0.215	0.04	0.026	0.046	3.622	0.039	4.367
PAN	0.837	0.051	0.058	0.022	0.019	0.032	0.024	0.051	0.065	0.021	0.048	0.026	0.936	0.041	1.261
net spl wt[3]	51.373	47.529	46.308	53.017	46.94	51.178	50.013	51.237	54.503	51.326	54.163	49.945	51.695	53.848	51.51

[1]Summary data reported by Parker and others (1997). All weights in grams. Appendix 3 of Kopaska-Merkel and Rindsberg (2005).

[2]Site number plus suffix indicating bottom grab sample.

[3]Sum of weights of sieve fractions.

[4]Lithofacies; GSS, Graded Shelly Sand; ES, Echinoid Sand of Parker and others (1997).

APPENDIX E															
SIEVE ANALYSES OF GULF OF MEXICO BOTTOM GRAB SAMPLES--continued															
SCREEN	**SR-16-BG**	**SR-17-BG**	**SR-18-BG**	**SR-19-BG**	**SR-20-BG**	**SR-21-BG**	**SR-22-BG**	**SR-23-BG**	**SR-24-BG**	**SR-25-BG**	**SR-26-BG**	**SR-27-BG**	**SR-28-BG**	**SR-29-BG**	**SR-30-BG**
OPENING	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**	**SAND**
(phi units)															
					GSS (ES)***	GSS (ES)	GSS	GSS	GSS (ES)	GSS	GSS	GSS	GSS		
-2	2.346	0.041	0.06	0.068	0	0.216	0	6.778	0	0	0.026	11.773	0.048	0	0.058
-1.5	0.551	0.037	0.08	0.218	0	0.13	0.043	2.171	0	0.029	0	3.193	0.058	0.006	0
-1	0.349	0.07	0.243	0.165	0.036	0.097	0.101	2.074	0.046	0.002	0.017	2.603	0.087	0.043	0.058
-0.5	0.251	0.114	0.219	0.288	0.018	0.083	0.137	2.245	0.035	0.03	0.033	2.321	0.169	0.077	0.032
0	0.296	0.126	0.323	0.402	0.033	0.135	0.218	3.315	0.104	0.096	0.062	2.163	0.199	0.063	0.046
0.5	0.332	0.133	0.385	0.71	0.091	0.281	0.612	8.568	0.23	0.313	0.144	2.257	0.23	0.134	0.091
1	0.862	0.292	1.075	1.626	0.485	1.111	2.476	13.38	1.221	1.92	0.909	3.764	0.885	0.954	0.419
1.5	2.301	1.271	4.339	3.766	2.428	3.107	7.187	8.284	3.463	5.517	2.949	3.543	4.677	3.535	1.713
2	7.632	7.099	19.044	6.85	11.341	11.972	17.844	4.612	10.772	14.299	9.848	4.432	20.528	12.019	7.538
2.5	16.55	23.095	22.493	12.819	24.613	24.327	17.712	1.638	20.29	23.227	22.393	4.981	18.578	20.778	21.185
3	13.964	14.051	2.971	11.068	10.89	7.728	4.156	0.255	9.512	7.661	12.129	4.569	3.657	8.46	16.003
3.5	6.033	2.495	0.5	6.091	1.995	1.989	0.811	0.122	1.769	1.346	2.299	4.106	0.7	1.58	3.999
4	0.902	0.198	0.024	1.733	0.073	0.17	0.048	0.03	0.083	0.052	0.099	0.482	0.024	0.062	0.189
PAN	0.238	0.066	0.024	0.41	0.025	0.055	0.026	0.064	0.044	0.03	0.043	0.178	0.013	0.025	0.062
net spl wt[3]	52.607	49.088	51.78	46.214	52.028	51.401	51.371	53.536	47.569	54.522	50.951	50.365	49.853	47.736	51.393

APPENDIX E

SIEVE ANALYSES OF GULF OF MEXICO BOTTOM GRAB SAMPLES--continued

SCREEN OPENING (phi units)	SR-31-BG SAND	SR-32-BG SAND	SR-33-BG SAND	SR-34-BG SAND	SR-35-BG SAND	SR-36-BG SAND	SR-37-BG SAND	SR-38-BG SAND	SR-39-BG SAND	SR-40-BG SAND	SR-41-BG SAND	SR-42-BG SAND	SR-43-BG SAND	SR-44-BG SAND	SR-45-BG SAND
-2	0.032	0.038	5.419	0.418	0.147	0	0.036	1.289	0	0.506	0	0.421	0.734	0.14	0.09
-1.5	0.247	0.071	1.353	0.344	0.275	0.043	0.08	0.328	0.02	0.167	0	0.037	0.117	0.072	0.127
-1	0.156	0.222	1.626	0.5	0.302	0.121	0.104	0.354	0.01	0.114	0.003	0.095	0.201	0.105	0.095
-0.5	0.372	0.223	1.203	0.672	0.295	0.078	0.175	0.452	0.049	0.238	0.038	0.082	0.151	0.152	0.099
0	0.509	0.292	0.974	0.681	0.347	0.147	0.25	0.559	0.072	0.286	0.052	0.091	0.308	0.243	0.155
0.5	0.893	0.457	0.922	1.126	0.953	0.162	0.461	1.278	0.089	0.653	0.123	0.186	0.804	0.529	0.387
1	4.779	2.692	1.247	4.331	4.111	0.374	1.651	4.401	0.345	2.739	1.246	1.09	3.073	2.322	2.251
1.5	12.022	9.136	2.112	10.259	9.117	0.892	4.87	8.567	1.419	6.876	7.251	4.485	6.999	5.968	7.429
2	18.431	21.501	4.402	15.29	16.529	4.35	11.052	14.133	6.243	15.911	21.99	11.103	15.808	13.306	20.709
2.5	12.49	13.917	11.02	12.415	16.102	18.169	19.419	14.545	21.683	16.263	16.768	14.939	19.393	19.005	17.931
3	3.507	2.59	12.843	3.991	4.623	21.013	11.248	6.453	17.26	4.859	2.473	11.998	5.741	7.092	2.427
3.5	1.095	0.547	7.965	0.835	1.014	7.559	2.343	2.031	2.7	0.979	0.513	3.667	1.196	1.355	0.815
4	0.059	0.029	0.87	0.034	0.034	0.897	0.12	0.066	0.071	0.019	0.008	0.107	0.028	0.018	0.012
PAN	0.032	0.029	0.227	0.032	0.027	0.256	0.044	0.056	0.045	0.017	0.013	0.038	0.024	0.019	0.024
net spl wt[3]	54.624	51.744	52.183	50.928	53.876	54.061	51.853	54.512	50.006	49.627	50.478	48.339	54.577	50.326	52.551

APPENDIX E

SIEVE ANALYSES OF GULF OF MEXICO BOTTOM GRAB SAMPLES--continued

SCREEN OPENING (phi units)	SR-46-BG SAND	SR-47-BG SAND	SR-48-BG SAND	SR-49-BG SAND	SR-50-BG SAND	SR-51-BG SAND	SR-52-BG SAND	SR-53-BG SAND	SR-54-BG SAND	SR-55-BG SAND	SR-56-BG SAND	SR-57-BG SAND	SR-58-BG SAND	SR-59-BG SAND
-2	0.414	0.746	0	0	0	0.039	0.862	0.5	1.43	0.592	0.08	1.713	0.264	0.294
-1.5	0.311	0.092	0.023	0.064	0	0.035	0.207	0	0.304	0.268	0.216	1.267	0.159	0.559
-1	0.088	0.056	0.086	0.204	0	0.119	0.167	0.072	0.219	0.175	0.172	1.539	0.166	0.86
-0.5	0.087	0.107	0.123	0.112	0	0.171	0.237	0.149	0.373	0.331	0.259	1.984	0.265	1.077
0	0.164	0.189	0.272	0.159	0.024	0.413	0.243	0.286	0.495	0.556	0.329	2.431	0.376	1.161
0.5	0.224	0.273	0.37	0.207	0.061	0.626	0.368	0.715	0.835	1.368	0.597	2.791	0.8	1.441
1	0.448	0.531	0.828	0.324	0.087	1.251	0.747	1.986	2.116	2.941	1.775	6.456	1.863	5.15
1.5	0.893	1.299	3.153	1.305	0.435	4.595	1.636	4.293	3.424	3.674	3.373	14.144	2.722	16.765
2	2.971	5.018	10.909	6.365	4.734	18.732	4.751	9.805	7.331	6.526	10.854	14.073	6.536	21.648
2.5	8.465	12.138	11.835	17.177	12.905	19.926	6.861	13.097	10.983	14.511	23.482	5.596	13.327	5
3	20.245	12.441	13.694	18.54	17.761	4.365	11.073	9.925	10.647	13.453	8.44	1.322	8.222	0.496
3.5	12.168	9.635	7.974	8.073	9.941	1.29	14.264	4.97	11.025	8.727	2.041	0.409	10.084	0.237
4	3.627	3.017	0.864	1.016	1.705	0.111	5.027	0.612	3.903	1.567	0.198	0.04	4.153	0.052
PAN	1.227	0.923	0.246	0.212	0.349	0.039	1.448	0.15	0.947	0.442	0.069	0.041	1.016	0.049
net spl wt[3]	51.332	46.465	50.377	53.758	48.002	51.712	47.891	46.56	54.032	55.131	51.885	53.806	49.953	54.789

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