GEOLOGICAL SURVEY OF ALABAMA

Ernest A. Mancini
State Geologist

Energy and Coastal Geology Division
Robert M. Mink, Director

Final Report

GEOLOGICAL, ECONOMIC, AND ENVIRONMENTAL CHARACTERIZATION OF SELECTED NEAR-TERM LEASABLE OFFSHORE SAND DEPOSITS AND COMPETING ONSHORE SOURCES FOR BEACH NOURISHMENT

by

Steven J. Parker, David J. Davies, and W. Everett Smith

with contributions on Economic Evaluation by

T. Gerald Crawford and Robert Kelly

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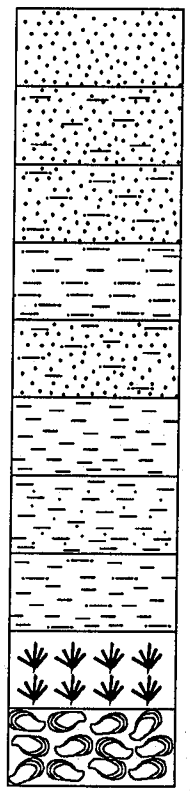
EXPLANATION OF PATTERNS AND SYMBOLS

SEDIMENT TYPES



- SAND
- CLAYEY SAND
- SILTY SAND
- CLAYEY SILT
- SAND-SILT-CLAY
- CLAY
- SANDY CLAY
- SILTY CLAY
- PEAT
- OYSTER BIOSTROME

CONTACTS

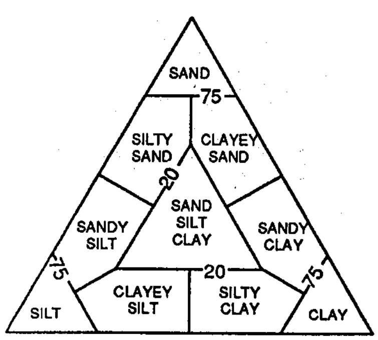
- SHARP
- GRADATIONAL

SAMPLE INDEX

— 310 - SEDIMENT SAMPLE

NOTE: Mean grain size and texture graphs on vibracore columnar sections extend only to lowest sample in vibracore.

SEDIMENT TEXTURE NOMENCLATURE



ACCESSORIES

- OYSTER SHELL
- ARTICULATED PELCYPOD
- INARTICULATED PELCYPOD
- SHELL FRAGMENT
- PEBBLE
- GRANULE
- ECHINOID FRAGMENT
- PEAT BALL
- ROOTS
- ORGANIC MATTER
- RIP UP CLAST

SEDIMENTARY STRUCTURES

- SAND POCKET
- CLAY POCKET
- CLAYEY SAND POCKET
- SHELL POCKET
- MUD BURROW
- SAND BURROW
- CLAY DRAPE
- GRADED BED
- HORIZONTAL LAMINATIONS

BIOTURBATION INDEX*

(1) No bioturbation recorded; all original sedimentary structures preserved.
(2) Discrete, isolated trace fossils; up to 10% of original bedding disturbed.
(3) Approximately 10 to 40% of original bedding disturbed. Burrows are generally isolated, but locally overlap.
(4) Last vestiges of bedding discernable; approximately 40 to 60% disturbed. Burrows overlap and are not always well defined.
(5) Bedding is completely disturbed, but burrows are still discrete in places and the fabric is not mixed.
(6) Bedding is nearly or totally homogenized.

*(Droser and Bottjer, 1986)

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EXECUTIVE SUMMARY

Since 1986, the Minerals Management Service (MMS) of the U. S. Department of Interior has directed the Gulf Task Force, composed of representatives of the states of Alabama, Mississippi, Louisiana, and Texas, to assess the occurrence and economic potential of hard mineral (non-fuel) resources in the Exclusive Economic Zone (EEZ) of those states. Sand and gravel, shell, and heavy minerals were the prominent hard minerals identified in the Gulf of Mexico EEZ, with sand being identified as the most abundant mineral and having the highest near-term leasing potential.

The primary goal of present study by the Geological Survey of Alabama is the identification and characterization of high quality clean sand deposits in the Alabama EEZ to determine their potential for beach nourishment of eroding coastal shoreline segments in Alabama. Characteristics of the offshore sand deposits were compared with competing onshore deposits to identify the most suitable material for use in beach nourishment projects. In addition, a preliminary evaluation of the physical and biological environmental impacts was completed.

Evaluation of the regional geologic framework of the Alabama EEZ indicates the onshore sedimentary units are late Cenozoic in age; sediments in the EEZ consist of Holocene marginal and marine sediments overlying an irregular erosional surface of late Pleistocene-early Holocene age. These Holocene sediments consist of a sand sheet and incised valley fill with sand ridges east of the Main Pass of Mobile Bay, a sandy tidal delta associated with the Pass, and muddy nearshore sediments west of the Pass.

Eroding Gulf shorelines in Alabama were identified, and preliminary shoreline restoration areas were prioritized. While most Alabama coastal shoreline exhibits a long-term erosional trend, highest priority areas of beach replenishment were two areas on the Gulf beaches of Dauphin Island; the west side of Perdido Pass; and the west side of the inlet at Little Lagoon. The Gulf shoreline of southeastern Dauphin Island could be restored to near the 1955 shoreline position by application of about 1.8 million yd^3 (cubic yards) of sand. On the Baldwin County Gulf shoreline, the continually eroding beaches adjacent to the west sides of Perdido Pass (40,000 yd^3) and Little Lagoon Pass (120,000 yd^3) could also be nourished from offshore sand sources.

Five offshore target areas were delineated based on the potential for appropriate sand volumes in the form of sand ridges, sand sheets or ebb tidal deltas. These were located in water depths of a few tens of feet, all within a few miles of the critically eroding shorelines outlined above. Core data within these areas could potentially yield as much as 700 million yd^3 of sand for beach nourishment.

Existing geological data was compiled to delineate the geologic framework of selected potential offshore resource sites. Additionally, this study collected 59 vibracores and 59 bottom sediment samples which were analyzed and modeled with respect to grain size, sedimentary texture, lithofacies patterns, and three dimensional distribution of sediment type.

Geologic data and resource characterization were analyzed in terms of areal extent and volume of sand, sediment size, and compatibility for beach nourishment. Six lithofacies comprised of thirteen microfacies were delineated based on sediment characterization, spatial extent, and environment of deposition; of these, two (Clean Sands and Graded Shelly Sands) were deemed to have highest potential as beach nourishment sources. All five offshore target areas were determined to be potential sand sources for beach replenishment. This was based on their sand aesthetic compatibility with beach samples, estimated sand volume, and surface sand distributions.

Sand samples from ten potential onshore sand resource sites were evaluated with respect to grain size, sand extent, and color to determine if they would be appropriate for beach replenishment. Production figures for sand mining in coastal Alabama were evaluated; it was determined there is insufficient clean white sand available from onshore sources for major beach replenishment projects.

An economic analysis based on information in this draft report was completed by the MMS using a mathematical model referred to as QUIKSAND. The economic analysis was accomplished for three identified beach replenishment projects; Dauphin Island, Little Lagoon Pass, and Perdido Pass utilizing two of the sand resource areas identified in this report. Additionally, an assessment of heavy minerals was to be completed; however, as no concentrations of heavy minerals were identified in any bottom sample or core, it was not possible to accomplish this task.

Three types of preliminary environmental analyses were accomplished for this study, including the impacts of offshore sand dredging on shelf circulation;

on ongoing human marine activities; and on local benthic biota. It was determined that dredging may not significantly alter background wave regimes; however, data are insufficient to model effects of major storms. Any dredging activities would need to avoid man made structures and shipping fairways. Preliminary evidence indicates that there would likely be little long-term impact on benthic biota, assuming livebottoms are avoided. Additional work is required to confirm or refute these preliminary findings, however.

This study concludes that since much of the Alabama shoreline is undergoing significant, long-term erosion, critical threatened shorelines will need to have ongoing programs of replenishment if shoreline retreat is to be even temporarily halted. For the Alabama coastal zone, there are no local onshore volumes of appropriate sand available for any such large scale program. Five target areas appear to hold sufficient reserves of appropriate sand resource material in the Alabama EEZ. Sand distribution within these target areas, however, is complex, based on a patchy facies pattern. A detailed geological, economic and environmental evaluation of these sites prior to initiation of dredging would be needed to ensure a cost-effective and environmentally sound mining program.

ACKNOWLEDGEMENTS

Appreciation is expressed to T. John Rowland, of the U.S. Department of Interior, Minerals Management Service (MMS), Office of Strategic and International Minerals, Herndon, Virginia, and Gary Lore of the MMS Office in New Orleans, Louisiana for assistance in the successful completion of this project. We would like to thank T. Gerald Crawford and Robert Kelly of the MMS office in New Orleans, Louisiana for providing the economic analysis.

We would like to thank the staff of the University of Mississippi Marine Minerals Technology Center, Oxford, Mississippi, and especially the crew of the R/V *Kit Jones*, for assistance with marine vibracoring. Likewise, the field assistance received from the University of Alabama, Dauphin Island Sea Lab, is appreciated.

We wish to thank Lewis Dean and Richard Hummell of the Geological Survey of Alabama (GSA), and Lisa Markland of the Department of Geology, University of Alabama, for assistance with field sampling and laboratory analyses.

Discussions with Charles Copeland, Dorothy Raymond, and Michael Szabo of the GSA regarding Alabama coastal stratigraphy added immeasurably to our understanding of subsurface formations. Their opinions and expertise are included in the section on regional geology.

INTRODUCTION

OBJECTIVES

Hard mineral resources in the Exclusive Economic Zone (EEZ) have been the target of much research in recent years due to a growing need to delineate additional supplies of sand and gravel, shell, heavy minerals, phosphates and other economic minerals. In 1986, the U. S. Department of Interior Minerals Management Service (MMS) established the Gulf Task Force, composed of representatives of Alabama, Mississippi, Louisiana, and Texas to assess the occurrence and economic potential of hard mineral (non-fuel) resources in the EEZ, offshore Alabama, Mississippi, Louisiana, and Texas based on available data. Sand and gravel, shell, and heavy minerals were the prominent hard minerals identified in the Gulf of Mexico EEZ. Sand was identified as being the most abundant mineral and having the highest near-term leasing potential. Based on these results, ensuing studies by the task force have been directed at characterizing high quality sand deposits for use in beach restoration projects.

The present study, by the Geological Survey of Alabama (GSA), is aimed at continuing the goals of the Gulf Task Force. The primary objectives for this study were to identify and characterize high-quality clean sand deposits in the EEZ, offshore Alabama, to determine the development potential for use in beach nourishment of specific eroding shoreline segments in Alabama's coastal area. Characteristics of the offshore sand deposits were compared with competing onshore deposits to identify the most suitable material for use in beach nourishment projects. In addition, a preliminary evaluation of the physical and biological environmental impacts was completed. Based on evaluation of previous studies of the Gulf Task Force, the Alabama EEZ study area was limited to an area within the EEZ from approximately the state-federal boundary to the 30° Latitude line (fig. 1).

TASKS ACCOMPLISHED AND APPROACH FOLLOWED

The objectives of this study were to be accomplished through completion of ten tasks designed to evaluate the potential of offshore sand resources for use as beach nourishment. The plan of study was designed to ensure that a coordinated effort was maintained throughout the project that resulted in fulfilling the project objectives and specific identified tasks. These tasks, and the approach utilized for each, include the following:

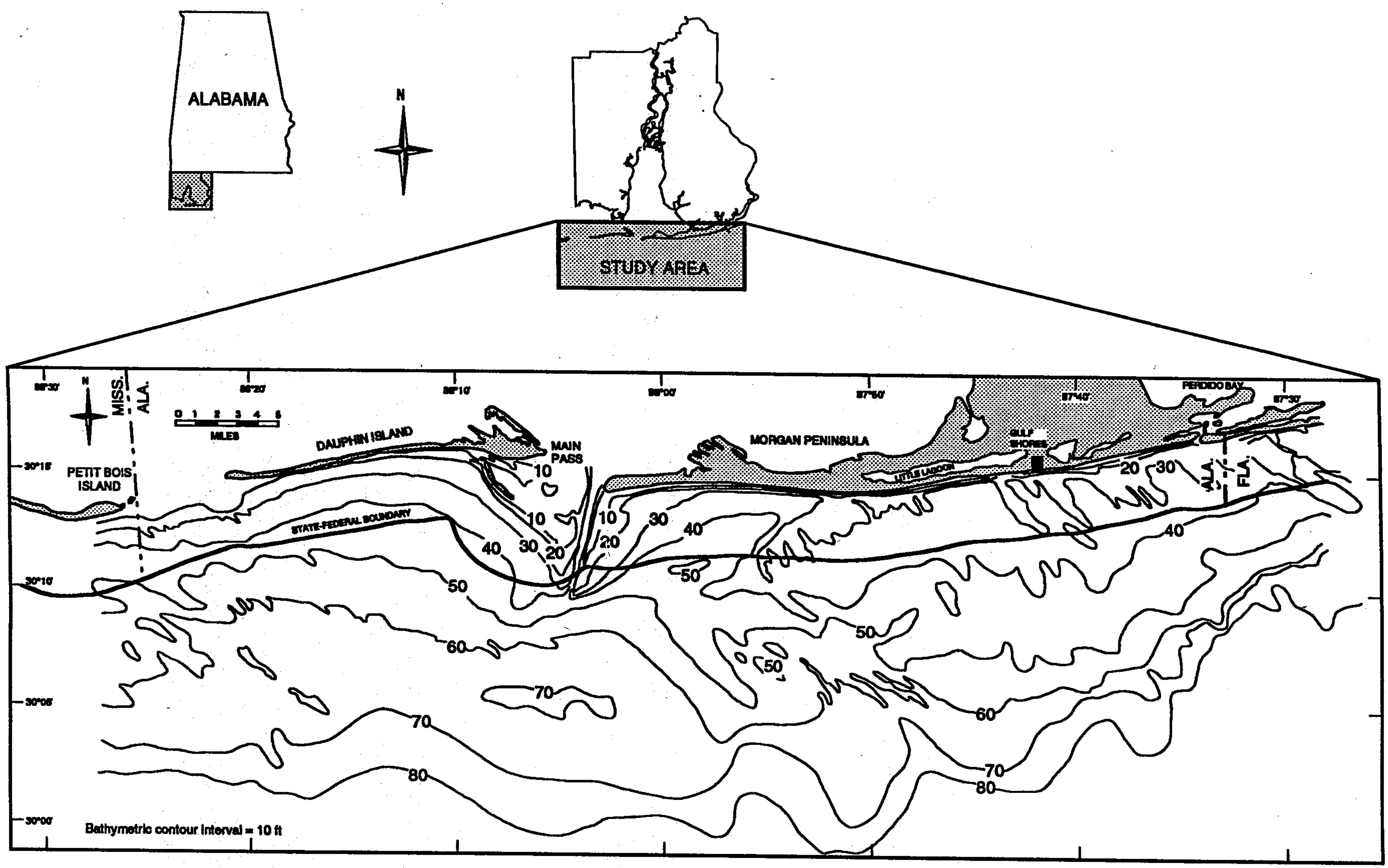


Figure 1.--Map of the Alabama EEZ study area.

1. **Prior knowledge of the regional geologic framework for coastal Alabama and the Alabama EEZ was to be delineated, especially with respect to sandy units.** The approach utilized was to evaluate available published information and ongoing regional stratigraphic work of the GSA to determine onshore and offshore near surface stratigraphy and shelf morphology.

2. **Eroding Gulf shorelines in Alabama were to be identified, and preliminary prioritization of need for shoreline restoration was to be accomplished.** The approach to accomplish this task was to identify and prioritize Alabama Gulf shoreline segments undergoing critical erosion by utilizing beach profiles, aerial photos and published data. These data provided information on areas that might be potential sites for near-term beach replenishment projects.

3. **Potential offshore sand resource sites were to be selected based on near-term leasing potential for beach replenishment of nearby shorelines.** The approach followed was to identify and characterize specific sand resource sites in terms of granulometry, sand volume, and resource potential. Criteria for selecting resource sites were determined; these included proximity to eroding shoreline segments, potential of material to meet beach sand quality and volume specifications, and environmental impacts of sand dredging.

4. **Existing geological data relevant to selected sites was to be compiled. This required that data compiled in the year 1 report of the task force study be reexamined and updated.** These data

consisted of scientific reports, geophysical data, foundation boring logs, and bottom sampling data. Bathymetric data was to be compiled from National Oceanic and Atmospheric Administration (NOAA) nautical charts.

5. **Additional geologic data to adequately describe sand resource sites was to be acquired.** The approach to accomplish this task required that sufficient bottom samples (bottom grabs) and vibracores (cores) be collected during the study to adequately determine the geologic framework of the study area and to characterize the offshore resource sites.

6. **Geologic data were to be analyzed in terms of resource characterization including areal extent, volume, sediment size, and compatibility for beach nourishment.** These critical parameters were to be determined from laboratory and computer analyses of data collected for this study. These included sediment grain size analyses, sediment descriptions, and facies determinations, as well as the production of several types of maps, cross sections, and lithologic columnars to determine regional and site-specific trends.

7. **An analysis of sand samples from onshore sites was to be performed to evaluate the potential of onshore sand resources.** This was to be accomplished by field sampling and laboratory analysis of onshore sand sources and evaluation of recent sand production data.

8. **MMS was to provide an economic analysis based on information in this draft report to be included in the final report.** The data collected for this study will provide the background information to complete a

detailed economic analysis and determine the resource areas with the greatest potential.

9. **An assessment of heavy minerals was to be completed.** This required that all sample areas be evaluated to determine the presence of significant concentrations of heavy minerals, and appropriate samples would be analyzed for heavy mineral content.

10. **The physical environmental impacts of sand dredging in resource areas were to be determined from existing wave and current data; analysis of benthic samples taken for this study was to permit determination of possible impacts on the benthic biota.** Available wave and current data were to be evaluated to assess physical environmental impacts. Biological samples were to be collected within each offshore resource site and analyzed to determine potential biological environmental impacts of dredging activities.

REGIONAL GEOLOGY

Previous knowledge of the regional geology of coastal Alabama and the Alabama EEZ and the morphology of the EEZ were delineated to complete task 1 of this project.

STUDY AREA LOCATION

The study area, the inner part of the Federal waters in the Alabama EEZ, is part of the east Louisiana-Mississippi-Alabama Shelf (ELMAS), a triangularshaped region which includes portions of offshore Louisiana, Mississippi, Alabama, and northwest Florida (fig. 2). The shelf extends from the Mississippi River Delta on the west to DeSoto Canyon on the east. It is approximately 80 miles (mi) wide in the west and narrows to approximately 35 mi in the east. It is a broad relatively flat plain with an average width of 59 mi and a mean seaward slope of 5.5 feet/mile (ft/mi). Directly north of the study area are two large estuary systems, Mississippi Sound and Mobile Bay. The Alabama Coastal Plain occupies the onshore areas adjacent to Mississippi Sound and Mobile Bay.

STRATIGRAPHY OF ONSHORE UNITS, COASTAL ALABAMA

The geology of onshore coastal Alabama consists of dissected Late Cenozoic sedimentary deposits that dip gently seaward in Mobile and Baldwin Counties (fig. 3). The age ranges from Holocene to Miocene in different areas (table 1), with the age of outcropping formations decreasing seaward. Raymond and others (1988) indicate that the Holocene and most of the Pleistocene is undifferentiated "alluvial, coastal and terrace deposits" composed of "sand, silt, clay and gravel, varicolored; locally [it] may contain organic matter, peat, shells, and shell debris". These undifferentiated Quaternary deposits range from 0 to 150 ft thick. Szabo and Copeland (1988) indicate that this unit is exposed over all of Dauphin Island (including the formation of the spit on the western end of the island during historic times), Morgan Peninsula, and the Mobile River Delta. They also indicate that it is exposed in a band from the shoreline to approximately 2 to 3 mi inland on the northern Alabama shore of Mississippi Sound, for approximately 5 mi inland

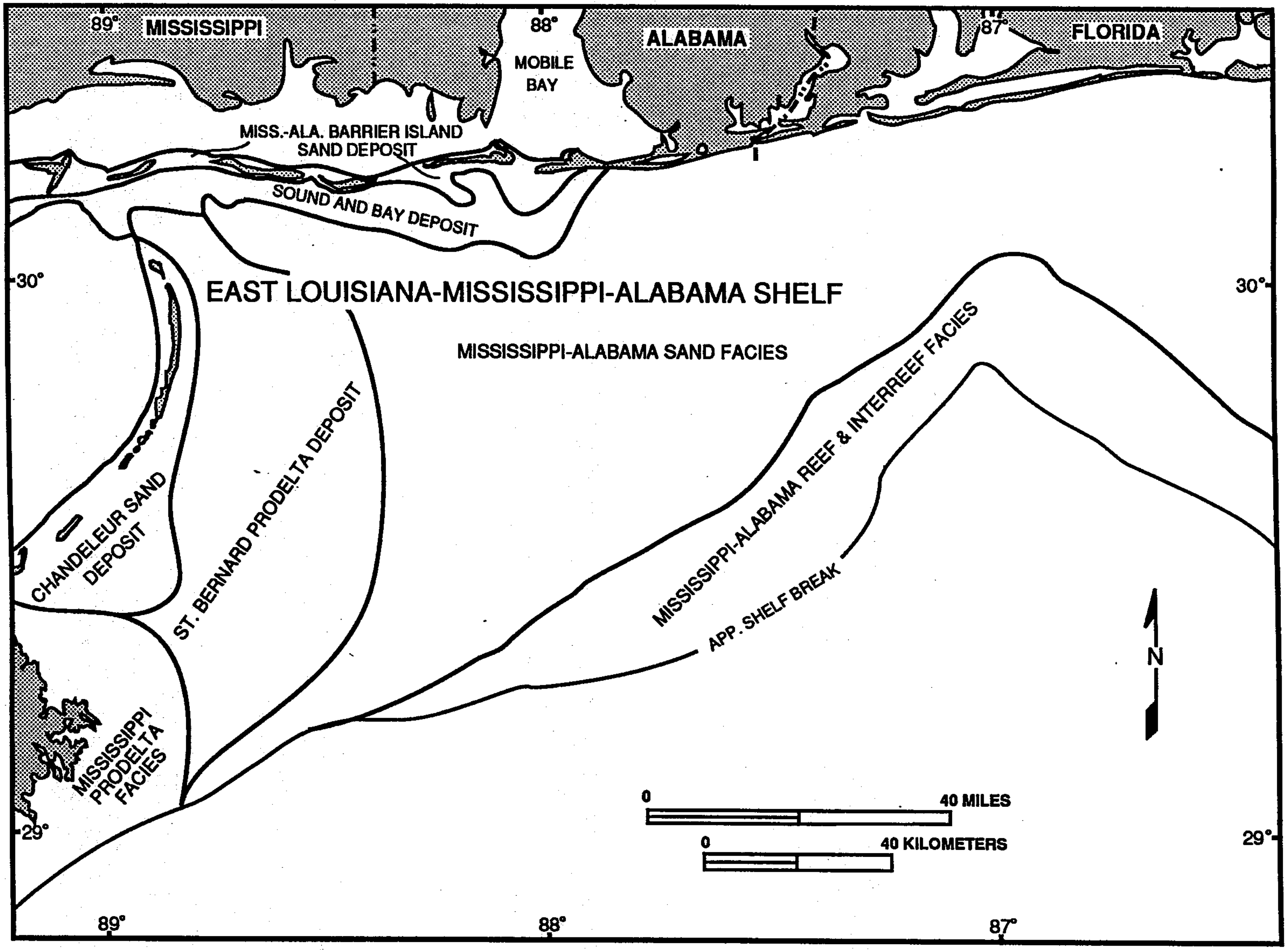


Figure 2.--Sedimentary facies on the east Louisiana-Mississippi-Alabama shelf (modified from Ludwick, 1964).

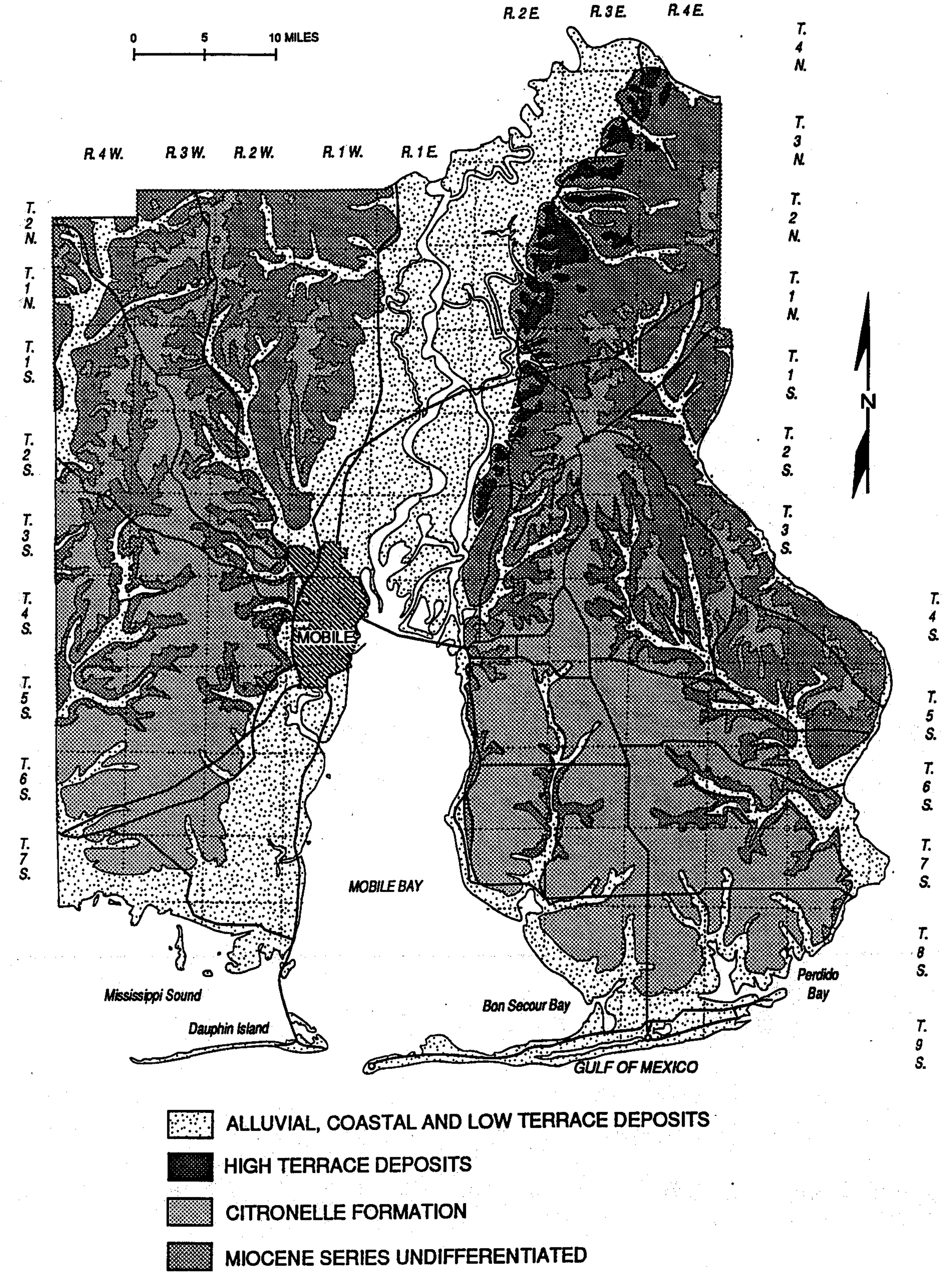


Figure 3.--Geologic map of Mobile and Baldwin counties.

Table 1.--Chart of sedimentary formations that crop out or occur in the shallow subsurface in Baldwin County, Alabama (stratigraphy modified from Reed, 1971).

ERA	PERIOD	TIME SUB-DIVISION	EPOCH	AGE (THOUSANDS OF YEARS)	GEOLOGIC UNIT	LITHOLOGY
CENOZOIC	QUATERNARY		HOLOCENE	10	ALLUVIAL AND TERRACE DEPOSITS	Alluvial deposits consist of alluvium, beach, estuarine, swamp, stream, and deltaic deposits, including white, gray, black, orange, and brown, very fine- to coarse-grained sand, clayey sand, sandy clay, and peat. May include variable amounts of organic material with peat consisting primarily of organic material. Gravel may occur locally.
			PLEISTOCENE			High terrace deposits consist of white, gray, brownish-red, and orange, fine- to coarse-grained sand that is gravelly in many exposures. Lenticular beds of light-gray, orange, and yellow sandy clay occur locally.
	TERTIARY	NEOGENE	PLIOCENE	1,800	CITRONELLE FORMATION	Sand, dark-reddish-brown, gravelly, locally containing clay balls and clay partings; light-gray, orange, and brown sandy clay, and clayey sand; and quartz gravel. Yellowish-brown iron oxide-cemented sandstone at base of formation.
			MIOCENE	5,000 23,000	MIOCENE UNDIFFERENTIATED	Clay, sand, and sandy clay, light-gray, yellowish-gray, yellow, and white, laminated to thin-bedded, and massive.

from the shoreline on the west side of Mobile Bay, and for a much shorter distance (0-2 mi) on the eastern shore of Mobile Bay.

The inland limit of the undifferentiated Quaternary coincides approximately with the Pamlico terrace as mapped by Carlston (1950); he indicates that the present shoreline surficial sediments represent "marine, estuarine and stream deposits" of Pamlico (Pleistocene) age. So far, it has not been possible to consistently differentiate the Holocene from Pleistocene sediments based on their lithology. The present study indicates that there are at least intermittent exposures of the "Pre-Holocene transgression" sediments that crop out from under the thin Holocene veneer along the western shoreline of Mobile Bay, and on the eastern (wide) portion of Dauphin Island. This Pamlico terrace is the youngest (most seaward) of several supposed Pleistocene terraces mapped in the Alabama coastal plain by Carlston (1950), each having marine to stream deposits preserved between it and the next seaward (younger) terrace.

Along the eastern margin of the Mobile River Delta, and further upstream along the Alabama and Tombigbee Rivers, are a series of Pleistocene river terraces, marking downcutting episodes from the various Pleistocene sea level fluctuations (fig. 3). Few have been adequately dated and none have been directly correlated with the coastal terraces. They consist of typical fluvial sediments, ranging from sandy gravels to point bar sands to fine grained deposits.

Inland from the coastal Pleistocene terraces crops out the Citronelle Formation (table 1); it is exposed over large areas of southern Mobile and Baldwin Counties. Raymond and others (1988) and Carlston (1950) both agree with Matson's 1916 designation of it being Pliocene to Pleistocene in age. Raymond and others (1988) describe the Citronelle as being "moderate-reddish-brown deeply weathered sand containing quartz and chert pebbles and lenticular beds of red, purple, yellow and gray clays that are typically mottled". Matson (1916) indicates that there is great variability in lithology from place to place. It is presumably largely fluvial in origin. Berry (1916) indicates that it contains a diverse Pliocene terrestrial flora preserved in clays while Roy (1939) indicates that the plant-bearing clays predate the Citronelle Formation in its sandy type locality. It has a thickness of 0 to 200 ft and is unconformity bounded. It is not known whether these Pliocene deposits remain in the Pleistocene paleolows of Mobile Bay and the EEZ fluvial channels, or whether they may have been eroded during Pleistocene lowstands.

Otvos (1976, 1985, 1991) agrees that the Citronelle is largely Pliocene in age, perhaps extending into the earliest Pleistocene. Remnant deposits of early Pleistocene age in some places overlie either the Citronelle formation or pre-Sangamonian (Pleistocene) alluvial units. He has proposed an alternative Pleistocene stratigraphy for coastal Alabama and Mississippi.

He recognizes the "Pamlico" as being the only Pleistocene terrace associated with a high sea level stand; it is underlain by Sangamonian to early Wisconsinan brackish and marine deposits. These consist of his (proposed) Prairie, Biloxi, and Gulfport Formations, which are equivalent to the upper part of the Quaternary in table 1. The Prairie Formation consists of Sangamonian fluvial-floodplain deposits (point bars and channels) of coarse to fine sand with occasional silt and gravel inclusions. It crops out over a broad area on the north shore of Mississippi Sound and western Mobile Bay seaward of the Citronelle outcrop. It interfingers seaward with the Biloxi Formation; under Mississippi Sound, it occasionally rests over the eroded Biloxi Formation. Its upper surface is coincident with the Beaumont surface of Texas and the Pamlico surface of Florida. Thus, Prairie deposition continued following initial marine retreat from its interglacial high stand.

The Biloxi Formation is the silty-sandy, sandy-muddy basal unit of Sangamonian marine transgression. It represents open marine to estuarine bay facies based on commonly preserved foraminifera. It typically overlies Neogene sandy to muddy deposits, and is overlain shoreward by the Prairie Formation, the Gulfport Formation near the outer margin of the Sound, and Holocene flooding surface deposits in parts of the Sound.

The Gulfport Formation is composed of regressive barrier sands representing coastal beach ridges during the peak Sangamonian high stand. This shoreline occurred in approximately the same location as the Morgan Peninsula-Dauphin Island-Petit Bois Island arc, and in fact sands attributed to the Gulfport Formation crop out on eastern Dauphin Island and eastern Morgan Peninsula. It overlies the Biloxi Formation. This interpretation of Pleistocene stratigraphy by Otvos is still controversial, and its validity is open to debate.

Undifferentiated Miocene and Pliocene sediments lie under the Citronelle Formation (fig. 3). Raymond and others (1988) describe these as "red and orange quartz sand, thin gravel beds and massive mottled varicolored clay" with a thickness of 0-2000 ft. It is defined as being capped by the first subsurface zone of common macrofossils, including Rangia johnsoni. It crops out in stream valleys in the Citronelle uplands east and west of Mobile Bay where younger sediments have been stripped away by downcutting; it is felt that much of the Plio-Pleistocene may also have been removed by similar processes from the floor of Mobile Bay during Pleistocene low stands. It also extensively covers the uplands areas of northern Mobile and Baldwin Counties.

Underlying these undifferentiated Miocene-Pliocene sediments is the Middle-Upper Miocene Pensacola Clay, found in the subsurface of Mobile and Baldwin Counties. It is composed of "greenish-gray to light-olive-gray slightly calcareous, slightly micaceous, in part fossiliferous, silty to sandy marine clay containing beds and lenses of sand. The formation consists of upper and lower clay members separated by the Escambia Sand Member, a gray fine- to very coarse-grained micaceous quartz sand locally containing pebbles and granules of quartz, shells, and carbonaceous plant fragments" (Raymond and others, 1988). Raymond (1985) shows that this formation does not extend to near the surface and therefore could not be utilized as a sand resource. All sediments seen in this study directly beneath the Holocene unconformity must be younger than the Pensacola Clay.

ALABAMA EEZ SHELF GEOLOGY

Seafloor topography and sediment distribution on the ELMAS, which includes offshore Alabama, are the result of a combination of deltaic progradation, regression with concomitant dissection of the exposed shelf by ancient fluvial systems, and reworking by coastal processes associated with sea level rise (Ludwick, 1964; Coleman and others, 1989; Doyle and Sparks, 1980; Kindinger and others, 1982; Kindinger, 1988; Van Andel, 1960; Van Andel and Poole, 1960). During regression associated with this sea level fall, Mesozoic and Cenozoic Gulf Coastal Plain sediments were exposed on the shelf and eroded by fluvial systems that developed on the broad, low lying plain. Marine, coastal, and fluvial environments probably prograded seaward to successively lower elevations until sea level reached a maximum lowstand which was approximately 406 ft below its present level (Smith, 1986a).

A significant problem is determining the age, and thus the formation name, of the deposits beneath this Late Pleistocene-Holocene unconformity in any particular Alabama EEZ location. The seaward subsurface extent of the previously described onshore Cenozoic formations is poorly constrained.

Sediments underlying the thin Holocene sedimentary cover partly consist of relict fluvial sands and gravels that were deposited during the latest low sea level stand which ended about 15,000 to 18,000 years before present (YBP) (Smith, 1986a; Lockwood and McGregor, 1988). A piece of wood from a depth of 8.7 ft was C-14 dated at 19,450+/- 220 years before present (YBP) from a location off Barron Point in the northeastern part of Mississippi Sound (Geological Survey of Alabama, 1992). This indicates that just offshore, at least in this area, the non-marine to estuarine sediments underlying the Holocene veneer are Late Pleistocene (Wisconsinan) in age.

Subsequent sea level rise beginning after 15,000 to 18,000 YBP allowed marine processes to rework and redistribute sediments, partially or totally destroying geomorphic features associated with the environments mentioned above. Sea level fluctuations, associated with Wisconsinan Glaciation, and the impact of these fluctuations on the continental shelf and slope of the ELMAS are depicted in a series of idealized cross sections constructed by Kindinger and others (1982) (fig. 4). The transgressive-regressive episodes have been preserved in the stratigraphic sequence as periods of transgressive sedimentation and regressive deltaic progradation and erosion and reworking of sediments (Kindinger and others, 1982).

It is likely that all Citronelle has been eroded away seaward of the "Pamlico" terrace escarpment during Pleistocene transgressive-regressive cycles; except for possible pockets of Pleistocene low stand fluvial deposits, it is believed therefore that Miocene sediments may subcrop beneath the Holocene estuarine fill in Mississippi Sound, Mobile Bay, and further out on the shelf. Much of the Plio-Pleistocene may also have been removed by lowstand stream downcutting processes from the floor of Mobile Bay and the inner shelf during Pleistocene low stands. Otvos (1985) indicates that Upper Miocene to Upper Pliocene

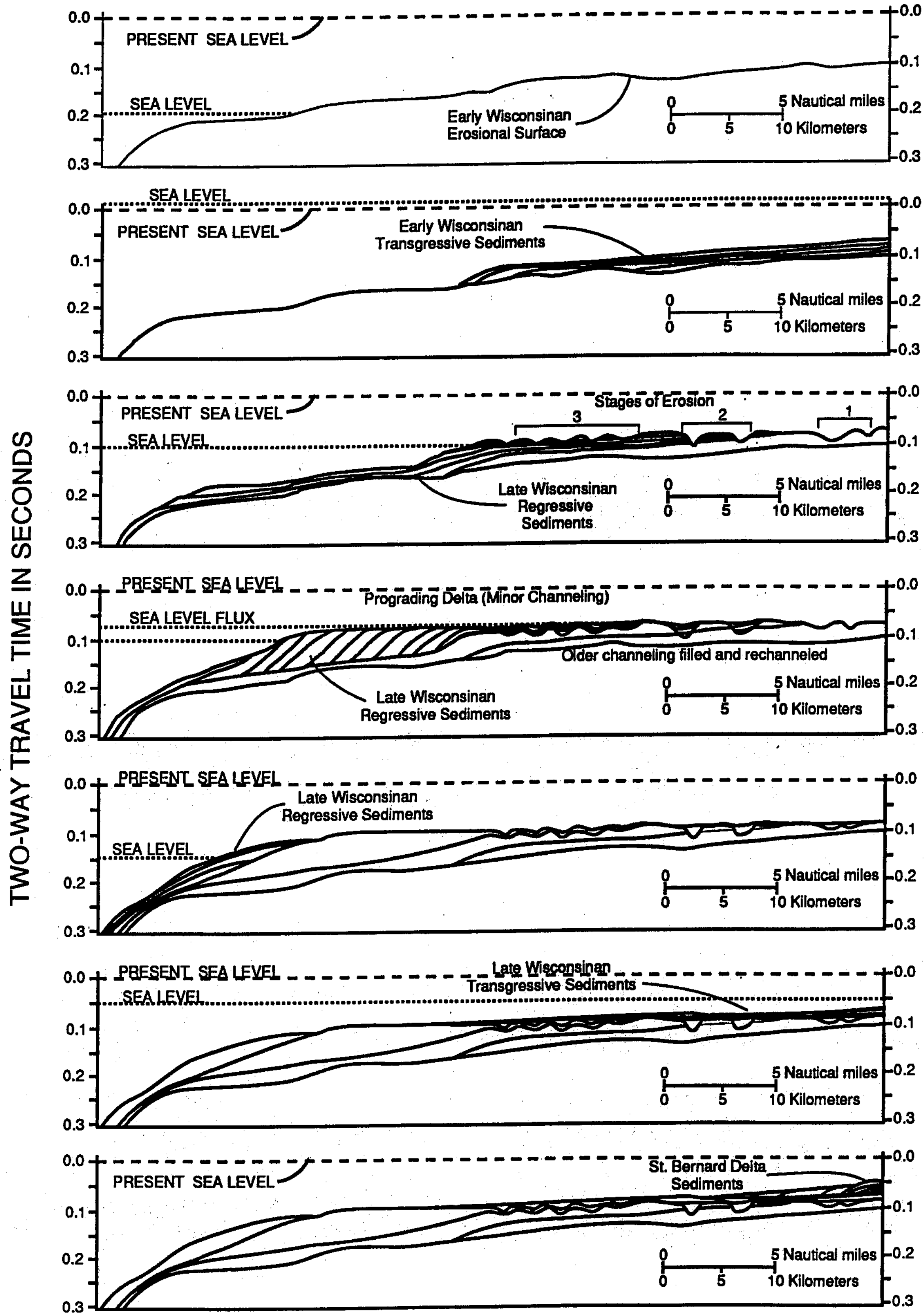


Figure 4.--Composite cross section of the east Louisiana-Mississippi-Alabama shelf (modified from Kindinger and others, 1982).

foraminifera are found at a depth of -49 ft within Mississippi Sound sediments just north of the west end of Dauphin Island; due to the uncertainties in age dates for most of these sediments, he recommends utilizing the term "undifferentiated Miocene-Pliocene clastics" and dropping the older term of Graham Ferry Formation.

At present, without additional biostratigraphic control, the range in lithologies of these formations is so great that it is problematic to determine the particular unit present from looking at just a few cm of sediment in the vibracores. Thus, as there are insufficient age dates available for the Pre-Holocene sediments, presently it is not possible to determine the formation name of the subcropping sediments at any particular EEZ location.

Recent studies of the geologic framework of the ELMAS indicate that very little Holocene deposition occurred in this area with the exception of the late Holocene progradation of the St. Bernard delta complex of the Mississippi River delta (Kindinger, 1988). Much of the deposition associated with the delta was restricted to the shelf offshore of eastern Louisiana and Mississippi where prodelta sediments average 13 ft thick (Kindinger and others, 1982). These sediments thin from northwest to the southeast and only a thin veneer of prodelta sediment occurs on the shelf offshore of Alabama (Kindinger and others, 1991). Other framework studies of offshore Alabama indicate that Holocene sediment thickness on parts of the shelf is only a few feet (McBride and others, 1991). McBride and others (1991) show that south of Petit Bois Pass, the Pre-Holocene surface crops out on the shoreface approximately 25 to 30 ft below mean low water. Otvos (1985) suggests that within the main paleochannel of the Mobile River system, Holocene sediment thickness may be as much as 100 ft below sea level at Main Pass.

Earlier studies of the ELMAS surficial sediment distribution indicate that, on a regional scale, much of the shelf offshore of Alabama is covered with sand (fig. 2) (Ludwick, 1964; Upshaw and others, 1966; Doyle and Sparks, 1980). On the inner shelf, offshore Alabama, an extensive deposit of mud lies south of Dauphin Island (fig. 2). Detailed studies of this area show that these sediments are a mixture of sand, silt and clay and are the accumulation of effluent from the mouth of Mobile Bay (fig. 5) (Vittor and Associates, 1982, U.S. Army Corps of Engineers, 1985, Exxon, 1986). Recent studies indicate that sediment type can change from sand to shell gravel to mud over distances of several tens of feet within the large sand facies (Shultz and others, 1990; Parker and others, 1992). Much of this variation is due to bathymetric changes in the seafloor. Large ridges, primarily on the eastern part of the Alabama shelf, extend for several hundred feet in length and a few hundred feet wide and are comprised primarily of sand. Shell gravel is common on the landward flanks of the ridges with mud occurring in troughs between ridges (Parker and others, 1992).

SHELF MORPHOLOGY

The Alabama continental shelf contained within the study area can be divided into two regions, the eastern shelf region and the western shelf region, based on morphological characteristics. The eastern shelf region extends from the Alabama-Florida state boundary to Main Pass and the western shelf region extends from Main Pass to the Alabama-Mississippi state boundary (figs. 1, 6, 7). Separating the two regions at Main Pass is a large ebb-tidal delta that extends 6 mi offshore and is approximately 10 mi wide. The emergent part of the delta consist of Sand Island, which occurs in the western shelf region.

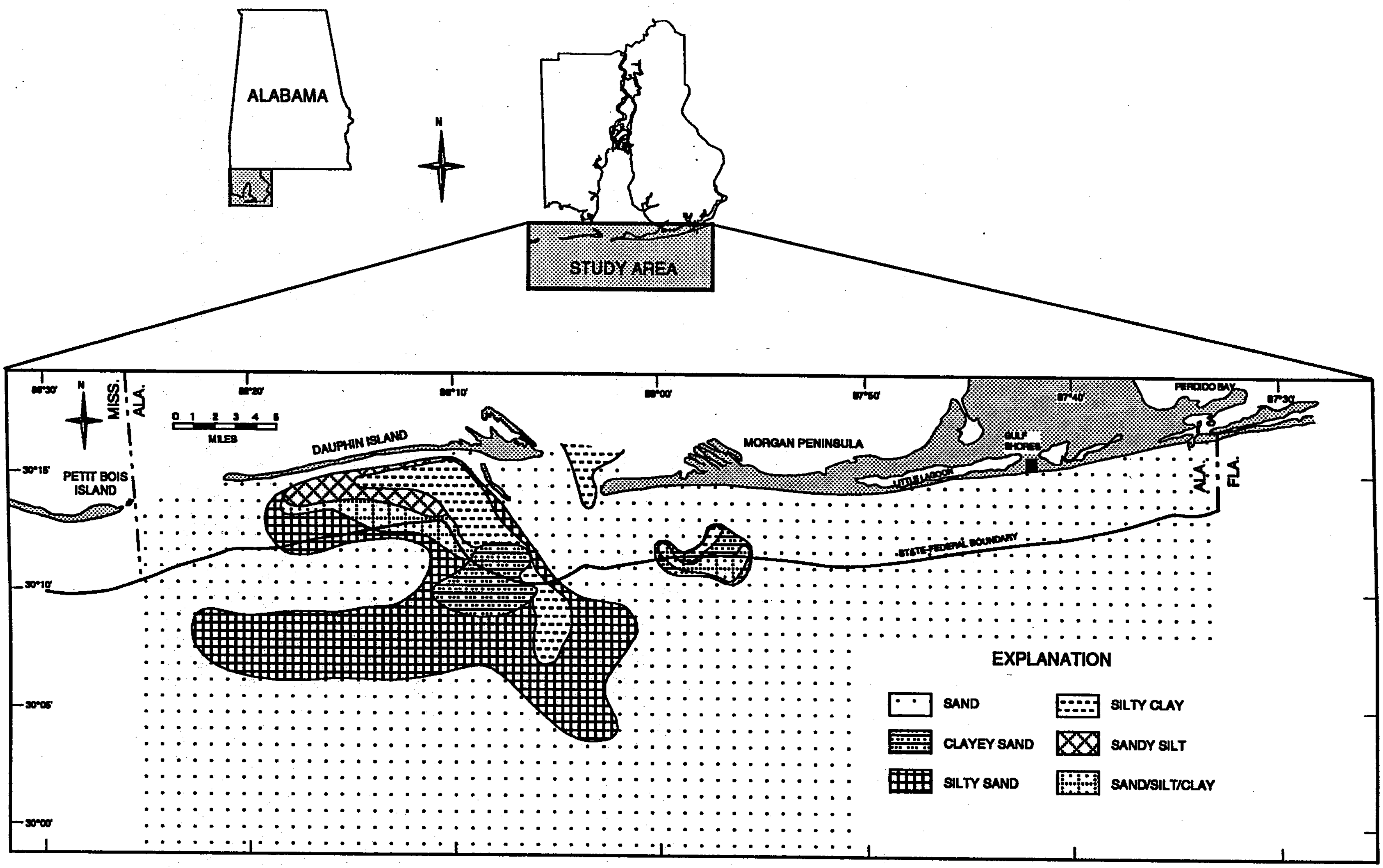


Figure 5.--Surface sediment texture map compiled from previous sediment texture data in the study area (modified from U.S. Army Corps of Engineers, 1984, 1985; Vittor, 1982; Exxon, 1986).

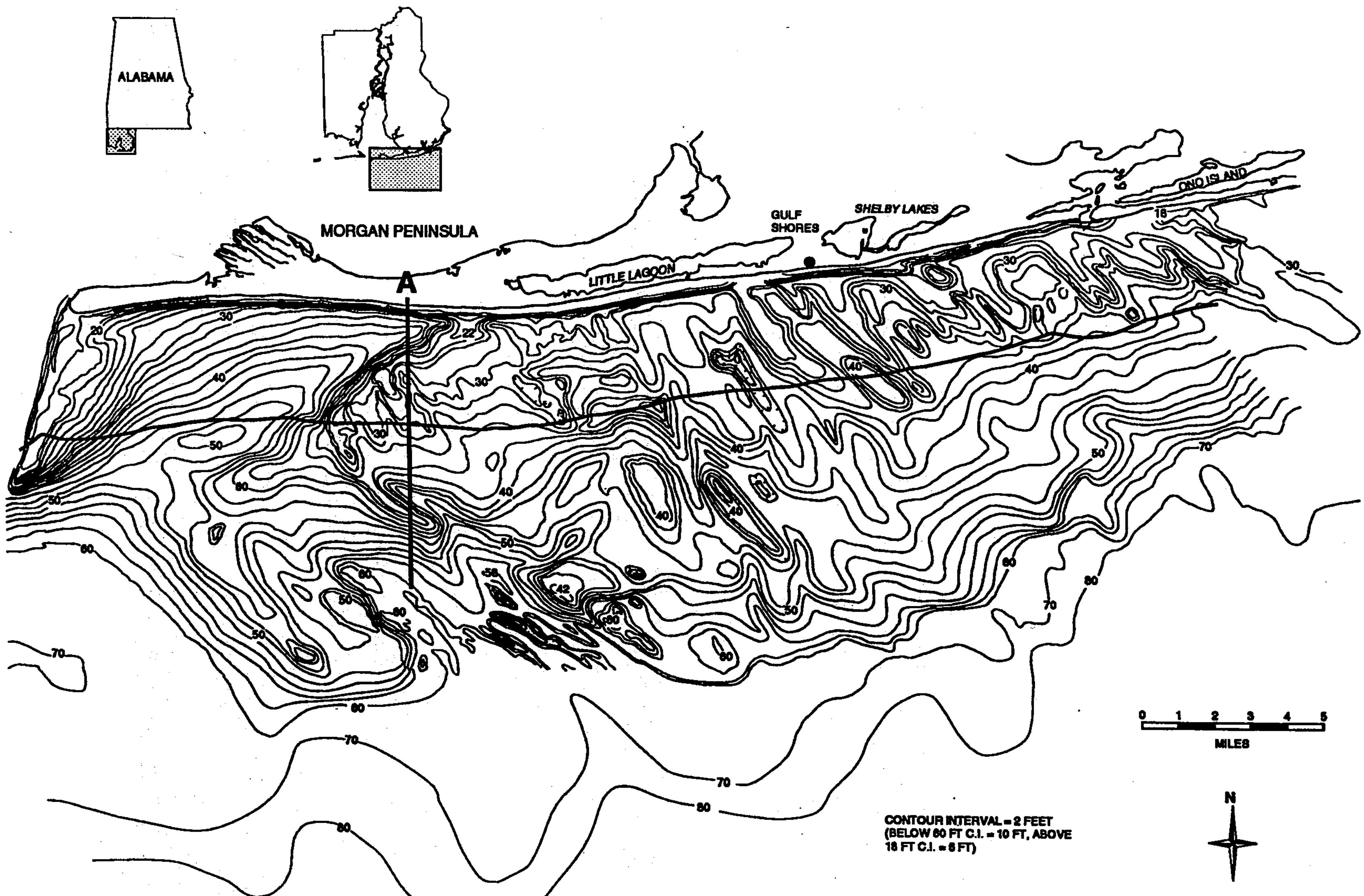


Figure 6.--Bathymetry of the eastern Alabama shelf region.

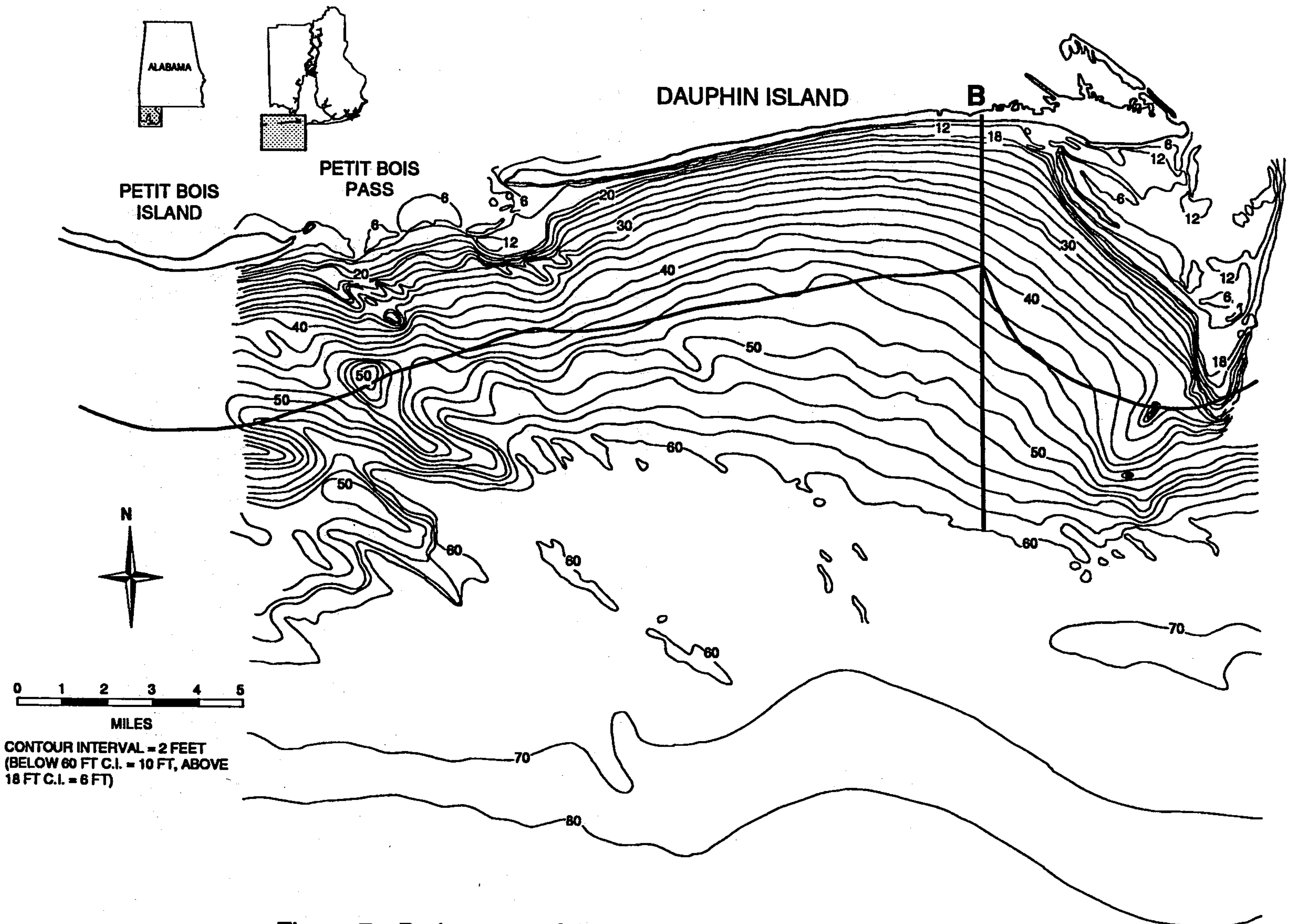


Figure 7.--Bathymetry of the western Alabama shelf region.

The eastern shelf region is characterized by numerous ridges and swales that trend primarily northwest to southeast (figs. 1, 6, 7, 8). Many of these ridges have been characterized as shoreface attached and detached ridges (Parker, 1990; Parker and others, 1992). Some ridges that were considered to be shoreface ridges have been identified in this study as paleohighs cored by Pre-Holocene material. The ridges average 3.8 mi in length and range from 1.1 to 6.8 mi long. The average width of the ridges is 1 mi and the range in width is 0.7 to 1.8 mi. Relief along these ridges varies from approximately 2 to 12 ft. The ridges identified as shoreface-detached or -attached ridges generally form southeast opening angles of 30 to 60 degrees with the east-west trending shoreline. Azimuths of the ridge crest range from 120 to 150 degrees. Paleohighs form angles more close to perpendicular with the shoreline. This difference likely reflects the different mode of origin of the two ridge types. One characteristic feature on the eastern shelf region is a large southwest-trending shoal located approximately 10 mi from the western end of Morgan Peninsula. Although the exact origin of the feature is unknown, evidence from this study suggest that it may be a drowned spit formed during the early Holocene development of Morgan Peninsula or remnants of a large ebb tidal delta formed when an inlet through Morgan Peninsula was present directly north of the feature (Geological Survey of Alabama, 1991). The shoal extends offshore about 9 mi and has almost 20 ft of topographic relief.

The shoreface of the eastern shelf region is much steeper than the western shelf region and ranges from about 50 to 90 ft/mi (figs. 6, 7, 8). Overall, the seafloor in the eastern shelf region slopes at approximately 5 ft/mi.

The western shelf region is almost featureless compared to the eastern shelf region (figs. 6, 7, 8). Some ridge features are apparent at about the 60 ft isobath; however the dataset for this area was incomplete, therefore these

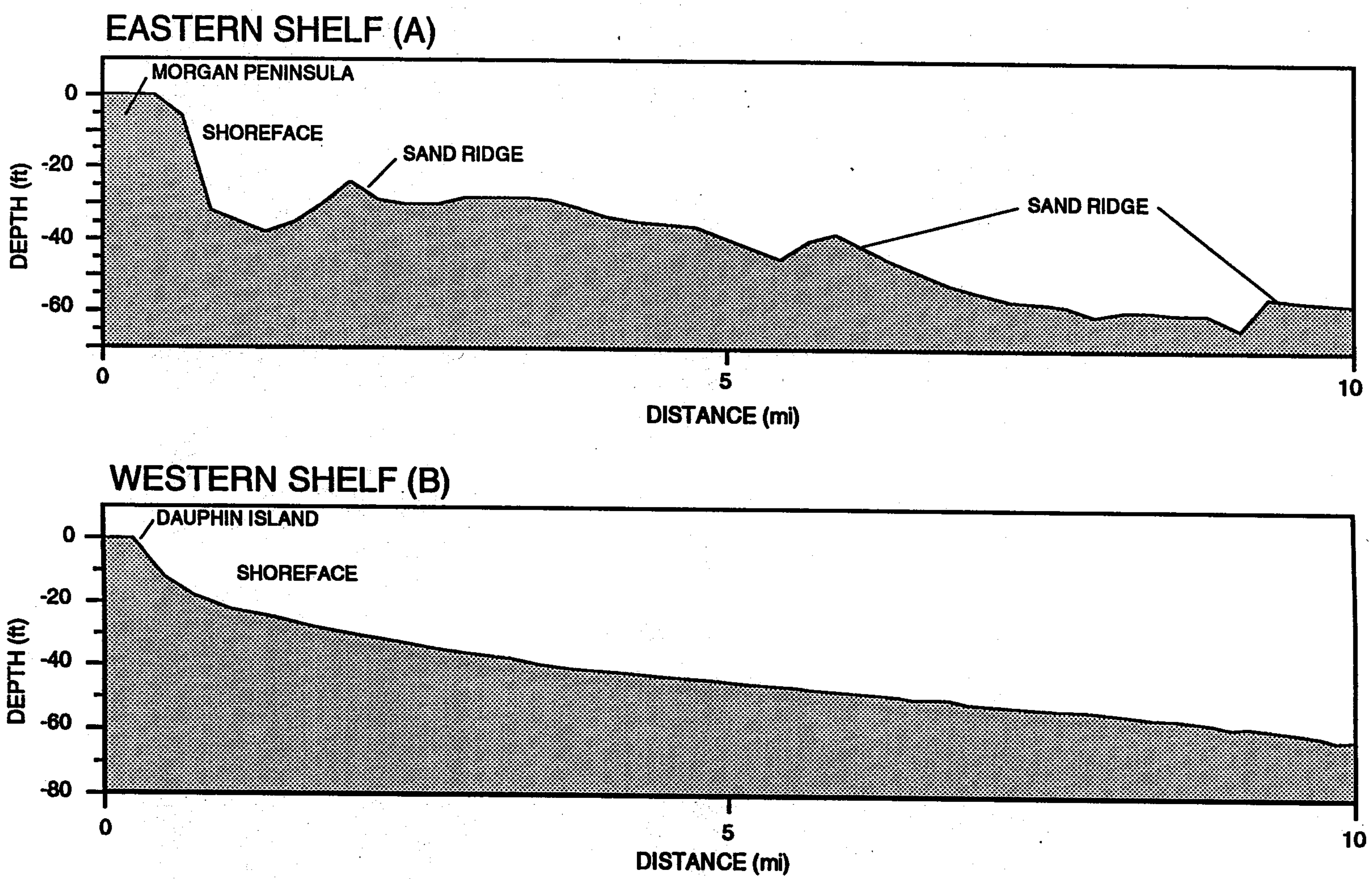


Figure 8.--Bathymetric profiles contrasting the eastern and western shelf regions (see figures 6 and 7 for profile locations).

ridges are not clearly delineated. This region deepens offshore much more abruptly than the eastern shelf region. The shoreface in this region slopes at approximately 30 to 45 ft/mi. In general, the shelf slopes on the average of about 8 ft/mi in the western region.

A few ridges occur at the western boundary of this region south of Petit Bois Pass (fig. 7). These ridges are associated with the processes associated with the tidal inlet (McBride and others, 1991). These ridges extend for an average length of 4.5 mi and average width of 1.5 mi. They are oriented at about 40 degrees relative to the shoreline trend of Dauphin Island.

DATABASE AND METHODOLOGY

ERODING SHORELINE CHARACTERIZATION

Identification of Alabama Gulf shoreline showing significant erosion in recent years was accomplished by reviewing the available data pertaining to historical and current erosional-accretionary trends on Alabama's Gulf shoreline, by reviewing tentative results of ongoing Geological Survey of Alabama studies of Alabama Gulf shoreline dynamics, and by study of aerial photographs. For detailed studies of potential restoration and nourishment areas on Gulf shoreline aerial photographs of 1955 (U.S. Department of Agriculture Commodity Stabilization Service) for Mobile County, and U. S. Geological Survey 1985 aerial photographs of coastal Mobile County were utilized. At the time of this study the 1985 coverage was the latest available.

The aerial photographs for 1955 and 1985 are of slightly different scales, requiring rectification of measurement data taken from the two sets of photographs. For studies of Dauphin Island Gulf shoreline leading to estimation of sand volumes required to achieve a shoreline position of 1955, overlays of the shoreline were made for the two sets of photographs. The 1955 shoreline overlay was then rectified to the scale of the 1985 photograph. Based on the information conveyed by the composited overlays, shoreline areas showing significant erosion for the 1955-85 period were identified.

In work leading to estimation of sand volumes possibly required for future nourishment of erosional areas of Baldwin County Shoreline in the vicinity of Perdido Pass and Little Lagoon pass, the measurement data for the planimetric dimensions of probable nourishment areas were taken directly from the 1985 aerial photographs.

For the potential restoration and nourishment sites on Dauphin Island the planimetric areas of the sites were measured. Based on the bathymetric data available for the immediate offshore areas at these sites, present water depths coincident with the 1955 shoreline position were used in calculating the volume of sand required for restoring the eroded sections of shoreline to the 1955 position. Although erosion on some shoreline sections of Dauphin Island has been progressing significantly since 1985 (over 20 ft/year at some sites), the estimates of sand volume given in this report do not include estimates of sand lost during the 1985-92 period. Should restoration of eroded areas of the island be considered in the future, a recalculation of required sand volumes should be accomplished to accommodate erosional loss between the period of 1985 to the time of restoration. For localities of significantly eroding Gulf shoreline estimates were made of sand volumes required for restoration of the eroded areas (table 2).

Table 2.--Summary of estimated sand volumes required for restoration of selected erosional shorelines in coastal Alabama

Erosional area	Sand volume (yds³)
Dauphin Island	1,800,000[1]
Grande Batture Islands	2,500,000[2]
Pt. Aux Pins	90,000[3]
Isle Aux Herbes	1,800,000[4]
Barron Pt. (southwest Mon Louis Island)	1,800,000[5]
Little Lagoon Pass	40,000[6]
Perdido Pass	120,000[7]
Mobile Bay natural shoreline[9]	1,300,000[8]

[1]Southwestern Gulf shoreline restoration to 1955 shoreline position.
[2]Berm width of 300 feet, average height of 8 feet and total length of 5 miles.
[3]Berm width of 300 feet, average height of 8 feet and total length of 1.8 miles.
[4]Berm width of 300 feet, average height of 8 feet and total length of 3.8 miles.
[5]Berm width of 300 feet, average height of 8 feet and total length of 3.8 miles.
[6]Periodic nourishment as required.
[7]Periodic nourishment as required.
[8]Berm width of 200 feet, average height of 3 feet and total length of 10 miles.
[9]Volumes required for restoration of erosional developed Mobile Bay shoreline not estimated.

BATHYMETRY OF ALABAMA EEZ

Bathymetric data compiled for this study were derived from NOAA nautical charts Nos. 11373, 11376, and 11382 (NOAA, 1991a, 1991b, 1991c). Charts Nos. 11373 and 11376 extended offshore to the 30° Latitude line and No.11382 extended offshore to 30° 6'. Soundings from each of these charts were plotted on a single base map and contoured at 2 ft intervals. A review of historic nautical charts of this area indicate that bathymetry data on the maps is a collection of many years of data with only certain areas having been recently updated. These data were the best available and are probably adequate for describing the general seafloor morphology of the study area; however, to accurately identify and delineate specific morphologic features new detailed bathymetry is required. Bathymetric readings taken at core sites were recorded and compared with existing data. It was obvious from this comparison that some discrepancies are present in some areas and that modification of the seafloor has taken place since bathymetric data were collected in these areas. However, a comparison of recent nautical charts with the historical charts shows that large scale morphologic features such as shoals and large sand ridges have been present in approximately the same location. New data are needed to determine the degree of modification to which the seafloor has been subjected in this area.

GEOLOGIC FRAMEWORK AND LITHOFACIES: VIBRACORES, BORINGS AND SEDIMENT SAMPLES

Existing data compiled in the year 1 report of the task force study were reexamined and updated with information pertinent to identification and characterization of offshore sand resources. These data consist of scientific reports, geophysical data, foundation boring logs, and bottom sampling data. Although the data were inadequate for characterizing specific sand deposits, the information was useful in siting new vibracores and bottom samples within areas of high potential for sand occurrence. The database used for describing the geologic framework and sand resources in the study area included 59 vibracores, 59 bottom sediment samples, and 1 foundation boring.

Based on the existing data, vibracores and bottom samples were located in areas that would be most useful for describing the framework geology and characterizing sand resources. Fifty-nine vibracores were collected in the study area between May 4 and May 14, 1992. The cores were collected in water depths ranging from 29 to 85 ft and from 3 to 15 mi offshore. The majority of the cores were collected in an area from approximately 3 to 10 mi offshore. The cores ranged from 2.3 to 19.1 ft long and totaled 597 ft of core. The vibracore locations are shown in figure 9. Appendix A contains information about the length, location, and water depth of each core. A columnar section illustration for each vibracore appears in Appendix B (figs. B-1 to B-37).

Vibracoring is a technique used to collect relatively undisturbed cores in unconsolidated sediments. The vibracores for this project were collected aboard the R/V *Kit Jones* from the Marine Minerals Technology Center, in Biloxi, Mississippi. The vibracoring system employed in this study consisted of a 25 ft tower that served as a guide for a pneumatic vibrator that drove the core tube into the sediment. A 20 ft long, 3 inch (in) diameter aluminum core tube was used which yielded a maximum core length of approximately 19 ft. Prior to submerging the coring apparatus, the core tube was filled with air which allowed for better penetration. The core was driven into the sediment to the maximum core length or until refusal. After coring ceased, pressure was

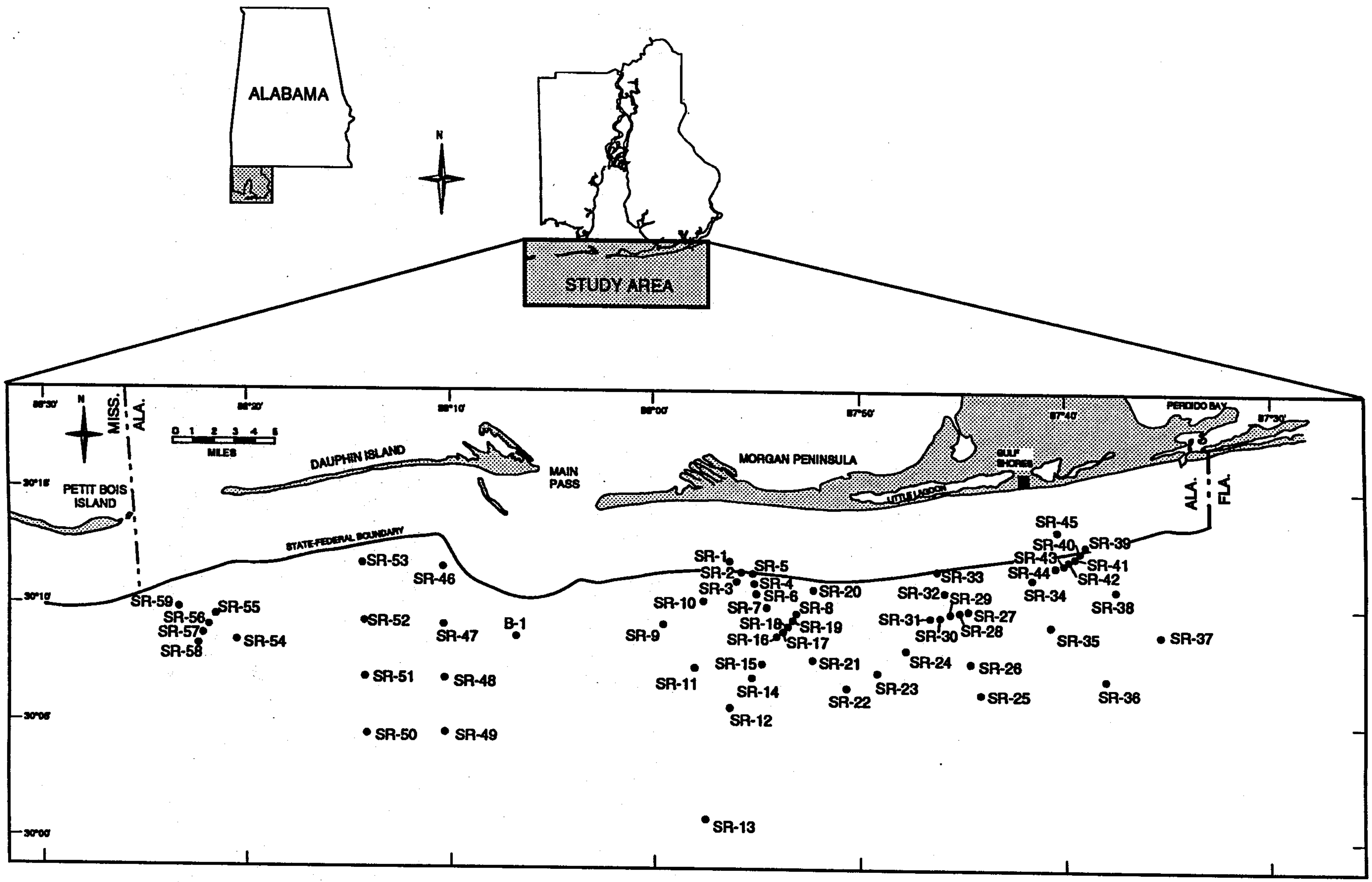


Figure 9.--Vibracore, boring, and bottom grab locations in the Alabama EEZ study area.

released and the core tube was allowed to fill with water to provide a suction and prevent loss of the core during extraction. The cores were extracted using a hydraulic winch and the "A-frame" rigging at the stern of the boat. On deck, the cores were cut into 5 ft sections, capped, and stored on board until the vessel came ashore. The core sections were then transported back to the laboratory for storage, splitting, and analysis. Navigation aboard the vessel was by LORAN-C.

Bottom grab samples were also collected at each of the vibracore sites using a Peterson grab. This grab collects a 76.5 square inches (in^2) sample of the upper few inches of the seabed. Bottom samples were split into sediment samples and biological samples on board and placed in Zip-loc bags for storage. Biological samples were stored in 80 percent alcohol and 20 percent distilled water to preserve organic material. Samples were stored at ambient temperature until transported to the laboratory.

The major steps involved in the laboratory analysis of the vibracores are presented in figure 10. The core was first clamped into a wooden trough device and split longitudinally using a hand-held router equipped with a high speed steel router bit. After making two length-parallel cuts, a knife was run lengthwise down the core tube dividing the core into equal halves. Once all sections of a core had been cut, both halves of the core were assembled on a platform for photographing. A 35 mm color slide was made of each core.

After photography, both halves of the core were described with regards to texture, sedimentary structures, facies, grain size characteristics, facies thickness, and color. Characteristics of each core were entered on data sheets and then into a computer database. The most intact core half was selected, placed in a plastic sleeve, and archived for use in X-radiography analysis or epoxy peels. The remaining half was processed for granulometry and

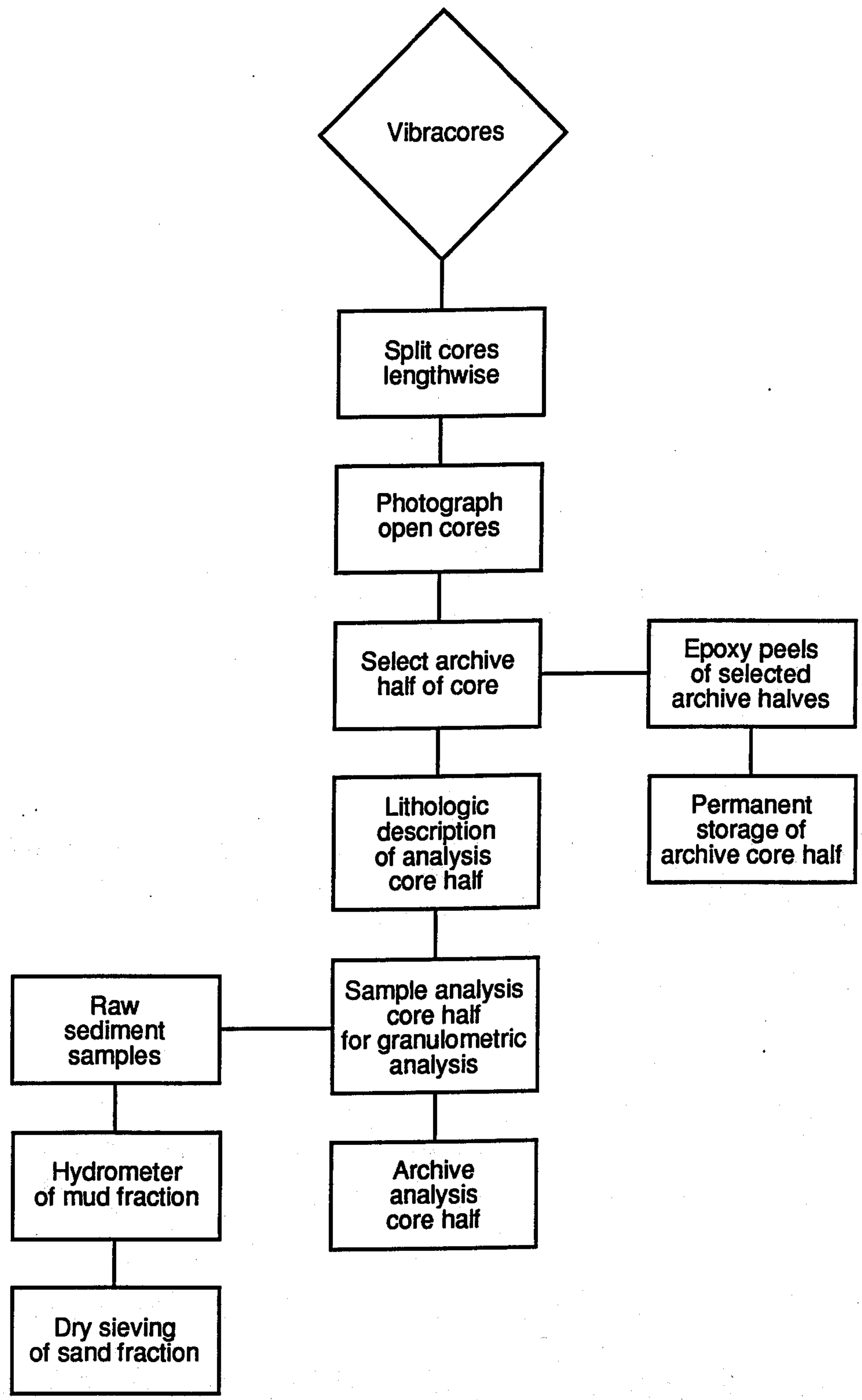


Figure 10.--Flow chart for the laboratory processing of vibracores.

radiocarbon dating materials when present. Samples were taken on the average every 2-3 ft or less as needed to characterize lithologic units. After sampling, the processed half was placed in a plastic sleeve and stored. Organic samples, when encountered, were collected and archived for future radiocarbon dating. Several samples were collected and prepared for radiocarbon dating. In the past, the survey has used Beta Analytic in Miami, Florida to process organic samples. However, the week the samples were to be shipped coincided with the passing of Hurricane Andrew.

Sediment samples from bottom grabs and select cores were subjected to granulometric analysis by hydrometer and dry sieving. Each sample was washed with deionized water prior to analysis to remove saltwater. This process aids in dispersing the clays during the hydrometer process since ions in seawater can cause flocculation. The samples were wet sieved through a 63 micron sieve which separated the mud and sand fractions. The mud fraction (finer than 4.0 Ø) (phi) was analyzed using standard hydrometer procedures following Lewis (1984) to determine the percentage of silt and clay. The sand fraction was oven dried at 80° C to prevent aggregation. A 35 to 60 gram sample was mechanically sieved through brass wire mesh sieves ranging in size from -2.00 Ø (pebble) to 4.0 Ø (very fine sand) at a 0.5 Ø interval. Each sieve fraction was weighed on a top pan Sartorius electronic digital balance to an accuracy of ± 0.001 gram, the units used by the balance.

The raw hydrometer and sieve data were entered into a computer spread sheet to determine the percentages of gravel, sand, silt, and clay for each sample processed. Individual weights for each size fraction were entered into a computer program designed to calculate the first four moments (mean, sorting, skewness, and kurtosis) and produce a histogram and cumulative frequency curve.

Some samples had sand fractions weighing less than 35 grams. The probability that a small sample would yield unreproducible results is significant; thus a mode for the sand fraction was estimated for selected samples weighing less than 35 grams. This estimate was determined by examining the grain size properties of the sand fractions in samples within the same vibracore. Half the weight of the sand in these samples was placed in the mode with the other half being distributed around the mode (0.5 Ø above and below) to determine the whole sample moment measures.

Lithofacies and their subdivisions, microfacies, were determined for each sedimentary unit using grain size data, sediment texture, and other lithologic characteristics. Average and the range of parameters were determined by comparing all samples of a microfacies. The stratigraphic distribution of each microfacies was determined by construction of a series of cross sections, tables and sediment distribution maps.

ONSHORE SAND SAMPLES

Sand samples were collected from two sand pits in Baldwin County and eight sand pits in Mobile County (fig. 11). The location and stratigraphy of each site was described (app. C, tables C-1, C-2). Particular attention was paid to clean sand thickness, sand color, and thickness of overburden. Grain size, sorting, percent sand, percent silt/clay and color were determined for each sand sample using techniques described for the EEZ samples.

Information on sand production in 1990 for these two counties is contained in Dean (1990). This information was evaluated to determine whether sufficient volumes of sand would be available to be an effective source of replenishment materials.

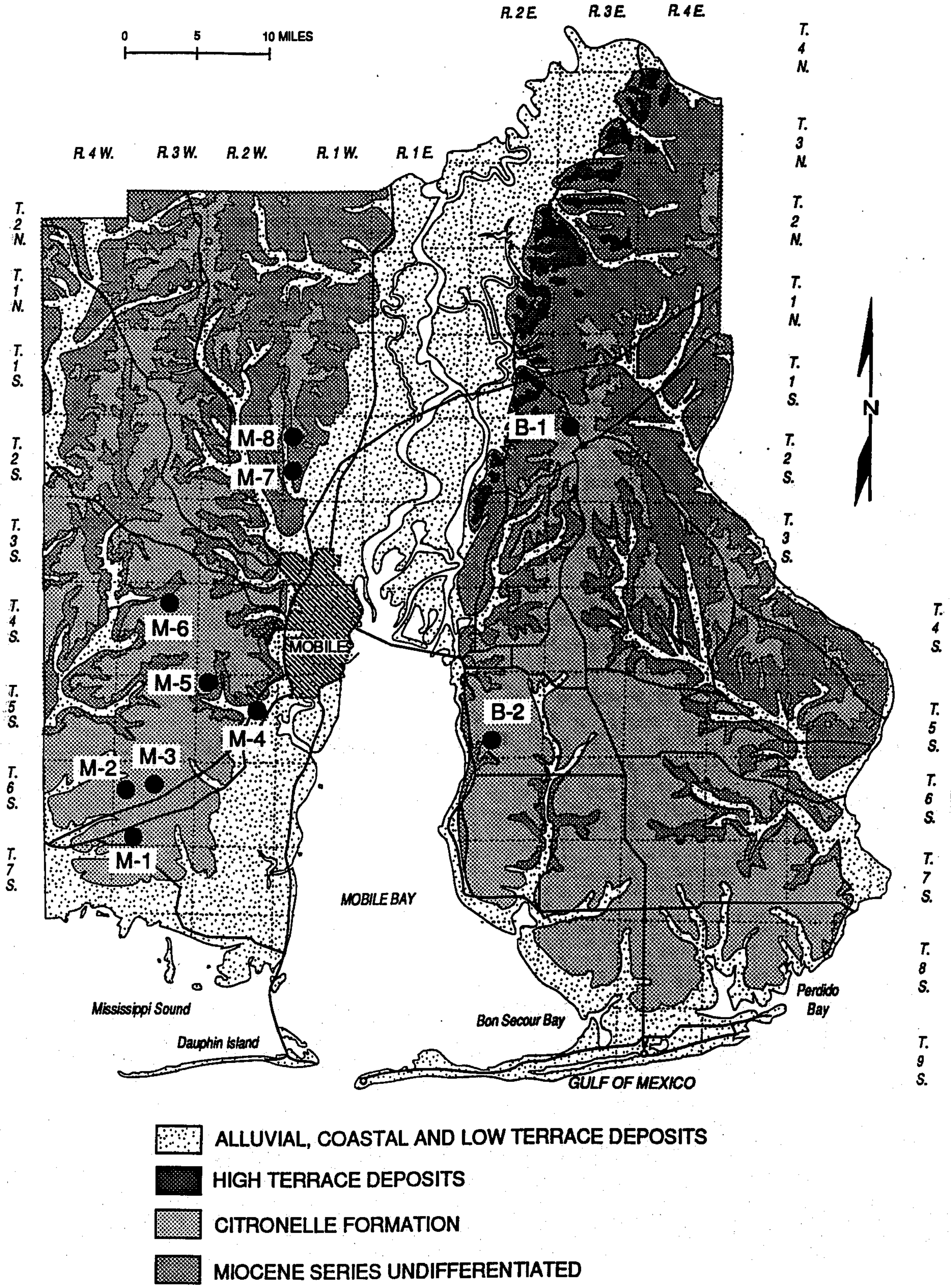


Figure 11.--Geologic map of Mobile and Baldwin counties showing locations of onshore sampling sites.

OFFSHORE SAND RESOURCES

A review of available data including previous works on shoreline erosion and shelf sediment distribution, sediment and core samples, and bathymetric maps was used to identify sand resource target areas in the study area. Five preliminary resource sites were identified based on assessment of these data (fig. 12). Vibracores, bottom samples, and biological samples were positioned within each of these areas to provide adequate coverage to delineate and characterize the sand deposits in each of the areas. Detailed laboratory analyses were performed on bottom and core samples from each of the areas to determine grain size characteristics and aesthetic quality. From this information, the potential of sand resource target areas to provide material for beach nourishment projects was evaluated based on several criteria including: 1) proximity to eroding shoreline segments, 2) potential of nourishment material to meet specifications of beach sand quality and volume, and 3) physical and biological environmental impacts of sand dredging.

Within each of the resource areas, the sediment was divided into coarse sand and shell gravel, fine to medium sand, very fine sand, silt, and clay, and Pre-Holocene for the cross sections and isopach maps. Sediment types on the surface sediment texture maps were classified according to the ternary diagram on the explanation page at the front of the report. The primary resource deposits, medium to fine sand, include deposits with greater than 75 percent sand content with mean grain sizes in the fine to medium sand range. Grain size characteristics tabulated for each of the areas are based on samples taken only from deposits with greater than 75 percent sand content. Bathymetric profiles, geologic cross sections, sand isopach maps, and surface sediment

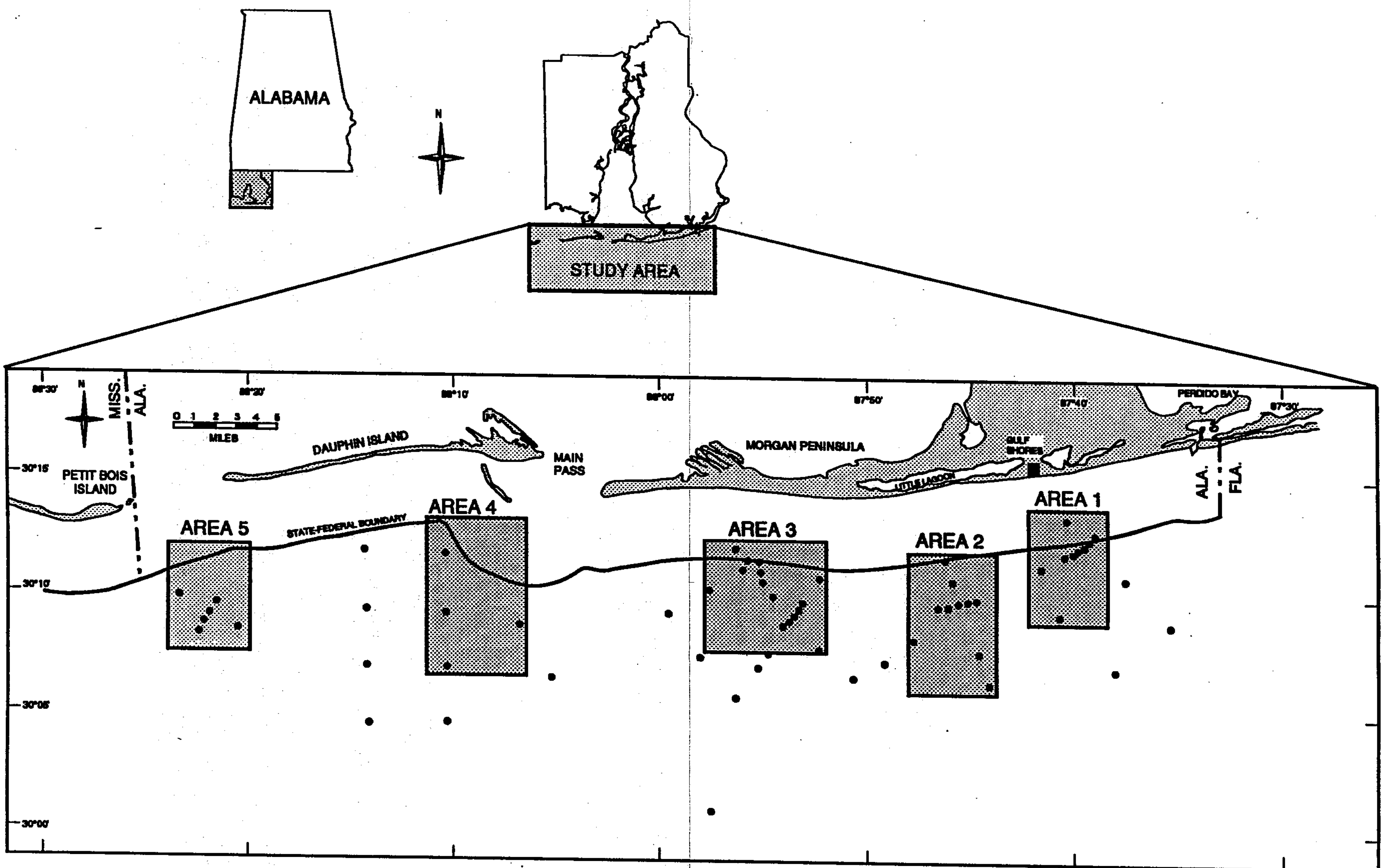


Figure 12.--Index map for EEZ sand resource target areas.

distribution maps were prepared for each of the target areas to delineate and characterize the sand deposits.

RESOURCE POTENTIAL ANALYSIS

The sediment character of offshore and onshore deposits delineated in this study was evaluated based on grain size and aesthetic quality to determine the suitability of a deposit for use as beach nourishment material for any of the identified eroding Gulf shoreline segments. When considering a potential deposit for use in beach nourishment, it is important to calculate an overfill factor to determine the amount material required to restore the beach. James (1975) and Hobson (1977) explained methods of comparing the grain size characteristics of native beach sediment with borrow material using mean grain size and sorting (fig. 13). An overfill factor (R_A) was determined to account for winnowing processes that affect borrow material placed on the beach (fig. 13). The overfill factor is an estimate of the amount of borrow material required to produce 1 unit volume of native beach material. Aesthetic quality was determined by comparing the color of dry samples of offshore and onshore sediment with the beach sediment. Physical and environmental impacts of sand dredging were also considered for offshore deposits. The resource potential of the offshore and onshore deposits will be discussed for each of these Gulf shoreline areas as well as for eroding shorelines of Mississippi Sound and Mobile Bay.

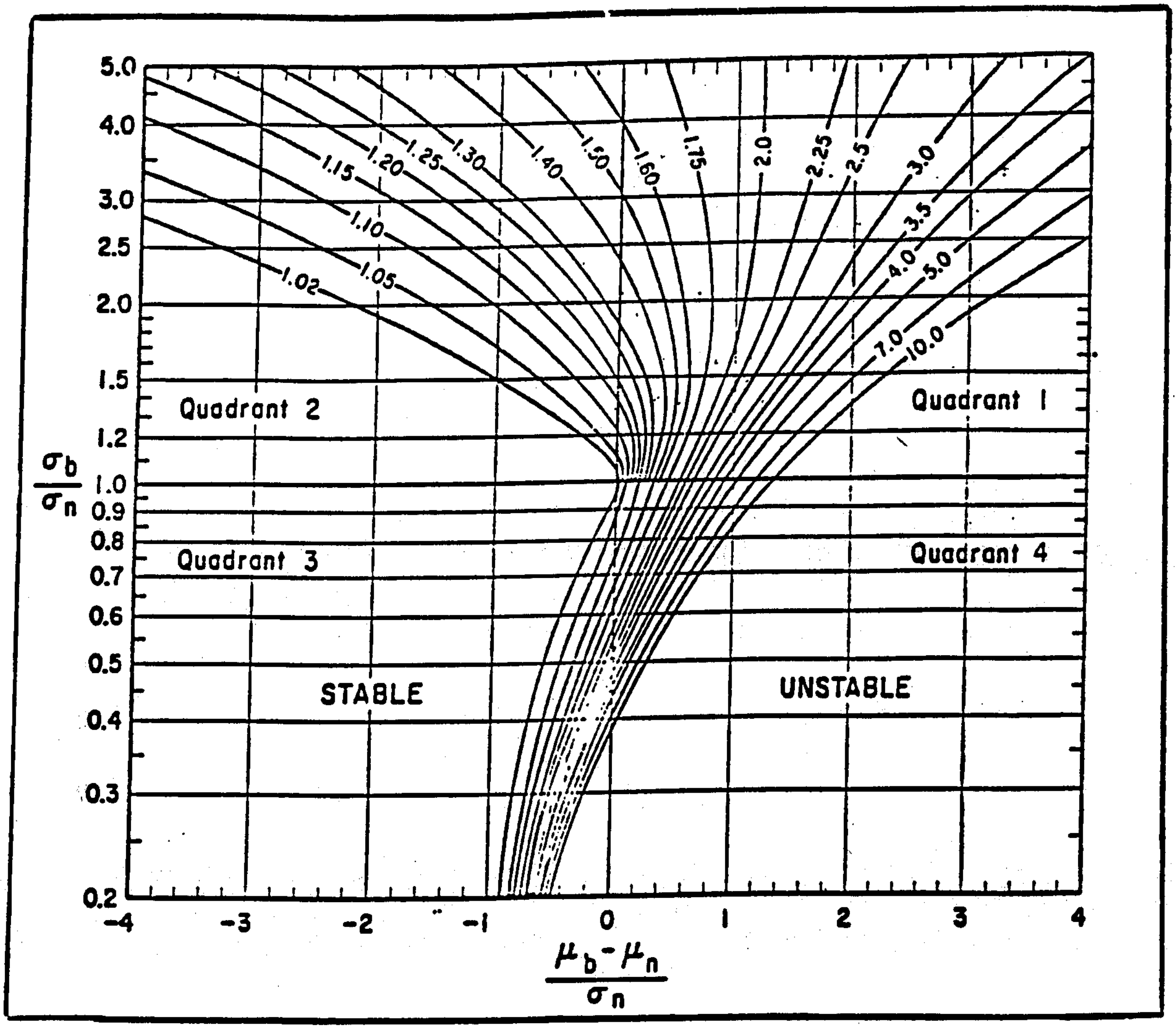


Figure 13.--Isolines of the adjusted SPM fill factor (R_A) versus phi mean difference and phi sorting ratio (modified from James, 1975).

BENTHIC FAUNAL ANALYSIS

A benthic biology sample was collected at each station by using a Peterson Grab to collect the upper few in of sediment. This sediment, which varied in volume between samples due to ability of the Peterson Grab to penetrate the different microfacies was stored in seawater filled bags. As soon as practical, the sediment was sieved on a 63 micron screen, and the coarse fraction was preserved in a greater than 80 percent ethanol solution. Ten of the 59 samples were selected for analysis based on their location within the sand resource target areas.

Laboratory analysis required randomly splitting some samples using a sediment sample splitter to reduce the volume of sediment present, and thus facilitate picking for organisms. Thus, table 3 shows the amount of the sample that was actually picked; for example, for SR-16 BG (bottom grab) one half of the sediment was evaluated. For this sample, the number of preserved organisms would be expected to be approximately double that actually picked; the number of species actually present at a site may well be somewhat greater than that actually tabulated (Koch, 1991).

Organisms were tabulated as shown in table 4. Taxa were identified, and ecology and abundance determined utilizing Abbott (1954), Abbott (1984), Barnes (1974), Barwis (1985), Hickman and others (1974), Morris (1973), Romashko (1974), and Warmke and Abbott (1961). In addition to determining the taxon name and ecology, other information was collected for each individual. These include the size class in millimeters (mm), whether the organism was alive or dead at the time of collection, whether it was a whole organism or just a fragment, whether it appeared to be a "new" or "old" shell (sensu Powell and Davies, 1990), and whether it was a left or right valve for

Table 3.--Benthic sample sizes and splits

Sample	Split analyzed	Organisms counted	Organisms present
SR-16 BG	one half sample	68	136
SR-18 BG	one half sample	43	86
SR-32 BG	entire sample	34	34
SR-36 BG	entire sample	45	45
SR-39 BG	entire sample	43	43
SR-43 BG	one eighth sample	35	280
SR-46 BG	one half sample	65	130
SR-48 BG	entire sample	56	56
SR-54 BG	one eighth sample	50	400
SR-56 BG	one fourth sample	42	168

Table 4.--Benthic organism counting procedures

Type of organism	Counting procedure
Live organisms	All counted
Dead organisms	
Whole organisms	All counted; articulation noted
Fragments	
Pelecypod beaks	All counted (left/right determined)
Gastropod apices	All counted
Echinoderms	Mouth counts as one individual
Arthropods	One claw counts as one individual
Other fragments of solitary organisms	Not counted
Colonial organisms	Major fragment counts as one colony

pelecypods (bivalves) (e.g., modified methodology of Davies and others, 1990). All organisms larger than 4 mm were tabulated. Fragments were counted only if a unique part was present, as indicated in table 4. This additional information is essential to distinguishing present biocoenoses (currently living assemblages) from thanatocoenoses (long dead assemblages), as well as species that survive to adulthood to those that frequently die prior to reaching full size, due to a suboptimal environment (e.g., Mancini, 1978). Data from all organisms analyzed were tabulated by sample and shown in Appendix D (tables D-1 through D-10).

Additionally, data were compiled from all samples for all shelled organisms, all soft bodied organisms, and a composite of all organisms (table 5). A complete faunal list indicating which species were collected live, dead-only "new", and dead-only "old" is shown in table 6.

ECONOMIC ANALYSIS

An economic analysis utilizing a computer mathematical model was accomplished for the three identified beach replenishment projects; Dauphin Island, Little Lagoon Pass, and Perdido Pass, utilizing two of the offshore sand resource areas. The mathematical model used to perform the economic analysis is referred to as QUIKSAND. This computer model was developed by the Branch of Resource Assessment within the Offshore Resource Evaluation Division of the Minerals Management Service. The purpose of this model is to assess the value to a prudent investor or an educated seller of the resources contained in deposits of sand and gravel on the Federal OCS.

The model uses the basic Monte Carlo simulation technique where the pertinent variables are sampled from cumulative probability distributions over

Table 5.--Benthic data summary

Sample	Individuals	Number of species	Percent live	Percent old	Percent whole	Size mode (mm)
Shelled animals						
SR-16 BG	42	18	0	55	81	4 to 6
SR-18 BG	41	19	0	59	83	4 to 6
SR-32 BG	32	19	0	56	78	4 to 6
SR-36 BG	39	17	0	38	90	4 to 6
SR-39 BG	29	17	3	55	62	4 to 6
SR-43 BG	33	15	0	67	85	4 to 6; 6 to 8
SR-46 BG	65	18	0	51	80	8 to 10
SR-48 BG	51	21	2	53	80	4 to 6
SR-54 BG	41	23	0	59	66	4 to 6
SR-56 BG	42	18	0	38	74	4 to 6
Total	**415**	**64**	**<1**	**55**	**78**	**4 to 6**
Soft bodied						
SR-16 BG	26	5	77	0	31	10 to 15
SR-18 BG	2	1	0	0	0	10 to 15; 15 to 20
SR-32 BG	2	1	100	0	100	20 to 30
SR-36 BG	5	5	20	0	0	10 to 15
SR-39 BG	14	4	14	0	7	>40
SR-43 BG	2	2	0	0	50	8 to 10; 15 to 20
SR-46 BG	0	0	--	--	--	--
SR-48 BG	5	3	80	0	20	10 to 15
SR-54 BG	9	5	11	0	67	15 to 20
SR-56 BG	5	3	0	0	0	6 to 8; 8 to 10
Total	**70**	**11**	**48**	**0**	**26**	**10 to 15**
All animals						
SR-16 BG	68	23	29	34	62	10 to 15
SR-18 BG	43	20	0	56	79	4 to 6
SR-32 BG	34	20	6	53	79	4 to 6
SR-36 BG	45	22	2	33	78	4 to 6
SR-39 BG	43	21	7	37	44	4 to 6
SR-43 BG	35	17	0	63	83	4 to 6; 6 to 8
SR-46 BG	65	18	0	63	80	8 to 10
SR-48 BG	56	24	9	48	73	4 to 6
SR-54 BG	50	28	2	48	66	4 to 6
SR-56 BG	42	18	0	38	74	4 to 6
Overall total	**485**	**75**	**7**	**48**	**71**	**4 to 6**

Table 6.--Species collected, benthic survey

Species	Live	Fresh appearance
Aequipecten gibbus		x
Anadara transversa		x
Anomia simplex		x
Antillophos candei		x
Arcid sp.		
Balanus sp.		x
Balcis conoidea		x
Bailya parra		x
Brachidontes recurvus		
Cadulus sp.	x	x
Cap-shaped bryozoan		x
Cardiid sp.		
Chione cancellata		x
Chione grus		x
Chione latilirata		
Chione paphia		
Corbula sp.		x
Crab claw		x
Crassostrea virginica		
Crassinella lunulata		
Crepidula fornicata		
Crepidula plana		x
Dentalium eboreum		x
Dentalium sp.		
Dentalium texasianum		x
Diopatria, sp. A	x	x
Diopatria, sp. B	x	
Diplondonta nucleiformis		x
Diplondonta punctata		x
Fish vertebra		
Gouldia cerina		x
Jaspidella jaspidea		
Laevicardium laevigatum		x
Lucina amiantus		x
Macoma sp.		
Macoma constricta		
Macoma extenuata		
Macrocallista maculata		x

Table 6.--Species collected, benthic survey—Continued

Species	Live	Fresh appearance
Macrocallista nimbosa		x
Mactra fragilis		x
Melanella bilineata		x
Mellita sp.		x
Mulinia lateralis		x
Mysella planulata		
Nucula proxima		
Nucula viridis		x
Nuculana acuta		x
Nuculana concentrica		x
Oliva sayana		x
Olivella sp.		x
Pandora trilineata		x
Pectenid sp.		
Pitar fulminata		x
Polinices duplicatus		x
Serpulid sp.		x
Strigilla carnaria		x
Solen viridis		x
Tellina alternata		x
Tellina sp.		x
Tellina texana		x
Tellina versicolor	x	x
Terebra dislocata		x
Turbonilla sp.		x
Turrid sp.		
Varicorbula sp.		
Venericardia ventricosa		
Venerid sp.		x
Worm sp. A		x
Worm sp. B		x
Worm sp. C		x
Worm sp. D		x
Worm sp. E	x	x
Worm sp. F	x	
Worm sp. G	x	x
Worm sp. H	x	x
Zoantharia sp.	x	

many trials to yield results derived from an averaging process taken over the number of trials. It provides a means to handle subjective judgments about each individual variable. Expressing the uncertainty is transferred from one or two individuals to the many experts in the various disciplines involved in the evaluation. This method explicitly recognizes the probabilistic nature of variables affecting the evaluation and calculates possible outcomes based on random samples from input probability distributions.

Much of the geologic and engineering data (e.g., areal extent and thickness of the resource, recovery factors, production rates, product prices, costs, etc.) used to evaluate economic potential of the resource is known with varying degrees of uncertainty. Providing a single number for the resource economic value is somewhat misleading because it provides no insight into the relative uncertainty involved. The Monte Carlo technique provides a range of resource economic values (Net Presént Worth [NPW]) for the venture, with the probability of each occurrence being a direct consequence of the data uncertainty. The logic of the Monte Carlo simulation method can be described as a five-step process:

Step 1. Estimate the range and distribution of the possible values of each variable that will affect the outcome of the venture. This requires judgments from the various disciplines involved in the project. Judgments depend on the amount of information available and the experience of those making the determination.

Step 2. Select, at random, one value from the distribution of each variable and compute the venture value using a yearly discounted cash flow analysis which accounts for inflation and the combination of selected values for each variable. This determines one point in the final distribution of possible venture values. Then randomly select a second value from the distribution of the variables and again compute the resulting venture value. This is the second point in the distribution of possible values. This random selection is statistically done in such a way that, if a large number of random selections is made (1,000 or more), the distribution for each variable closely resembles the initial distribution.

Step 3. Repeat the process 1,000 or more times, each time with a set of values selected at random from the distribution of each variable. Enough combinations of variable should adequately describe the shape and range of the distribution of venture values.

Step 4. The final output is a number of possible NPW values for the venture. The program generates a cumulative probability distribution for the NPW values. The method in effect constitutes a shift of emphasis regarding subjective judgment. Instead of requiring a single judgment about how a series of variables will interact collectively, a series of judgments is made on how each individual variable will occur.

Step 5. The means of the NPW distributions are determined. This is the Mean of the Range Of Values (MROV) and is calculated by the following equation:

$$MROV = (1-S)(NP\$) + (S)(P\$)$$

where S = the likelihood of project success (0-1)

NP\$ = present worth of nonproducing venture

P\$ = present worth of producing venture.

Because there is no geologic risk associated with this project relative to exploring for and identifying the sand body resource, success is therefore unity, and the MROV becomes equal to the net present worth of the venture. Furthermore, the economic risk is accounted for in calculation of the present worth, which is derived by summation of the economic result of each individual trial divided by the total number of trials. Therefore, the application of this mathematical model provides a valid analysis of the economics involved in any sand dredging project for beach or barrier island replenishment.

ASSESSMENT OF ERODING COASTAL SHORELINE

"To know the beaches is to know the beaches are moving", Kaufman and Pilkey (1979). In the present study assessments were made of Alabama coastal shoreline to identify and prioritize shoreline characterized by significant erosion that might be mitigated by the application of restorative and nourishment sand obtained from Gulf offshore areas (task 2). Alabama includes approximately 57 mi of Gulf shoreline extending from the Alabama-Florida State line on Perdido Key to the Alabama-Mississippi State line near the west end of Dauphin Island (fig. 1). Related estuarine areas include Mobile Bay, Mississippi Sound and the Perdido estuary. In this work priority was given to shoreline of the Alabama barrier system, but the Alabama estuarine shoreline was also assessed to identify potential restoration or nourishment sites.

The overall purpose of this task has been to identify and describe only in a general sense those coastal areas that could be considered for restoration or sediment nourishment. Specific projects leading to restoration or nourishment of any of these areas are not herein proposed. Prior to this study there have not been formal GSA assessments of the benefits, costs, technical feasibility or permitability of any restoration work for the Alabama Gulf beaches.

PREVIOUS INVESTIGATIONS

Studies of historical changes in Alabama Coastal shorelines based on review of available historic charts and maps were carried out by Hardin and others (1976), resulting in estimates of the magnitude of erosion for specific segments of shoreline and compilation of maps showing changes in coastal shoreline in historic time. For the most part, the data provided by this study do not apply directly to the present assessment of shoreline changes which is focused on the period 1955-85 and to the present. However, the study provides insight to the general nature of Alabama Gulf shoreline evolution during historical time.

Smith (1989) studied shoreline changes in the Alabama portion of Mississippi Sound, and compiled maps showing shoreline changes for the period 1955-85. This work included estimation of erosion rates for specific shoreline segments. Of particular interest in this study was the assessment of changes in the Grande Batture Islands. Most of the Grande Batture Islands have now been destroyed by erosion that has occurred primarily in historical times. These islands were mostly within the State of Mississippi with only a small eastern part of the islands being formerly a part of Alabama.

Smith (1990) estimated erosion rates for selected Alabama coastal shoreline and discussed regimes contributory to progressive loss of Alabama coastal shoreline and wetlands. Surveys of Alabama Gulf beach profiles were initiated by Smith and Parker (1990) with the purpose of developing a data base useful in assessment of changes in Alabama Gulf shoreline in Baldwin County and for the Gulf shoreline of the eastern part of Dauphin Island, Mobile county.

Hummell (1989) reviewed available information on the main pass and the ebb-tidal delta of Mobile Bay, summarizing data on bathymetric changes of this area and describing the general dynamic conditions of this area. Such information is useful in assessment of the probable causes of significant erosion that is now in progress on the Gulf shoreline of eastern Dauphin Island. The shoreline of Bon Secour Bay which comprises the southeastern part of Mobile Bay was described by Smith (1992). This work included estimation of erosion rates for selected shoreline segments and description of natural processes of the Bay shoreline. This report also calls attention to erosional trends on shoreline that comprises most of the remaining natural shoreline of Mobile Bay.

DAUPHIN ISLAND SHORELINE

HISTORICAL BACKGROUND

Studies of historical charts and maps of the Alabama coastal area by Hardin and others show that in 1917 the Gulf barrier complex of Mobile County, Alabama consisted of a group of islands, as illustrated generally by figure 14. The geometry and spatial relationships of these islands imply that one or more hurricanes breached the island prior to 1917. By 1942 Dauphin Island had developed to a configuration similar to that of today's island; however between 1942 and the present erosion apparently has persisted on the Gulf shoreline of the island. In 1957 a system of groins was established on the eastern end of the island, resulting in stabilization of this area. In recent years erosion has flanked several of the groins on the southeastern Gulf shoreline, isolating these groins in the Gulf. At the Dauphin Island Park erosion has now undermined park structures near the beach and has exposed numerous stumps of pine and other species related to former Holocene forest areas of the island, indicating long-term landward retreat of the island. This erosion has resulted in the closing of the beach for swimming. In connection with this, attempts were made in 1992 to forestall erosion with the addition of dredged material that included quartz sand as well as oyster shells and carbonaceous clay and silt. Most of this material has now been eroded from the site.

Under the present erosional regimes associated with the island, a combination of circumstances related to sediment sources and erosional wave and current systems is responsible for the erosional nature of the southeastern shoreline of the island. No detailed studies have been done to conclusively

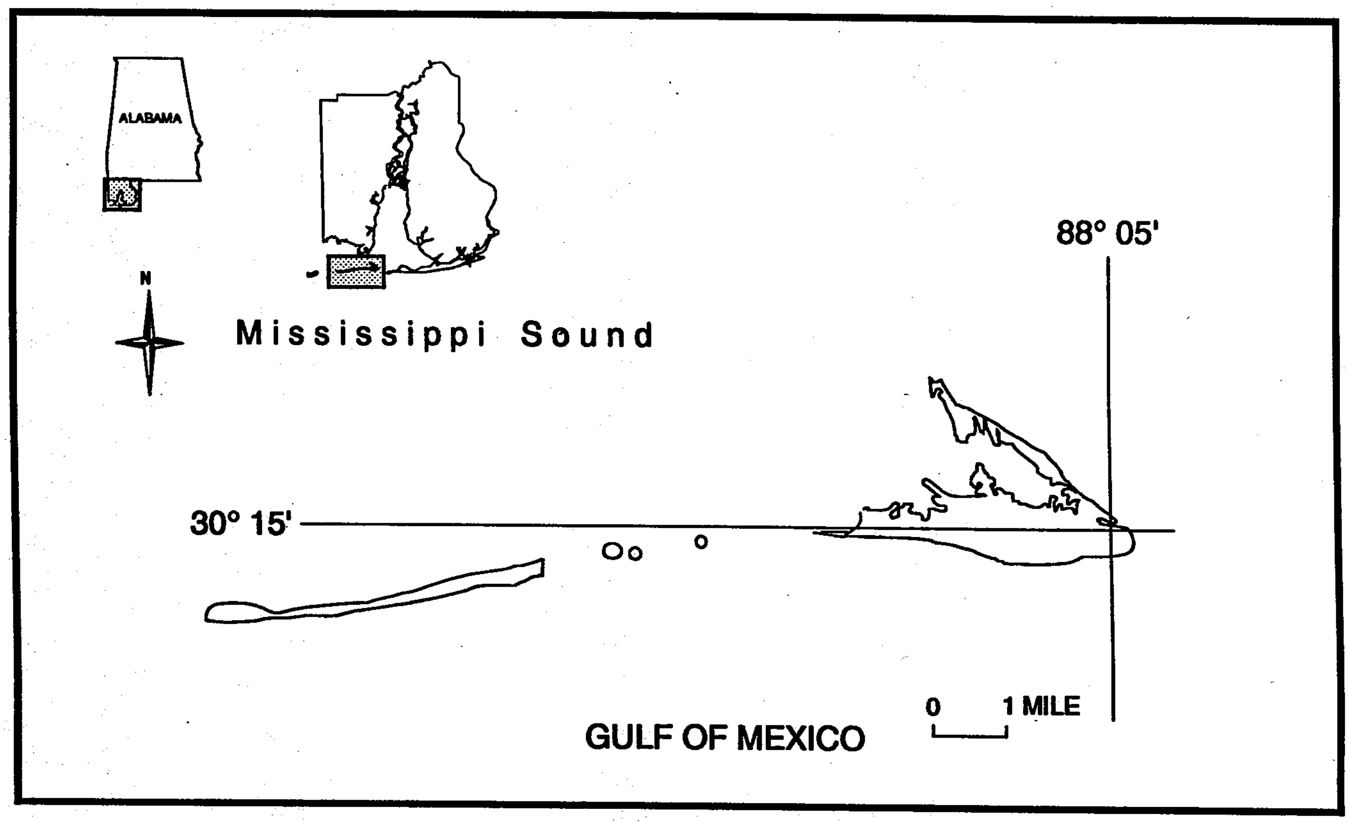


Figure 14.--Approximate configuration of the Dauphin island barrier system in 1917. Prior to this a hurricane apparently breached the island, resulting in two separate primary islands and several smaller islands.

identify the specific factors involved or to recommend corrective methods. No studies are known to have been made concerning restoration of eroded areas.

SEDIMENT CHARACTER

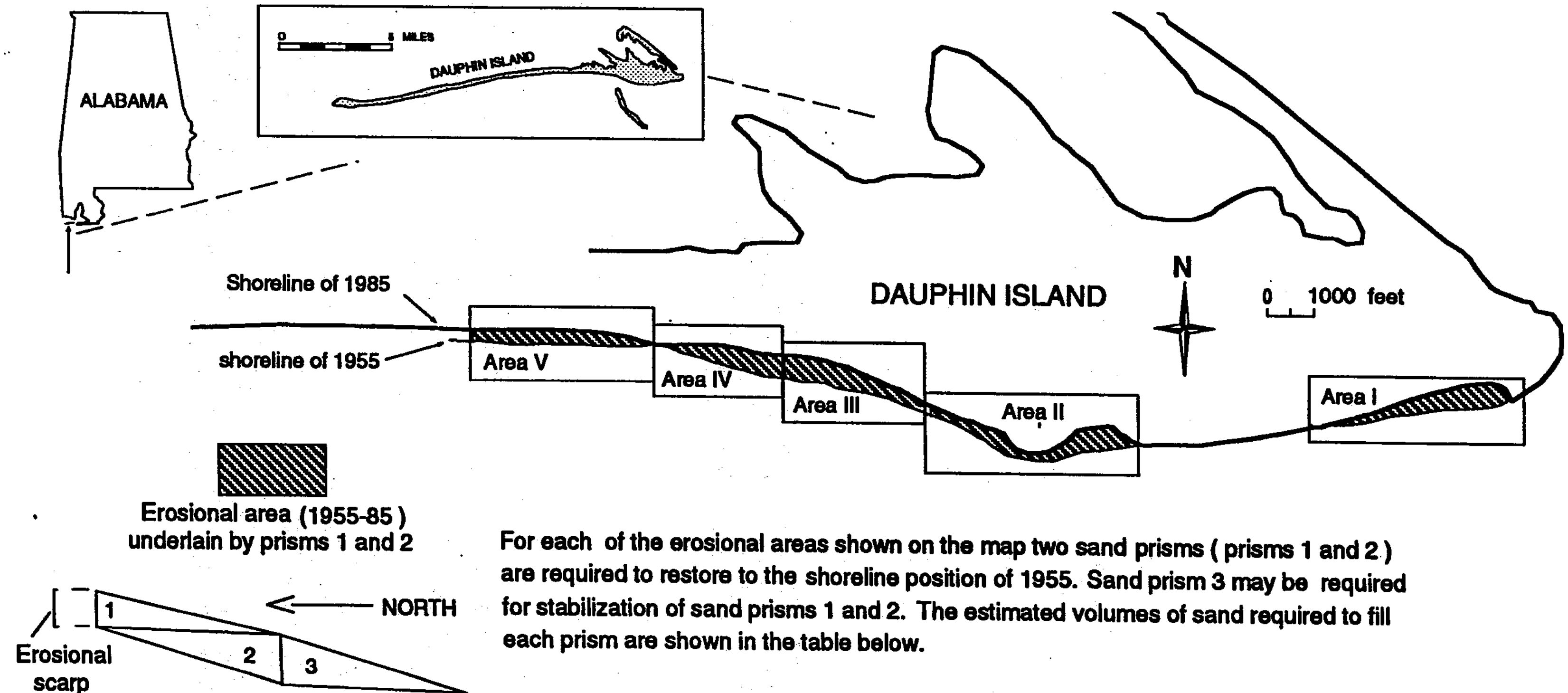
Dauphin Island beaches are characteristically brilliant white to slightly buff in color, and consist primarily of fine to medium grained quartz sand with minor amounts of shell fragments and accessory detrital minerals At some localities along the eroding beaches, particularly in the vicinity of the Dauphin Island Park, various other sediment types are exposed in erosional scarps. These include sediments deposited within former environments associated with the island, including those of swamp, forest floor, estuary, sound, and other environments. Sediment samples taken on the beach in the eroding shoreline areas indicate a composite mean grain size of 1.89 Ø (medium sand) and sorting of 0.38 Ø (well sorted) (table 7). The native beach sediment averages 99.91 percent sand, 0.09 percent silt and clay, and is light gray in color.

EROSIONAL AREAS

Figure 15 illustrates the character of the erosion that has occurred on the southeastern Gulf shoreline of the island since 1955 (shaded areas). Although since 1955 erosion apparently has continued along the island's Gulf shoreline west of the area shown on the map the present investigation did not estimate volumes of sand for restoration of this shoreline, owing to imprecise data on erosional areas. Although attempts were made to define Gulf shoreline changes on the western two thirds of the island, this was precluded by the lack

Table 7.--Grain size characteristics of Alabama Gulf shoreline segments

Sample location	Mean (Ø)	Sorting (Ø)	Percent sand	Percent silt & clay	Color
Dauphin Island	1.89	0.38	99.91	0.09	10YR7/2-light gray
Little Lagoon	1.11	0.29	99.94	0.06	10YR8/1-white
Perdido Pass	1.63	0.44	99.97	0.03	10YR8/1-white



For each of the erosional areas shown on the map two sand prisms (prisms 1 and 2) are required to restore to the shoreline position of 1955. Sand prism 3 may be required for stabilization of sand prisms 1 and 2. The estimated volumes of sand required to fill each prism are shown in the table below.

Volumes of sand (cubic yards) required for Areas I-V

	Area I	Area 11	Area III	Area IV	Area V	Totals
PRISM 1	96,125	96,124.	94,355	32,394	75,943	394,941
PRISM 2	172,382	144,186	283,065	122,165	113,915	835,713
PRISM 3	140,423	158,226	211,207	67,961	45,303	623,120
TOTAL	408,930	398,536	588,627	222,520	235,161	1,853,774

Figure 15.--Map of southeastern Dauphin Island Gulf shoreline showing principal areas of erosion during the period 1955-85 and estimated volumes of sand required for restoration of eroded areas (shaded) to the approximate position of the 1955 shoreline.

of geographic reference points needed for comparison of 1955 and 1985 aerial photographs.

As illustrated by figure 15 estimates were made of the volumes of sand that would be required to restore eroded areas to the 1955 shoreline position. To facilitate the estimation of restorative sand volumes the eroded shoreline was considered to consist of five areas as shown by figure 15. Estimated quantities of sand required to reclaim these areas to the 1955 shoreline position are shown in figure 15 and table 2.

As shown by figure 15 the estimated dimensions of the space to be filled with sand at eroded areas on Dauphin Island are represented by three hypothetical prisms numbered 1, 2 and 3. Prism 2 represents the space to be occupied by sand if it were placed from the 1985 shoreline seaward to the 1955 shoreline, with the top of this sand body approximately at sea level.

Prism 1 represents the space to be occupied by sand necessary to raise the elevation of the nourished area (prism 2) to that of the estimated 1955 shoreline topography. The vertical face (north face) of prism 1 represents the essentially vertical erosional scarp associated with the 1985 shoreline.

Prism 3 represents the space to be filled with sand at each nourishment site to achieve stabilization of prisms 1 and 2. While the seaward slope of the upper surface of prism 3 should be similar to that of the 1955 seabed, this probably cannot be achieved owing to the water depths that possibly now exist in these areas. Volume requirements for restoring the entire Dauphin Island beach to the 1955 shoreline position have been estimated at 1.85 million yd^3.

BALDWIN COUNTY SHORELINE

Geological Survey of Alabama studies carried out in cooperation with the U.S. Geological Survey from 1990 to the present (Geological Survey of Alabama, 1991, 1992) have included studies of the nature of Alabama Gulf shoreline change. Information resulting from this work is currently under evaluation. Some of the data related to these studies imply that the Gulf shoreline of Baldwin County Alabama is characterized by localized erosion and accretion and a prevailing long term erosional trend.

PERDIDO PASS

HISTORICAL BACKGROUND

The pass between Perdido Bay and the Gulf (fig. 16) has been at various locations east and west of the present pass during historic time and has shown a tendency for westward migration, resulting in formation of Perdido Key. In 1960 a sea wall was constructed to prevent further westward migration of the pass, and between 1955 and 1982 two rip-rap jetties were installed. Hurricane Frederic partially destroyed the eastern jetty in 1979. As a result of the prevailing westward movement of longshore currents in the vicinity of the pass, sand accumulates on the eastern side and beach erosion occurs on the western side. This has necessitated periodic bypass nourishment of the beaches immediately west of the pass to prevent compromising the integrity of the western jetty and to avoid erosion on the beaches seaward of private property.

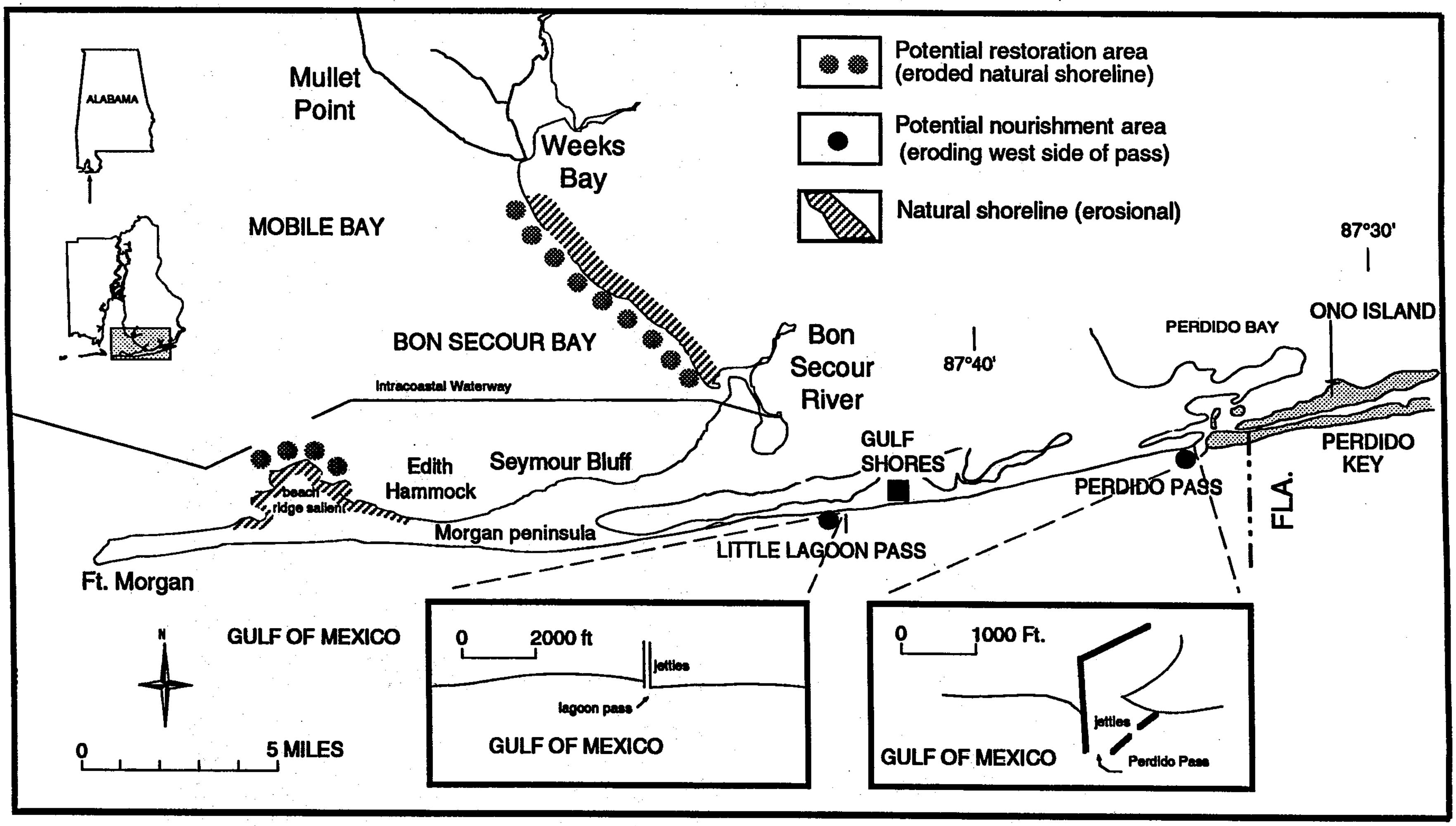


Figure 16.--Gulf and Bon Secour Bay shoreline of Baldwin County, Alabama, showing locations of potential shoreline restoration and nourishment.

Although it is probable that nourishment of the beaches west of the pass will continue to utilize sand pumped from the eastern side of the pass and from the pass itself, a need may arise in the future for volumes of sand not locally available without destroying part of the present key.

ESTIMATED SAND REQUIREMENTS

It is estimated that approximately 120,000 yd^3 of sand would be required to restore beaches adjacent to the western side of the pass if erosion of the western beach is allowed to progress to a point approximately half the length of the west stone jetty (table 2). This would include sand sufficient to bring the western shoreline approximately to the seaward end of the western jetty. Composite mean grain size for samples taken along this stretch of shoreline is 1.63 Ø (medium sand) and sorting is 0.44 Ø (well sorted). Sand content averages 99.97 percent with silt and clay averaging 0.03 percent. Beach sand color is white.

LITTLE LAGOON PASS

HISTORICAL BACKGROUND

Prior to the early 1980's the pass from Little Lagoon to the Gulf was located a various points on the lagoon barrier. In the early 1980's when the pass was located approximately at its present position. the Alabama Highway Department constructed a weir structure through the Little Lagoon barrier at this pass (fig. 16). This structure included reinforced concrete jetties extending seaward from the existing Gulf shoreline. This work was carried out in connection with the construction of a roadway bridge over the pass area. In following years sand accumulated on the eastern side of the pass resulting in a broadening the beach immediately east of the pass. Concurrently, erosion progressed on the beaches immediately west of the pass structures, resulting in erosion of the foundations of houses built adjacent to the western beaches. This resulted in litigation between private property owners and the State of Alabama, and eventually a legal mandate for the Alabama Highway department to maintain the pass and mitigate beach erosion on the western side of the pass. Thus far, nourishment sand for the eroding western beach has been taken from the bottom of Little Lagoon immediately in the vicinity of the pass. It is possible that at some point in time, and for various reasons it will not be feasible to utilize this sand source, giving rise to consideration of other sources of sand, such as offshore sand.

ESTIMATED SAND REQUIREMENTS

It is estimated that approximately 40,000 yd^3 of sand could be periodically placed on the western beach to maintain a reasonable width of western beach (table 2). The amount of sand actually needed will depend on the maintenance plan for the beach. Beach sediment at Little Lagoon averages 99.94 percent sand and 0.06 percent silt and clay (table 7). Mean grain size averages 1.11 Ø (medium sand) and sorting averages 0.29 Ø (very well sorted). Beach sand color is white.

FUTURE BREACHED BARRIER AREAS

Breaches in the Alabama barrier system can be expected to occur in the future as a result of hurricanes that make landfall in coastal Alabama. In the past, major modifications of the Alabama coastline have been effected by hurricanes, for example the changes in Dauphin Island implied by figure 14. It is possible that reestablishment of barrier breach areas will be considered in the future, particularly for areas that were developed for housing prior to breaching of the barrier. At present such development exists on Dauphin Island and along much of the barrier in Baldwin County.

The westward-most developed areas of Dauphin Island are sufficiently low topographically to allow some Gulf washover even under some non-hurricane coastal storm conditions. A hurricane breach in these areas could be expected to permit requests for restoration particularly if the breach effectively isolated developed areas to the west from the main part of the Island

A breach in the Little Lagoon barrier in Baldwin County would not only result in destruction of property on the lagoon barrier, it would also threaten developed areas along the north shore of Little Lagoon by exposing such property to wave systems and tides of Gulf waters. Generally, houses on this shoreline are not constructed to withstand the direct exposure to Gulf storm surge. A breach in Perdido Key could result in damage or destruction of private property in the breach zone and exposure of housing on Ono Island behind the Key to Gulf storm surge.

Although that part of the Alabama barrier system between Little Lagoon and the west end of Cotton Bayou appears to be securely attached to the mainland, it actually lies seaward of topographically low Holocene beach ridge terrain, marsh and freshwater lakes that formerly were lagoons (Shelby Lakes), and is at risk of being breached during a hurricane. Such a breach could occur on barrier areas now occupied by housing and requests for breach restoration undoubtedly would be made.

Whereas some sand for restoration of breached barrier areas might be available at the breached area, it is possible that sand from the breached barrier will have been so widely distributed that it cannot be utilized to restore the barrier, necessitating utilization of other sand sources.

OTHER POTENTIAL RESTORATION AREAS

A number of other areas within Mississippi Sound, Mobile Bay and other estuary areas in coastal Alabama could be considered for restoration, using sand resources acquired from offshore areas. These might include the former Grande Batture Islands, certain islands and wetlands along the north shore of Mississippi Sound, the natural shoreline areas of Mobile Bay, and developed erosional shoreline of Mobile Bay.

GRANDE BATTURE ISLANDS

Restoration of at least part of the erosionally destroyed Grande Batture Islands (Smith, 1986b) (fig. 17) might be considered as a means of minimizing erosional loss of the wetlands that formerly lay behind the Islands. Currently, a series of submerged bars occur in the places of the former islands. The raising of these bars an average of 2 ft above sea level utilizing sand from offshore areas would provide significant erosional protection to the existing wetlands, some of which are eroding at rates of more than 10 ft per year (Smith, 1989).

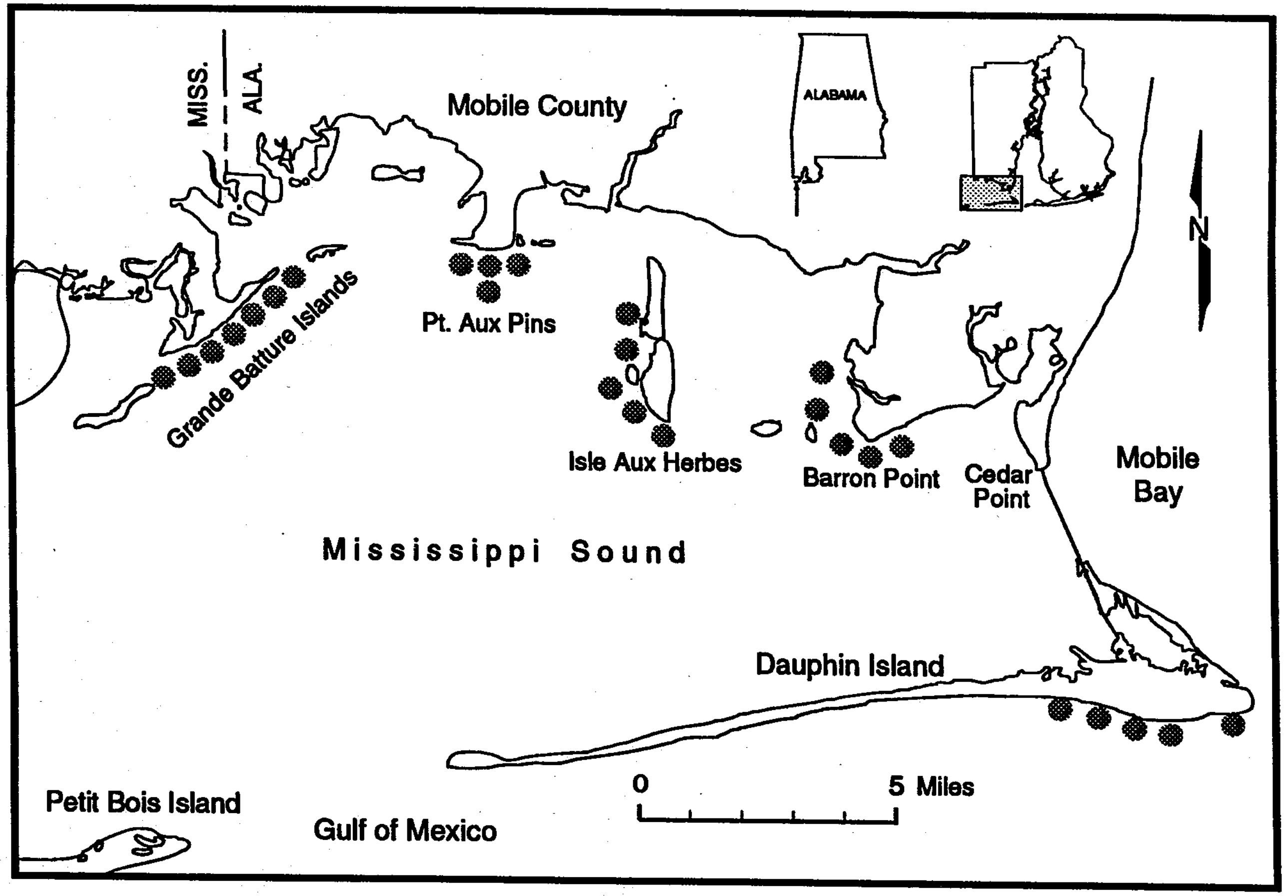


Figure 17.--Gulf and Mississippi Sound shoreline in Mobile County, Alabama showing locations of potential shoreline restoration (shaded).

MISSISSIPPI SOUND EROSIONAL WETLANDS

Most of the wetlands along the north shore of Mississippi Sound (fig. 17) that are exposed to open water of the Sound are now undergoing rapid erosion (Smith, 1989). Development of new wetlands and marsh on these shorelines by sediment accretion related to coastal stream discharge is negligible. It is possible that continued loss of the valued wetlands can be forestalled by the establishment of sediment sources within the eroding areas. This action would involve the building of isolated sediment berms (fig. 17) immediately offshore of the rapidly eroding wetlands to serve as sediment sources for nourishment of eroded shoreline and for development of new marsh areas.

NATURAL SHORELINES OF MOBILE BAY

Less than 20 mi of Mobile Bay natural shoreline now remain (fig. 16). Natural shorelines with potential for restoration include Bon Secour Bay between Weeks Bay and Bon Secour River and the Morgan Peninsula beach ridge salient (fig. 16). These shorelines lie inshore from broad, shallow shelf areas of a few feet depth, but are frequently exposed to erosional wave and current systems of the Bay with the result that shoreline erosion rates are commonly between 5 and 10 ft per year (Smith, 1992). At present no conservation or shoreline management plan includes measures to minimize erosion on these natural areas. Restoration of these areas at least to the position of the 1955 shoreline would result in a bayward extension of the shoreline of more that 200 ft for some areas. Examples of the type of natural environments that would develop following such restoration can be observed at several localities on Bon Secour Bay Shoreline where natural accretion on formerly erosional shoreline has occurred. It is estimated that approximately 1.3 million yd^3 of offshore sand would restore most of the remaining natural shoreline of Mobile Bay to approximately 200 ft bayward of the present shorelines of these areas.

DEVELOPED ERODING SHORELINES OF MOBILE BAY

Some segments of Mobile Bay Shoreline currently developed as residence areas are susceptible to erosion despite efforts of property owners to erect and maintain erosion prevention structures such as bulkheads and retaining walls. Examples of such shoreline can be seen in the Seymour Bluff area of Bon Secour Bay (southeast Mobile Bay), Bon Secour Bay shoreline between Weeks Bay and Mullet Point (fig. 16) and on the western shore of Mobile Bay north of Cedar Point (fig. 17). To restore property damaged or lost by erosion, property owners must repair the damaged erosion-prevention structures and purchase fill from some inland sand source. Such fill must be hauled many miles from these inland sources, and in most cases available fill materials are not compatible texturally and mineralogically with the local sediments of the Bay and adjacent terrain. The availability of offshore sand for purchase by private or cooperative enterprises for stockpiling and sale would enable private property owners to reclaim eroded shoreline property economically using materials compatible with local environments.

DISCUSSION

Most Alabama Gulf shoreline appears to be exhibiting a long term erosional trend and most Alabama estuarine shoreline is classified as erosional. The Gulf shoreline segments identified in this report as potential areas for sand nourishment are 1) shoreline immediately west of Perdido Pass, Baldwin County, 2) shoreline immediately west of Little Lagoon Pass in Baldwin County, 3) certain shoreline segments on the eastern part of Dauphin Island , Mobile County, and 4) undesignated sites on the Little Lagoon barrier beach and Dauphin Island where future hurricanes could result in breaches. Erosional estuarine shoreline areas with potential for restoration or nourishment include 1) the former Grande Batture Islands, 2) wetland shoreline on the north shore of Mississippi Sound, 3) natural shoreline on Mobile Bay and 4) certain segments of developed shoreline on Mobile Bay.

Many eroded and eroding shoreline areas in the Alabama coastal area could benefit from application of restorative and nourishment sand obtained from Gulf of Mexico offshore areas. The currently eroding Gulf shoreline areas of southeastern Dauphin Island could be restored approximately to the 1955 shoreline position by application of about 1.8 million yd^3 of sand. At present, erosional regimes remain in effect on the southeastern shoreline of the island resulting in continuing loss of property. In the vicinity of the Dauphin Island Park, erosion is against a relatively narrow section of dunes that protect inland developed areas, including a public school.

Extensive eroded areas in Mississippi Sound could be restored or nourished with offshore sand. Restoration of at least part of the former Grande Batture Islands in Mississippi Sound would minimize erosion now progressing rapidly on wetlands formerly behind the Grande Batture Islands. An estimated 2.5 million yd^3 of sand would be required to build an effective barrier and provide sediment stabilization for adjacent wetlands.

On Baldwin County Gulf shoreline, the continually eroding beaches adjacent to the west sides of Perdido Pass and Little Lagoon Pass could be nourished from offshore sand sources in circumstances when local sand is not available.

Sand obtained from offshore areas could potentially be used for restoration of barrier areas breached by a hurricane. Restoration of at least part of such a breached area probably would be seriously considered, particularly if developed areas were isolated from other developed area, or if the loss of land area was significant.

Eroding natural shoreline areas of Mobile Bay could be restored using an estimated 1.3 million yd^3 offshore sand, resulting in hundreds of acres of new terrain that would develop characteristics of natural nearshore estuary terrain. Restoration of currently developed shoreline to some former shoreline position might be considered for those developed areas might be considered for such restoration.

Many segments of Mobile Bay developed shoreline are now experiencing progressive erosional loss despite erosion prevention measures being taken by property owners. The Edith Hammock area and some areas on the rapidly eroding west shore of Mobile bay are examples of this. Repair of shoreline property damaged by periodic storms, and restoration of property to former shoreline conditions by owners of private property could be facilitated by the availability of low cost fill material.

The purpose of the above described work has been to identify and describe only in a general sense those coastal areas that could be considered for restoration or sediment nourishment. Specific projects leading to restoration or nourishment of any of these areas are not herein proposed. To the present no formal assessments of the benefits, costs or technical feasibility or permitability of any restoration or nourishment work has been carried out by the Geological Survey of Alabama.

GEOLOGIC FRAMEWORK OF THE ALABAMA EEZ

If we are to evaluate an area of the Alabama EEZ for its sand resource potential, it is essential that its geologic framework and lithofacies patterns be well documented. Such understanding was not available prior to this study.

A database of available information pertaining to hard mineral occurrence in the EEZ, offshore Alabama, was compiled by Parker (1989). Evaluation of this database indicated a potential for significant deposits of sand, shell gravel, and heavy minerals to occur in this area; however, available data were not adequate to identify specific resource sites. The lack of vibracore and bottom sample data resulted in an effort in this study to collect new vibracore and bottom sample data to adequately describe the framework geology and hard mineral resources in the proposed study area. Recent MMS Gulf Task Force studies of hard mineral resources in the Gulf of Mexico-EEZ (Louisiana Geological Survey, 1991) have emphasized evaluation of offshore sand resources for beach nourishment. The efforts of this aspect of the current study are to describe in detail the framework geology of the Alabama inner continental shelf with the intent of identifying and characterizing specific sand resources in the EEZ study area, offshore Alabama. This portion of the study completed tasks 3, 4, 5, and part of task 6 of the project.

LITHOFACIES OF THE ALABAMA EEZ

The sediments obtained from the 59 vibracores and 59 surface sediment samples collected for this study were divided into a series of lithofacies. A lithofacies is a lateral, mappable subdivision of a stratigraphic unit that may be distinguished from adjacent subdivisions on the basis of lithology (Moore, 1949). All characteristics of lithology may be utilized, including the composition, grain size, sedimentary texture and fabric, sedimentary structures, color, biota, and lateral or vertical variation of the unit.

Utilizing these criteria, six separate lithofacies were delineated for the study area. These may be subdivided into 13 discrete microfacies (e.g., Wilson, 1975), lithologic units with very similar characteristics that, presumably, formed under nearly identical conditions.

The lithofacies described and the microfacies for each include the Graded Shelly Sand Lithofacies; the Clean Sand Lithofacies (including the Orthoquartzite Microfacies, the Echinoid Sand Microfacies, the Shelly Sand Lithofacies, and the Sand with Mud Burrows Microfacies); the Dirty Sand Lithofacies (including the Muddy Sand Microfacies and the Muddy Shelly Sand Microfacies); the Biogenic Sediment Lithofacies (including the Oyster Biostrome Microfacies and the Peat Microfacies); the Muddy Sediment Lithofacies (including the Silty/Clayey Sand Microfacies, the Sand-Silt-Clay Microfacies, and the Mud-Sand Interbeds Microfacies); and the Pre-Holocene Lithofacies.

Grain size characteristics for each lithofacies and microfacies are listed in table 8. Distribution of facies thickness by cores is shown in table 9. Core columnars showing a typical example of each microfacies are shown in figures 18 through 22.

GRADED SHELLY SAND LITHOFACIES

The Graded Shelly Sand Lithofacies is the most common facies encountered, represented by 74 of a total of 179 samples evaluated for grain size (e.g., 41 percent of all samples analyzed) (table 8). Total thickness sampled was 246.0 ft, or 41.8 percent of total core length (table 9).

Table 8.--Grain size characteristics of facies

Facies	Mean grain size[2]			Standard deviation[2]			Gravel[3]			Sand/gravel[3]			Silt[3]			Clay[3]			Number of samples	Facies thickness[4]
	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum	Minimum	Average	Maximum		
Sands	3.39	1.99	-1.71	0.46	0.96	2.14	0.0	4.0	84.9	78.0	95.8	99.6	0.0	1.6	12.8	0.0	2.5	14.5	159	497.4
Clean sands	2.93	2.07	.78	.46	.85	1.87	0.0	2.5	23.2	88.1	97.2	99.6	0.0	.8	4.5	0.0	2.0	7.4	60	175.8
Orthoquartzite	2.67	2.16	1.56	.49	.81	1.29	0.0	1.1	5.8	92.4	96.9	99.6	0.0	1.1	3.1	0.4	2.0	4.7	17	65.1
Sand w/mud burrows	2.93	2.26	1.69	.49	.85	1.92	0.0	1.4	6.0	88.1	96.1	99.1	0.0	1.2	4.5	0.0	2.8	7.4	19	83.1
Echinoid sand	2.40	1.81	.78	.46	.82	1.87	.1	3.5	23.2	95.6	98.3	99.1	0.0	.4	2.7	0.0	1.3	2.6	17	13.4
Shelly sand	2.40	2.05	1.4	.52	.98	1.75	.1	5.6	17.6	96.3	98.2	99.1	0.0	.3	.8	.6	1.5	3.3	7	12.2
Graded shelly sand	2.59	1.76	-1.71	.47	.87	2.15	0.0	5.1	84.9	96.8	98.5	99.6	0.0	.4	2.0	0.0	1.1	2.7	75	246.0
Dirty sands	3.39	2.55	1.43	1.06	1.45	2.03	0.0	2.7	10.8	78.0	85.0	91.5	2.8	7.0	12.8	2.4	7.8	14.5	24	75.6
Muddy sand	3.39	2.68	2.12	1.06	1.36	1.68	0.0	1.7	4.5	78.0	84.8	91.5	2.8	6.9	12.8	2.4	8.1	14.5	17	57.9
Muddy shelly sand	2.75	2.23	1.43	1.28	1.68	2.03	.9	3.1	10.8	79.6	85.4	90.5	4.5	7.4	12.4	3.8	7.2	12.7	7	17.7
Biogenic sediments																				2.4
Oyster biostrome	x	2.38	x	x	2.23	x	x	12.1	x	x	71.5	x	x	8.9	x	x	19.6	x	1	1.2
Peat[1]																				1.1
Muddy sediments	5.45	3.56	2.74	1.24	1.62	2.32	0.0	.7	4.6	10.6	57.8	82.0	6.6	21.0	43.5	3.5	21.2	45.8	19	68.5
Silty/clayey sands	3.81	3.36	2.74	1.27	1.56	2.06	0.0	1.1	4.6	57.2	67.9	77.1	10.5	18.1	25.9	3.5	14.0	26.4	11	37.0
Sand-silt clay	5.45	4.28	3.36	1.38	1.67	1.85	0.0	0.0	0.0	10.6	33.5	51.5	22.9	29.8	43.5	25.6	36.7	45.8	5	15.5
Mud-sand interbeds	3.69	3.10	2.78	1.24	1.76	2.32	0.0	.4	1.1	33.3	61.1	82.0	6.6	17.0	26.9	11.4	21.9	39.8	3	16.0
Pre-Holocene[1]																				20.9

[1] No samples taken
[2] in Ø
[3] in %
[4] in feet

Table 9.--Facies distribution by core

	Core number														
	SR-1	SR-2	SR-3	SR-4	SR-5	SR-6	SR-7	SR-8	SR-9	SR-10	SR-11	SR-12	SR-13	SR-14	SR-15
Sands															
Clean sands															
Orthoquartzite		133	53					147	113		299	242			
Sand w/mud burrows				98		136				266	47	136			
Echinoid sand						23					10	30		50	
Shelly sand			4			38		242				137			
Graded shelly sand			183	192	507	265	250			217	33	30		208	137
Dirty sands															
Muddy sand	74	55						145					198		
Muddy shelly sand								19					56		
Biogenic sediments															
Oyster biostrome															
Peat															
Muddy sediments															
Silty/clayey sands	50														
Sand-silt-clay	186		11												
Sand-mud interbeds													40		
Pre-Holocene															152

Table 9.--Facies distribution by core—Continued

	Core number														
	SR-16	SR-17	SR-18	SR-19	SR-20	SR-21	SR-22	SR-23	SR-24	SR-25	SR-26	SR-27	SR-28	SR-29	SR-30
Sands															
Clean sands															
Orthoquartzite										398					
Sand w/mud burrows	231	163	305		128					124					
Echinoid sand		35	10		20	10			10						
Shelly sand		12													
Graded shelly sand	21	51	127		362	64	189	269	202		311	19	249	210	89
Dirty sands															
Muddy sand				14								35			
Muddy shelly sand				26											
Biogenic sediments															
Oyster biostrome															
Peat										27					
Muddy sediments															
Silty/clayey sands				264											
Sand-silt-clay															
Sand-mud interbeds															
Pre-Holocene					21	95		11	10			68		29	

Thickness measured in centimeters

Table 9--Facies distribution by core—Continued

	Core number														
	SR-31	SR-32	SR-33	SR-34	SR-35	SR-36	SR-37	SR-38	SR-39	SR-40	SR-41	SR-42	SR-43	SR-44	SR-45
Sands															
Clean sands											216				
Orthoquartzite							296								
Sand w/mud burrows								473	24	22			143		122
Echinoid sand		30	12								20	121		10	10
Shelly sand															
Graded shelly sand	33	160		369	381	182	50		232	380			141	174	220
Dirty sands															
Muddy sand		11							140						90
Muddy shelly sand															
Biogenic sediments															
Oyster biostrome		28													
Peat								7							
Muddy sediments															
Silty/clayey sands		317								130					
Sand-silt-clay															75
Sand-mud interbeds								26			25				
Pre-Holocene	89		57						17			7			

Table 9.--Facies distribution by core—Continued

	Core number														Total length	Percent of total core length
	SR-46	SR-47	SR-48	SR-49	SR-50	SR-51	SR-52	SR-53	SR-54	SR-55	SR-56	SR-57	SR-58	SR-59		
Sands															15210	84.4
Clean sands															5375	29.8
Orthoquartzite			21		20			10			42				1990	11.0
Sand w/mud burrows											32		91		2541	14.1
Echinoid sand														10	411	2.3
Shelly sand															433	2.4
Graded shelly sand				312		162					14	164		264	7523	41.8
Dirty sands															2312	12.8
Muddy sand	183	51			153		60	212		159			190		1770	9.8
Muddy shelly sand				18					283		140				542	3.0
Biogenic sediments															72	0.3
Oyster biostrome													10		38	0.02
Peat															34	0.01
Muddy sediments															2096	11.6
Silty/clayey sands	135	65	129				43								1133	6.3
Sand-silt-clay	55									148					475	2.6
Sand-mud interbeds		397													488	2.7
Pre-Holocene							82								638	3.5

[1]No samples taken

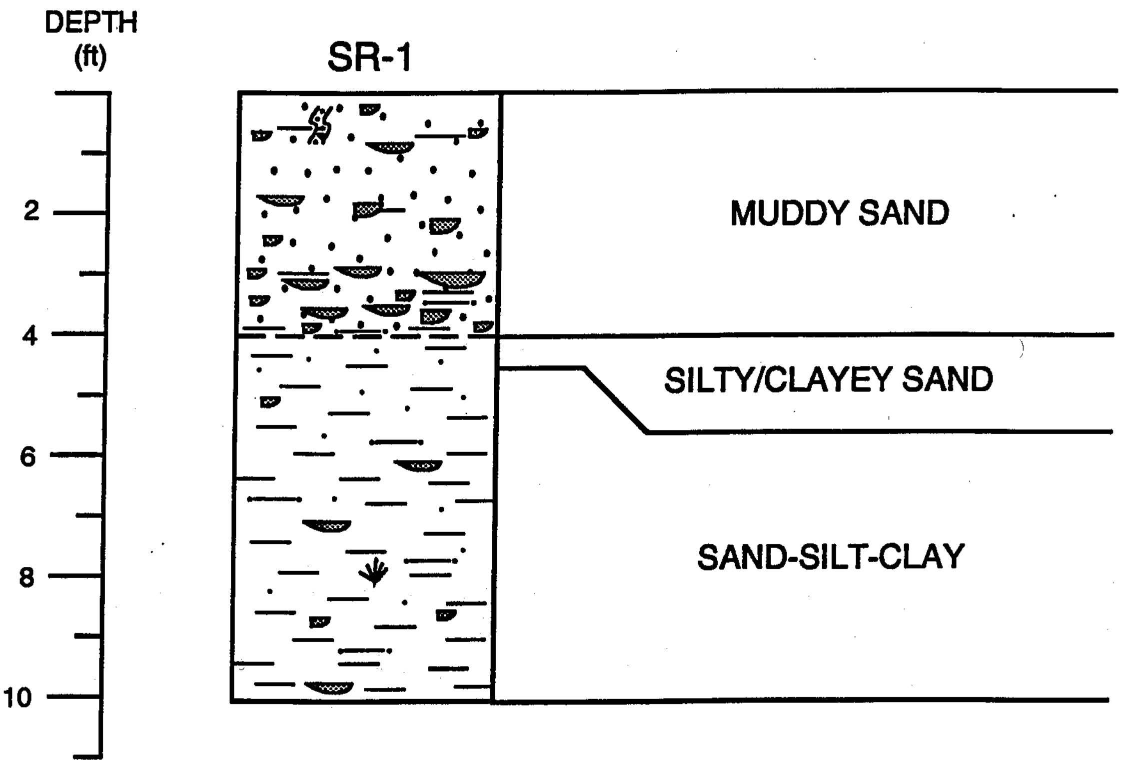


Figure 18.--Columnar section illustrating facies distribution in core SR-1 (see figure 9 for core location).

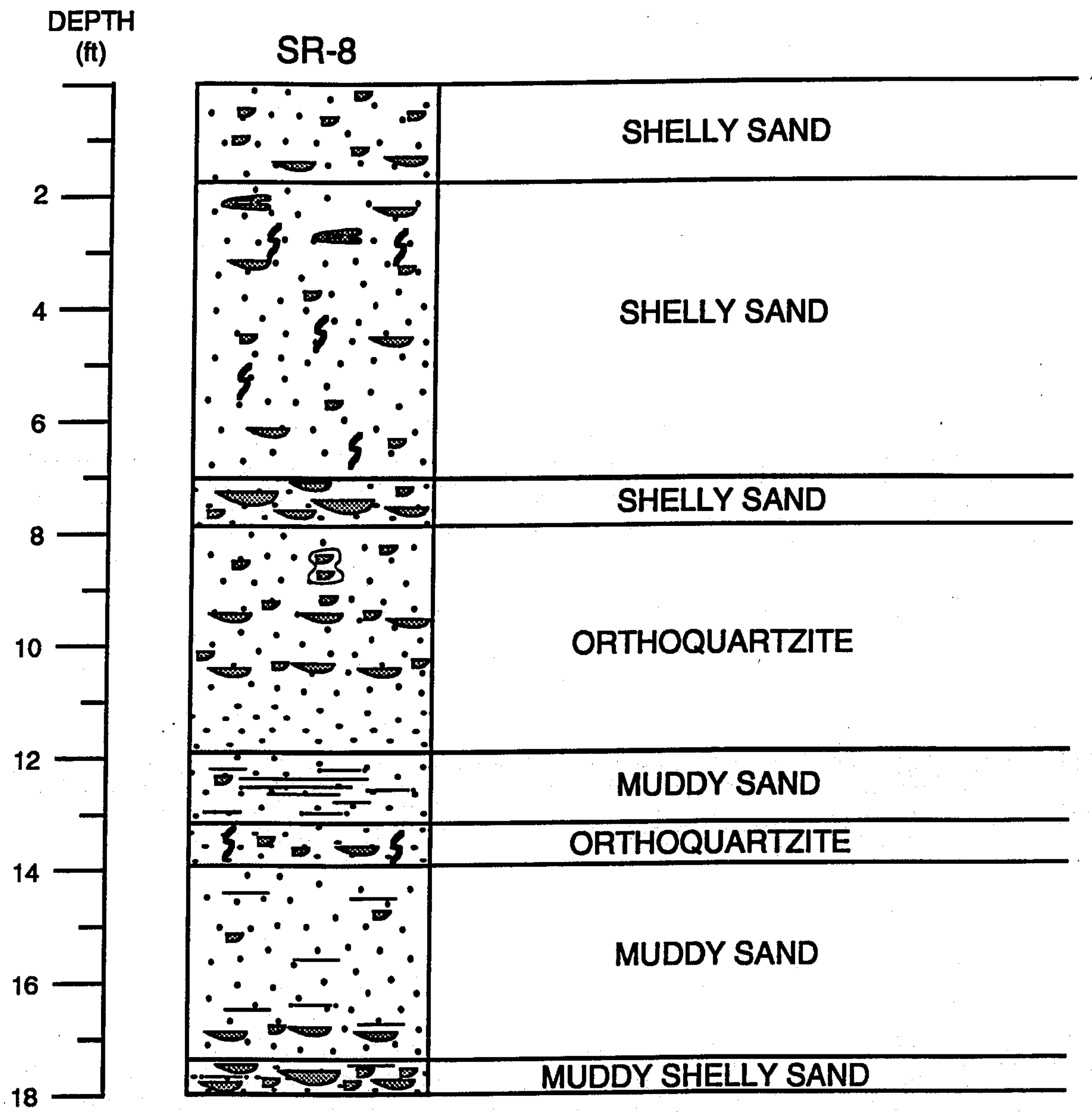


Figure 19.--Columnar section illustrating facies distribution in core SR-8 (see figure 9 for core location).

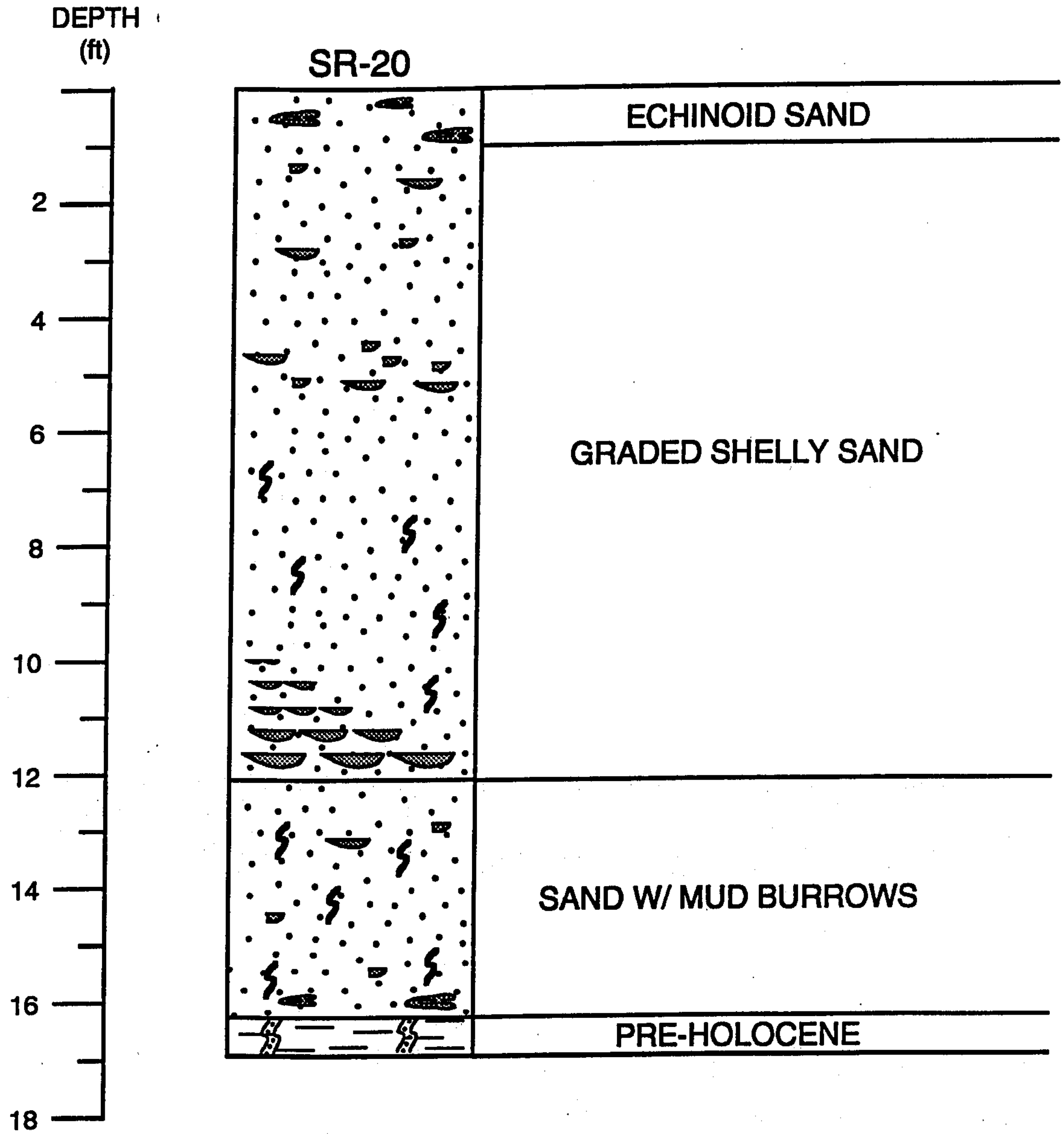


Figure 20.--Columnar section illustrating facies distribution in core SR-20 (see figure 9 for core location).

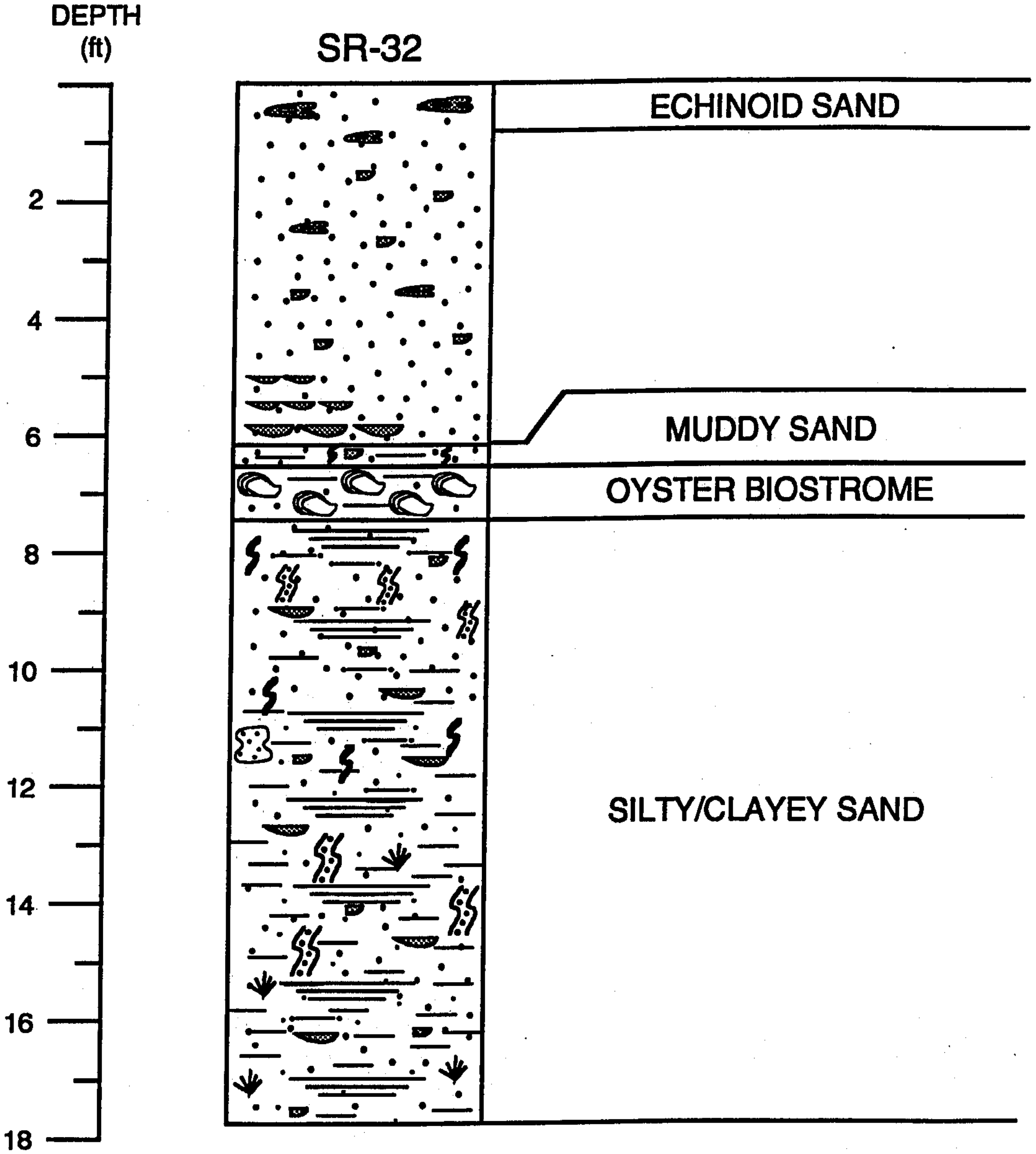


Figure 21.--Columnar section illustrating facies distribution in core SR-32 (see figure 9 for core location).

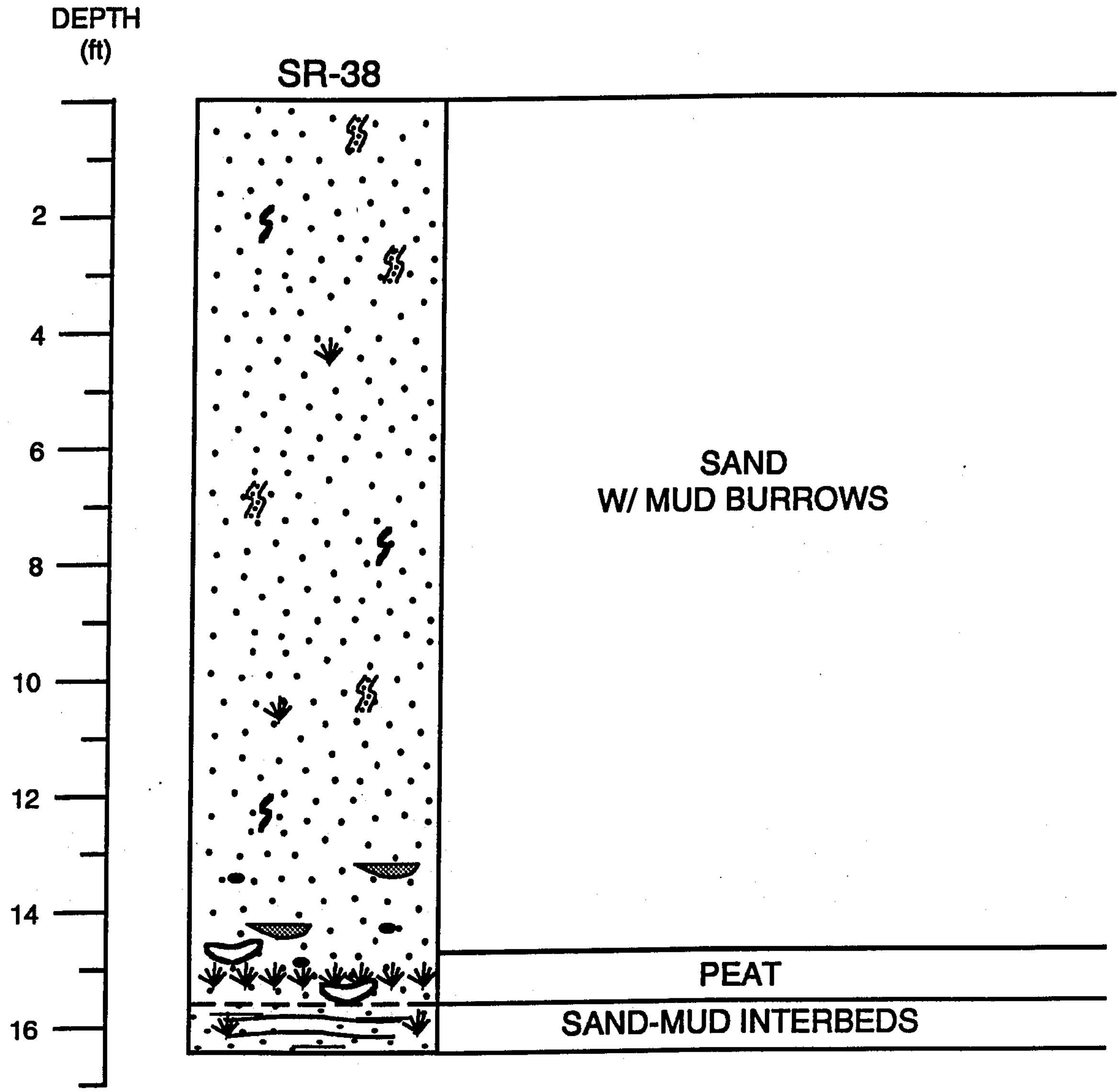


Figure 22.--Columnar section illustrating facies distribution in core SR-38 (see figure 9 for core location).

This lithofacies is represented by a fining-upwards graded sequence of shell and clean sand in core SR-5. All units show a sharp to relatively sharp base, in some cases containing mud clasts interpreted as rip-ups of the underlying sediments during high-energy erosive events (core SR-35); this is typical in shelf environments (Herbich and others, 1984). The basal portions of the units are the coarsest parts, with a high concentration of shell material (cores SR-6 and SR-34), some of which may be a few in in size (core SR-39). This portion of the unit is typically a densely packed shell bed (Kidwell and Holland, 1991). This basal unit is typically chaotic, with random shell orientations; upwards, the shell fragments more commonly are subhorizontal (core SR-7). The shell material both decreases in mean grain size as well as relative abundance upwards within the unit (core SR-51). The sand component typically does not appreciably fine upwards; rather, the relative abundance of the sand fraction increases due to the decrease in shell content (loosely packed to finally dispersed packing in the upper portion, categories of Kidwell and Holland, 1991). Some units are very thick, with individual shell gravel to sand couplets greater than 11 ft thick (core SR-34). Average mean grain size for the graded shelly sand lithofacies is 1.76 Ø (medium sand), table 8); the range for mean grain size is from -1.71 Ø (granules) to 2.54 Ø (fine sand). The average standard deviation for graded shelly sand samples is 0.87 Ø (moderately sorted); values for standard deviation range from 0.47 Ø (moderately well sorted) to 2.15 Ø (very poorly sorted). Overall, the facies represents the coarsest average mean grain size, and the second best sorting among all facies. It also, however, represents a much larger range in both mean grain size (from coarsest to finest sample mean is 4.25 Ø) and standard deviation (from the most well-sorted to most poorly-sorted sample is a difference of 1.65 Ø) than any other lithofacies. These trends are to be expected and are not contradictory, given the graded nature of the lithofacies. As the basal sediments are much coarser than sediments that cap the units, there is a wide range of mean grain sizes as a whole for samples from the facies, depending on whether the sample was taken near the top or bottom of the unit. The inferred origin of these units is rapid deposition of resuspended sediment during storms; this may lead to poor sorting among basal, coarse portions, as material of a wide range of sizes is quickly dumped (Aigner, 1985; Hayes, 1967; Morton, 1981) .

Sediment coarser than 4 Ø (i.e., sand and gravel) (table 8), is by far the dominant constituent of the facies, on average making up 98.5 percent of the unit. The range of values for this material is quite low, 96.8 percent to 99.1 percent. This coarse material comprises two primary components: Quartz-rich sand and shell hash. The quartz-rich sand is a clean, rounded white to clear fine to medium quartz sand with minor amounts of feldspars (especially orthoclase, albite and oligoclase), calcite, muscovite and various heavy minerals, among other constituents (Fairbank, 1962; Goldstein, 1942; Griffin, 1962). Parker (1989) showed that the sand-sized component may contain up to approximately 20 percent carbonate in the form of comminuted and juvenile shell material. The gravel-sized component, virtually all shell material, makes up an average of 5.1 percent of the sediment weight. Range for the gravel component is from 0.0 (quartz sand) to 84.9 percent (e.g., a shell bed of the "shell gravel" type, Davies and others, 1989a). Some samples, especially at the base of the units, contain a preponderance of very coarse (a few in) whole shells and major fragments (e.g., the shell gravels); other samples, especially those near the tops of the units, may contain only rare fine, comminuted shell material. The relative importance of the quartz sand and shell gravel constituents varies; generally, there is more shell gravel near the base of the unit, which commonly fines upwards to a clean, shell-poor sand. The thickness of the shelly base of the unit ranges from a few in to several tens of in. In nearly all cases, however, a general decrease in shell content occurs upwards in the unit. The shell hash is composed of a variable mixture of original colored to blackened, discolored shell material that ranges from whole shells and major fragments to comminuted shells and platy fragments (Davies and others, 1989a). Shells from some samples are almost entirely blackened, discolored "old" material; others show original coloration on most shell material, with only occasional discolored shells (see section on "Benthic Fauna: Results and Interpretation" for discussion of implications).

The average sand content would therefore be calculated as 93.4 percent for the lithofacies, the second highest of any lithofacies.

Silt (4 to 8 Ø) is rare in all samples, with a mean of 0.4 percent and a range from 0.0 to 2.0 percent. Likewise, clay content (greater than 8 Ø) is extremely low, with a mean of 1.1 percent and a range of 0.0 to 2.7 percent. These are the lowest values for any facies. In no case do these two size classes together constitute more than 3.2 percent of the sample. Therefore, both mean grain size and sorting values effectively represent the sand and shell gravel components only, with only very secondary influence from the fine grained components. This lithofacies has very good potential as a source of material for beach replenishment projects.

CLEAN SAND LITHOFACIES

The Clean Sand Lithofacies is the second most common lithofacies encountered in the EEZ, represented by 60 grain size samples (34 percent) (table 8), and a total thickness of 175.8 ft, or 29.8 percent of total core length (table 9). It consists of four microfacies: Orthoquartzite Microfacies; Echinoid

Sand Microfacies; Shelly Sand Microfacies; Sand with Mud Burrows Microfacies. While each of these microfacies is a quartz-rich sand, they vary in texture, fabric and other aspects; thus, these characteristics will be discussed separately for each.

Mean grain size for the Clean Sand Lithofacies averages 2.07 Ø (fine sand) (table 8), with a range from 0.78 Ø (coarse sand) to 2.93 Ø (fine sand). This relatively wide range (2.15 Ø) from most coarse to finest grain size is largely due to the presence of coarse sand and pebble-sized shell fragments mixed with the fine to medium quartz sand seen in some of the Clean Sand microfacies. Standard deviation for the facies averages 0.85 Ø (moderately sorted), with a range from 0.46 Ø (well sorted) to 1.87 Ø (poorly sorted). The facies has the lowest average standard deviation, and thus represents in general the best sorted lithofacies. Nonetheless, it also encompasses the second highest range of values for standard deviation among the lithofacies, again likely representing the grouping of shell-rich and shell-poor microfacies.

The sand/shell gravel size class is by far dominant, comprising an average of 97.2 percent of the sample. This is the second most sand/shell gravel-rich lithofacies, and represents the highest average sand content (94.7 percent) of any lithofacies. The range of sand/gravel content is 88.1 to 99.6 percent. Only three samples contain less than 93 percent sand/shell gravel.

Shell gravel content averages 2.5 percent, with a range from 0.0 to 23.2 percent. This is the second highest range of gravel content values of the lithofacies. Much of the shell material, especially in the echinoid sand microfacies, is soft echinoderm hash. This material is rapidly destroyed in a high energy (e.g., beach) setting (Chave, 1964). Three samples contain greater than 15.9 percent shell (largely echinoderm hash); these are the only samples from the facies with greater than 85 percent sand, and thus would not present a problem for utilization as beach replenishment material.

Silt content is very low, with a mean of 0.8 percent and a range from 0.0 to 4.5 percent. Likewise, clay content is low, with a mean of 2.0 percent and a range from 0.0 to 7.4 percent. The highest values for both silt and clay come from the same sample, which has mud-lined burrows in the clean sand. This lithofacies would be an excellent source for replenishment materials.

ORTHOQUARTZITE MICROFACIES

The Orthoquartzite Microfacies is a clean sand, composed almost completely of quartz grains. It includes very little coarse or fine grained material. Seventeen samples were analyzed from this microfacies (table 8); it comprises 65.1 ft of core material, or 11.0 percent of total core length.

Laminations are difficult to observe in such a homogeneous sediment. However, some units do possess layers and/or pockets of increased shell content (still only a minor constituent). There may be an upwards increase in shell content (e.g., core SR-8). The shells are always sand supported (loose packing, Kidwell and Holland, 1991). Occasional mud filled burrows are present. Most units have sharp to fairly sharp bases; however, a gradational base was noted in core SR-41.

Average mean grain size for the microfacies is 2.16 Ø (fine sand), with a range in values from 1.56 Ø (medium sand) to 2.67 Ø (fine sand), indicating homogeneity within the microfacies. Average standard deviation for the microfacies is 0.81 Ø (moderately sorted), with a range from 0.49 (well sorted) to 1.29 Ø (poorly sorted). This represents the best sorting of any microfacies analyzed.

Sand/shell gravel content averages 96.9 percent, with a range from 92.4 to 99.6 percent. Shell gravel content is low, averaging 1.1 percent with a range of 0.0 to 5.8 percent. This is the lowest shell gravel content of any sand microfacies. Therefore, the average sand fraction is 95.8 percent, the highest sand content of any microfacies analyzed.

Shell material is a mixture of mollusc and echinoderm comminuted shell fragments, with varying degrees of discoloration. There are relatively few whole shells or large fragments.

Silt content is very low, with an average of 1.1 percent and a range of 0.0 to 3.1 percent. Likewise, clay content averages only 2.0 percent, with a range from 0.4 to 4.7 percent. Therefore, this clean orthoquartzitic sand would make an excellent beach replenishment source.

ECHINOID SAND MICROFACIES

The Echinoid Sand Microfacies was analyzed in 17 samples (table 8), and represents 13.4 ft of collected core (2.3 percent) (table 9). It is composed of clean quartz-rich sand with a variable component of echinoid shell hash.

Primarily a sediment surface accumulation (16 of 17 samples), this microfacies represents incorporation of recently dead echinoid tests and fragments into the surficial clean sands. Most of the echinoderm material is comminuted; a large portion shows evidence of intense dissolution. This is to be expected for such chemically unstable shell material in a surficial accumulation where rapid dissolution dominates chemical reactions (Davies and others, 1989b). The microfacies typically grades into the underlying unit. Undoubtedly, the older clean sands beneath many of these deposits originally contained echinoderm fragments as well; they have been dissolved away through time. Therefore, the presence of echinoid remains would not decrease the excellent potential of this microfacies for beach replenishment.

Average mean grain size for this microfacies is 1.81 Ø (medium sand) (table 8), the second most coarse for any microfacies. It has a range of mean grain size from 0.78 Ø (coarse sand) to 2.40 Ø (fine sand). Standard deviation of grain size for samples from this microfacies averages 0.82 Ø (moderately sorted), with a range from 0.46 Ø (well sorted) to 1.87 Ø (poorly sorted). These are the greatest ranges for any microfacies in the Clean Sand Facies, indicating a wide range in echinoid fragment size. Overall, however, this microfacies shows the second best sorting of any microfacies analyzed.

The average sand/shell gravel content of this microfacies is 98.3 percent, higher than any sediment type except the Graded Shelly Sand Facies. The range of values is 95.6 to 99.1 percent, the second lowest for any microfacies, indicating good homogeneity between samples. Shell gravel content averages 3.5 percent, with a range of 0.1 to 23.2 percent. However, only 2 samples contain more than 5 percent shell gravel. This is the highest average and range for any Clean Sand microfacies, and may indicate patchiness in the presence of echinoderm material. The average sand fraction would therefore be calculated as 94.8 percent, the second highest for any microfacies.

Both silt and clay contents are extremely low. Silt content averages 0.4 percent, with a range from 0.0 to 2.7 percent. Clay content averages 1.3 percent, with a range from 0.0 to 2.6 percent. Both averages are the second lowest for any microfacies analyzed.

SHELLY SAND MICROFACIES

The Shelly Sand Microfacies is an uncommon sediment type that is represented by 7 grain size samples (table 8) from 12.2 ft of core (2.4 percent of core length) (table 9).

This microfacies consists of 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) than those of the Graded Shelly Sand Facies, and bases may not be as sharp.

The average mean grain size for this microfacies is 2.05 Ø (fine sand), with a range from 1.40 Ø (medium sand) to 2.40 Ø (fine sand). This average value is nearly the same as that for the Clean Sand Facies as a whole. The average standard deviation for the microfacies is 0.98 Ø (moderately sorted), the most poorly sorted of any Clean Sand microfacies. The range of values is 0.52 Ø (moderately well sorted) to 1.75 Ø (poorly sorted); differences in the shell gravel content control the degree of sorting.

Average sand/shell gravel content is 98.2 percent, with a range of less than 3 percent (96.3 to 99.1 percent). Therefore, this microfacies is consistently very sand/shell gravel rich. Shell gravel averages 5.6 percent, higher than any other microfacies analyzed. The range of values for shell gravel content is 0.1 to 17.6 percent; however, all but one sample contain less than 5 percent shell. On average, therefore, the microfacies contains 92.6 percent sand sized material, the lowest sand content for any Clean Sand microfacies.

Biota for this microfacies is primarily molluscan. Some units (e.g., cores SR-6 and SR-8) contain some large whole shells and major fragments (larger than one half inch), while other units (core SR-17) contain smaller whole shells and shell fragments only. Some units (core SR-8) have an appreciable quantity of echinoderm hash in part of the unit.

Silt and clay contents for this microfacies are extremely low. Silt content averages 0.3 percent, with a range from 0.0 to 0.8 percent. This is the lowest average and range for any microfacies. Clay content averages 1.5 percent, with a range of 0.6 to 3.3 percent. Based on its composition, this microfacies would make excellent beach replenishment source material.

SAND WITH MUD BURROWS MICROFACIES

The Sand with Mud Burrows Microfacies is represented by a total of 19 samples (table 8) taken from 83.1 ft of core length (14.1 percent of total) (table 9).

The fabric and texture of this microfacies is similar to that of the Orthoquartzite Microfacies; it is a clean sand, but generally with a lower shell content. Some units may have a few clay laminations (e.g., core SR-4). The distinguishing characteristic is the presence of common mud-filled or mud-lined burrows, ranging from 0.1 to 0.5 in in diameter. Some units (core SR-4) may have bioturbation indices as high as 4 or 5 (indices from Droser and Bottjer, 1986). In some cases, the burrows decrease in abundance toward the top of the unit (core SR-16); in these cases, mean grain size would increase upwards. Bases to the units are generally fairly sharp.

Average mean grain size for this microfacies is 2.26 Ø (fine sand), and ranges from 1.69 Ø (medium sand) to 2.93 Ø (fine sand). This is the finest-grained mean, minimum, and maximum value for any of the microfacies of the Clean Sand Facies, indicative of the slightly higher content of fines. Average standard deviation for the microfacies is 0.85 Ø (moderately sorted), the same as for the Clean Sand facies as a whole. This sediment type has the third best average sorting of any microfacies analyzed. The range of values for standard deviation is 0.49 Ø (well sorted) to 1.42 Ø (poorly sorted). Differences in shell gravel content control the sorting, with more shell-poor (i.e., sand-rich) samples generally being better sorted.

Sand/shell gravel dominates the composition of this microfacies, making up an average of 96.1 percent of the unit. The range of sand/shell gravel is 88.1 to 99.1 percent. This microfacies has the lowest percentage of sand/shell gravel, and the widest range in content, of any Clean Sand microfacies. Nonetheless, 16 of 19 samples (84 percent) contain greater than 95 percent sand/shell gravel. Shell gravel content averages 1.4 percent, with a range from 0.0 to 6.0 percent. This is the second lowest shell content of any sand microfacies. Therefore, sand content averages 94.7 percent of the sediment, the same as for the Clean Sand Facies as a whole.

Silt content averages 1.2 percent, with a range from 0.0 to 4.5 percent. Clay content averages 2.8 percent, with a range from 0.0 to 7.4 percent. While still very low, these are the highest average and maximum silt and clay contents for any Clean Sand microfacies. The sand itself is typically no more mud-rich than that of the Orthoquartzite Microfacies; the additional fines are found in discrete mud-filled burrows. This microfacies would make an excellent source for beach replenishment materials.

DIRTY SAND LITHOFACIES

The Dirty Sand Lithofacies is the third most common lithofacies analyzed in this study (24 samples from 75.6 ft of core, or 12.8 percent of core length, table

9). It consists of two microfacies: The Muddy Sand Microfacies, and the Muddy Shelly Sand Microfacies. While these share some grain size characteristics, they differ in texture, fabric and other aspects; thus these characteristics will be discussed separately for each.

Mean grain size for the Dirty Sand Lithofacies averages 2.55 Ø (fine sand), with a range from 1.43 Ø (medium sand) to 3.39 Ø (very fine sand) (table 8). This lithofacies is considerably finer grained than either the Graded Shelly Sand Lithofacies or the Clean Sand Lithofacies. For example, while only 2 of 135 samples (1.5 percent) from those two lithofacies have a mean grain size greater than 2.60 Ø, 12 of 24 samples (50 percent) from the Dirty Sand Lithofacies do so. Average standard deviation for the lithofacies is 1.45 Ø (poorly sorted); sorting ranges from 1.06 Ø (poorly sorted) to 2.03 Ø (very poorly sorted). Again, these values are much higher than for the other two sand lithofacies, indicating incorporation of much more fine-grained material in these sediments. In fact, the best sorted sample from the Dirty Sand Lithofacies (1.06 Ø) is not as well sorted as the average sample from the other two sand lithofacies (0.85 Ø and 0.87 Ø).

Sand/shell gravel content averages 85.0 percent, with a range from 78.0 to 91.5 percent. This average is much lower than either of the other sand lithofacies. Twenty two of 24 samples (92 percent) from this lithofacies contain less than 90 percent, while only 1 of 135 samples (0.7 percent) from the other two sand lithofacies contain less than 90 percent of this size fraction. Shell gravel averages 2.7 percent for this lithofacies, with a range of 0.0 to 10.8 percent. This average is comparable to that for the Clean Sand Lithofacies (2.5 percent). The Dirty Sand Lithofacies averages 82.3 percent sand.

Silt and clay are significant constituents of sediments from this lithofacies. Silt content averages 7.0 percent, with a range from 2.8 to 12.8 percent. This average is an order of magnitude higher than for the other two sand lithofacies. Clay content averages 7.8 percent, with a range of 2.4 to 14.5 percent. This average is 4 to 5 times higher than for the other two sand lithofacies. Due to the much lower sand content, this lithofacies is not as viable a resource objective as are the Clean Sand and Graded Shelly Sand Lithofacies.

MUDDY SAND MICROFACIES

The Muddy Sand Microfacies is the more common of the Dirty Sand Microfacies, representing 17 samples (table 8) from 57.9 ft of core (9.8 percent of total core length, table 9).

This microfacies is composed of a mud-rich sand that may preserve occasional laminations (core SR-8), but often is highly mottled due to poorly preserved burrowing (cores SR-8, SR-19), with a bioturbation index up to 5. The burrows may be sand filled (cores SR-27 and SR-58) or mud filled (core SR-32). The units generally contain only occasional shells or shell fragments, but may have a few shells concentrated at the base (core SR-55), or may contain clay rip-up clasts (core SR-46). Bases of the units are often gradational. Units may grade up into clean sand (core SR-39), or may themselves cap muddier units.

Average mean grain size is 2.68 Ø (fine sand), the finest size of any sand microfacies. The range of mean grain sizes for samples from this microfacies is from 2.12 Ø (fine sand) to 3.39 Ø (very fine sand). Both end members of this range are much finer grained than comparable values for any other sand microfacies. Average standard deviation for this microfacies is 1.36 Ø (poorly sorted); the range is from 1.06 to 1.68 Ø (poorly sorted). Except for the Muddy

Shelly Sand Microfacies, this sediment type has on average the poorest sorting of any sand microfacies.

Sand/shell gravel is the dominant grain size class, representing 84.8 percent of the microfacies on average. The range of values is from 78.0 to 91.5 percent. The average value and the minimum represent a lower sand/shell gravel content than any other sand microfacies. Shell gravel content is low, 1.7 percent on average, with a range from 0.0 to a maximum of 4.5 percent. This maximum value is lower than the maximum value for any other sand microfacies. The sand size fraction on average would represent 83.1 percent of the unit; among the sand microfacies, only the Muddy Shelly Sand Microfacies contains less sand.

This microfacies contains a relatively high component of silt and clay. Among sand microfacies, it contains on average the second highest amount of silt (6.9 percent), with a range for samples of 2.8 to 12.8 percent. For example, 13 of 17 samples (77 percent) contain as much as 4.5 percent silt; only 1 of 135 samples (0.7 percent) from the Clean Sand or Graded Shelly Sand Lithofacies contains that much. Clay content averages 8.1 percent, with a range from 2.4 to 14.5 percent. This is the highest clay content of any sand microfacies. Fifteen of 17 samples contain greater than 5 percent clay (88 percent), compared to 1 of 135 (0.7 percent) from the Clean Sand and Graded Shelly Sand Lithofacies. This microfacies, while containing a reasonably high sand content, should not be the primary source of beach replenishment materials.

MUDDY SHELLY SAND MICROFACIES

The Muddy Shelly Sand Microfacies is uncommon, consisting of 7 samples (table 8) representing 17.7 ft of core (3.0 percent of total core collected, table 9.

There are few sedimentary structures visible in this microfacies; the unit is a homogeneous muddy sand with few burrows, but contains common molluscan shells and shell fragments in a sand supported fabric (core SR-54). No burrows are visible. Some units contain large clay paleosol rip-up clasts (core SR-56).

Average mean grain size for the microfacies is 2.23 Ø (fine sand), with a range from 1.43 Ø (medium sand) to 2.75 Ø (fine sand). It is therefore much coarser on average than the Muddy Sand Microfacies due to its higher shell content, and in fact is as coarse on average as the Sand with Mud Burrows Microfacies (2.26 Ø). Due to its higher shell gravel, silt and clay content, however, it would not be as good a sand resource. Average standard deviation for the microfacies is 1.68 Ø (poorly sorted), with a range in values from 1.28 Ø (poorly sorted) to 2.03 Ø (very poorly sorted). Based on the average value, this is the most poorly sorted of the sand microfacies.

Sand/shell gravel content is the dominant size class, comprising on average 85.4 percent of the unit. This is the second lowest average among the sand microfacies. The range of values is from 79.6 to 90.5 percent; this is the widest range among the sand microfacies, indicating relative diversity in sediment type due to differences in shell content. Shell gravel content averages 3.1 percent, with a range from 0.9 to 10.8 percent. Of the five shell-rich microfacies (Graded Shelly Sand, Echinoid Sand, Shelly Sand, Muddy Shelly Sand, and Oyster Biostrome), this microfacies has the lowest average and maximum shell content. It is, in fact, lower in shell content than the average for all sand microfacies (4.0 percent). The average sand fraction for this sediment type would be 82.3 percent, the lowest sand concentration for any sand microfacies.

Silt and clay are both common constituents of this microfacies. Silt makes up on average 7.4 percent of the unit, with a range from 4.5 percent to 12.4

percent. Thus, this is the most silt-rich of any sand microfacies. Every sample contains as much or more silt than the single most-rich sample from the Clean Sand and Graded Shelly Sand Lithofacies (4.5 percent). Clay content on average is 7.2%, with a range of 3.8 to 12.7 percent. Only the Muddy Shell Microfacies contains more clay on average. Four of 7 samples (57 percent) contain greater than 5 percent clay; only 1 of 135 samples (0.7 percent) of the Clean Sand and Graded Shelly Sand Lithofacies contains that much. This microfacies, while it contains a reasonably high sand content, would not be the primary target for exploitation of beach replenishment materials.

BIOGENIC SEDIMENTS LITHOFACIES

Biogenic sediments are produced by the production of sedimentary particles by the physiological activities of organisms, either plant or animal (Grabau, 1924). Two biogenic microfacies exist in the cores analyzed for this project: The Oyster Biostrome Microfacies, and the Peat Microfacies. Neither was common, as together they represent only 2.4 ft of core (0.3 percent of total core length, table 9). One sample from the Oyster Biostrome Microfacies was analyzed for grain size; none from the Peat Microfacies was so analyzed.

OYSTER BIOSTROME MICROFACIES

Grain size from the Oyster Biostrome Microfacies was analyzed from a sample collected at a within-sediment depth of 6.5 ft in core SR-32; total core thickness observed for this microfacies was 1.2 ft or 0.2 percent of total recovered core (table 9).

This microfacies consists of shells and shell fragments of the edible oyster, *Crassostrea virginica*, in a fine grained matrix. The shell material is disarticulated, abraded, often broken and has a chalky appearance (e.g., it is undergoing dissolution, Davies and others, 1989b). The material is not in-situ, but has been reoriented or has undergone local transport. Shell orientations range from horizontal to high angle. The material represents a dense packed (shell supported) fabric (Kidwell and Holland, 1991). The base is sharp, over a discolored fine grained nearshore bay mud.

The mean grain size for this sample was 2.38 Ø (fine sand), and the standard deviation was 2.23 Ø (very poorly sorted) (table 8). This indicated a finer mean grain size than for any lithofacies except the Muddy Sediment Lithofacies; however, the standard deviation was higher than the average standard deviation for any other lithofacies. Therefore, this microfacies is a mixture of parautochthonous very coarse oyster shell material in an allochthonous muddy sand matrix.

Sand/shell gravel content (71.5 percent) was lower than all but the Muddy Sediments microfacies. The shell gravel component was 12.1 percent, the highest for any microfacies, indicating the importance of the coarse *Crassostrea* material. The sand component, therefore, would be only 59.4 percent, lower than all microfacies except for the Sand-Silt-Clay Microfacies..

Fine grained material was very common, as is typical for oyster biostromes, as *Crassostrea* is a very efficient filter feeder that deposits filtered fines as pseudofeces. Silt content was 8.9 percent; clay content was 19.6 percent. These values are the highest for any microfacies except those of the Muddy Sediment Lithofacies. This microfacies would not be an appropriate source for beach replenishment materials.

PEAT MICROFACIES

No grain size samples were taken in this uncommon microfacies (table 8), as it is composed of organic materials inappropriate for beach replenishment; it makes up a total of 1.1 ft of core length (0.1 percent of total core length, table 9).

This microfacies is composed of brown terrestrial plant debris, from comminuted organic material (core SR-15) to phytoclasts a few in in size (core SR-25), in a muddy or sandy mud matrix (core SR-38). Peat layers are thin to medium bedded (less than 4 to 6 in), and may be interbedded with either very thin beds of clay or sand (core SR-25). These units may directly or closely overlie the Pre-Holocene unconformity surface. Rhizoliths (preserved root traces) may extend down into the underlying unit. This microfacies would make an inappropriate source for beach replenishment materials.

MUDDY SEDIMENT LITHOFACIES

The Muddy Sediment Lithofacies is an uncommon lithofacies; it comprises 19 samples (table 8) representing 68.5 ft of core, or 11.6 percent of total recovered core (table 9). It is composed of three separate microfacies: The Silty/Clayey Sand Microfacies; Sand-Silt-Clay Microfacies; and Mud-Sand Interbed Microfacies. Lithologic characteristics for each of these will be described separately.

The Muddy Sediment Lithofacies has an average mean grain size of 3.56 Ø (very fine sand), with a range from 2.74 Ø (fine sand) to 5.45 Ø (medium silt). It is therefore by far the finest grained lithofacies encountered, with an average mean grain size of 1.18 to 1.80 Ø finer than those from the other lithofacies. In fact, there are only 9 samples out of 160 (6 percent) from all other lithofacies together with a mean grain size smaller than the single coarsest grained sample (2.74 Ø) in this lithofacies. No other lithofacies has a single sample with a grain size as fine grained as the average for this facies. The average standard deviation for the facies is 1.62 Ø (poorly sorted); values range from 1.24 Ø (poorly sorted) to 2.32 Ø (very poorly sorted). Except for the single sample analyzed from the Biogenic Sediment Lithofacies, no other facies is so poorly sorted on average. The most poorly sorted sample from this facies is the most poorly sorted of all samples analyzed.

This facies has, by far, the lowest sand/shell gravel component of any lithofacies analyzed, 57.8 percent. The range of values is 10.6 to 82.0 percent. There are only 6 samples (4 percent) from all other lithofacies together that have as low a value as the maximum value (82 percent) for this facies. Fourteen of 24 samples (58 percent) from this lithofacies have a lower sand/shell gravel content than the lowest value for the rest of the samples (71.5 percent). Shell gravel content is also by far the lowest of any facies, with an average of 0.7 percent and a range of 0 to 4.6 percent. Sand content, therefore, would be on average 57.1 percent, again the lowest of all the lithofacies.

Not surprisingly, fine grained sediment was very abundant in the lithofacies. Silt content averaged 21 percent, with a range of 6.6 to 43.5 percent, the highest of any lithofacies (2.4 to 52.5 times the amount in other facies). Clay content was also the highest of any lithofacies, with an average of 21.2 percent and a range of 3.5 to 45.8 percent. No other lithofacies contained a single sample with as high a clay concentration as the average for this lithofacies. Given the available sandy sediments, the Muddy Sediment Lithofacies is not a promising target for beach replenishment resources.

SILTY/CLAYEY SAND MICROFACIES

The Silty/Clayey Sand Microfacies is the most common of the Muddy Sediment microfacies, being represented by 11 samples (table 8) taken from 37.0 ft of core (6.3 percent of total core length, table 9).

This microfacies often contains primary sedimentary structures including shelly sand beds (cores SR-19 and SR-32), mud and sand laminae (core SR-32), sand pockets (core SR-19), shell pockets (core SR-40), and muddy sand pockets (core SR-40). The pockets may represent reworked or bioturbated beds and laminae. Mud drapes may be seen (core SR-48). Other units are either structureless (core SR-1) or show slight coarsening upwards (core SR-40), at times from a stiff clay base (core SR-40). The base may be gradational to the underlying unit (core SR-52). Occasional shell and wood fragments (cores SR-19 and SR-32) are seen. Bioturbation is present, including sand-filled burrows (core SR-19), large shelly sand-filled burrows (core SR-32), and mud-filled burrows (core SR-32).

Mean grain size is small in comparison to most sampled microfacies from the EEZ, with an average of 3.36 Ø (very fine sand), and a range from 2.74 Ø (fine sand) to 3.81 Ø (very fine sand). This average is the finest grain size for any microfacies except the Sand-Silt-Clay Microfacies. The standard deviation for the microfacies averages 1.56 Ø (poorly sorted), with a range from 1.27 Ø (poorly sorted) to 2.06 Ø (very poorly sorted). The lack of better sorting is due to the presence of abundant fine grained material in the unit.

Sand/shell gravel content is very low, with an average of 67.9 percent and a range from 57.2 to 77.1 percent. This is lower than any microfacies other than those also from the Muddy Sediment Lithofacies. Shell gravel content is also low, with an average of 1.1 percent and a range from 0.0 to 4.6 percent. This average is as low as any microfacies not in the Muddy Sediment Lithofacies. The average sand content would be 66.8 percent, again much lower than any microfacies from another lithofacies.

Silt and clay content are high. Silt averages 18.1 percent of the microfacies, with a range from 10.5 to 25.9 percent. This is a higher average than any microfacies except the Sand-Silt-Clay Microfacies. Only two samples from other lithofacies contained as much silt as the sample from this microfacies with the least silt content. Clay content was also quite high, with an average of 14.0 percent and a range from 3.5 to 26.4 percent. As for the silt, only two samples from other lithofacies contained as much clay as the sample from this microfacies with the least clay content. The Silty/Clayey Sand Microfacies would not be a primary target for beach replenishment resources.

SAND-SILT-CLAY MICROFACIES

The Sand-Silt-Clay Microfacies is uncommon, with 5 samples representing 15.5 ft of core (2.6 percent of total core) being analyzed for grain size (tables 8 and 9).

This unit often displays laminations of sand (core SR-45) or sand and mud (core SR-46). It may, however, be structureless except for a slight coarsening up trend (core SR-1). It may be, especially in the lower parts, a slightly stiff mud (cores SR-55 and SR-1). Bioturbation levels are variable, up to a bioturbation index of 3 (core SR-46); there may be occasional mud- or sand-filled burrows (core SR-45) or shelly sand-filled burrows (core SR-46). Bases may be gradational to fairly sharp. There are occasional shell fragments in some units (core SR-46), with or without wood fragments (core SR-1); all units are matrix supported.

This is by far the finest-grained microfacies analyzed, with an average mean grain size of 4.28 Ø (coarse silt, and a range of values from 3.36 Ø (very fine sand) to 5.45 Ø (medium silt). The average is considerably finer than the next finest grained microfacies (a difference of 0.92 Ø). Only three other microfacies have as many as a single sample as fine grained as the coarsest sample from this microfacies; of these, two are also in the Muddy Sediment Lithofacies. The variation in mean grain size from coarsest to finest sample (2.09 Ø) is greater than any microfacies except Graded Shelly Sand Lithofacies. The average standard deviation of grain size is 1.67 Ø (poorly sorted), with a range from 1.38 to 1.85 Ø (poorly sorted). This average represents the third worst average sorting of any microfacies, after the Mud-Sand Interbeds and Muddy Shelly Sand Microfacies. Nonetheless, the range in values for sorting from best to poorest sorted sample (0.47 Ø) is the lowest for any microfacies examined. This is partly due to the lack of coarse shell gravel in the microfacies.

As befits its name, this microfacies does not have a dominance of sand/shell gravel; it is the only microfacies that does not. It contains on average 33.5 percent coarse fraction, with a range from 10.6 to 51.5 percent. Four of five samples (80 percent) from this microfacies contain less than 50 percent sand/shell gravel; from all other microfacies together there is only 1 sample (of 174, or 0.6 percent) with less than 50 percent. No shell gravel was found in any sample in this microfacies. Therefore, sand content would average 33.5 percent.

Silt and clay are each as dominant in this facies as is sand/shell gravel. Silt content averages 29.8 percent, with a range from 22.9 to 43.5 percent. This is by far the most silt content of any microfacies; only 1 sample from all other microfacies combined contains more silt than the least silty sample from this microfacies. Clay content averages 36.7 percent, with a range from 25.6 to 45.8 percent. This is also by far the most clay-rich microfacies, containing on average 14.8 percent more clay than the next most clay-rich unit (the Mud-Sand Interbeds Microfacies). Only two samples from all other microfacies together contain as much clay as the least clay-rich sample from this microfacies. The Sand-Silt-Clay Microfacies would be a poor target for beach replenishment sands.

MUD-SAND INTERBEDS MICROFACIES

The Mud-Sand Interbeds Microfacies is uncommon; it is represented by 3 samples (table 8) taken from 16.0 ft of core (2.7 percent of total core length, table 9).

This microfacies contains very thin beds of sand and mud interbedded with each other (cores SR-41 and SR-47). These discrete units are thicker than the laminations sometimes seen in the Sand-Silt-Clay Microfacies. There are occasional small shell fragments throughout. Sand-filled burrows may be seen on occasion (core SR-47). All units are at the base of cores, so the nature of the base cannot be determined. This microfacies may coarsen upwards (core SR-47).

Average mean grain size for this microfacies is 3.10 Ø (very fine sand), with a range from 2.78 Ø (fine sand) to 3.69 Ø (very fine sand). This is the coarsest of any of the Muddy Sediment microfacies. Nonetheless, it is still 0.42 Ø smaller than the finest grained microfacies from any of the other lithofacies. Standard deviation of grain size averages 1.76 Ø (poorly sorted), with a range from 1.24 Ø (poorly sorted) to 2.32 Ø (very poorly sorted). Only one microfacies, the Oyster Biostrome, has a higher average standard deviation; therefore, the

Sand-Mud Interbeds Microfacies shows much less size sorting than virtually any other analyzed sediment type. The most poorly sorted sample from this microfacies is the single most poorly sorted sample analyzed.

The percent sand/shell gravel size fraction is low for this microfacies, representing only 61.1 percent on average, with a range from 33.3 to 82.0 percent. Only the Sand-Silt-Clay Microfacies contains a lower percentage. The extremely wide range in sand/shell gravel content is the highest for any microfacies (a difference of 44.7 percent from most sand-rich to most sand-poor); this is not surprising, given the differences in relative thickness of the sand and mud layers of the samples. Shell gravel content is very low, with an average of 0.4 percent and a range of 0.0 to 1.1 percent. This is the lowest average and range of any microfacies except the Sand-Silt-Clay Microfacies. Total sand content for the microfacies would therefore average 60.7 percent, the second lowest sand fraction after the Sand-Silt-Clay Microfacies.

Silt and clay are both major components of the Mud-Sand Interbeds Microfacies. Silt averages 17.0 percent, with a range from 6.6 to 26.9 percent. While this is the lowest average for any Muddy Sediment microfacies, it is still 2.3 times larger than for any microfacies from another lithofacies. The range of values is the second greatest range of any microfacies (after the Sand-Silt-Clay Microfacies), again indicating the variability between relative amounts of sand and mud layers in this sediment type. Clay content averages 21.9 percent, with a range from 11.4 to 39.8 percent. Only the Sand-Silt-Clay Microfacies has a higher average clay content or a greater range of values. The Mud-Sand Interbeds Microfacies is a poor source for beach replenishment materials.

PRE-HOLOCENE LITHOFACIES

The Pre-Holocene Lithofacies was represented by 20.9 ft of core (3.5 percent of total core length, table 9); the facies was not analyzed for grain size data, as it is too consolidated to be utilized as a possible source of beach replenishment materials.

In coastal Alabama, there is an extensive unconformity at the base of the Holocene transgressive tract sediments that is recognizable from several criteria, not all of which are present at any one locality. Cores typically show evidence of subaerial exposure or erosive truncation, including borings and rip-up clasts, paleosol formation, or marsh deposits. Specifically they may show a marked change in lithology, often with dense gray/green stiff clay or a mixture of stiff clay with sand lenses underneath the unconformity (core SR-20); in other cores, the underlying material is sand to muddy sand (core SR-33). Marking the unconformity there is often an oxidized zone of reddish/yellowish sediment (i.e., a paleosol) (cores SR-21 and SR-24) with a decrease in oxidation downward through the uppermost few in to 2 ft. This surface is often highly burrowed or bored leading to an irregular surface (core SR-31), often with the large burrows filled with coarse sand and shell (cores SR-23 and SR-29). There is often no preserved primary stratification (core SR-29). There may also be plant debris or thin peats associated with this subaerial erosional surface (cores SR-15 and SR-27) with abundant roots extending downward into the underlying pre-transgressive sediments. Thin transgressive lag shell deposits with abundant oriented *Oliva* shells are locally present in the basal Holocene transgressive deposits, as are peat balls and large rip-up clasts of the underlying lithology (cores SR-42 and SR-56).

Additionally there are offshore continental shelf hardbottoms at several water depths within the study area (fig. 23) (Parker, 1989). They are well cemented (sometimes sideritic) and host encrusters and other epifauna. These deposits certainly indicate areas with long-term low rates of net sediment accumulation; they may well be hiatal/transgressive lag accumulations at, or near, the transgressive surface. This could indicate very near surface Pre-Holocene Lithofacies expression in these shelf areas. They were not sampled for this study. Due to the variability in lithology, thickness of Holocene overburden, and consolidated nature of the Pre-Holocene Lithofacies, it is not an exploration target for beach replenishment materials.

LITHOFACIES DISCUSSION

The six lithofacies delineated for this study vary tremendously in their sedimentological characteristics. They range from almost pure quartz sands (Clean Sand Lithofacies) to sandy mud units (Muddy Sediments Lithofacies) to indurated, eroded Cenozoic sedimentary rocks (Pre-Holocene Lithofacies). Likewise, the thirteen microfacies that make up these lithofacies are equally diverse, although the microfacies that comprise a lithofacies are similar.

Based on their composition, grain size, and color, some lithofacies would make appropriate beach replenishment materials, while others are definitely inappropriate. Excellent choices include the Graded Shelly Sand and Clean Sand Lithofacies, which is composed of the Orthoquartzite, Echinoid Sand, Sand with Mud Burrows, and Shelly Sand Microfacies. These are also the most abundant lithofacies in the study area. The Dirty Sand Lithofacies, comprised of the Muddy Sand and Muddy Shelly Sand Microfacies, would be a less attractive resource target. The three remaining lithofacies, the Biogenic

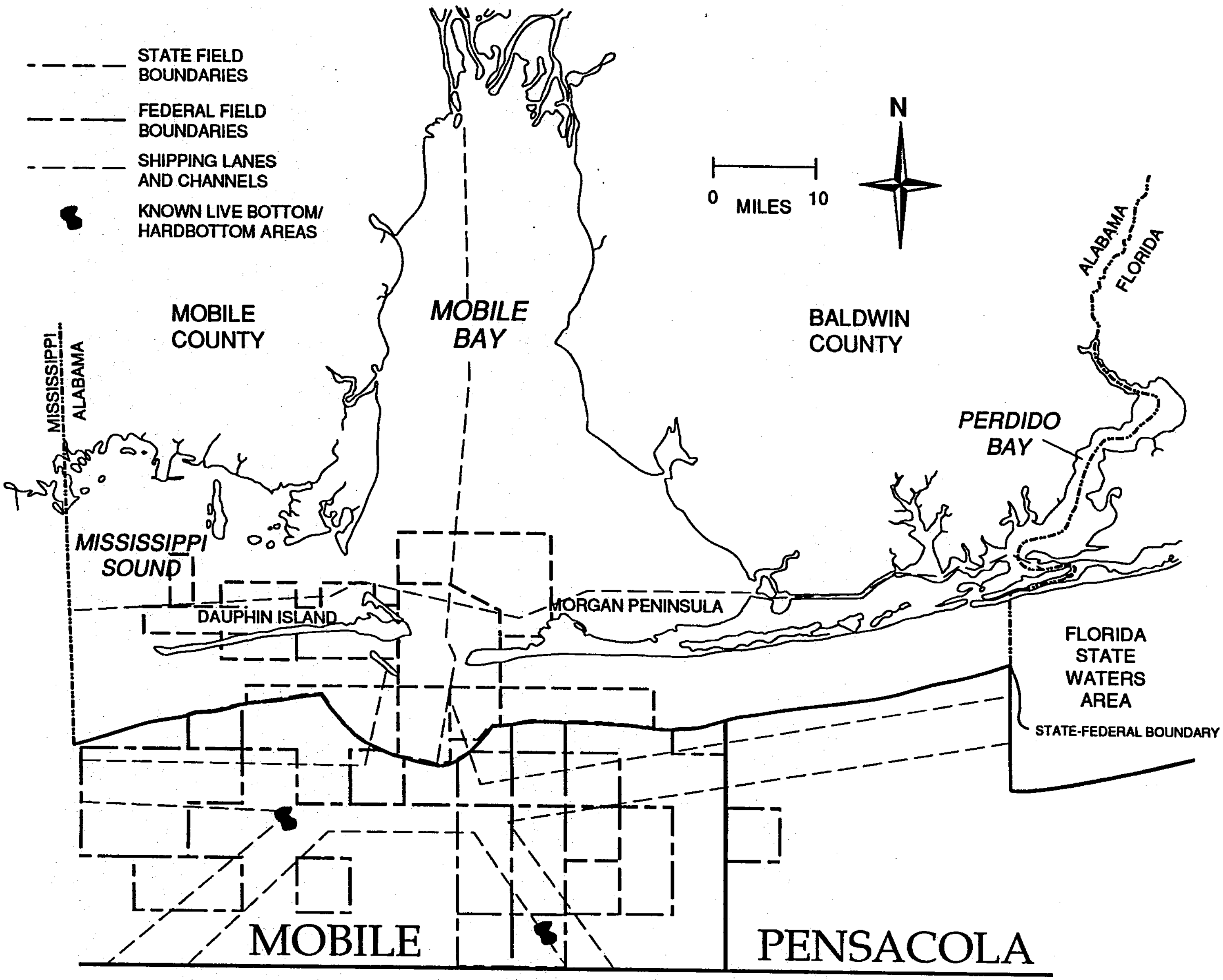


Figure 23.--Map showing oil and gas fields, shipping lanes, and known hardbottom/livebottom areas in coastal and offshore Alabama.

Sediments Lithofacies (Oyster Biostrome and Peat Microfacies); the Muddy Sediments Lithofacies (Sand-Silt-Clay, Silty/Clayey Sand, and Sand-Mud Interbeds Microfacies), and the Pre-Holocene Lithofacies, are all inappropriate as beach nourishment sources due to improper aesthetics regarding their composition, grain size, or color.

SPATIAL DISTRIBUTION OF FACIES

In order to effectively estimate the volume of potential resources that may be available in each microfacies present in the study area, it is essential to describe the spatial distribution of these facies. Figure 24 is a surface facies distribution map that shows the microfacies on the seafloor at each sample locality. Figure 25 is a map that shows the location of each cross section. Figures 26 through 34 are geologic cross sections that show subsurface distributions of each facies. Table 9 shows the thickness of each microfacies at each core location. In order to indicate the vertical sequences and show the types of overburden that might need to be removed to reach the resource zone, table 10 tabulates the frequency with which each microfacies is overlain by the others.

SURFICIAL DISTRIBUTION OF MICROFACIES

Of the 13 microfacies evaluated for this study, only 8 can be found today at the sediment surface (table 10, fig. 24). Three microfacies that are not found at the sediment surface could not form there today: The Pre-Holocene Lithofacies (due to age considerations), and the Oyster Biostrome and Peat Microfacies (due to environmental restrictions). Of the 8 microfacies found at the sediment

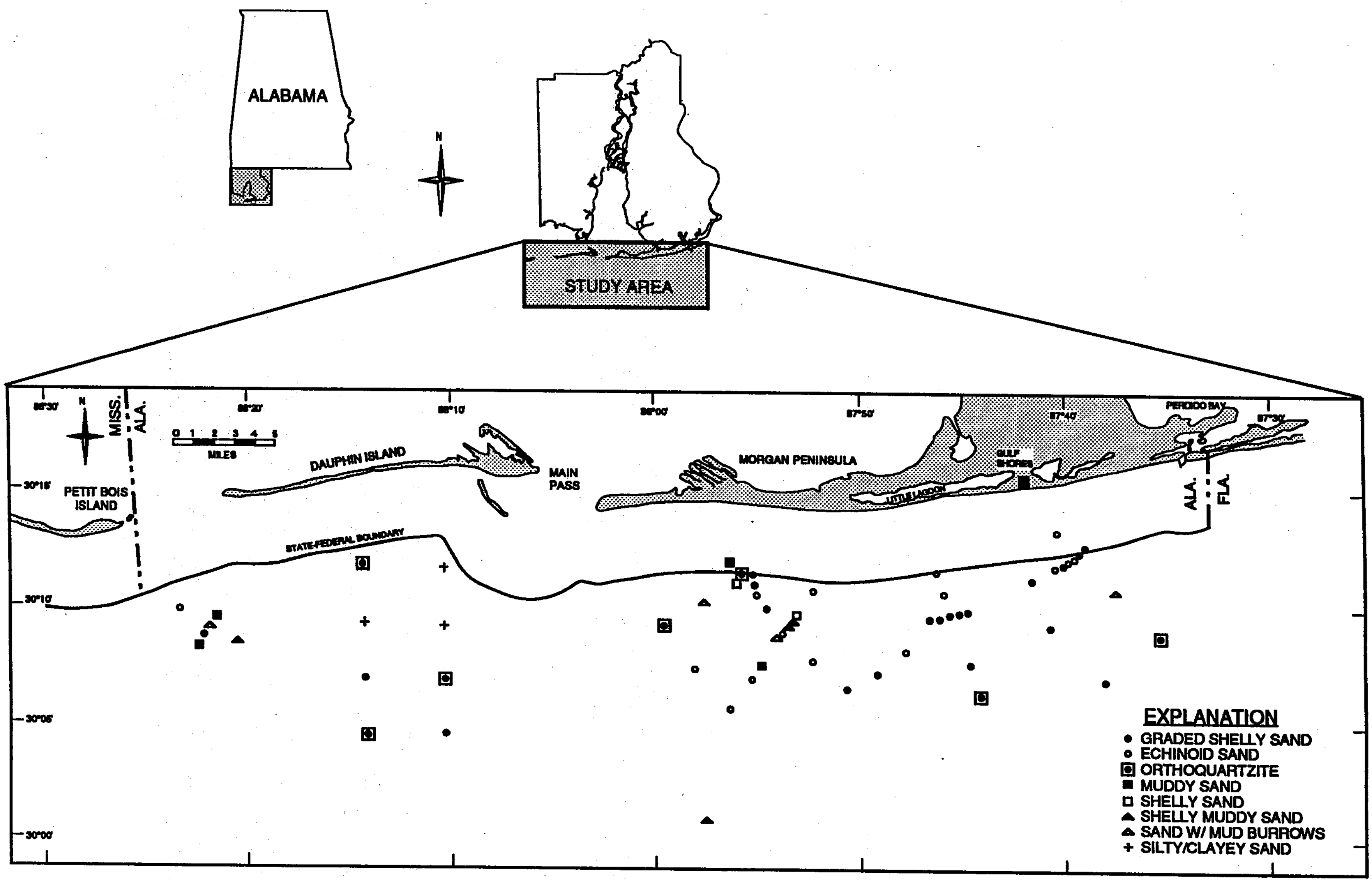


Figure 24.--Surface facies distribution in the Alabama EEZ study area.

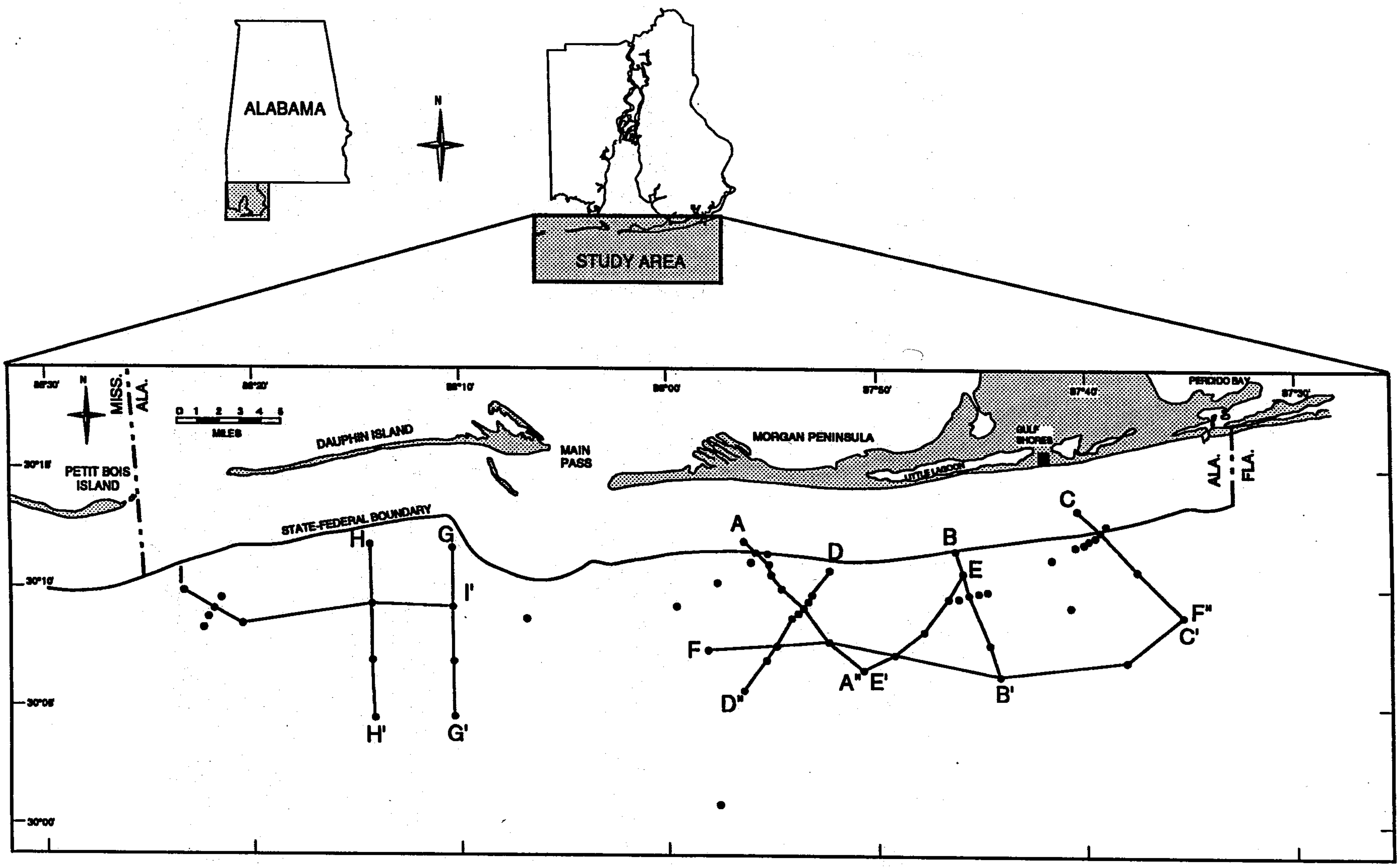


Figure 25.--Map of Alabama EEZ cross section locations.

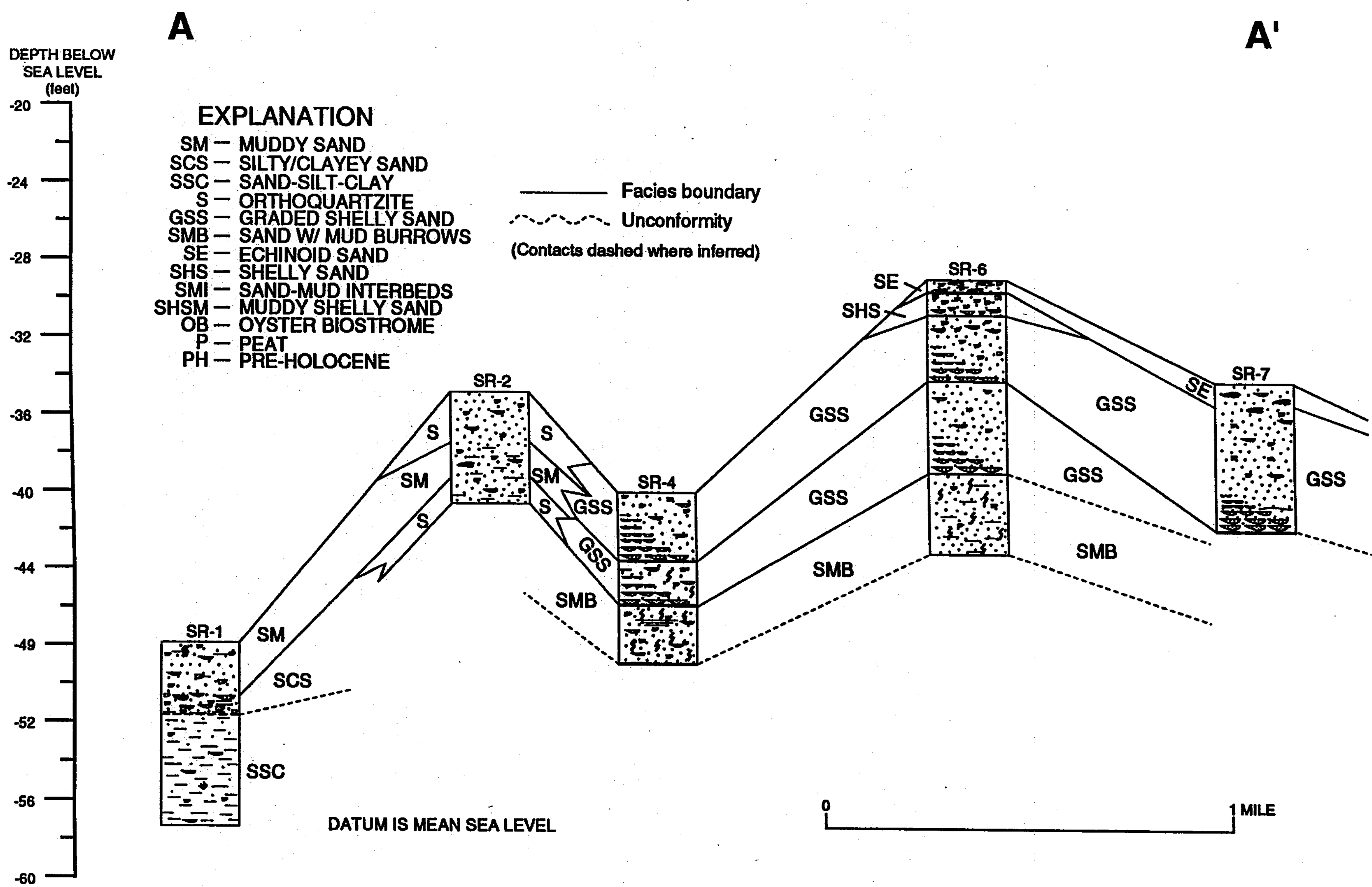


Figure 26.--Cross section A-A" (See figure 25 for cross section location).

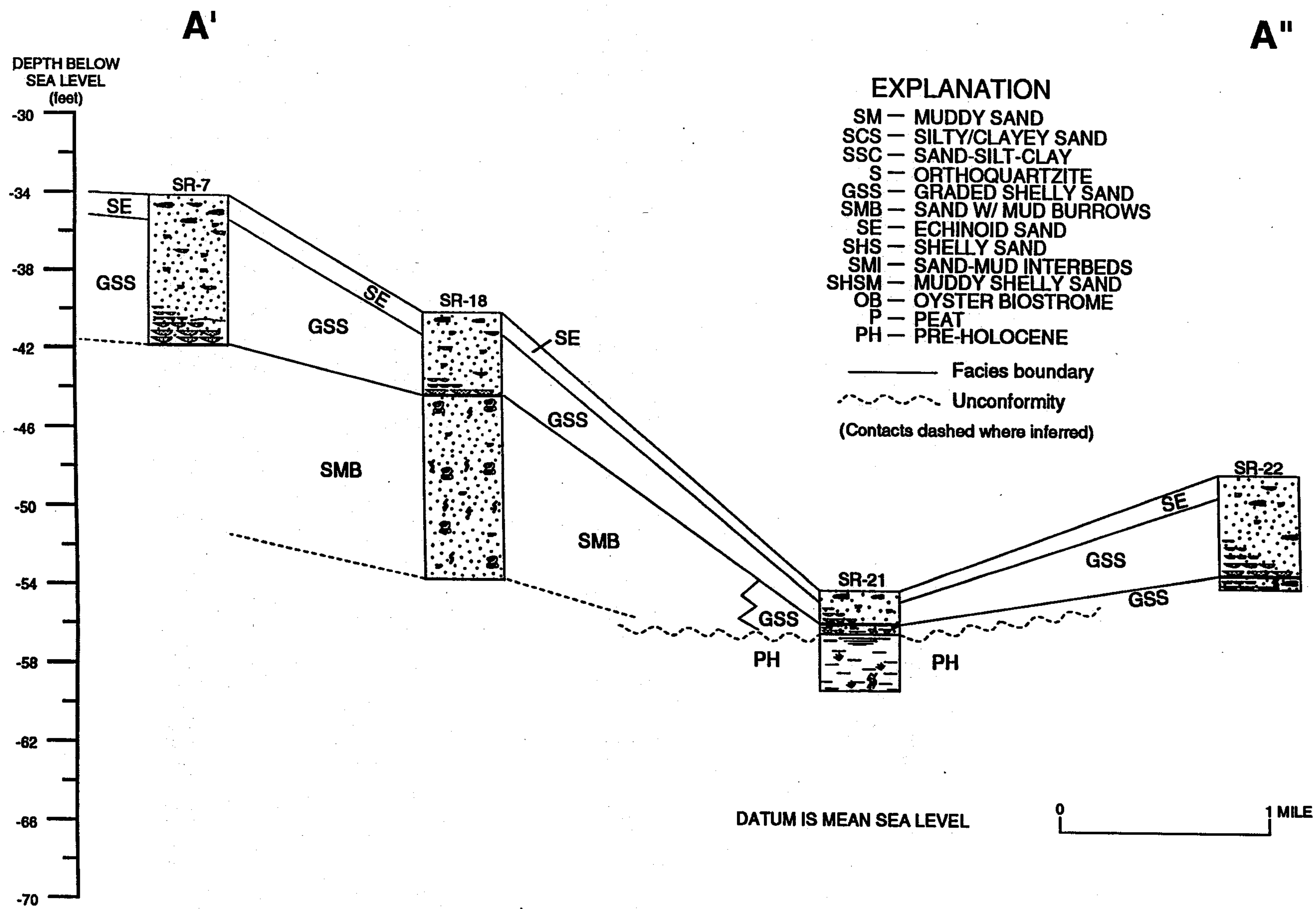


Figure 26.--Cross section A-A"--Continued.

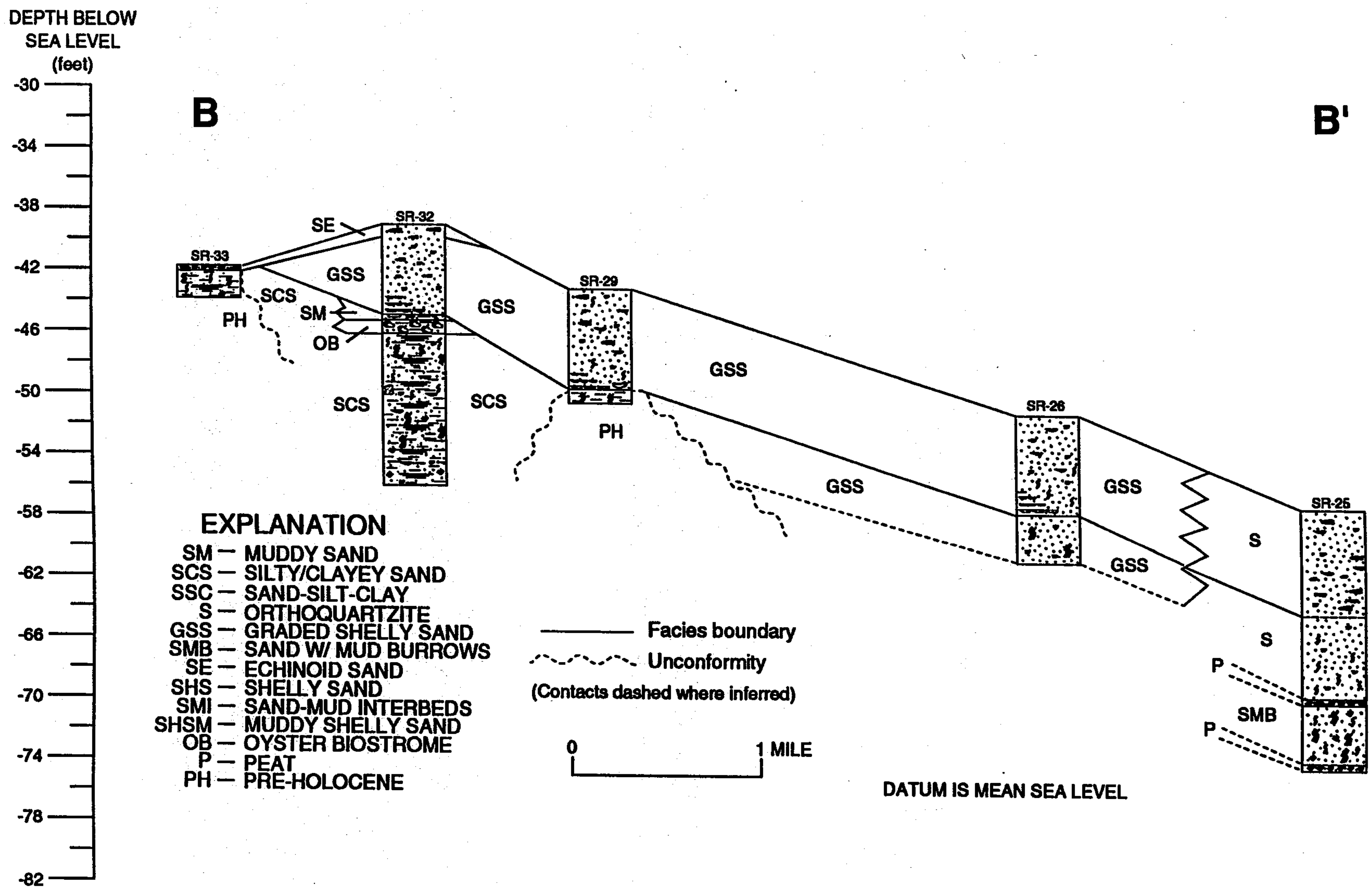


Figure 27.--Cross section B-B' (see figure 25 for cross section location).

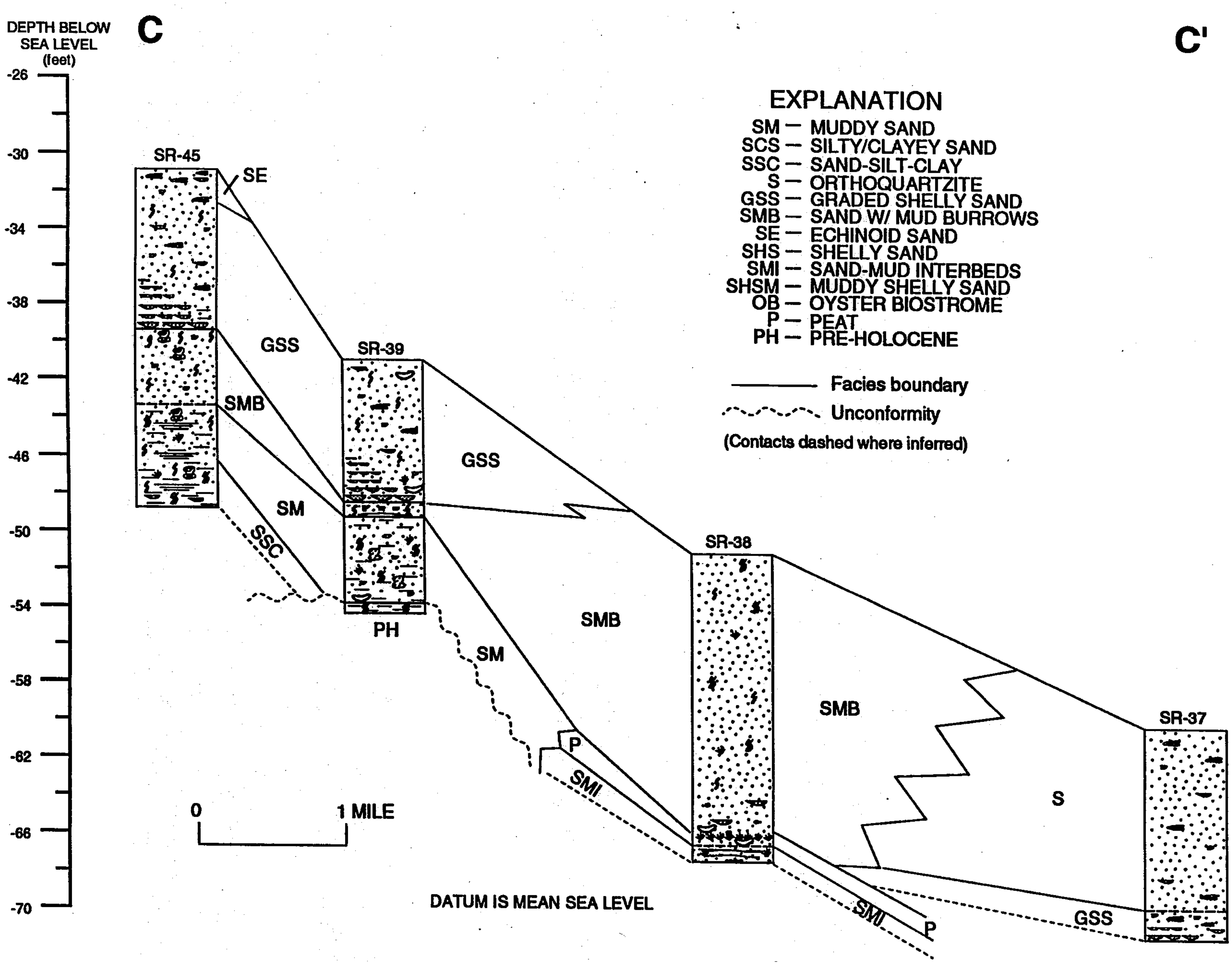


Figure 28.--Cross section C-C' (see figure 25 for cross section location).

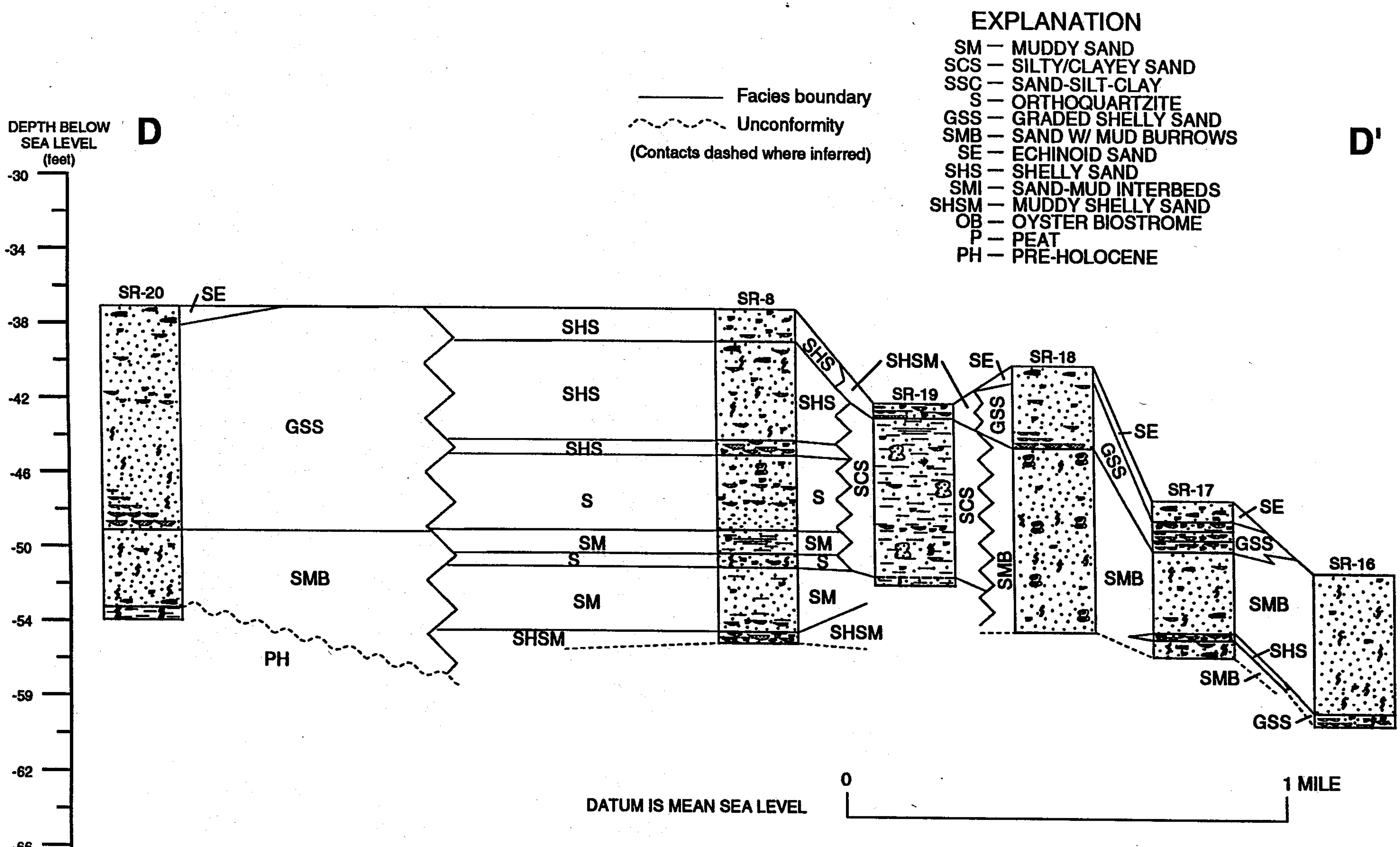


Figure 29.--Cross sectionD-D" (see figure 25 for cross section location).

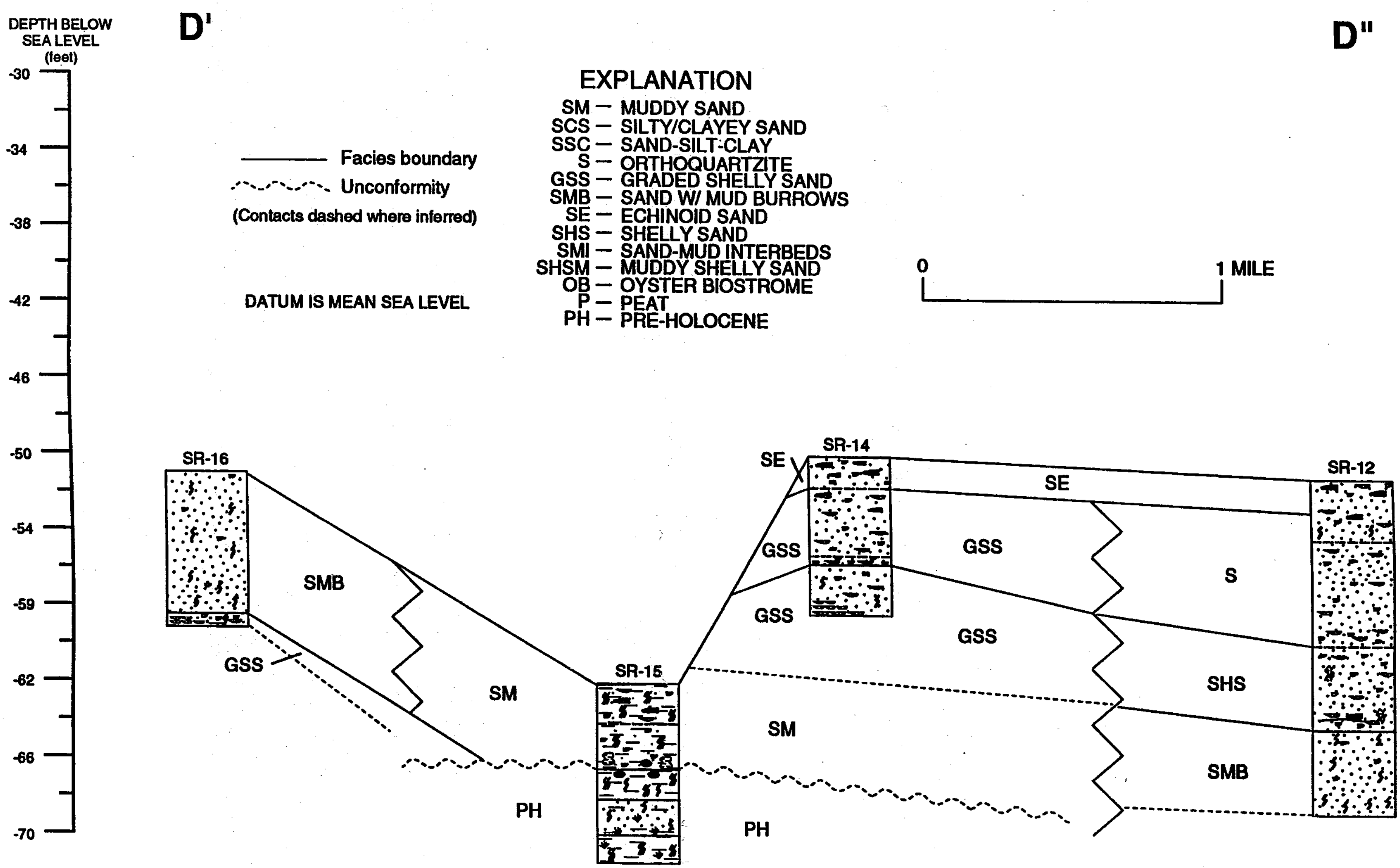


Figure 29.--Cross section D-D"--Continued.

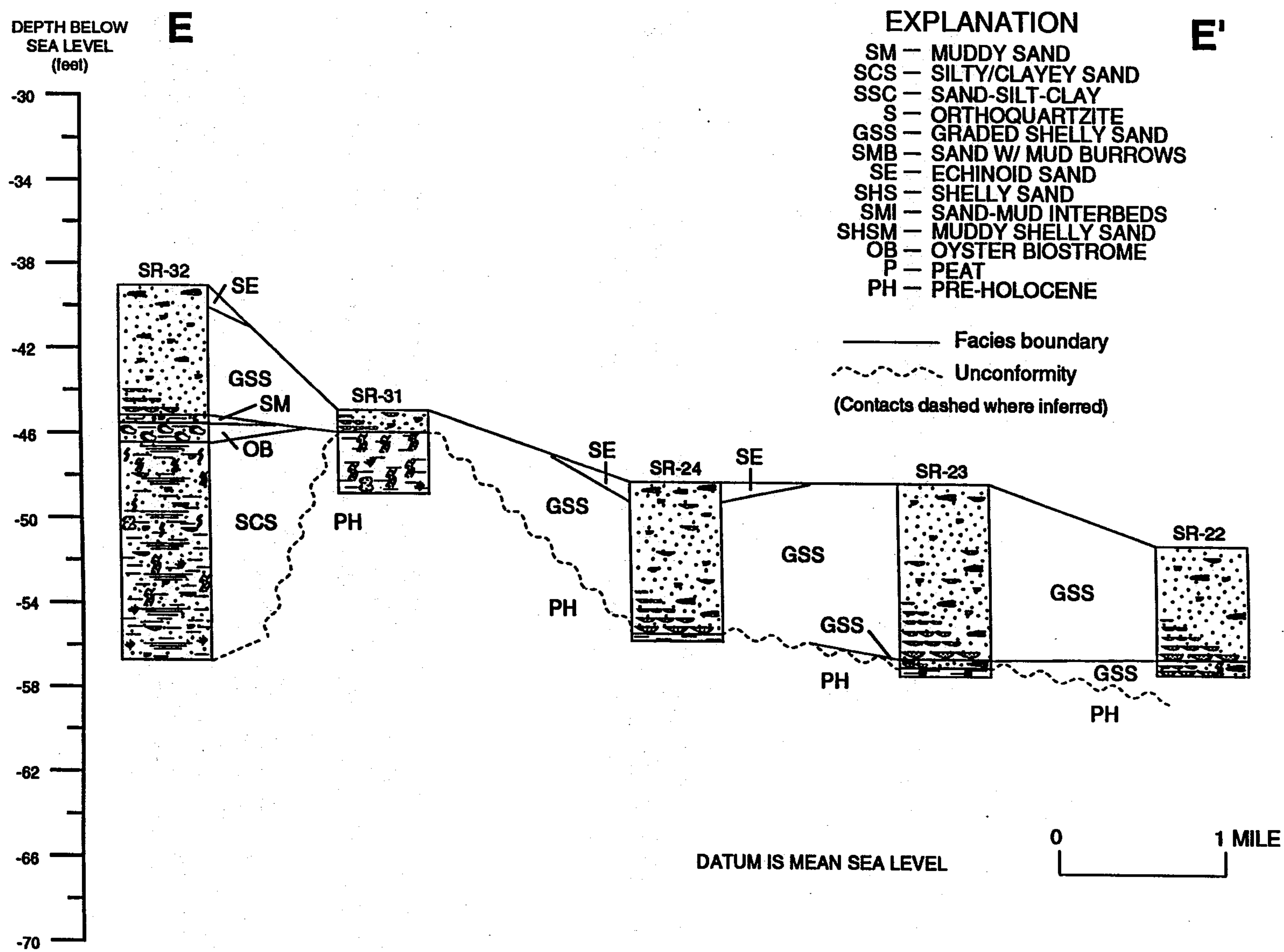


Figure 30.--Cross Section E-E' (see figure 25 for cross section location).

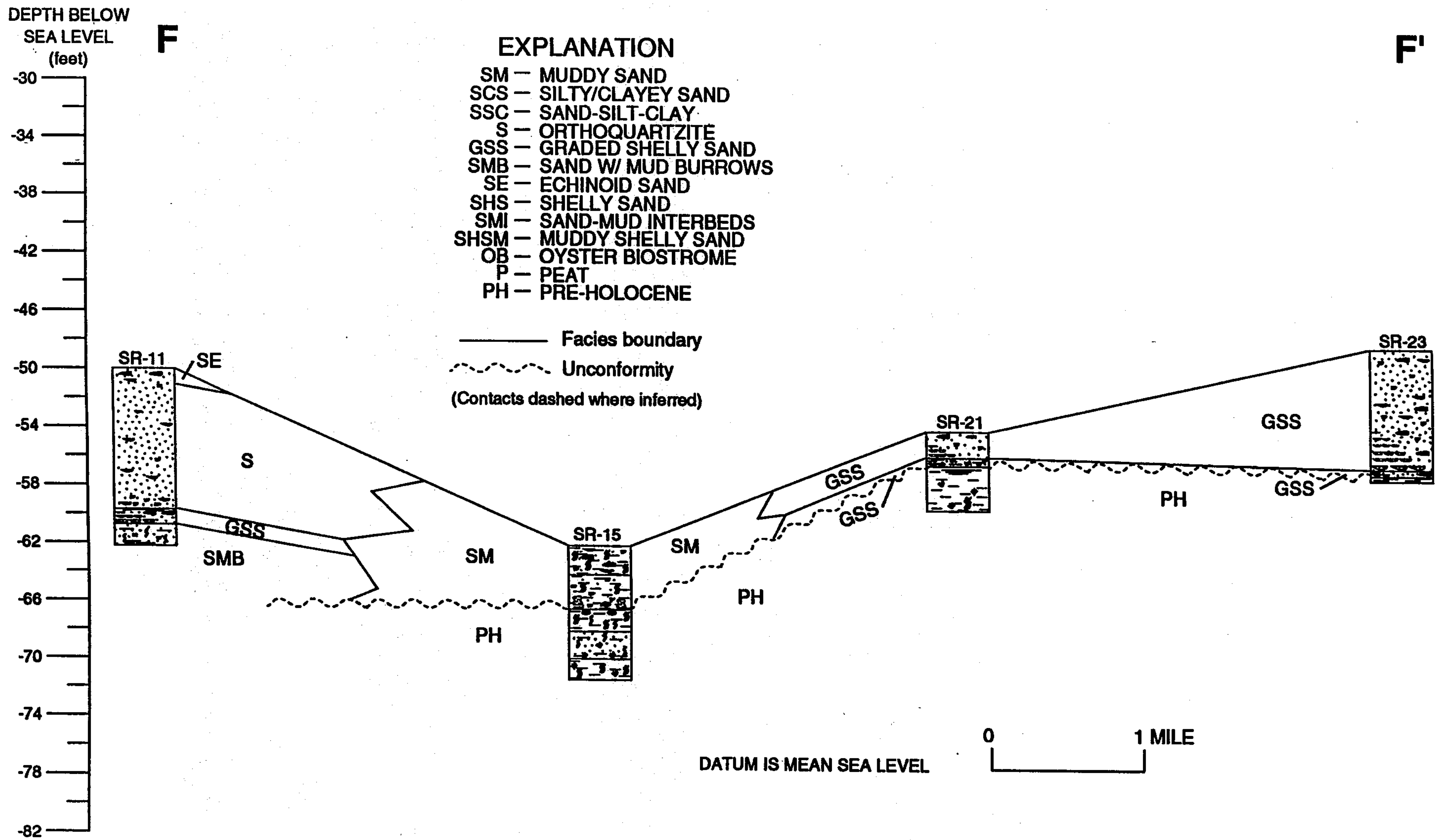


Figure 31.--Cross section F-F" (see figure 25 for cross section location).

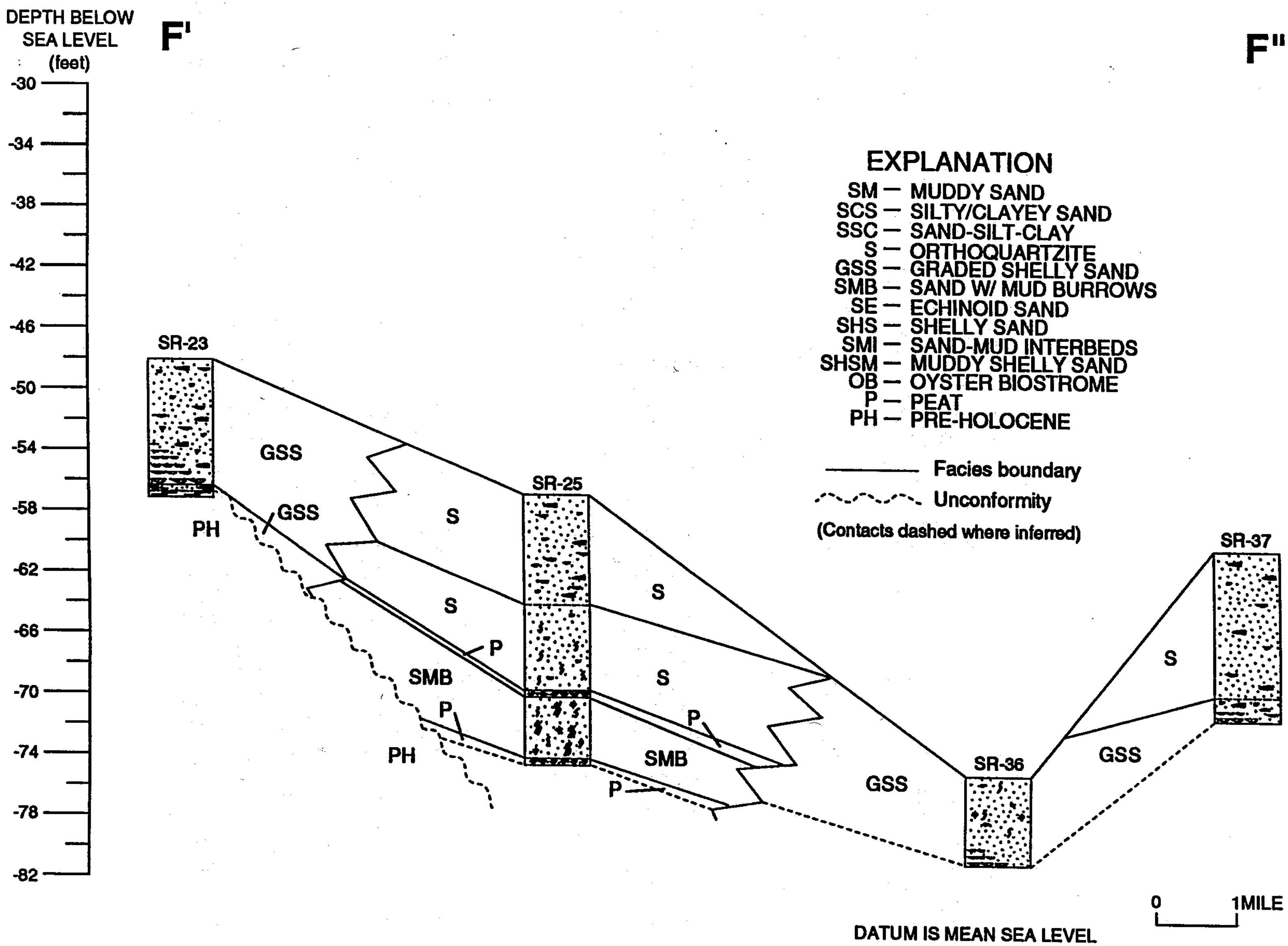


Figure 31.--Cross section F-F"--Continued.

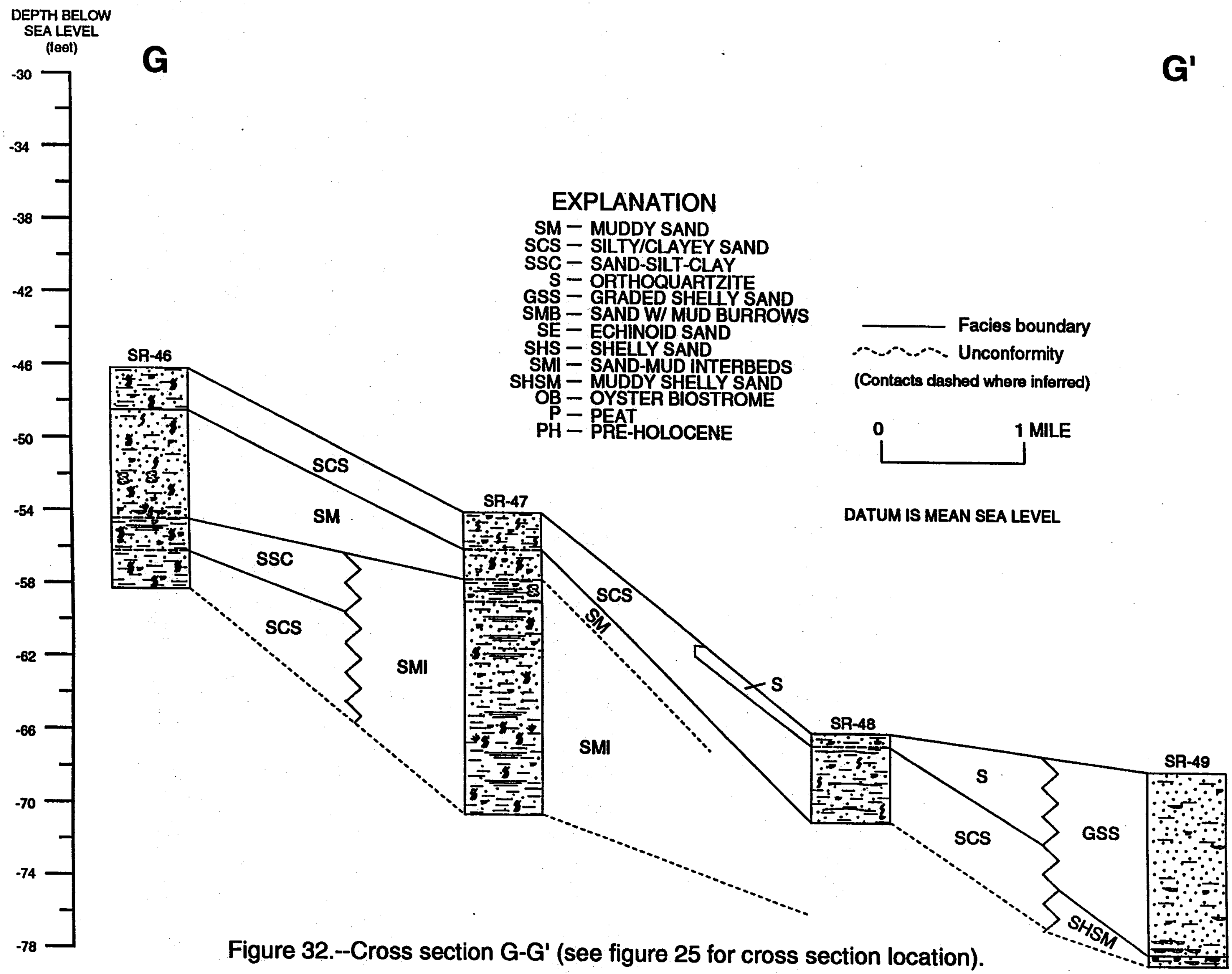


Figure 32.--Cross section G-G' (see figure 25 for cross section location).

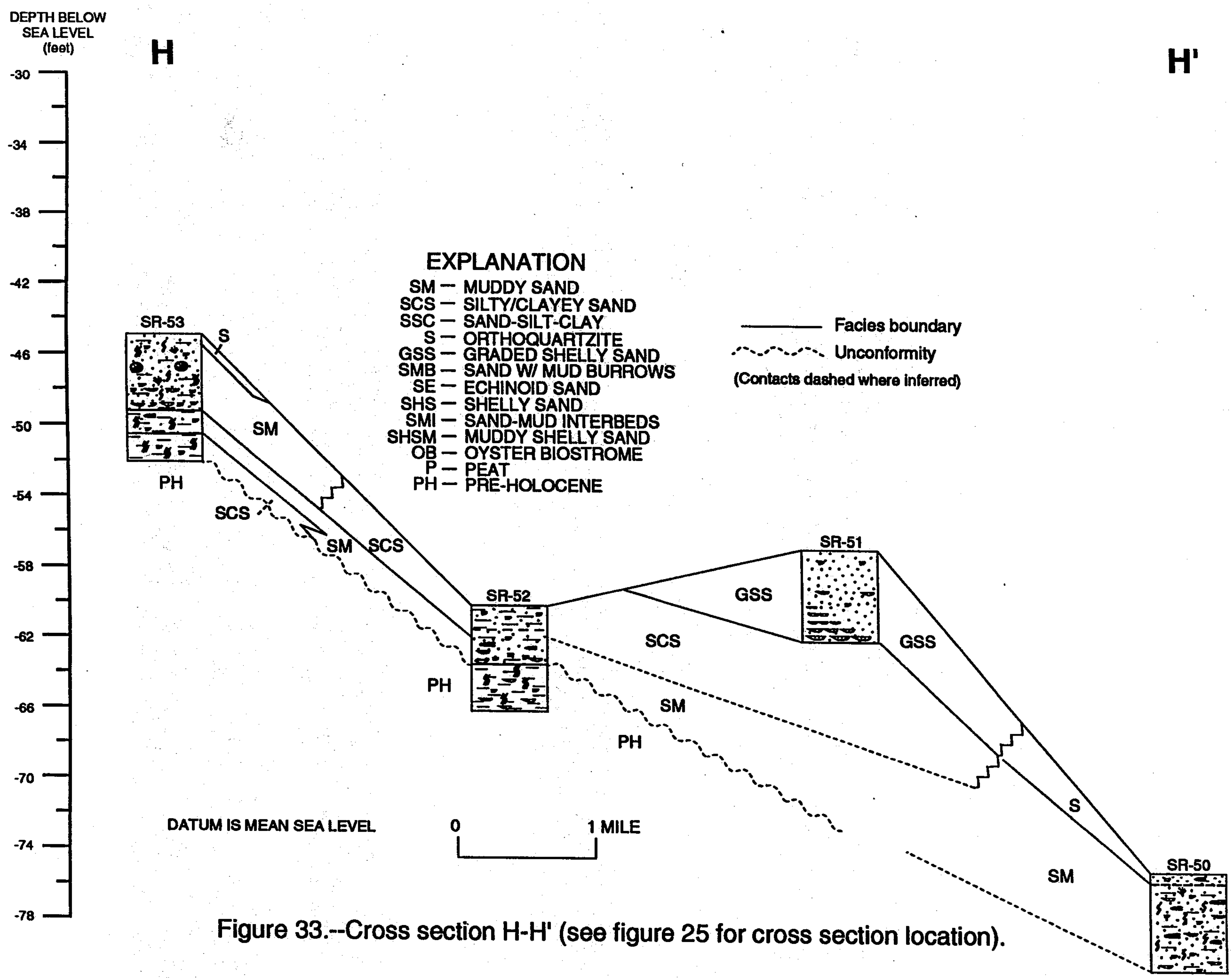


Figure 33.--Cross section H-H' (see figure 25 for cross section location).

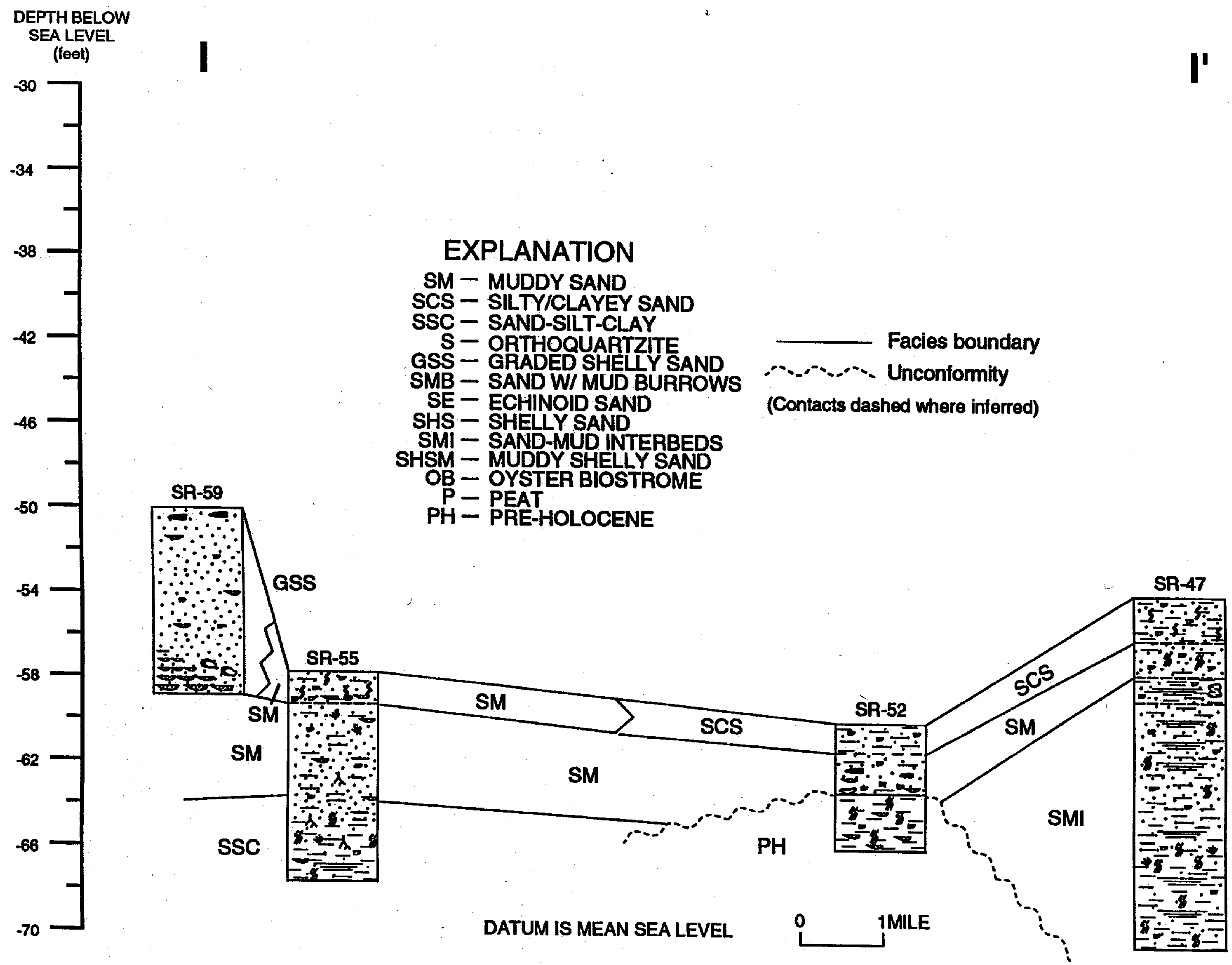


Figure 34.--Cross section I-I' (see figure 25 for cross section location).

Table 10.-- Vertical facies associations

Facies below	Facies above						
	Orthoquartzite	Sand w/mud burrows	Echinoid sand	Shelly sand	Graded shelly sand	Muddy sand	Muddy shelly sand
Orthoquartzite	1		3	2	2	2	
Sand w/mud burrows		1		2	10		
Echinoid sand	1						
Shelly sand	1	1	1	3			
Graded shelly sand	1	2	12	1	11		
Muddy sand	5	2			2	4	1
Muddy shelly sand	1				1	1	3
Oyster biostrome						2	
Peat	1	2					
Silty/clayey sands	1	1				1	1
Sand-silt-clay	1					3	
Sand-mud interbeds	1					2	
Pre-Holocene		1	2		5	4	

Table 10.--Vertical facies associations—Continued

Facies below	Facies above						
	Oyster biostrome	Peat	Silty/clayey sand	Sand-silt-clay	Sand-mud interbeds	Pre-Holocene	Sediment surface
Orthoquartzite							8
Sand w/mud burrows	1	1					2
Echinoid sand							16
Shelly sand							1
Graded shelly sand			1	1			21
Muddy sand			3				4
Muddy shelly sand							3
Oyster biostrome							
Peat							
Silty/clayey sands	1			1			3
Sand-silt-clay			1				
Sand-mud interbeds		1			1		
Pre-Holocene							

Measured in number of times the "facies above" was found directly above the "facies below" surface, two (Graded Shelly Sand and Echinoid Sand Microfacies) are found in a total of 37 of 59 sample locations (62.7 percent). The third most common surface microfacies, the Orthoquartzite Microfacies, is found at 8 locations. Therefore, the 2 most promising lithofacies for possible sand resources (Graded Shelly Sand and Clean Sand) can be found on the sediment surface in 48 of 59 sampled locations (81.4 percent). This pattern can also be seen on figure 35, which shows surface sediment type based on grain size only. While these certainly indicate that clean sand resources are common on the Alabama EEZ shelf, the sampling strategy deliberately intensively sampled the transverse ridges; these were presumed to be the most sand-rich areas. Therefore, in fact, the surface aerial distribution of prime target facies may be smaller than indicated by these numbers alone.

Surface sediments range from clean Orthoquartzites to dirty Silty/Clayey Sands among the shell-poor microfacies; for shelly microfacies, some sediments represent the upper portion of Graded Shelly Sands, and one sample (SR-27 BG) is an encrusted surficial shell pavement.

One large scale pattern that is immediately apparent is the presence of more muddy facies near the Main Pass of Mobile Bay. Through this pass flows the vast majority of fresh water from the Alabama River system, including very muddy episodic flood waters. Much of the fine grained material is carried as sediment plumes westward just offshore from Main Pass due to tidal and current exchange of water between the Bay and the Gulf (Abston and others, 1987; Wiseman and others, 1988; Chuang and others, 1982). This distribution is immediately seen on figure 24; the three locations just to the southwest of the pass have Silty/Clayey Sand at the surface. In the area bounded by SR-46 BG to SR-59 BG and SR-58 BG to SR-47 BG, 7 of 9 samples are from the various sand-poor lithofacies. This same trend can be seen to a lesser extent just to the east of the pass. This pattern can also be seen on figure 35 (present study) and figure 5 (previous studies). Such a pattern is classified as a "nearshore mud belt" by McCave (1973); processes that cause this type of pattern were discussed by Drake (1976).

Further to the east of Main Pass, nearly all surface samples are sandy (fig. 24 and 35) (either Graded Shelly Sand, Echinoid Sand, or Orthoquartzite). This is especially true on the shelf sand ridges. This surficial sand sheet with ridges is also seen further offshore in deeper water in the area west of Main pass.

Within these general trends, however, the surface distribution of the microfacies is very patchy (Parker and others, 1992). In other shelf sand ridge studies, similar patterns are seen in the modern (Davis and Balson, 1992; Swift and others, 1973; Stubblefield and Swift, 1976; Louisiana Geological Survey, 1991). Similar patchy small scale patchy distributions are found in some ancient wide shelf sand ridge deposits (Beaumont, 1984; Hobday and Morton, 1984; Rice, 1984; Shurr, 1984; Stubblefield and others, 1984; Tillman and Martinson, 1984). In general, more sandy facies are distributed on the Alabama ridges, with finer grained material in the intervening swales. Nonetheless, even in areas with a scale of less than 1 mi spacing between core locations, there is variability in facies distribution. This patchiness may be the result of the interplay between relict sediment distribution, present topography and hydrodynamics, and local differences in shell content. Present knowledge of topography and circulation is not sufficiently advanced to definitely predict facies patterns on a small scale.

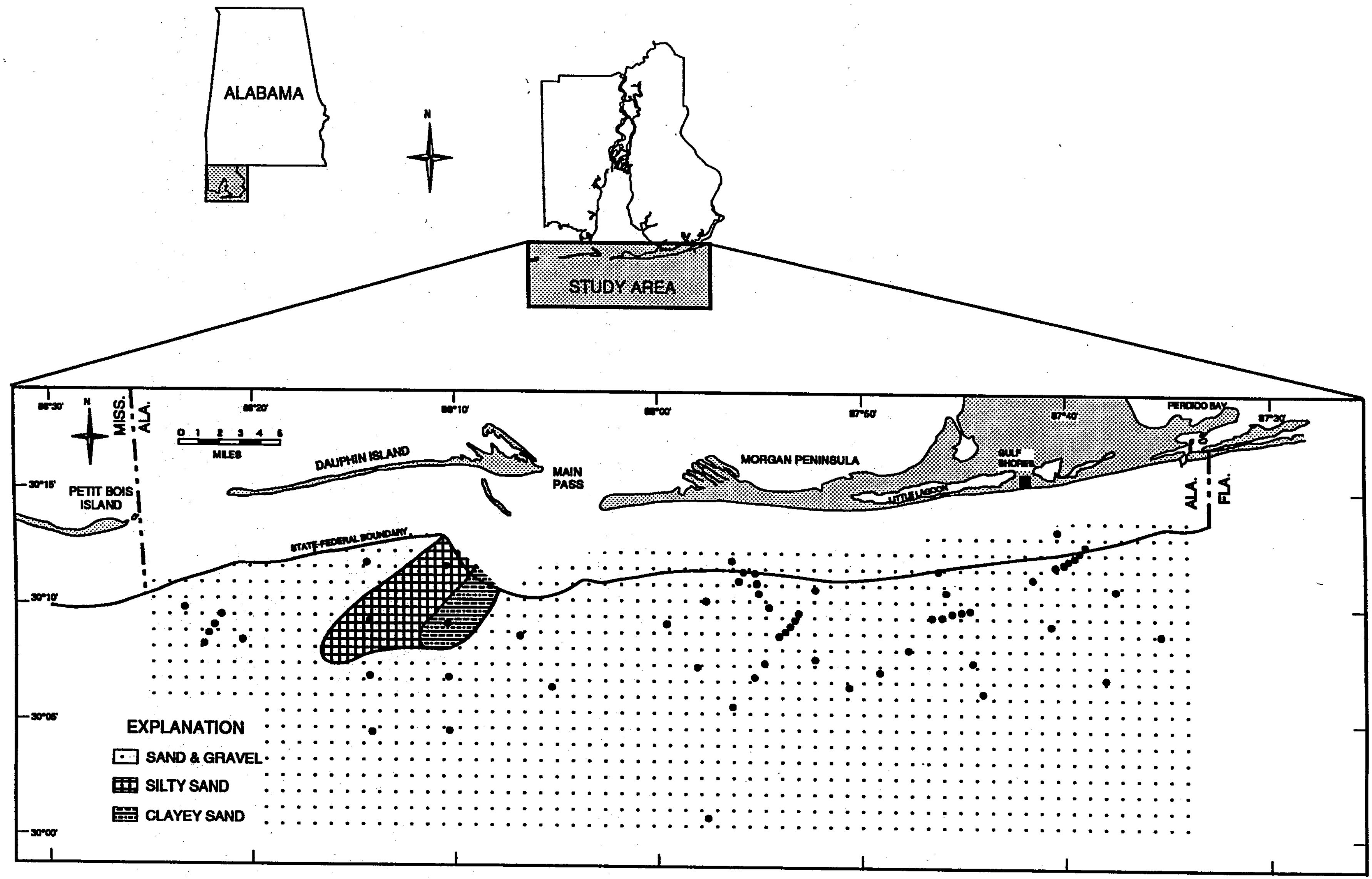


Figure 35.--Surficial sediment textures in the Alabama EEZ study area.

VERTICAL FACIES SEQUENCES AND INFERRED ENVIRONMENTS OF DEPOSITION

Determining the vertical facies pattern is essential in unraveling the sedimentary history of an area, and therefore is useful in predicting facies distributions in other, unsampled portions of the EEZ. Additionally, by delineating the facies that overlie a possible sand resource, depth of overburden can be determined; this enhances economic and environmental evaluations of proposed mining activities.

Utilizing the characteristics of the microfacies together with their vertical patterns, the conditions under which the sediments were deposited can be elucidated. By so doing, we can infer the depositional environment for the facies, e.g. the physical environment with its associated water depth, energy, etc., where the facies formed. Figure 36 shows a typical composite stratigraphic sequence of facies. It shows the general trend of bay or nearshore facies overlying the Pre-Holocene surface. These muddy sediments are gradually overlain by cleaner, sandy shelf facies.

Holocene microfacies from this study formed in four major depositional environments. Much of the inner shelf portion of the Alabama EEZ today represents a Shelf Sand Sheet Depositional Environment. This depositional environment represents widespread deposition of presumably reworked palimpsest clean sands (but see Swift and others, 1971) following transgression (review in Johnson, 1978; also see Ludwick, 1964, and Parker and others, 1992). It is a blanket sand that laterally may grade into, or have embedded in it, other sandy depositional environments. The sand in this environment may be reworked either by high energy storm events, or by background (non-storm) currents and bioturbation.

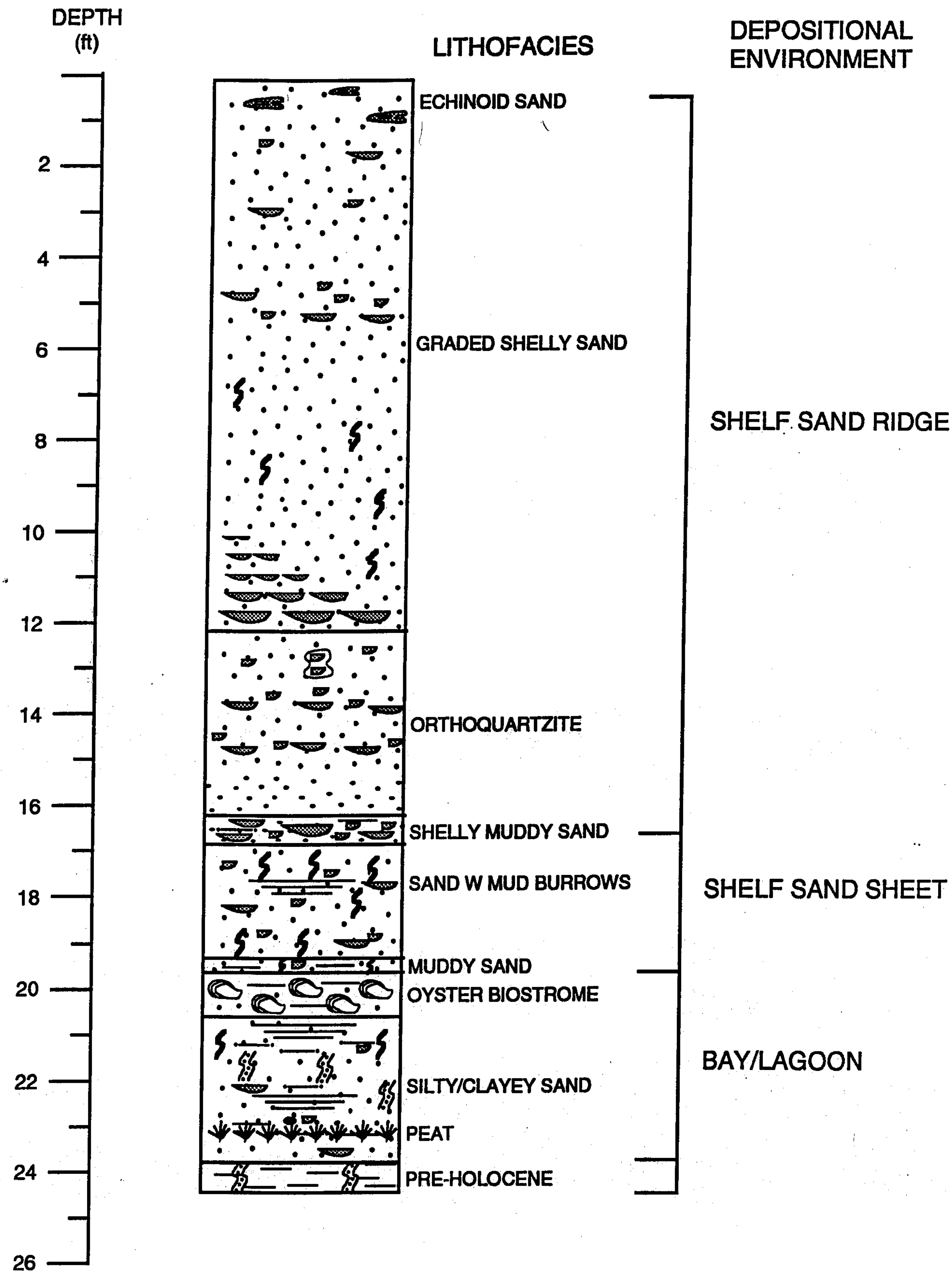


Figure 36.--Generalized stratigraphic sequence of the Alabama EEZ study area.

Embedded in the Shelf Sand Sheet is the Sand Ridge Depositional Environment, which includes both the ridge crest and inter-ridge trough subenvironments (Stubblefield and Swift, 1976; Caston, 1972). The oblique to the shoreline sand ridges are capped by mobile sands that are well above storm wave base. They are capped by coarse grained deposits that may well be locally moved by interstorm shelf currents. The inter-ridge troughs are the site of much quieter water deposition of fines between storms, and may receive coarse washovers during storms.

The Bay/Lagoon Depositional Environment partly consists of older sediments that formed during Holocene transgression of the EEZ (e.g., Bridges, 1975). It may include restricted circulation (e.g., variable, lower salinity and water energy) deposits typical of bays and lagoons, including bay muds, silty sands, nearshore interbedded sands and muds, oyster reefs, and bay margin peat deposits. Additionally, it may include mixed transitional mud and sand units formed on the open shelf during early stages of transgression. The Muddy Shelf Depositional Environment contains very similar low-energy muddy deposits that are still forming today on the unrestricted shelf. They represent muds carried offshore from Main Pass, especially to the west, by floods, storms, and tides. These deposits are difficult to distinguish from those of the Bay/Lagoonal Depositional Environment unless diagnostic offshore taxa are present; however, no oyster reefs, peat, or other bay margin deposits will be present.

The Pre-Holocene sediments represent a variety of marine and non-marine depositional environments. For the purposes of this study, no depositional environments were determined; the presence of these sediments implies subaerial exposure of the pre-erosional surface lithology.

Table 10 shows that some pairs of microfacies are found together in vertical sequence much more commonly than are others. For example, it is not surprising that the *in situ* Pre-Holocene is not found overlying other, more recent, units. The Pre-Holocene was cored at the base of 12 locations, 11 of which are on the Eastern Shelf (table 9). This supports the hypothesis that Holocene sediment thickness may be greater on the muddier, Western Shelf. Likewise, the Echinoid Sand is nearly always found at the sediment surface; as previously discussed, the echinoid fragments rapidly dissolve, and most are lost at depth in the precursors to these units.

The Graded Shelly Sand Lithofacies, the most common lithofacies, is inferred to represent shelf storm deposits of the Sand Ridge and Shelf Sand Sheet Depositional Environments. Its graded nature, sharp base, and variable thickness are typical of tempestites (Aigner, 1985). Not surprisingly, therefore, it can overlie a variety of units. Often, it is found as stacked storm deposits on top of other units of the same facies. It also commonly directly overlies the Pre-Holocene (as a transgressive lag deposit), and Sand with Mud Burrows. This latter microfacies is thought to represent quiet, interstorm bioturbational reworking of shelf sands; therefore resuspension of the upper part of the unit by the high energy events that produce the Graded Shelly Sands is to be expected. While the Graded Shelly Sand units may be overlain by any of 7 microfacies, typically they are overlain by the normal background shelf Echinoid Sand, other Graded Shelly Sands, and as sediment surface accumulations. Only rarely are they overlain by muddy sediments (table 10). They were collected in 39 cores, including 34 of 45 (75.5 percent) of locations on the Eastern Shelf (table 9). This is more locations than any other microfacies.

The Echinoid Sand Microfacies is interpreted as a background, agitated water, shelf sand deposit. It forms on the crest of the Sand Ridges, or on other parts of the low relief Shelf Sand Sheets. It is compositionally very similar to the Orthoquartzite Microfacies, except that it contains the component of very recently dead parautochthonous echinoid hash. Thus, it is restricted to being a surficial deposit in sandy areas of high concentrations of echinoid colonies. It commonly overlies clean Orthoquartzite or Graded Shelly Sands (table 10). It typically forms during background times between high energy events. This microfacies was evaluated at 16 core locations, all but one of which were on the Eastern Shelf (table 9) .

Orthoquartzite Sands form primarily in the Shelf Sand Sheet Depositional Environment, and may extend onto the Sand Ridges. They overlie all but three microfacies: Sand w/Mud Burrows, Oyster Biostrome, and Pre-Holocene (table 10). Most commonly, however, they overlie Muddy Sands; this may indicate that they are the reworked, winnowed upper portion of these underlying units. This view is strengthened by the fact that they are most commonly observed at the sediment surface; they are also common beneath Echinoid Sands, Shelly Sands, Graded Shelly Sands, and Muddy Sands. They are found in 13 core locations, scattered over the East and West Shelves (table 9).

Shelly Sands likely form both in the Sand Ridge Depositional Environment, especially on the flanks to troughs, and on the Shelf Sand Sheet. They are found interbedded with Orthoquartzites, Sands with Mud Burrows, other Shelly Sands, and Graded Shelly Sands (table 10). They likely represent slow winnowing of these units by waves or currents, producing a sand with an enhanced shelly concentration. This microfacies was collected in 5 core locations, all of which were just east of Main Pass on the Eastern Shelf (table 9).

The Sand with Mud Burrows Microfacies forms as interstorm background sedimentation, as infaunal filter feeders deposit mud into the previously clean sand. It is most commonly overlain by Graded Shelly Sands, although it can be overlain by Shelly Sands or be found at the sediment surface (table 10). It occasionally overlies 7 different microfacies, including shelly, clean sand, and muddy units. Likely, the upper parts of these microfacies have been reworked to produce the more shelly units. Thus, it apparently represents sedimentation under any shelf to marginal marine conditions where the sand substrate is stable enough to permit incorporation of mud by bioturbators. As such, it is most common in the Shelf Sand Sheet Depositional Environment. This microfacies was evaluated from 17 different core locations, only two of which were from the Western Shelf (table 9).

Muddy Sands form in the troughs of the Sand Ridge Depositional Environment, as well as possibly representing a transition between the Bay/Lagoon and Shelf Sand Sheet Depositional Environments. They typically overlie the muddier microfacies, and only rarely overlie clean sands (table 10). However, they are overlain not only by muddier sediments (other Muddy Sands, Silty/Clayey Sands and Muddy Shelly Sands), but also by clean or shelly sands (Orthoquartzites, Sands w/Mud Burrows, and Graded Shelly Sands). They are found on the surface in nearshore areas near Main Pass. The Muddy Sand Microfacies was collected from 17 core locations, including 7 of 14 (50 percent) from the Western Shelf (table 9).

Muddy Shelly Sands are uncommonly found on the surface on, or just off, the ridge crest of the Sand Ridge Depositional Environment. Some, which contain large paleosol rip-ups, represent early transgression environments. They are most commonly overlain by other units of the same microfacies, but occasionally also by Orthoquartzites, Graded Shelly Sands, and Muddy Sands (table 10). They are also occasionally seen overlying Muddy Sands and Silty-Clayey Sands. They were found in 6 core locations, equally split between the Eastern and Western Shelf (table 9).

The Oyster Biostrome Microfacies represents material derived from *Crassostrea virginica* reefs. While neither example evaluated for this study shows *in-situ* cemented reef material, nonetheless the large size and abundance of shell talus indicates very close proximity to the ancient reef depositional environment. This microfacies is not found at the surface today; it typically forms in euryhaline, brackish estuarine conditions, often near the shoreline (Galtsoff, 1954, Reid, 1961). Therefore it is not surprising that these examples are surrounded by Silty/Clayey Sand, Muddy Sand, and Sand w/Mud Burrows (table 10). It formed in the Bay/Lagoon Depositional Environment. This microfacies was collected at only 2 core locations, one each for the Eastern and Western Shelf (table 9).

The Peat Microfacies formed in quiet marshy environments, either low salinity estuarine intertidal salt marshes or non-marine palustrine wetlands (Cowardin and others, 1979). Therefore, they are seen overlying Sand-Mud Interbeds and Sand w/Mud Burrows; likely they could also be found over most muddy microfacies and the Pre-Holocene. They are overlain by higher energy, cleaner sands (Orthoquartzites and Sand w/Mud Burrows), indicating their nature as ephemeral, transgressive shoreline to nonmarine deposits (table 10). Peats were collected in only 2 locations, both on the Eastern Shelf (table 9). They were deposited in the Bay/Lagoon Depositional Environment.

The Silty/Clayey Sand Microfacies was deposited in the Bay/Lagoon and the Muddy Shelf Depositional Environment. It commonly overlies the Muddy Sand Microfacies (table 10). While it often is found near the bottom of cores and is overlain by a variety of muddy and sandy microfacies in a transgressive sequence, it can also be found on the sediment surface just southwest of the muddy outfall of Mobile Bay. This sediment type was evaluated from 8 core locations, including 4 of 14 (28.6 percent) from the Western Shelf (table 9).

The Sand-Silt-Clay Microfacies formed in the Bay/Lagoon Depositional Environment. It is commonly found near the base of cores, e.g., near the bottom of the transgressive systems tract, usually associated with other muddy microfacies. It was not collected on the sediment surface. It was found overlying Silty/Clayey Sand and Graded Shelly Sand one time each (table 10). It is seen being overlain most commonly by Muddy Sands, although also seen under Orthoquartzites and Silty/Clayey Sands. It was collected from 5 core locations from both the Western and Eastern Shelf (table 9).

The Sand-Mud Interbeds Microfacies is also most commonly seen near the bottom of cores associated with other muddy units. This sediment type may have formed in the Bay/Lagoon or, possibly, the Muddy Shelf Depositional Environment. It is not seen on the sediment surface (table 10). It is overlain by Muddy Sands, Orthoquartzites, Peat, and other Sand-Mud Interbed units. It was seen at 4 core locations, 3 of which are on the Eastern Shelf (table 9).

SUBSURFACE CROSS-SECTION INTERPRETATIONS

The series of geological cross sections (figs. 26 through 34) shows trends in subsurface microfacies distributions in both dip-trending and strike-trending directions (fig. 25) to facilitate determination of lateral variability patterns for the microfacies.

ONSHORE-OFFSHORE TRENDS

Sediments can be grouped into two major sequences that are separated by a type 1 unconformity (Van Wagoner and others, 1988), the major late Pleistocene - early Holocene low stand erosional surface. The transgressive surface is readily recognized on seismic lines as well as in cores. On seismic records, the reflective transgressive surface represents a significant change in lithology and density (velocity) between the unconsolidated surficial late Holocene sediments and the underlying much more consolidated deposits (Geological Survey of Alabama, 1991, 1992). As Otvos (1976) points out, the reflection "roughly, but not exactly coincides with the Pleistocene surface"; i.e., it represents the time-transgressive Holocene marine flooding surface (the time of most recent marine inundation) and as such there may well be early Holocene age non-marine to deltaic sediments below the surface in some updip areas.

Structure maps have been produced on this horizon in Mobile Bay and the Alabama portion of Mississippi Sound (Geological Survey of Alabama, 1991, 1992) as well as preliminary work by Brande (1983). Otvos (1976) and Carroll (1982) produced similar descriptions for the Mississippi part of Mississippi Sound. They indicate the transgressive surface gently dips seaward from near sea level on the northern shore of Mississippi Sound, and is deeply incised in places by Latest Pleistocene-Early Holocene fluvial channels. The largest of these now infilled channels is especially prominent along the axis of Mobile Bay and represents the latest Pleistocene low-stand valley of the Mobile River; it apparently bifurcates with a secondary distributary channel crossing the central area of Morgan Peninsula. Little detailed shallow seismic work has been completed, however, to extend these findings into the Alabama EEZ study area.

In this study, the surface can be seen in figures 26 through 31, 33, 34. Results from this study generally support those found in these previous works. In general, the erosional surface dips seaward at a rate of a few feet per mile (fig. 37), and is especially apparent in figure 30. At the shoreward boundary of the Federal waters, the surface is located from -42 to greater than -58 ft subsea. At the seaward margin of the sampled area, subsea depths to the erosional surface are in excess of 70 ft. This seaward dip, however, is neither planar, nor uniformly consistently seaward dipping, as seen in figure 27: Core SR-32 shows a thick sequence of muddy bay/estuarine fill in a paleotopographic low (possibly infill of a paleochannel or lagoon?) in the erosional surface. The surface seems to be deeper on the West Alabama Shelf than on the East Alabama Shelf.

By ignoring the local changes in Holocene sediment thickness due to the presence or absence of sand ridges, it appears that in general the Recent sediment cover above the unconformity thickens seaward. This is especially apparent in figure 26; there is only minor Holocene cover of the Pre-Holocene surface in the shoreward SR-33 location, but seaward of location SR-32 there is a progressive increase in sediment thickness. As a conservative estimate, it is assumed that the lowermost peat in core SR-25 is located just above the sequence boundary. Therefore, the sediment thickens from a few inches to over 17 ft in a dipwise distance of just over 5 mi.

Basal sediments that cover the Pre-Holocene are quite variable. In many cases, there is a thin, coarse shell-rich transgressive lag, or several thin fining upwards shelly deposits. These are indicative of high-energy, shallow open marine environments (Aigner, 1985) (figs. 26, 27, 30). Many show intense marine borings into the stiff Pre-Holocene, with lithoclasts of the underlying material incorporated into the basal Holocene transgressive sequence. In other

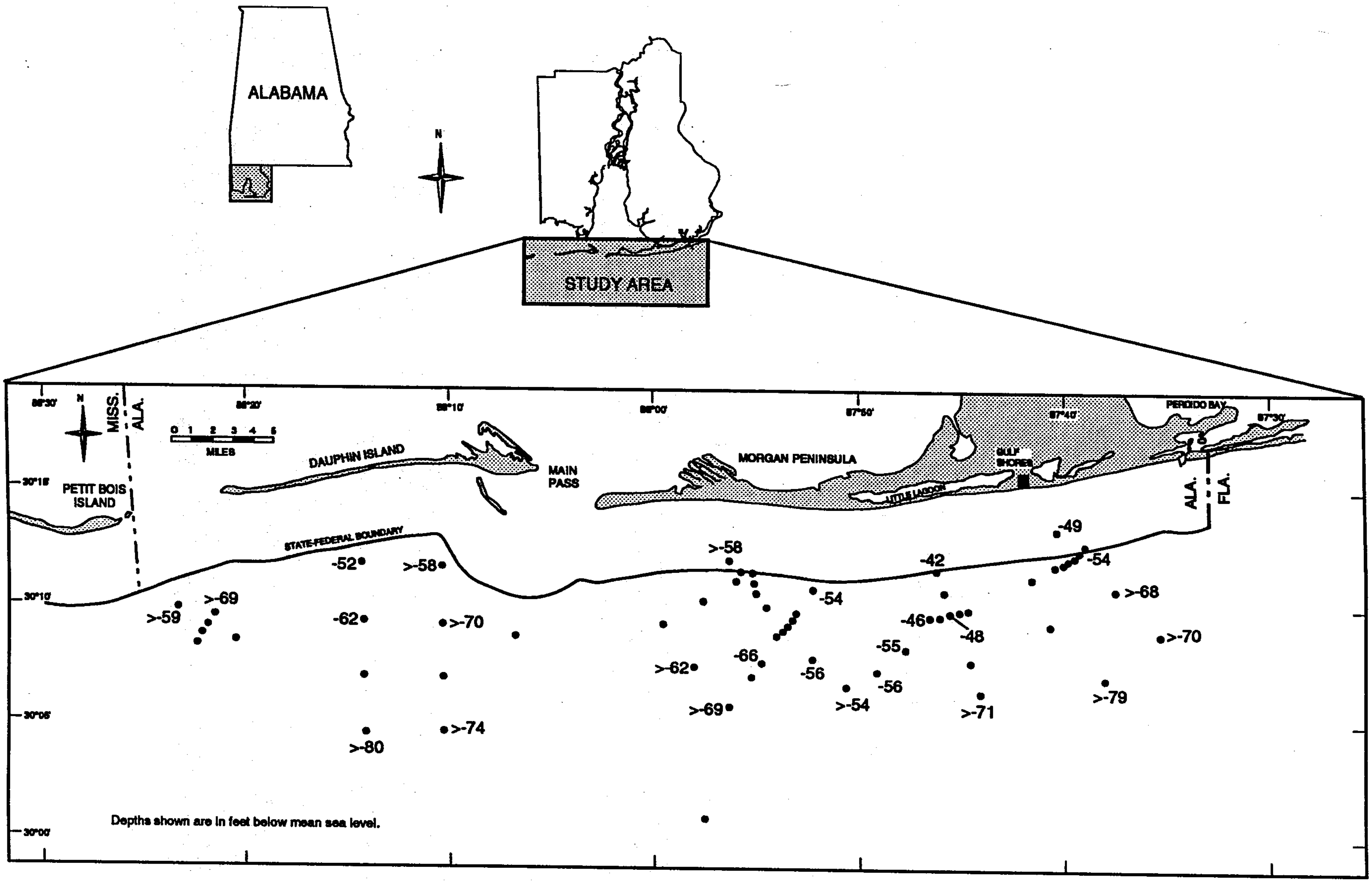


Figure 37.--Depths (ft) to the pre-Holocene surface.

areas, the basal sediments are much more fine grained, typically Muddy Sand or Silty/Clayey Sand (figs. 28, 29, 33). These are interpreted to represent pre-existing low lying areas that were rapidly inundated as sea level rose; fine grained sediment accumulated in these quiet water lagoonal and drowned river valley depocenters. Peats, rooted zones, and other organic-rich nonmarine deposits are also patchily distributed on the surface. Both open marine coarse shell lags and fine-grained bay deposits may be seen in the same cross section; there is no indication that either type is seen more frequently seaward. Instead, the time-transgressive surface is covered with whatever sediment was appropriate to the topography and hydrodynamics of the core location at the time of transgression.

Within the Holocene sequence, there is considerable lateral gradation between the various sandy and muddy microfacies. In many cases, such general categories of sediment can be correlated seaward along a cross section (fig. 26); however, specific microfacies grade into each other depending on patchy distribution of shells (Shelly Sand and Echinoid Sand of cores SR-6 grade into Graded Shelly Sand in core SR-4, which grades into Orthoquartzite and Muddy Sand in core SR-2).

LONGSHORE TRENDS

There are also differences in sediment type along strike, i.e., parallel to the shoreline, in the study area. This is especially true when comparisons are made between cross sections on the East Alabama Shelf (fig. 38) and the West Alabama Shelf (fig. 39). Holocene sediments at depth are generally much muddier west of Main Pass than they are to the east. Figure 33 shows primarily Muddy Sediment and Dirty Sand Lithofacies at depth on the West Shelf,

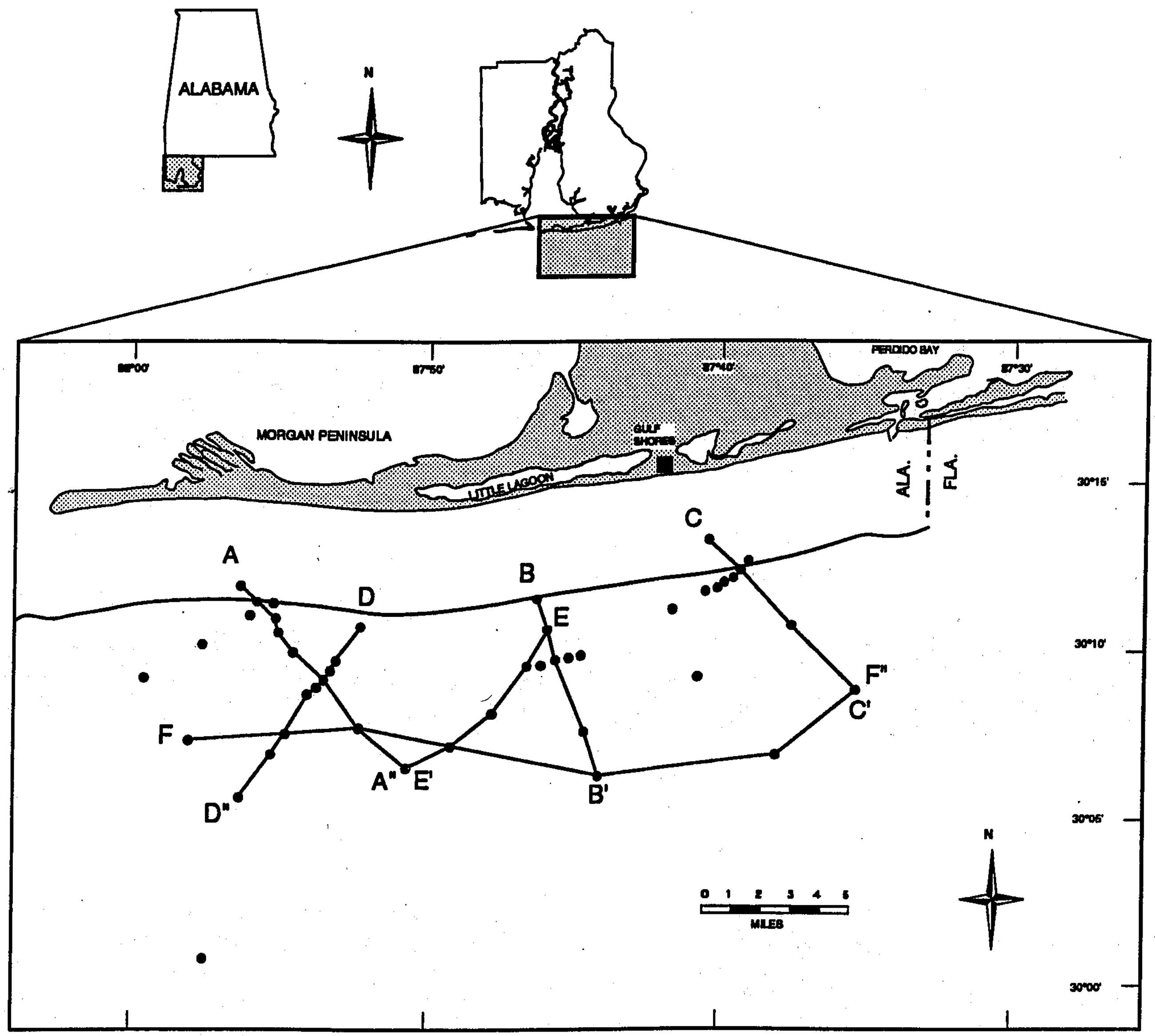


Figure 38.--Map of eastern Alabama shelf cross section locations.

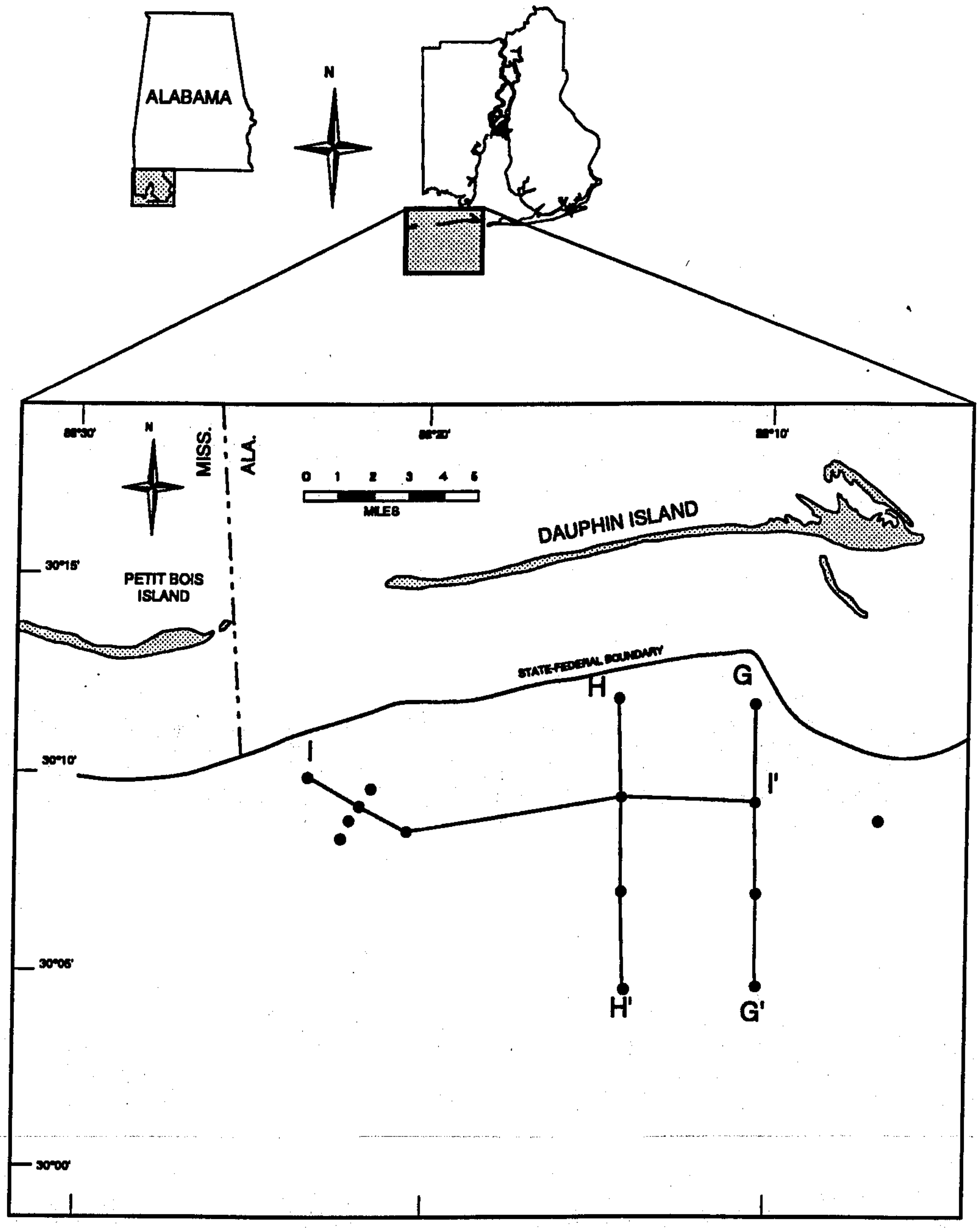


Figure 39.--Map of western Alabama shelf cross section locations.

whereas figure 30 shows primarily Clean Sand and Graded Shelly Sand Lithofacies in the subsurface on the East Shelf. This same trend was previously noted on the surface facies distribution map (fig. 24). Thus, present generally westward flow of mud-rich sediment plumes from Main Pass apparently represents a long-term trend; this prevailing westward circulation pattern may have been developed at the time of transgression and continues today.

In addition, there is considerable local relief seen on the Pre-Holocene surface, both in the Eastern and Western shelf area. Figure 34 shows a paleotopographic high at location SR-52, apparently the site of an interfluvial area west of the main Mobile-Alabama River Valley during the Late Pleistocene lowstand. Holocene sediment thickness is very minor over this high. A similar pattern is seen in figure 30 where a prominent high with a thin Holocene cover is seen at locations SR-21 and SR-23; sediments thicken into the paleodrainages east and west of the high. Such a pattern of occasional paleodrainages cutting the Late Pleistocene surface is also seen in some of the dip-trending cross sections. For example, the basal portion of core SR-32 consists of muddy sediments infilling an incised paleochannel.

The cross sections indicate that except for the episodic presence of shelf sand ridges, the mode and degree of lateral variability in facies distribution is similar in both strike and dip-trending directions; therefore on the inner portion of the Alabama shelf the facies are patchily distributed.

DISTRIBUTION AND STRATIGRAPHY OF SHELF SAND RIDGES

The Alabama EEZ contains an abundance of shelf sand ridges that generally are elongate in a NW-SE direction diagonally from the shoreline (figs. 6, 7). Local topographic relief on these highs can be greater than 12 ft. They are found most commonly in water depths of less than 50 ft, with many being shoreline attached, although they are found in all water depths on the inner shelf portion of the Alabama EEZ. They are abundant on the Alabama Eastern Shelf; they are almost entirely missing from the West Shelf area, however (figs. 6, 7). This difference in abundance presumably relates to the previously discussed differences in sediment source between the two areas: Muddy sediment input from the Mobile River system and the St. Bernard Delta onto the Western Shelf versus minimal fine grained input onto the largely palimpsest sediments of the Eastern Shelf.

The present distribution of the shelf sand ridges apparently is not controlled by the variation in elevation of the Pre-Holocene unconformable surface. As previously mentioned, the cross sections indicate that the paleotopographic highs are overlain by Holocene isopach thins, not thick sand units. Paleotopographic lows are typically filled with muddy sediments. The sand ridges in contrast are areas of thick Holocene sandy sediments. No core penetrated through the unconformity beneath a sand ridge into the Pre-Holocene Lithofacies, even though penetration in some cases exceeded 16-18 ft. Therefore, as in the cases of shelf sand ridges in the Middle Atlantic Bight (Swift and others, 1973; Stubblefield and others, 1984), the Alabama shelf sand ridges are apparently entirely Holocene in origin, and their location and morphology is controlled by the Recent hydrodynamic regime (Dinnel, 1989), not pre-existing structural or stratigraphic conditions. The process forming shelf sand ridges differs depending on shelf morphology and hydrodynamics (Johnson, 1978; Berg, 1986); some are primarily tidal in origin (Houbolt, 1968; Caston, 1972), or while others may be primarily storm wave generated (Stubblefield and Swift, 1976). Given the microtidal regime of the Alabama

EEZ, the shelf sand ridges described in this study are assumed to be dominantly storm wave in origin (Parker and others, 1992).

Differences in surface sediment type between ridge crest and inter-ridge swale were immediately apparent from surface grab samples. In general, sediments in the swales were much more mud-rich than those on the ridge crest and upper flanks. This may relate to higher ambient wave intensity on the shallow ridge crests (especially during storms), thus much more frequent sediment movement and winnowing, than in the more quiescent swales (Swift and others, 1973).

These general patterns are seen in the subsurface as well. The ridges are often capped by a thick sequence of coarse stacked Graded Shelly Sands, Echinoid Sand, or Shelly Sand. Relative microfacies thicknesses and specific sequences vary between core locations (e.g., cores SR-6 and SR-18); nonetheless these clean or coarse grained higher energy deposits make up the core of each sampled sand ridge. These units were deposited above storm wave base (Seilacher, 1982); they represent graded storm deposits and the sands deposited during inter-storm intervals, as biological and current reworking of the upper portion of the storm deposits dominated.

In the swales, coarse sediments may also be found on the sediment surface (e.g., core SR-21 on fig. 26); however, the overall thickness above the Pre-Holocene for these clean units may be much lower, and may represent thin stacked storm washovers. Where units may be correlative from ridge to swale, they often thin into the swales (coarse sediments of cores SR-18 and SR-22 thinning into the swale at SR-21). In other places, swale sediments are muddier, again with relatively less thickness above the Pre-Holocene surface (core SR-15, fig. 31. Therefore, the ridges contain thicker sequences of coarse, reworked Holocene sediments than do the surrounding swales; they therefore represent positive build-ups of Holocene sediment above the Pre-Holocene surface.

OVERALL LITHOFACIES PATTERNS

Three dimensional facies patterns are regionally predictable in the study area. On the sediment surface, the Clean Sand and Graded Shelly Sand Lithofacies dominate Federal waters on the Eastern Shelf; on the Western Shelf, muddier sediments are common on the inner portion of the Federal waters.

Sediments of possible use in beach nourishment are found only above the Pre-Holocene erosional surface, which dips generally seaward. The surface is not planar, as it is interrupted by many dip-trending paleochannels and strike-trending lows; these acted as quiet-water mud depocenters during the Holocene transgression. Sediment thicknesses also vary due to the location relative to the Holocene shelf sand ridges, with thickest and coarsest sediments generally located in storm deposits and reworked storm deposits on the ridges. Clean sands thin into the troughs between the ridges where they may be replaced by muddier sands. These ridges are concentrated on the Eastern Shelf.

RESOURCE POTENTIAL OF OFFSHORE AND ONSHORE SAND DEPOSITS

The resource potential of offshore and onshore sand deposits was determined by comparing the sediment character of these deposits with the native sediment occurring on each of the eroding Gulf shoreline segments. This portion of the study completed part of task 6 (offshore target areas) and task 7 (onshore sites) of the project. Since any new material added to the beach will be subjected to winnowing by coastal processes, it is important to determine the grain size characteristics of both the native beach sediment and the sediment from the borrow site. Sediment that is too fine will be removed and transported offshore by wave action and longshore currents, whereas coarser sediment may produce a steeper beach and will not be transported by wind to the backshore areas of the beach. Also important in considering beach replenishment of Alabama's Gulf beaches is the aesthetic quality of the replenishment material. Most of the Alabama Gulf shoreline is composed of clean white sand. Borrow material comprised of iron stained or dark colored sand would likely detract from the natural beauty of the beach and should not be considered suitable for beach nourishment.

OFFSHORE SAND RESOURCES

TARGET AREA 1

Sand resource target area 1 is located in the eastern shelf region south of the city of Gulf Shores, Alabama (fig. 12). This area encompasses approximately 24 square miles and extends from 2 to 8 mi offshore. Water depths in the area range from a minimum of 28 ft to a maximum of 48 ft. (fig. 40). Characteristic of this area are several sand ridges consisting of shoreface attached and detached ridges (figs. 6, 40). Relief on the ridges reaches a maximum of approximately 10 ft. Vibracoring and bottom sampling efforts focused on the prominent sand ridge extending south of Shelby Lakes (fig. 40).

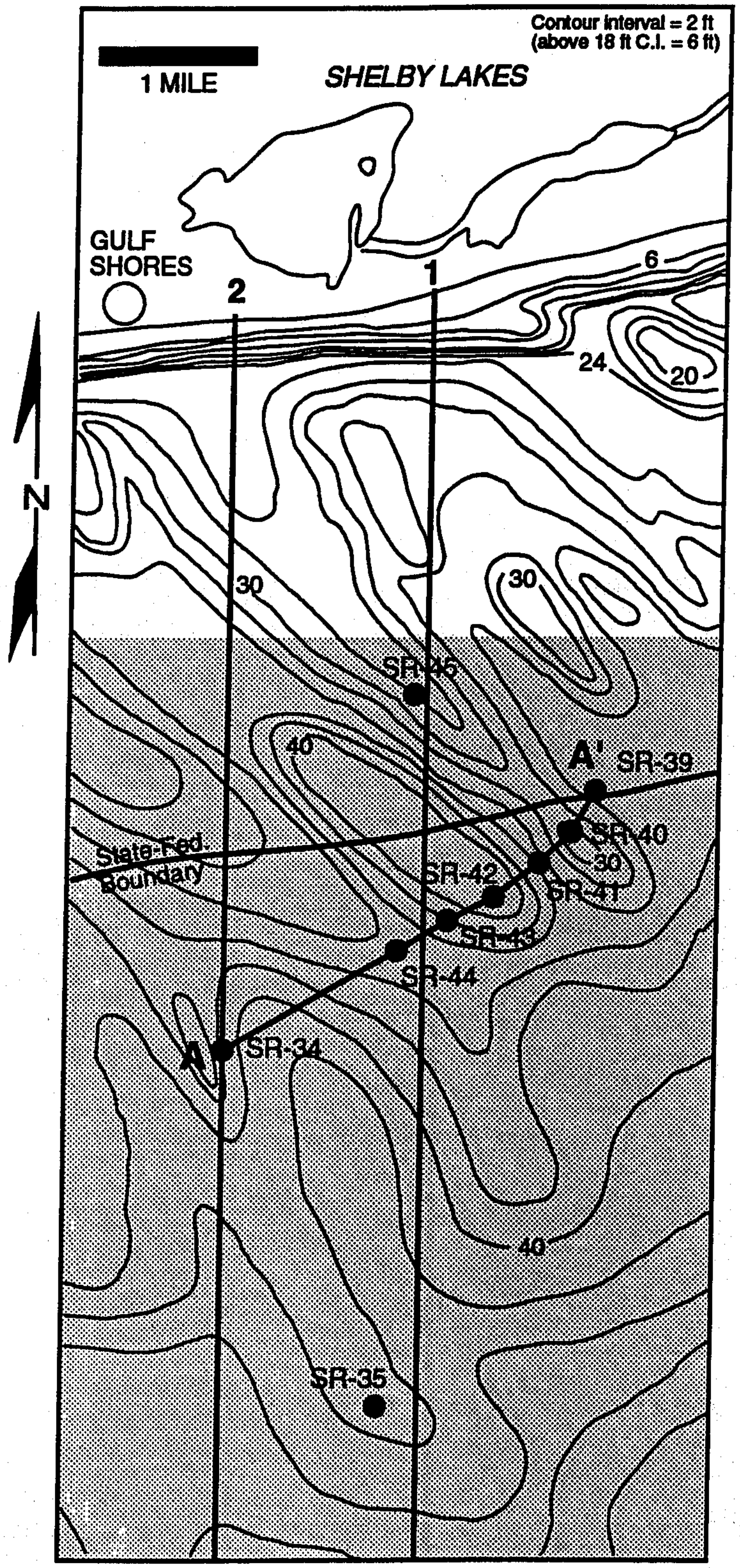


Figure 40.--Map of sand resource target area 1 showing location of cross section (A-A') and bathymetric profiles (1 and 2).

Based on the vibracores and bottom samples collected in this area, much of the region consists of medium to fine sand. At the surface, medium to fine sand covers the entire area (fig. 41). Grain size characteristics of core samples taken in the area are shown in table 11. The sand is clean with mean grain size averaging 1.99 Ø (medium sand), sorting averaging 0.86 Ø (moderately sorted). Average mean grain size ranges from 1.29 Ø (medium sand) to 2.30 Ø (fine sand) and average sorting ranges from 0.73 Ø (moderately sorted) to 1.10 Ø (poorly sorted) In general, sand deposits in the area average 96.55 percent sand, 1.2 percent silt, and 2.48 percent clay (table 11). Cores SR-34, SR-35, and SR-44 average over 98 percent sand (table 11). Silt and clay content is minor with a combined average of less than 4 percent. Some shell gravel does occur within the medium to fine sand deposits, however; it is generally less than 10 percent.

Sand deposits are thick in this area ranging from approximately 4 to 13 ft. (table 11) (figs. 41, 42). Cores SR-41 and SR-44 bottom out in sand, thus, the exact thickness of the sand is unknown. As expected, the thickest accumulations are associated with the ridges and the thinnest deposits are in the troughs. The sand tends to thin slightly in an offshore direction. A thin lens of fine sand, silt, and clay that is of much poorer quality for beach nourishment was encountered in cores SR-39 and SR-40. Also, the Pre-Holocene was encountered in cores SR-39 and SR-42. As previously explained, this material is highly indurated and consists almost entirely of clay deeming it unsuitable for use in beach nourishment projects

Estimations of the sand volume in sand resource target area 1 indicate over 160 million yd^3 of clean sand could potentially be available for use in beach nourishment projects. The characteristics of the sand deposits were compared with the eroding shoreline segments of Dauphin Island, Little Lagoon, and

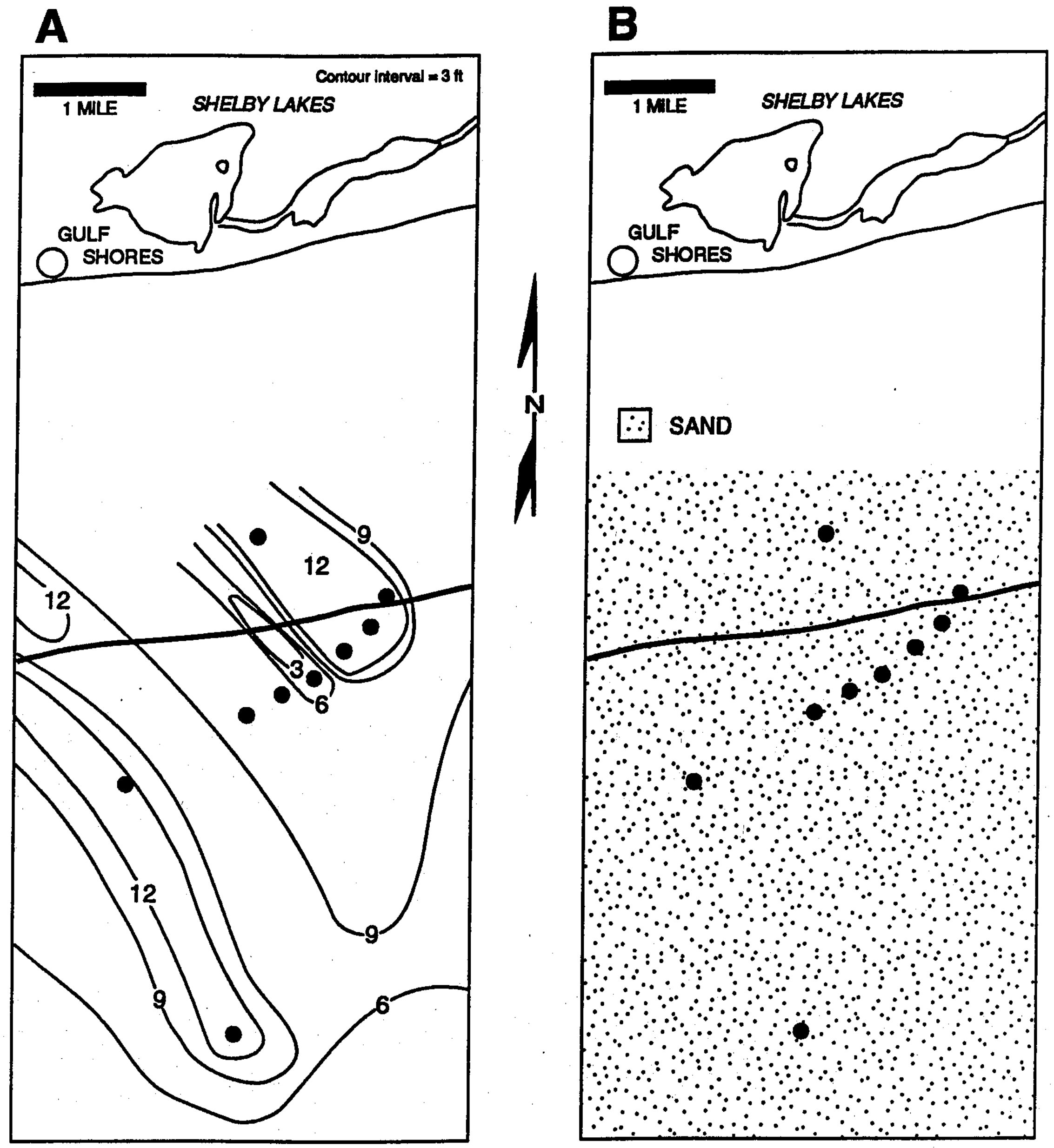


Figure 41.--Sand isopach (A) and surface sediment texture (B) maps for sand resource target area 1.

Table 11.--Sediment characteristics of offshore sand resource target areas

Target area 1-offshore

Total volume of sand for area 1 = 164 million yd^3

Core	Sand thickness (ft)	Average mean (Ø)	Sorting (Ø)	Average percent sand	Average percent silt	Average percent clay	Color (dry)
SR-34	12.0	1.29	1.10	98.35	0.19	1.49	10YR7/1, lt. gray
SR-35*	12.4	1.76	.76	98.84	.00	1.16	2.5Y7/2, lt. gray
SR-39	12.9	2.25	.82	93.54	2.42	4.04	2.5Y7/2, lt. gray
SR-40	13.0	2.14	.74	97.23	.79	1.98	2.5Y7/2, lt. gray
SR-41	>8.5	2.12	.79	94.68	1.75	3.58	2.5Y7/2, lt. gray
SR-42	3.9	1.96	.73	97.99	.18	1.84	2.5Y7/2, lt. gray
SR-43	9.3	2.30	1.00	95.47	1.43	3.11	2.5Y7/2, lt. gray
SR-44	>6.0	2.09	.89	98.13	2.44	1.47	2.5Y7/2, lt. gray
SR-45	13.0	2.04	.95	94.75	1.60	3.66	2.5Y7/2, lt. gray
Average	>10.0	1.99	.86	96.55	1.20	2.48	

*Surface sample only

Table 11.--Sediment characteristics of offshore sand resource target areas—Continued

Target area 2-offshore

Total volume of sand for area 2 = 139 million yd^3

Core	Sand thickness (ft)	Average mean (Ø)	Sorting (Ø)	Average percent sand	Average percent silt	Average percent clay	Color (dry)
SR-24*	6.9	2.14	0.56	98.72	0.06	1.28	2.5Y7/2, lt. gray
SR-25*	17.2	2.04	.56	99.61	.00	.38	2.5Y7/2, lt. gray
SR-26*	>10.1	2.22	0.54	98.37	.00	1.63	2.5Y7/2, lt. gray
SR-27	1.8	1.65	1.76	89.17	4.98	5.85	2.5Y7/2, lt. gray
SR-28	>8.1	1.86	.66	99.15	.56	.29	2.5Y7/2, lt. gray
SR-29	6.8	2.08	.79	98.15	.07	1.78	2.5Y7/2, lt. gray
SR-30	2.9	2.25	.58	98.75	.46	.79	2.5Y7/2, lt. gray
SR-31	.9	1.27	1.04	98.86	.46	.68	2.5Y7/2, lt. gray
SR-32	6.5	1.77	1.00	97.11	1.01	1.88	2.5Y7/3 pale yellow
SR-33*	.3	1.67	1.87	95.98	1.63	2.39	2.5Y7/2, lt. gray
Average	**>6.2**	**1.90**	**.94**	**97.39**	**.92**	**1.70**	

*Surface sample only

Table 11.--Sediment characteristics of offshore sand resource target areas—Continued

Target area 3-offshore

Total volume of sand for area 3 = 198 million yd^3

Core	Sand thickness (ft)	Average mean (Ø)	Sorting (Ø)	Average percent sand	Average percent silt	Average percent clay	Color (dry)
SR-1	2.4	2.86	1.37	85.87	9.54	4.59	2.5Y6/2-lt. brownish gray
SR-2	>6.1	2.26	.76	95.34	1.34	3.32	2.5Y7/2 lt. gray
SR-3	>8.1	2.04	.84	98.06	1.24	.70	2.5Y7/2 lt. gray
SR-4	>9.4	2.09	.80	98.88	.66	.46	2.5Y7/2 lt. gray
SR-5	>16.5	2.04	.82	98.81	.19	1.00	2.5Y7/2 lt. gray
SR-6	>15.0	1.57	1.21	97.67	.42	1.68	2.5Y7/2 lt. gray
SR-7	>8.1	1.05	.79	98.97	.11	.92	2.5Y7/2 lt. gray
SR-8	>18.0	2.24	1.21	94.57	2.46	2.97	2.5Y7/2 lt. gray
SR-10	>18.9	2.13	.69	98.22	.76	.89	2.5Y7/2 lt. gray
SR-16	>8.2	1.93	1.17	97.12	.77	2.12	2.5Y6/2-lt. brownish gray
SR-17	>8.5	2.27	.82	96.64	.87	2.49	2.5Y6/2-lt. brownish gray
SR-18	>14.4	2.01	.61	98.77	.42	.81	2.5Y6/3 lt. yellowish brown
SR-19	.8	2.52	1.34	89.11	7.08	3.81	2.5Y7/2 lt. gray
SR-20	16.3	2.10	.64	97.97	.26	1.77	2.5Y7/2 lt. gray
SR-21*	2.3	2.10	.66	98.17	.00	1.83	2.5Y6/2 lt. brownish gray
Average	>10.2	2.08	.92	96.28	1.74	1.96	

Table 11.--Sediment characteristics of offshore sand resource target areas—Continued

Target area 4-offshore

Total volume of sand for area 4 = 143 million yd^3

Core	Sand thickness (ft)	Average mean (Ø)	Sorting (Ø)	Average percent sand	Average percent silt	Average percent clay	Color (dry)
SR-46	5.9 (2.4 ob)	1.29	1.10	98.35	0.19	1.49	2.5Y6/2, lt. brownish gray
SR-47	8.9 (2.4 ob)	1.76	.76	98.84	.00	1.16	2.5Y6/2, lt. brownish gray
SR-48	.7	2.25	.82	93.54	2.42	4.04	2.5Y6/2, lt. brownish gray
B-1	25.0	–	–	–	–	–	
Average	>10.1	1.76	.89	96.91	.87	2.23	

(ob)-amount of overburden in feet

Table 11.--Sediment characteristics of offshore sand resource target areas—Continued

Target area 5-offshore

Total volume of sand for area 5 = 79 million yd^3

Core	Sand thickness (ft)	Average mean (Ø)	Sorting (Ø)	Average percent sand	Average percent silt	Average percent clay	Color (dry)
SR-54	>9.2	2.32	1.87	84.00	7.58	8.40	2.5Y6/2 lt. brownish gray
SR-55	4.9	2.43	1.37	84.78	5.63	9.60	2.5Y6/2 lt. brownish gray
SR-56	>5.6	1.83	1.30	90.02	3.95	6.02	2.5Y6/2 lt. brownish gray
SR-57	>5.3	1.28	1.18	98.10	.66	1.24	2.5Y6/2 lt. brownish gray
SR-58	>9.5	2.46	1.42	85.17	7.51	7.32	2.5Y6/2 lt. brownish gray
SR-59	>8.9	1.65	.76	98.46	.41	1.12	2.5Y6/2 lt. brownish gray
Average	>7.2	2.00	1.32	90.10	4.29	5.62	

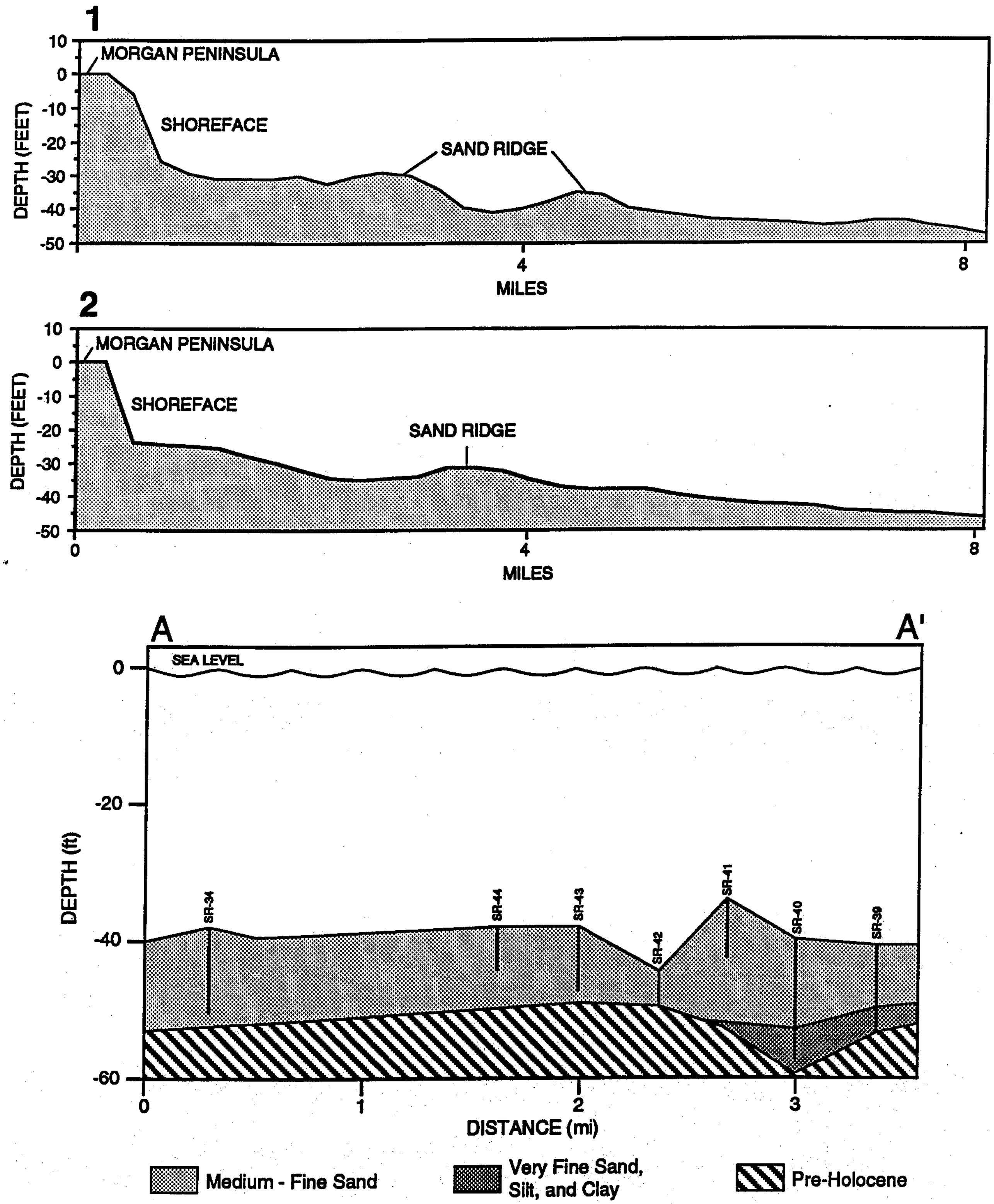


Figure 42.--Bathymetric profiles and cross section in sand resource target area 1.

Perdido Pass. Based on this comparison, the overfill factor for using sand from target area 1 for beach nourishment of Dauphin Island is 1.47. The eroding shoreline segments of Dauphin Island require 1.85 million yd^3 of sand to restore the beach to the 1955 shoreline position. Therefore, 2.72 million yd^3 of sand would be required from target area 1 to replenish beaches on Dauphin Island. The areas of Little Lagoon and Perdido Pass would require 40,000 and 120,000 yd^3 of sand for restoration, respectively. Overfill factors determined for Little Lagoon and Perdido Pass are 4.0 and 1.75, respectively. This implies that restoration of Little Lagoon would require 160,000 yd^3 of sand and Perdido Pass would require 210,000 yd^3 of sand from target area 1. The color of sand from target area 1 is light gray and therefore closely matches that of the beach.

TARGET AREA 2

Sand resource target area 2 is centrally located offshore of Morgan Peninsula in the eastern shelf region (fig. 12). The area extends from approximately 3 to 10 mi offshore and encompasses an area of approximately 32 square miles. Water depths reach a minimum of 32 ft at the top of a ridge and a maximum of 60 ft at the southern boundary of the area (fig. 43). Several ridges and troughs occur throughout the area including sand ridges and paleohighs (fig. 44). Ridges exhibit relief ranging from about 6 to 12 ft. Efforts were made to characterize the two prominent ridges in the center of the area using bottom grabs and vibracores (fig. 43).

Bottom samples taken in the area show that the surface is covered with mostly medium to fine sand except along the landward flank of the easternmost prominent ridge (fig. 45). Sample SR-27 BG contains 35 percent gravel size particles that are exclusively shell material. However, this deposit is only a thin

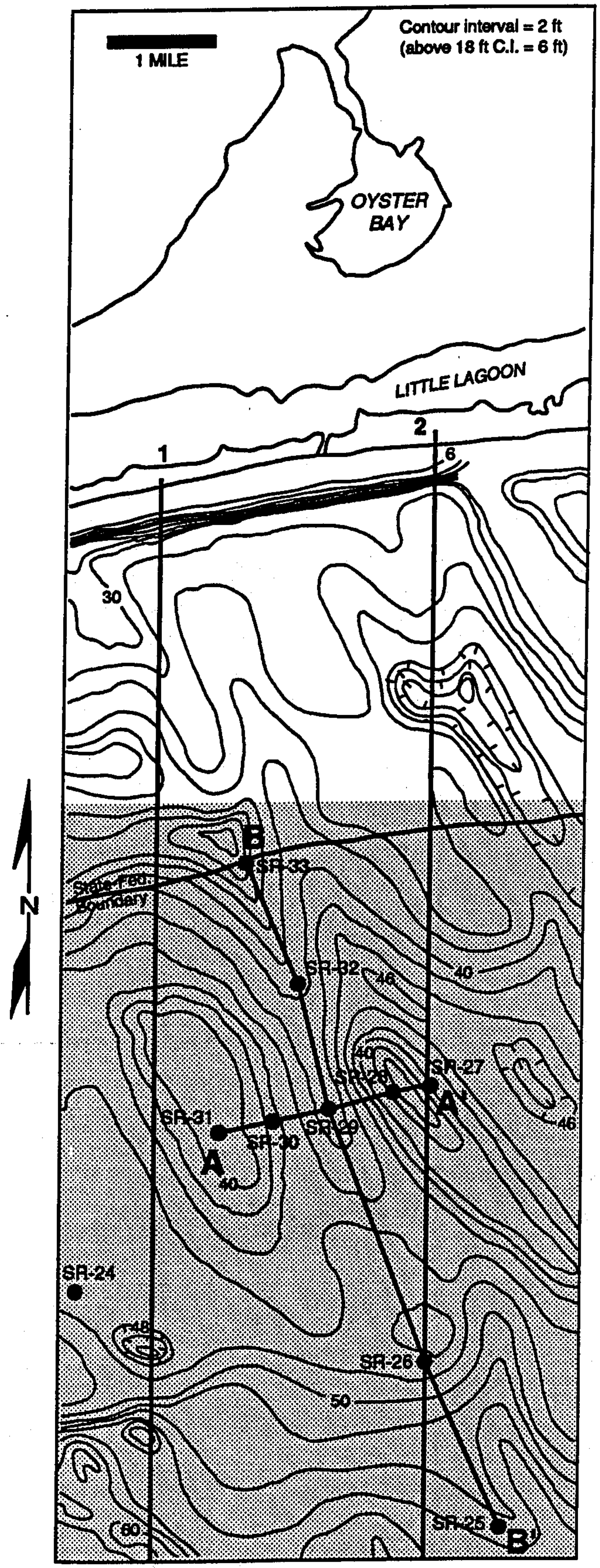


Figure 43.--Map of sand resource target area 2 showing location of cross sections (A-A' and B-B') and bathymetric profiles (1 and 2).

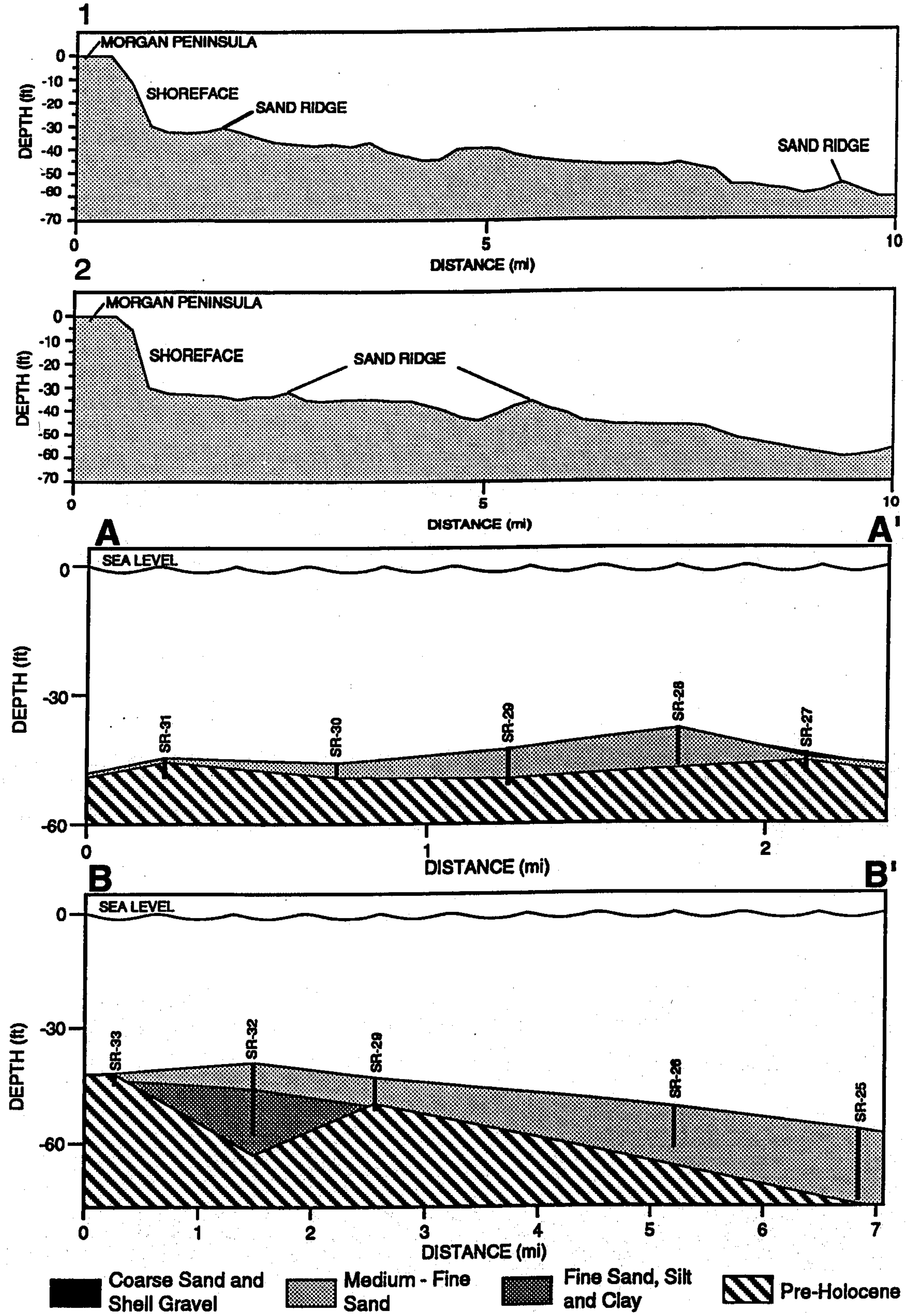


Figure 44.--Bathymetric profiles and cross sections in sand resource target area 2.

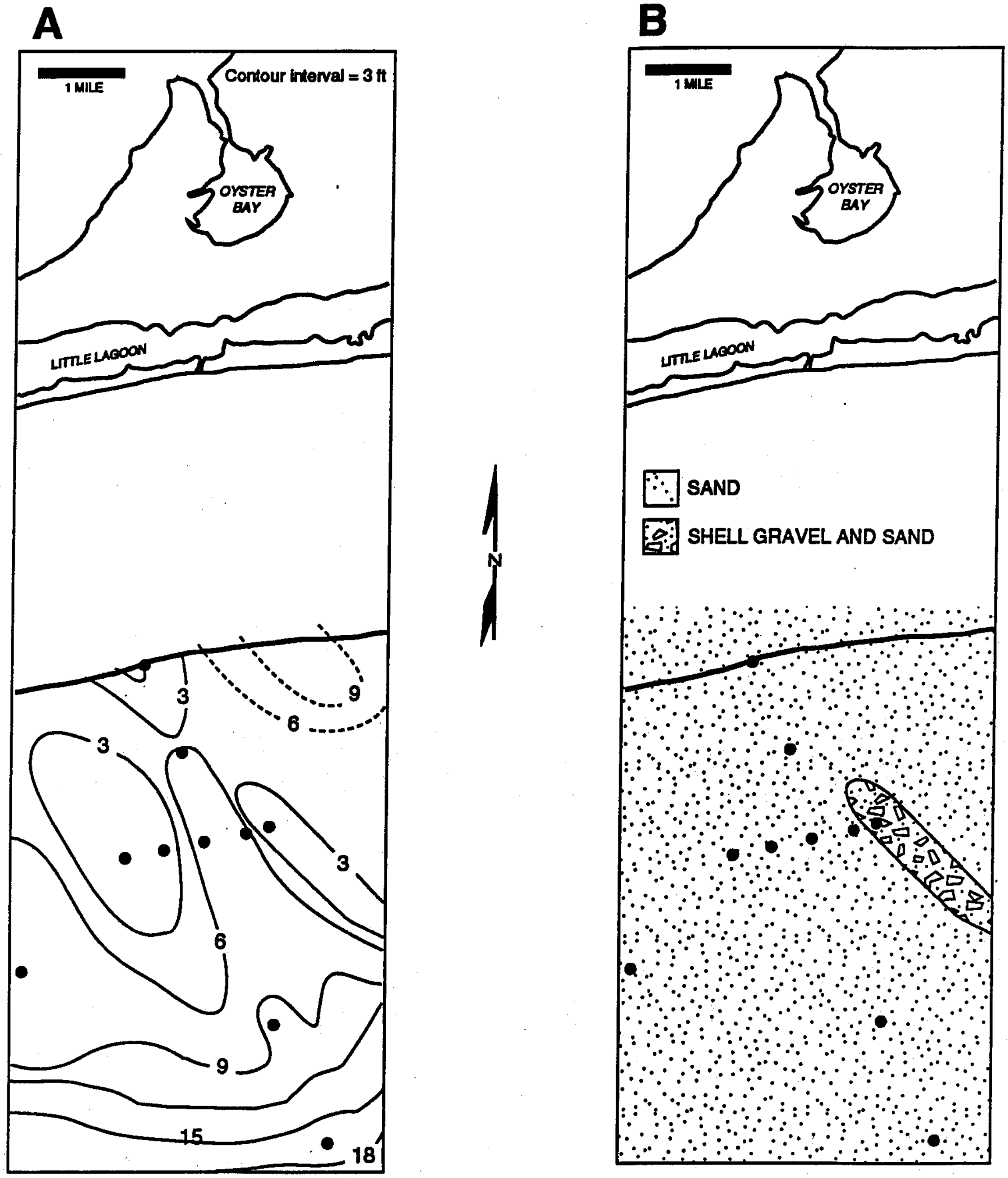


Figure 45.--Sand isopach (A) and surface sediment texture (B) maps for sand resource target area 2.

veneer of shell hash as seen in figure 45. Grain size characteristics of the core samples taken in the area are shown in table 11. Sand quality is similar to that of target area 1; however, the thickness of the sand deposits are less. The average mean grain size in the area is 1.90 Ø (medium sand) and ranges from 1.29 Ø (medium sand) to 2.25 Ø (fine sand). Sorting averages 0.94 Ø (moderately sorted) and ranges from 0.54 Ø (moderately well sorted) to 1.87 Ø (poorly sorted) (table 11). Sand content averages 97.39 percent, with silt and clay averaging 0.92 and 1.70, respectively. Sand content is generally high with seven of the ten cores in this area having over 98 percent sand (table 11). High amounts of silt and clay are present near the surface in core SR-27 averaging nearly 5 and 6 percent, respectively (table 11). This results from the Pre-Holocene occurring at a shallow depth below the sediment water interface.

Sand deposits are generally much thinner than in area 1, averaging approximately 6 ft (table 11) (figs. 44, 45). The range in thickness is from less than 1 ft at location SR-33 to over 17 ft at location SR-25 (fig. 45). Overall, this trend is consistent; sand deposits thicken offshore as seen in figure 26. Sand is also thicker on the easternmost ridge where it is over 8 ft thick (fig. 45). However, two other highs, the westernmost ridge in the center of the area and the high at the northern boundary of the target area are paleohighs (fig. 44). As depicted in figures 26 and 27, the Pre-Holocene comes within less than 1 ft of the surface in cores SR-31 and SR-33 producing the relict topography. A thick deposit of fine sand, silt, and clay occurs in a paleolow evidenced by core SR-32 (fig. 44). The Pre-Holocene was also encountered in cores SR-29, SR-30, and SR-27.

Overall, the area could yield as much as 139 million yd^3 sand for use in beach nourishment projects. Nourishment projects using sand from target area 2 would require an overfill factor of 1:1.41 for Dauphin Island, 1:3.25 for Little

Lagoon, and 1:1.68 for Perdido Pass. As a result, the volume of sand required from this area for replenishment of Dauphin Island is 2.6 million yd^3. Replenishment for Little Lagoon and Perdido Pass would require 130,000 yd^3 and 201,600 yd^3, respectively. Aesthetic quality is fairly high, with sand color ranging from light gray to pale yellow (table 11).

TARGET AREA 3

Sand resource target area 3 is located offshore approximately 8 mi from the west end of Morgan Peninsula in the eastern shelf region (fig. 12). The area encompasses almost 35 square miles and extends from approximately 2 to 8 mi offshore. Water depths range from a maximum of 60 ft at the southern boundary of the area to a minimum of 28 ft on top of a sand ridge (fig. 46). The most diagnostic feature in this area is a large northeast-southwest trending shoal that extends for approximately 9 mi offshore and exhibits almost 20 ft of topographic relief. On top of the shoal are several shoreface sand ridges oriented almost perpendicular to the leading edge of the shoal. Relief on the ridges ranges from about 4 to 8 ft. Vibracoring and bottom sampling efforts were directed at characterizing the shoal and the largest of the shoreface ridges in the center of the area (fig. 46).

Surface samples indicate the area is blanketed by medium to fine sand. Sand content decreases dramatically landward of the leading edge of the shoal where water depths drop abruptly (fig. 47). Grain size characteristics of the core samples are shown in table 11. Sand content averages over 96 percent with silt and clay averaging 1.74 percent and 1.96 percent, respectively. The maximum average sand content is 98.88. The average mean grain size is slightly finer than areas 1 and 2 at 2.08 Ø (fine sand). Mean grain size ranges

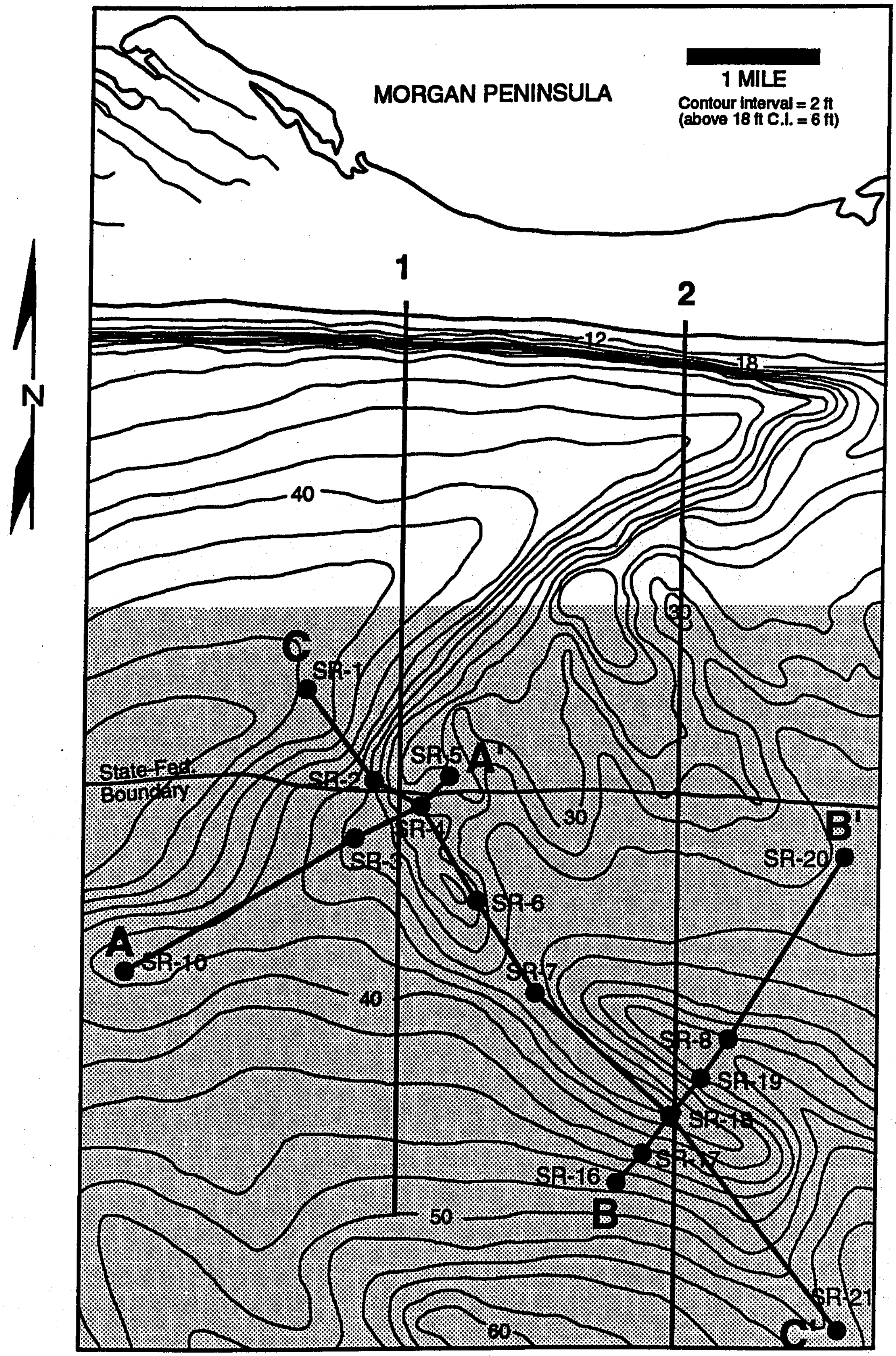


Figure 46.--Map of sand resource target area 3 showing location of cross sections (A-A', B-B', and C-C') and bathymetric profiles (1 and 2).

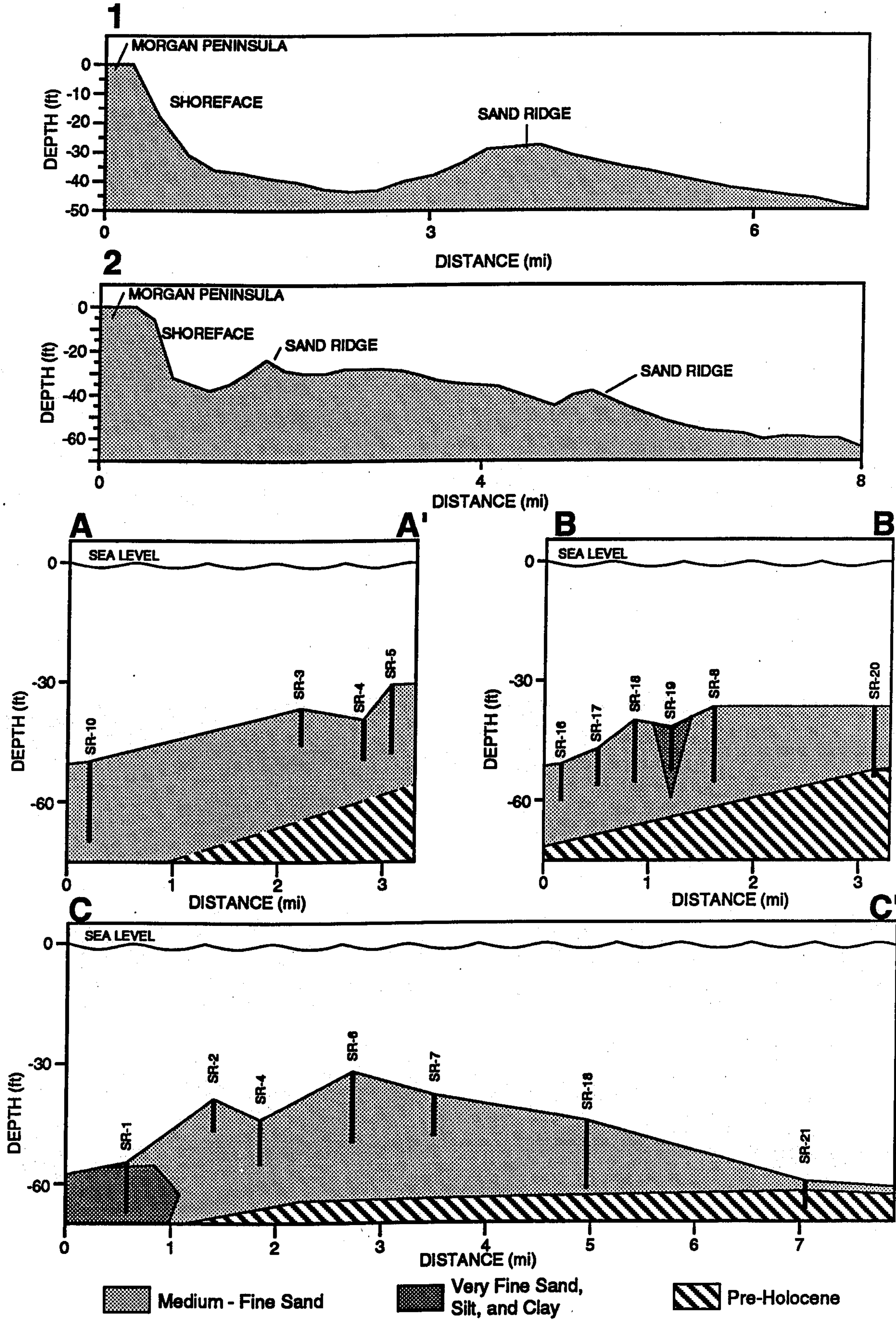


Figure 47.--Bathymetric profiles and cross sections in sand resource target area 3.

from 1.05 Ø (medium sand) to 2.86 Ø (fine sand). Sorting averages 0.92 Ø (moderately sorted) and ranges from 0.61 Ø (moderately well sorted) to 1.37 Ø (poorly sorted). The combined averages of silt and clay are less than 4 percent. Above average silt and clay percentages occur in cores SR-1, SR-8, and SR-19.

The average thickness of sand in the area was difficult to determine since most of the cores bottomed out in sand and did not penetrate the Pre-Holocene sediment. Based on the core data, sand thickness averages greater than 10 ft (table 11). Sand thickness reaches a maximum of over 19 ft in core SR-10 and a minimum of less than 1 ft in core SR-19 (figs. 47, 48). The thickest sand deposits are associated with the shoal and the sand ridges where sand is generally over 12 to 15 ft thick. Sand tends to thin offshore away from the shoal as seen in figure 47. Material unsuitable for beach nourishment was encountered in cores SR-1 and SR-19; most of these cores consisted of fine sand, silt, and clay (fig. 47). Core SR-21 contains 2.3 ft of sand and penetrated well into the Pre-Holocene.

Target area 3 has the potential to yield over 198 million yd^3 of sand for shoreline replenishment. Based on the composite mean grain size and sorting in the area, overfill factors were estimated at 1.42 for Dauphin Island shoreline, 3.6 for Little Lagoon, and 1.9 for Perdido Pass. These figures indicate that sand volume requirements from target area 3 would be 2.6 million yd^3 for Dauphin Island, 144,000 yd^3 for Little Lagoon, and 228,000 yd^3 for Perdido Pass. Sand color in the area ranges from light gray to light yellowish brown and would likely be suitable to maintain aesthetic quality (table 11).

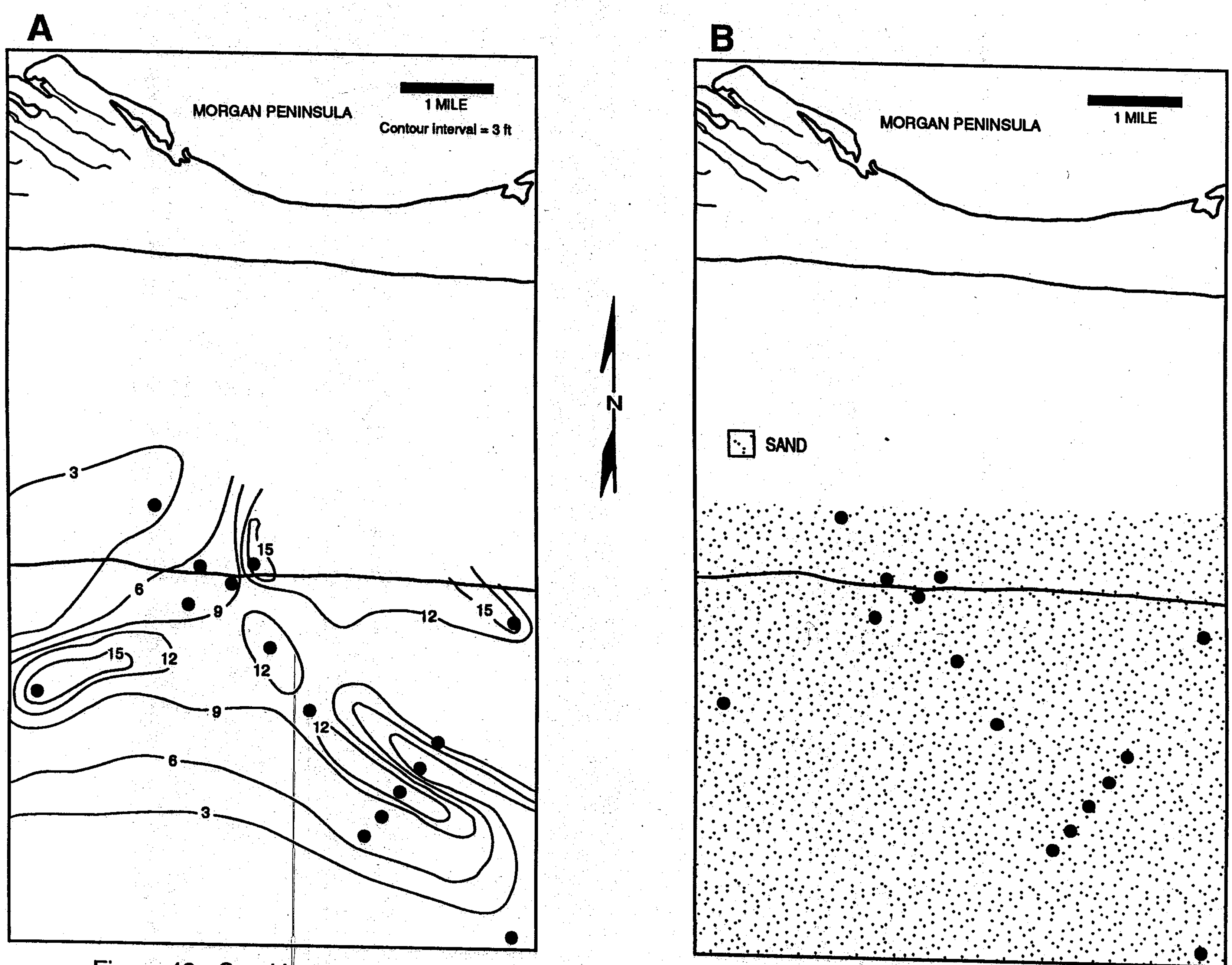


Figure 48.--Sand isopach (A) and surface sediment texture (B) maps for sand resource target area 3.

TARGET AREA 4

The largest of the sand resource target areas is area 4 which is located in the western shelf region offshore of the east end of Dauphin Island (fig. 12). The area extends from approximately 4 to 11 mi offshore and encompasses over 40 square mi. Water depths range from 36 ft deepening offshore to over 60 ft (fig. 49). The area is essentially featureless morphologically with the exception of a slight rise in the eastern part of the area associated with the seaward edge of the large ebb tidal delta extending from the mouth of Mobile Bay (fig. 49). A hint of some ridge features is apparent in figure 49 near the 60 ft isobath, however; bathymetric data in this area are inadequate to delineate these features. Vibracores and bottom samples were taken to document the offshore trend in sediment type. A foundation boring was also described to supplement the vibracore data.

Much of the eastern part of the area at the distal margin of the ebb tidal delta is covered with medium to fine sand (fig. 50). Sediment fines abruptly to the west where at the surface the area is covered with clayey sand and silty sand. Grain size characteristics are shown in table 11. The average mean grain size is 1.86 Ø (medium sand), average sorting is 0.86 Ø (moderately sorted) and sand content averages almost 97 percent. Sand deposits average 96.99 percent sand, 0.85 percent silt and 2.17 percent clay. The majority of sand in the area was mapped using the foundation boring B-1. These samples were not suitable to subject to granulometric analyses; however, sand characteristics are likely similar to the sand analyzed in the vibracores.

Very little quality sand occurs throughout most of the area, however; sand volume is greatly enhanced by the large accumulation of sand associated with the ebb-tidal delta. Approximately 25 ft of sand occurs in boring B-1 (table 11).

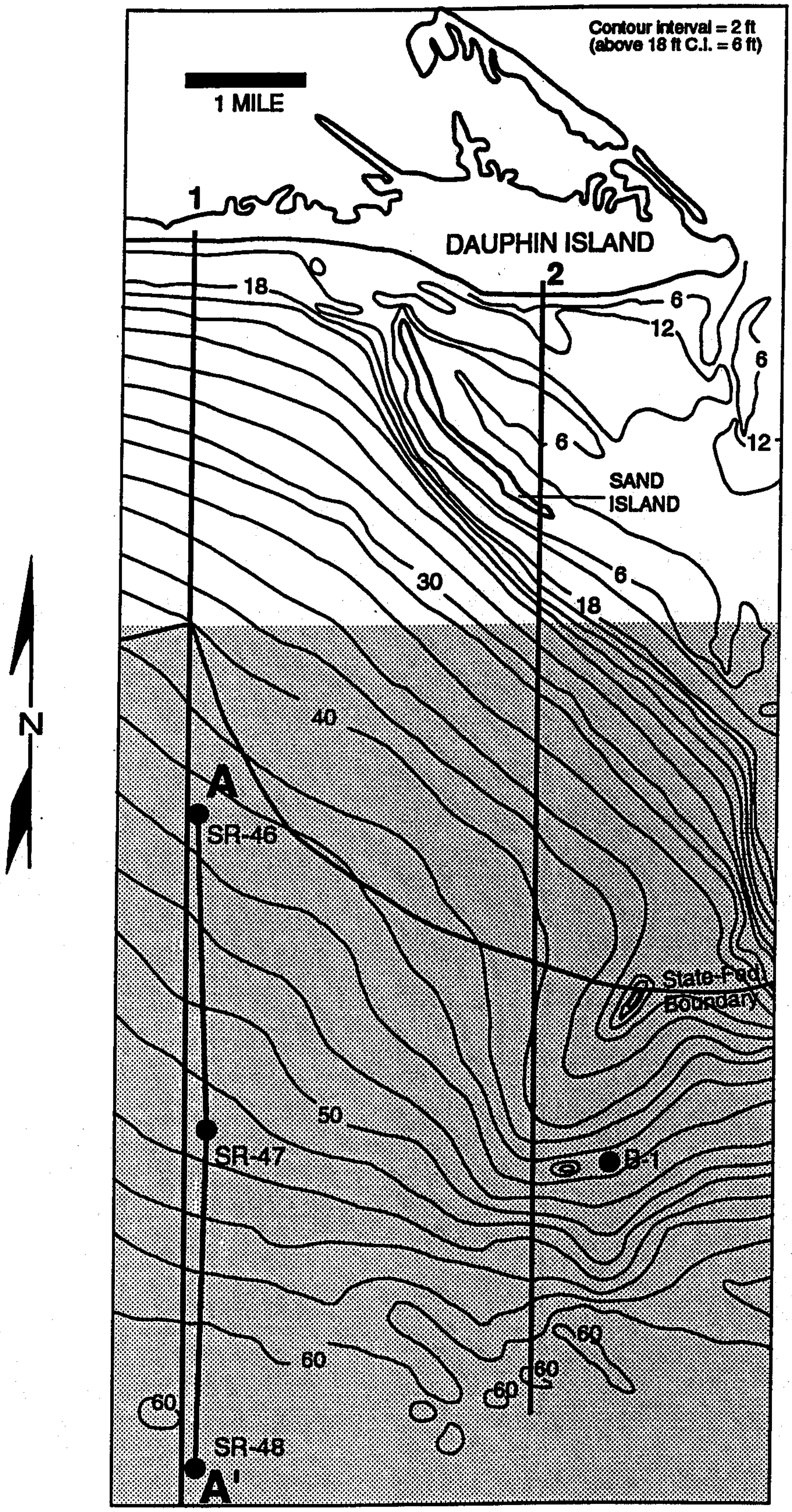


Figure 49.--Map of sand resource target area 4 showing location of cross section (A-A') and bathymetric profiles (1 and 2).

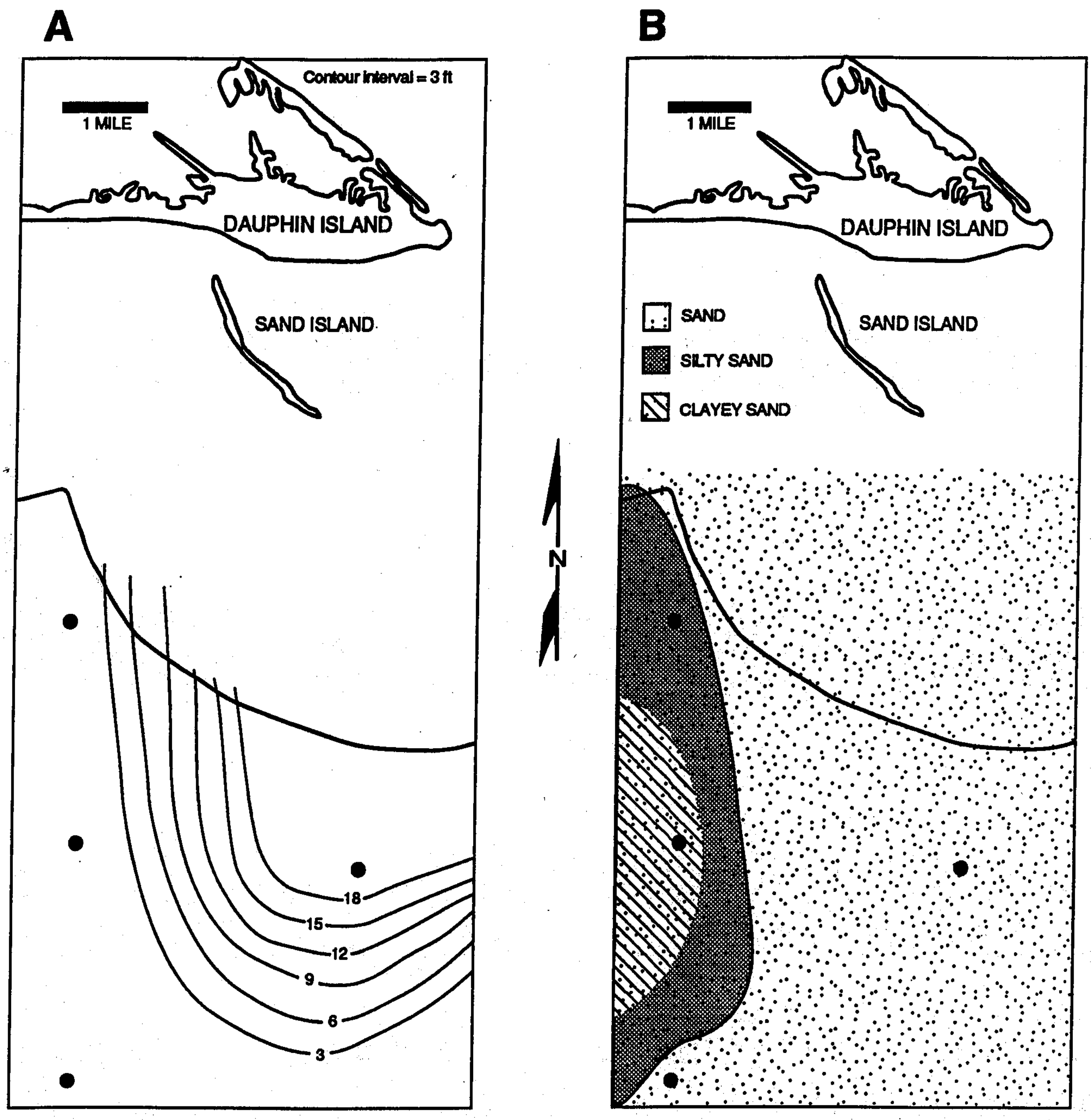


Figure 50.--Sand isopach (A) and surface sediment texture (B) maps for sand resource target area 4.

A few feet of sand occurs in cores SR-46 and SR-47 but over 2 ft of fine sand, silt, and clay overlies these deposits (fig. 51). Although medium to fine sand occurs at the surface at location SR-48, the sand is less than one ft thick. Much of the western part of the area contains sediment likely unsuitable for beach nourishment.

Target area 4 is immediately south of the eroding Dauphin Island shoreline, and could yield an estimated 143 million yd^3 of sand for replenishment. Grain size data indicate an overfill factor of 1.3 for Dauphin Island, inferring that 2.4 million yd^3 of sand would be required from target area 4 for restoration of the Dauphin Island shoreline. An overfill factor of 2.7 was estimated for the Little Lagoon shoreline indicating that 174,000 yd^3 would be required to restore this shoreline. Restoration of Perdido Pass would require 174,000 yd^3 based on an overfill factor of 1.45. The color of the sand deposits in area 4 is typically light brownish gray.

TARGET AREA 5

Sand resource target area 5 occurs at the western boundary of the study area in the western shelf region (fig. 12). The area is located offshore of the western end of Dauphin Island extending from 3.5 to 7.5 mi offshore south of Petit Bois Pass. The area encompasses approximately 17 mi^2. Water depths range from a minimum of around 40 ft to a maximum around 60 ft (fig. 52). The morphology of the area is characterized by one large prominent ridge in the center of the area exhibiting a relief of 10 ft. Vibracoring and bottom sampling efforts were focused on characterizing this ridge (fig. 52).

Based on vibracore and bottom sample data the surface is covered with medium to fine sand (fig. 53). Grain size characteristics in table 11 indicate the

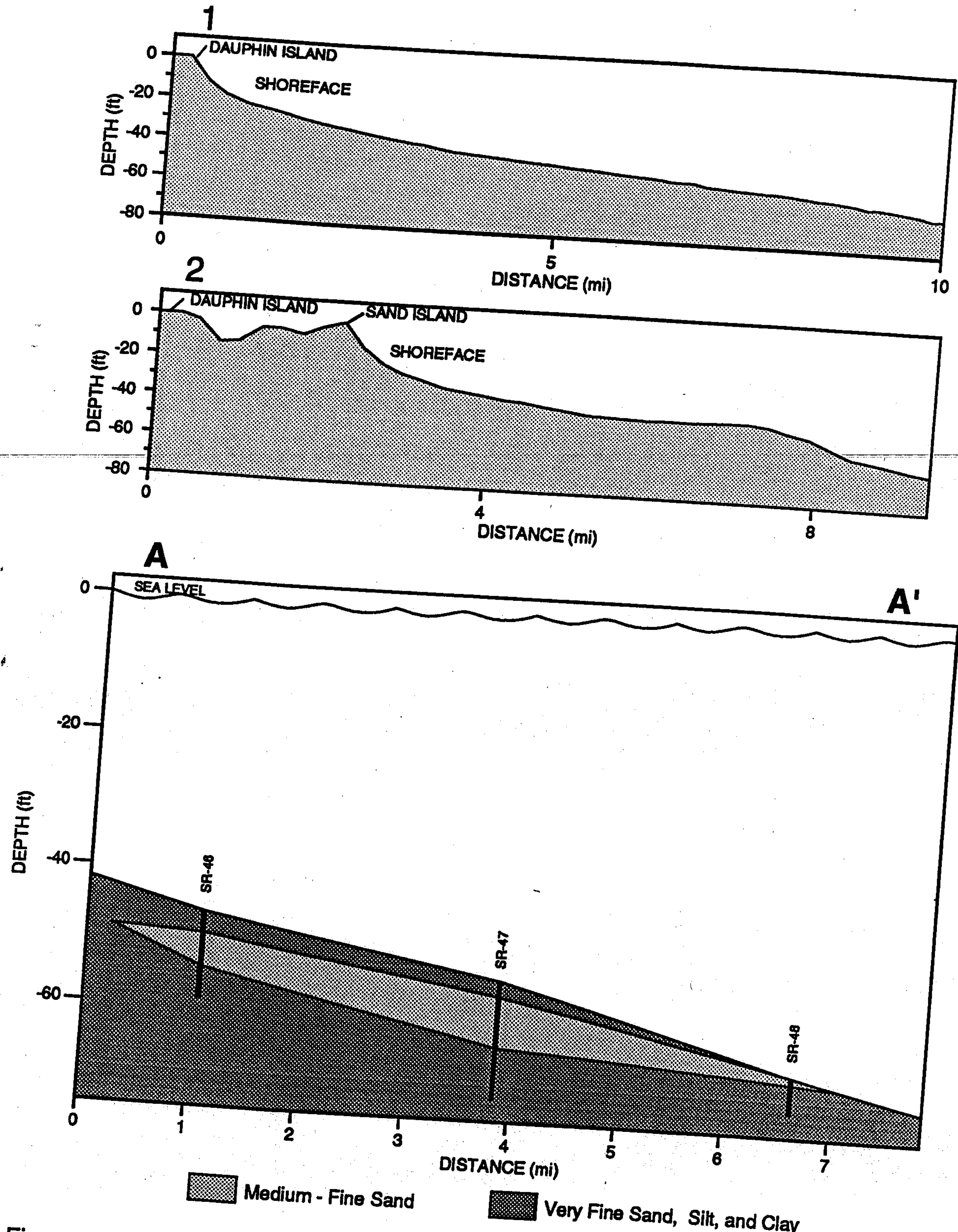


Figure 51.--Bathymetric profiles and cross section in sand resource target area 4.

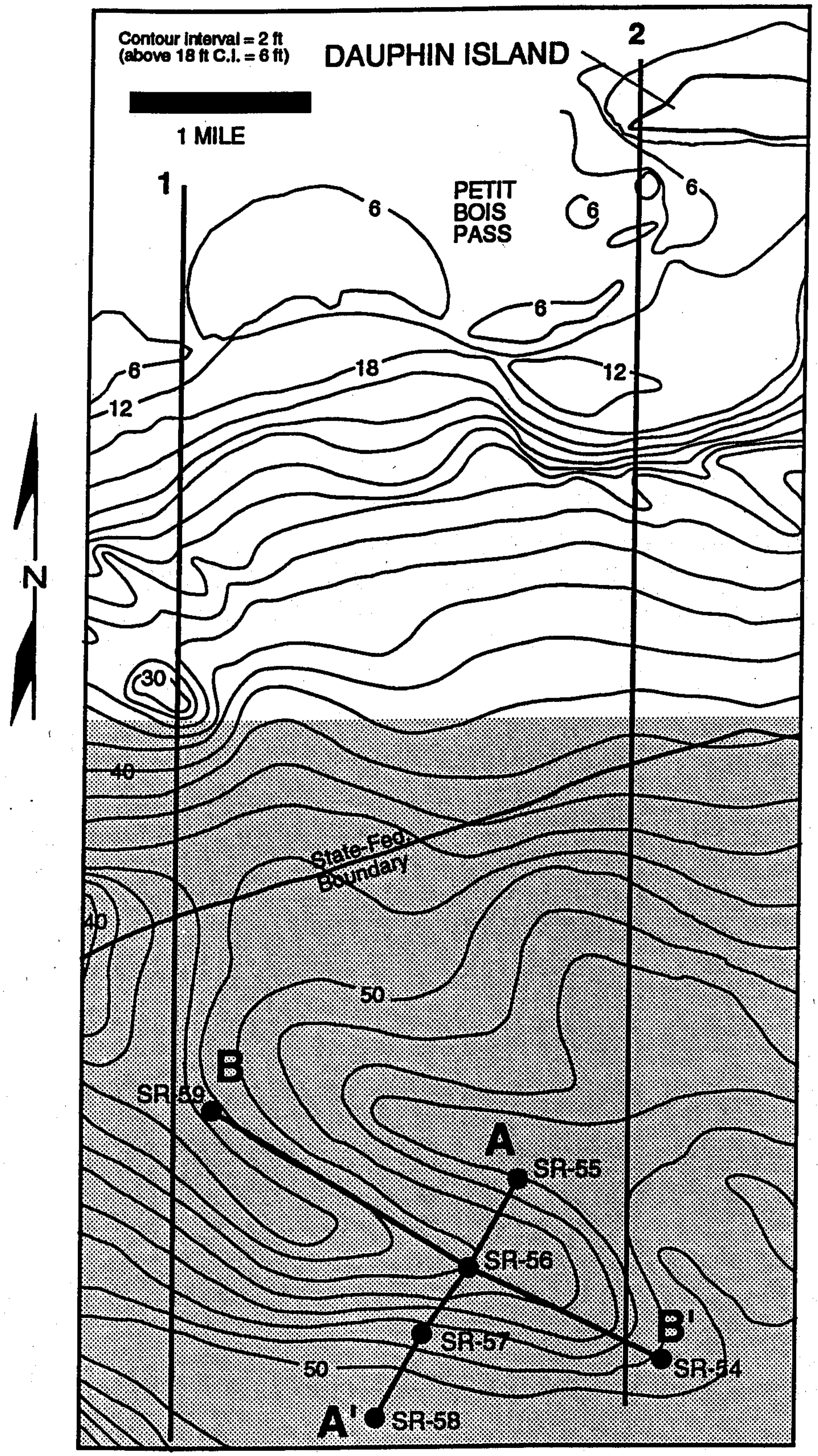


Figure 52.--Map of sand resource target area 5 showing location of cross sections (A-A' and B-B') and bathymetric profiles (1 and 2).

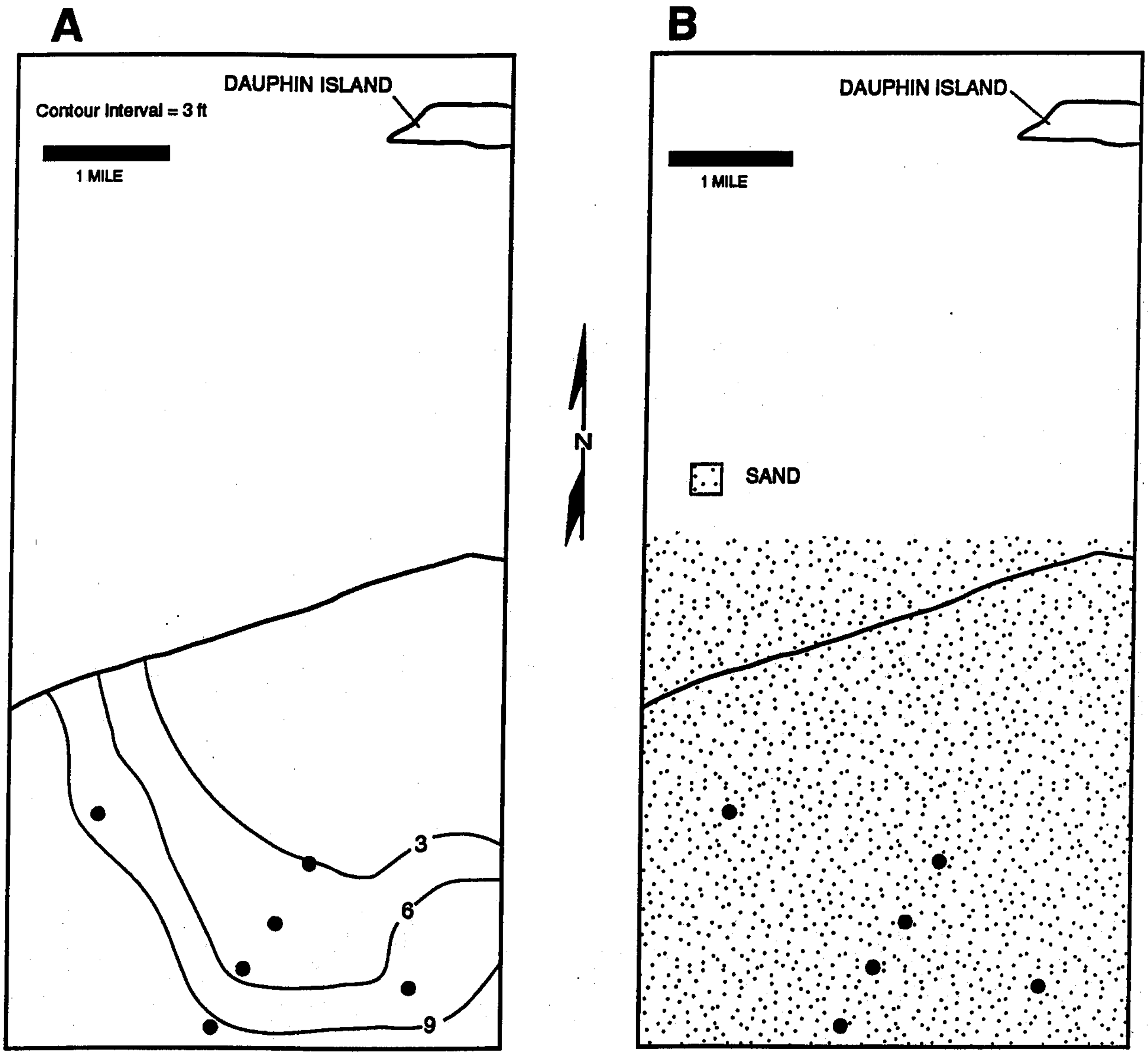


Figure 53.--Sand isopach (A) and surface sediment texture (B) maps for sand resource target area 5.

average mean grain size of the sand deposits is 2.00 Ø (fine sand) and average sorting is 1.32 Ø (poorly sorted). Mean grain size ranges from 1.28 Ø (medium sand) to 2.46 Ø (fine sand). The average sand content is 90.1 percent and ranges from 84 to over 98 percent. The average sand content is considerably lower compared to the other areas and consequently the average combined silt and clay content is over 10 percent. They contain on average 4.29 percent silt and 5.62 percent clay.

Sand thickness averages greater than 7.2 ft based on core data; however the exact thickness was difficult to determine since none of the cores penetrated the Pre-Holocene and only one (core SR-55) encountered material other than medium to fine sand (fig. 54). Although figure 54 shows a thickening of sand associated with the ridge and medium to fine sand throughout core SR-56, this core contained clasts of Pre-Holocene material throughout and the total sand volume is less than 3 ft. However, the core data seems to indicate the ridge contains primarily sand. Core SR-55 encountered a thick deposit of fine sand, silt, and clay that may not be suitable for beach nourishment. The thickness of sand tends to increase offshore but remains fairly constant along the ridge crest (fig. 54).

Target area 5 contains an estimated 79 million yd^3 of sand that could potentially be used in beach replenishment. The overfill factor for this area is the highest among the offshore target areas equaling 1.65 for the Dauphin Island shoreline. As a result, over 3 million yd^3 of sand would be required from area 5 to restore the Dauphin Island shoreline. Perdido Pass shoreline would require 288,000 yd^3 of sand for restoration based on an overfill factor of 2.4 and the restoration of Little Lagoon would require 116,000 yd^3 of sand based on an overfill factor of 2.9. Sand color in area 5 is generally light brownish gray and is likely suitable to maintain aesthetic quality (table 11).

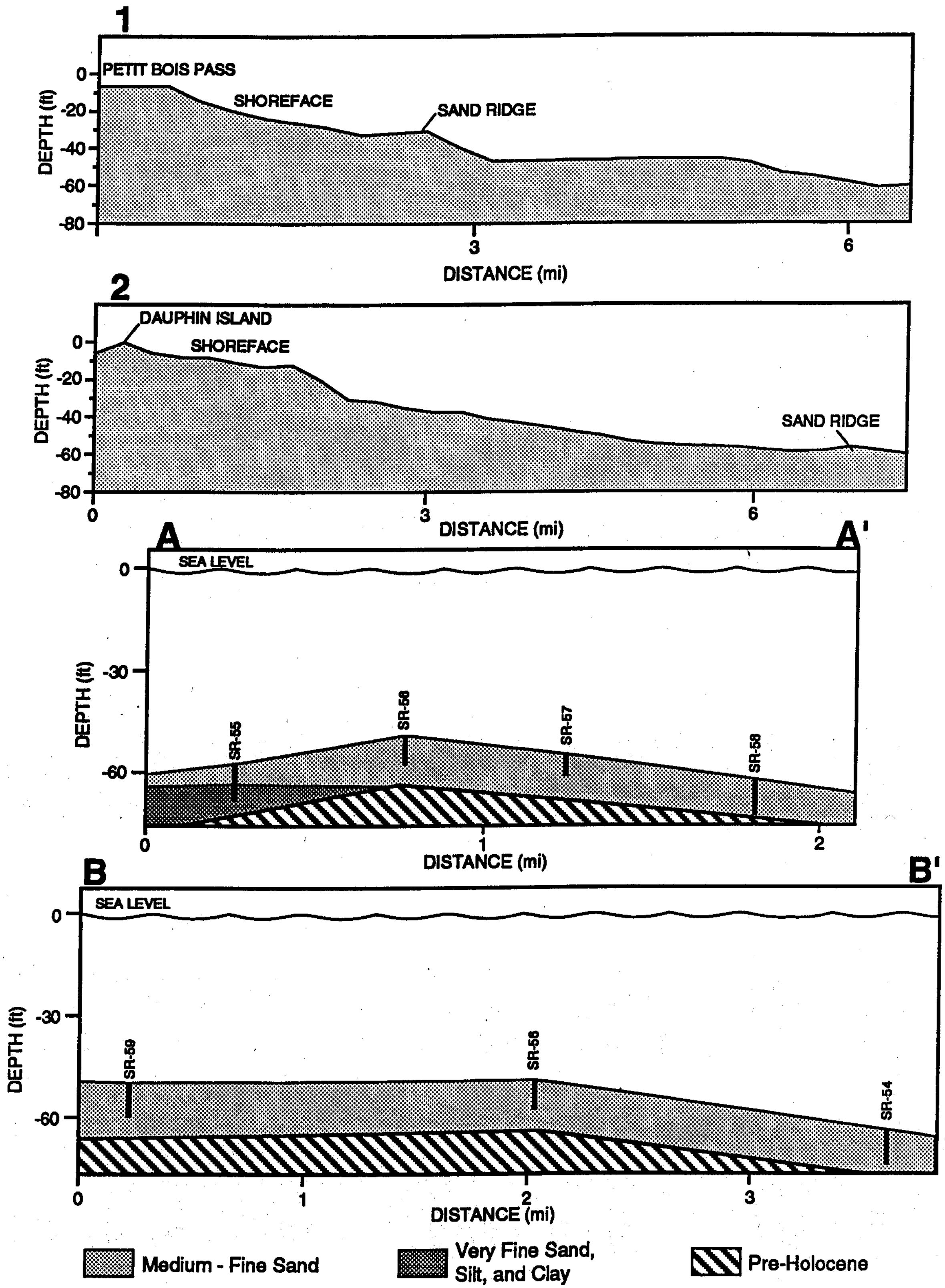


Figure 54.--Bathymetric profiles and cross sections in sand resource target area 5.

POTENTIAL ONSHORE SAND RESOURCES

One potential alternative source of beach replenishment sand for coastal Alabama is the sequence of onshore Cenozoic sediments in Mobile and Baldwin Counties (fig. 3). Some of the formations that crop out in these counties contain significant amounts of sand that could be utilized for beach nourishment, if their color and grain size are appropriate. This study evaluated the suitability of some of those units (task 7).

GEOLOGIC CHARACTERIZATION OF ONSHORE SAND RESOURCE SITES

Most onshore sand production from Coastal Alabama is from the Citronelle Formation (Dean, 1990) (table 1). In 1990, a total of four locations in Baldwin County produced sand from the Citronelle Formation; one of these also produced from the Miocene Series undifferentiated. Production per site ranged from 4,000 to 61,000 tons (2,600 to 40, 600 yd^3, based on a tonnage factor of 1.5 tons/yd^3) for a total production of 124,000 tons (82,600 yd^3) of sand from Baldwin County in 1990. Twenty three sites produced sand from Mobile County; 21 were from the Citronelle Formation and two were from the Quaternary alluvial, coastal and low terrace deposits. Per site production ranged from 2,000 to 101,000 tons (1,300 to 67,000 yd^3). Total Mobile County sand production was 761,000 tons (507,000 yd^3) in 1990. Dean (1990) gives yearly production figures for sand, sand and clay, and sand and gravel for these two counties. From 1980 through 1990, Mobile County averaged production of 1.17 million tons of sandy sediment per year; the range was from 0.76 to 1.70 million tons. Baldwin County averaged 187,000 tons per year, with a range from 55,000 to 870,000 tons. These figures include all sand mined (sand, sand and clay, sand and gravel), however, not just the clean sands appropriate for beach replenishment.

All samples analyzed for this study were collected from the Citronelle Formation in active or inactive sand pits (app. C, table 12). An effort was made to sample only the cleanest sand deposits identified in each of the pits. The clean sand being mined was located in discrete fluvial channel-fill deposits that ranged from 2 to 10 ft thick, with overburden up to 30 ft. Many showed excellent ripple to dune cross-stratification. While some contain clean white sands (M-4, M-6), many show interbeds, overburden or non-channel facies with iron oxide staining, with outcrop colors ranging from pinkish gray to moderate reddish orange. Most samples are colored pink, while one is light yellowish (table 12). Therefore, clean white sand units are not laterally extensive, and there could be difficulties in availability of appropriate sand volumes for beach replenishment. There are local restrictions on the use of reddish sand for fill or building; for example, the City of Dauphin Island forbids its importation onto the Island. These restrictions may severely limit the use of the Citronelle sands for beach replenishment.

The Citronelle samples have a mean grain size ranging from 0.85 (coarse sand) to 2.43 Ø (fine sand), with an average mean grain size of 1.69 Ø (medium sand) (table 12). They have an average sorting of 0.82 Ø (moderately sorted), with a range from 0.53 (moderately well sorted) to 1.35 Ø (poorly sorted). All Citronelle samples are very sand-rich; sand content ranges from 96.1 to 99.4 percent with an average of 98.3 percent. Silt and clay content is therefore very low for each of the Citronelle samples, with a content of fines ranging from 0.6 to 3.9 percent. The average silt and clay content is 1.7 percent.

Table 12.--Sediment characteristics of onshore samples

Sample no.	Mean (Ø)	Sorting (Ø)	Percent sand	Percent silt/clay	Color
M-1	1.15	0.84	98.54	1.46	5YR7/4-pink
M-2	.85	1.06	99.39	.61	2.5Y813- pale yellow
M-3	1.96	.69	98.73	1.27	5YR7/4-pink
M-4	1.88	.73	98.7	1.3	5YR7/4-pink
M-5	2.43	.51	98.11	1.89	5YR7/4-pink
M-6	1.63	.78	98.85	1.15	5YR7/4-pink
M-7	2.04	1.04	96.12	3.88	5YR7/4-pink
M-8	1.68	.68	98.82	1.18	5YR7/4-pink
B-1	1.15	1.35	97.37	2.63	10YR7/8- yellow
B-2	2.13	.53	98.47	1.53	10YR7/8 -yellow

M-Mobile County
B-Baldwin County

Samples taken from sand pits in Mobile County Alabama indicate that much of the deposits, although suitable from grain size standards, would not meet the volume requirements or aesthetic quality for use in beach nourishment. Sediment characteristics are similar and an overfill factor for deposits from Mobile County was estimated at 1.21, which indicates that 2.23 million yd^3 of sand from this area would be required to restore the beaches on Dauphin Island. For Little Lagoon, 103,200 yd^3 of sand would be required from Mobile County based on an overfill factor of 2.58. The sand volume requirements for Perdido Pass equal 165,600 yd^3 from Mobile County based on an overfill factor of 1.38.

Sand deposits in Baldwin County are similar to those in Mobile County, and an overfill factor of 1.24 was estimated for this area for restoration of the Dauphin Island shoreline. This implies that 2.3 million yd^3 of sand from this area would be required to restore the beaches on Dauphin Island. An overfill factor of 2.35 was estimated for Little Lagoon shoreline indicating that 94,000 yd^3 of sand from Baldwin County would be required to restore this shoreline. The Perdido Pass shoreline would require 162,000 yd^3 of sand from Baldwin County for restoration based on an overfill factor of 1.35.

DISCUSSION

Appropriate onshore sources of clean sand for beach replenishment are very limited. Most onshore sands are not aesthetically suitable due to their pinkish color; some have inappropriate grain size characteristics. In addition, while yearly summary production figures show that together Mobile and Baldwin Counties could, in principle, produce sufficient sand for a beach replenishment site, it would be difficult to find one mining site that could produce the required sand volume. Several onshore sources would be needed. In addition, since the clean sands necessary for beach replenishment are found in ancient fluvial channels, there is little volume available; most sand volume produced is not clean sand. Overall, these deposits are not suitable for beach restoration of the Alabama Gulf shoreline

The offshore sand sources in the study area would be appropriate for beach replenishment projects. All totaled, the five target areas contain over 700 million yd^3 of high quality sand. Obviously, not all the sand from a single area would be available for development; however, all the areas contain an over abundance of sand to meet the requirements of the shoreline restoration projects identified in this study. Although the data here indicate that each offshore target area could potentially be used for nourishing each of the shoreline areas, some areas are more suitable for specific eroding shoreline segments. Offshore sand target areas 4, 3, and 2 respectively, would be most suitable for nourishing the Dauphin Island shoreline segments based on sand quality, volume and proximity to the shoreline. Offshore areas 4 and 5 best match the grain size characteristics of the Little Lagoon shoreline; however, their distance from the shoreline would likely preclude the use of sand from these areas, especially since volumes of sand in areas 1, 2, and 3 are adequate and in closer proximity. The Perdido Pass shoreline could be replenished by offshore areas 1, 2, or 3. In addition, most offshore target area sands are aesthetically compatible with present beach sands, with regard to color, since these deposits would likely turn into white sand after a short exposure on the beach. Therefore, the offshore sand bodies are a much more viable sand source than are the Cenozoic sand deposits of the onshore coastal zone.

ENVIRONMENTAL IMPACTS OF SAND MINING IN OFFSHORE ALABAMA

If EEZ offshore sand resources were to be utilized for beach replenishment in Alabama, possible environmental impacts from the dredging operation must first be determined. Three types of preliminary environmental analyses were accomplished to complete task 10 of this study: Impacts of offshore sand dredging on shelf circulation; on ongoing human marine activities; and on local biota. The first two will be evaluated in the section on "Physical Environmental Considerations"; results of a preliminary benthic survey are presented in the section "Benthic Biological Analysis".

PHYSICAL ENVIRONMENTAL CONSIDERATIONS

IMPACTS ON SHELF CIRCULATION AND SHORELINE EROSION

Alabama coastal morphology and beach wave response is largely controlled by the interplay of landward-directed waves and their resultant longshore currents. The offshore wave and current regime of any particular shoreline segment is, to a large extent, controlled by the morphology and bottom roughness of the offshore continental shelf. Much of this "bottom roughness" is the morphology of the offshore shelf sand ridges. As Herbich and others (1984) state in the preface to their work Seafloor Scour, "when a structure is {on the seafloor}, scour around the structure occurs within a short time; however, such scour is not surprising, as any object placed in water causes diversion of streamlines and acceleration and deceleration of flow around the object, which in turn causes scour or erosion". The question that must be answered prior to consideration of resource dredging is "What would be the changes in intensity and location of beach and seafloor scour or deposition if a sand ridge were significantly altered in shape?"

Such a question is not simple to answer. It requires a thorough understanding of the wave, current, and tidal regimes of an area as they vary temporally over scales of tidal cycles, lunar cycles, seasons, and climatic cycles in addition to detailed bathymetric profiling. The additional problem of predicting the frequency and intensity of summer tropical and winter extra-tropical storms is also required. These data are often poorly constrained; such is the case for the Alabama EEZ. While individual, short term reports are common for Alabama waters (e.g., Wiseman and others, 1988; Shay and Elsberry, 1987; Seim and others, 1987; Abston and others, 1987; Chuang and others, 1982), long term studies, especially those generating data for several physical oceanographic processes simultaneously, are generally lacking. If these data were sufficiently robust to estimate ranges for the parameters, then assumptions regarding them would then be mathematically modeled; presently available models are not comprehensive and thus rarely give unique or convergent solutions.

Two recent studies show methods potentially useful in addressing this issue. Byrnes and Patnaik (1991) evaluated the possible physical environmental modifications caused by sand resource dredging of Ship Shoal, a large shelf sand body on the Louisiana EEZ. They relied primarily on analyzing wave convergence or divergence caused by seafloor modification to predict changes in scour rates. They used 6.5 years of monthly average wave height and period data collected from a production platform located just offshore from Ship Shoal. They did not, however, have detailed current or storm data. Their data were modeled using RCPWAVE, a powerful wave transformation modeling program, utilizing the bathymetry as it would appear following sand dredging operations. This study indicated that Ship Shoal presently exerts a strong influence on wave propagation toward the Louisiana shoreline. However, the model results indicate that alteration of the bathymetry due to dredging activities did not appreciably increase wave convergence (i.e., areas of erosion) over large areas of the coastline. Large storm impacts could not be measured with this data set, however. Therefore, negative shoreline impacts due to dredging, at least due to non-storm waves, appeared to be minimal.

In addition, Dinnel (1988) evaluated water circulation and sediment dispersal on the Alabama, Mississippi and Louisiana EEZ. He used historical hydrographic and current meter data, and was able to delineate general flow directions on a seasonal basis. There is a general pattern of offshelf flow on the Alabama inner EEZ with a westward component most of the year. He additionally utilized long-term hindcast wave statistics to evaluate sediment resuspension and transport on the inner shelf portion of the EEZ. The normal wave regime is relatively low, and unable to transport shelf sediment. He showed that high wave conditions produce sediment resuspension for water depths less than 120 ft; highest wave conditions (durations of hours per year) will resuspend sediment in water depths up to 240 ft. Neither tidal conditions nor normal bottom currents should produce sediment transport on the inner shelf. Sediment transport on the inner shelf occurs primarily during prefrontal winds conducive to long waves and cyclonic inner shelf flow in the winter and spring.

At present, therefore, these studies indicate that under background conditions, little shelf sediment is transported; high winds and waves are necessary to move sediment or to enhance offshore dredging impact on shorelines. No Gulf studies have modeled the possible impacts on shoreline or seafloor modification from such high wind or storm impact on a modified shelf ridge morphology. Therefore, it would be essential to model hydrodynamic flow caused by modified Alabama shelf sand ridges under extratropical prefrontal wind and wave conditions, as well as hurricanes, to determine any physical environmental impacts that mining activities may produce. In order to do so, however, a presently non-existent long-term data set integrating background wave, current and tide conditions would be required. In addition, data sets on local hurricane and winter storm effects on waves, currents, and tides would be needed to supplement the background conditions data set.

IMPACTS ON ECONOMIC ACTIVITIES

The Alabama EEZ is utilized very heavily by several industries; thus impacts on marine economic activities must be carefully evaluated.

Mobile, at the head of Mobile Bay, is a major port for seagoing and inland water transport. It is the primary port linking the inland Tenn-Tom Waterway and the Mobile River System with overseas ports. The artificially maintained Mobile Ship Channel runs from the Port of Mobile through Mobile Bay and Main Pass (fig. 23). Navigation fairways extend offshore from the Pass in several directions. Any dredging or alteration of water depths would necessarily have to avoid all such navigational waterways.

Both State and Federal waters in the EEZ have high potential for hydrocarbon reserves. Most of the area has been leased for hydrocarbon exploration. There are, at present, several producing fields in the EEZ (fig. 23). Drilling and production activities entail placing on the seafloor various facilities, including drilling platforms, production platforms, wellheads, pipelines, etc. These structures require a stable substrate; removal of sand nearby would threaten their foundation stability. Therefore, any sand resource dredging must avoid all such present facilities; identification of all such locations in a proposed mining area would be essential.

Fishing, both commercial and sport, is a major industry in the Alabama EEZ. Any impact to this industry would need to be carefully delineated. Preliminary studies indicate the likelihood of only minimal impact on the industry from sand resource mining. No hardbottoms or reefs, often sites of concentrations of fishes, would be mined. Two live bottom/hardbottom sites are known to exist in the study area; however, the sites do not occur in the sand target areas (fig. 23). These areas are known to local fisherman as attractive areas for recreational fishing. Other live bottom/hardbottom sites may occur in the study area but have not been delineated. In addition, no nurseries for juveniles of economically significant finfish or shellfish are thought to exist in the proposed areas of interest. Nonetheless, additional study to evaluate these preliminary findings would be required before mining could begin.

BENTHIC BIOLOGICAL ANALYSIS

If offshore sand resources were recovered for transport to beach replenishment sites, local biota would be impacted. This is especially true of the benthic biota, those organisms that live on or in the seafloor, which would be physically displaced or killed by dredging activities. Therefore, a preliminary survey of the benthic fauna was begun in the five main study areas. The purpose was to determine the feasibility of utilizing bottom grab samples to evaluate the benthic species composition, diversity, and presence of endangered or economically valuable species in each of these study areas.

RESULTS AND INTERPRETATIONS

TAXONOMIC COMPOSITION

As indicated in table 13, a total of 485 organisms from 10 different samples was evaluated. These range from 34 to 68 individuals analyzed per split sample; thus, an estimated range of 34 to 400 individuals were present in each sample. It is not surprising that an order of magnitude variation in number of organisms is present, due to the differences between samples in sand/mud/shell content that represent different degrees of environmental stability. These physical environmental differences would be expected to be expressed in significant differences in the number and types of organisms present.

Species richness is not so variable, however; all samples are in the range of 17 to 28 species present, regardless of sample size (table 13). Sample size is therefore poorly correlated with species richness. A total of 74 different species was collected. Most are readily preservable, shelled organisms (63 species, or 85 percent of all species), while only 11 species (15 percent of all species) are soft bodied, shell-free organisms. While all samples have at least 15 shelled species, the maximum number of soft bodied species in any sample is 5, and only 3 samples have that many. One sample, in fact, contained no soft bodied organisms at all.

As is common in today's oceans, mollusks (especially pelecypods) comprise the most abundant component of the fauna, both in taxonomic diversity (species richness) and numerical abundance (table 13). Of the 63 shelled taxa, 90 percent are molluscan, including 6 percent scaphopods, 21 percent gastropods, and 63 percent pelecypods. Additionally, there are two

Table 13.--Benthic species richness and numerical abundance

Taxon	Species richness	Numerical abundance
Shelled organisms	63	415
Arthropods	2	21
Bryozoans	3	6
Echinoderms	1	4
Mollusks	58	385
Gastropods	13	36
Pelecypods	41	334
Scaphopods	4	15
Soft bodied	11	70

arthropod species (1 barnacle, 1 crab), three bryozoans, and one echinoderm (sand dollar). Of 415 preservable (shelled) organisms, a comparable percentage are molluscan (93 percent). These include 4 percent of preservable organisms being scaphopods, 9 percent gastropods, and 80 percent pelecypods. Arthropods make up 5 percent of the preservable individuals, while bryozoans and echinoderms each make up 1 percent. In comparison, all soft bodied organisms together comprise only 14 percent of individuals collected, comparable to their relative taxonomic diversity. Thus, while bivalves are certainly dominant taxonomically, they are even more dominant when shear numbers of individuals are compared.

PATTERNS IN COMMUNITY STRUCTURE

Few living organisms were collected (table 6). Only two living shelled organisms were tabulated, one pelecypod and one scaphopod. Together, this is fewer than 0.5 percent of all shelled organisms sampled. Both were small (4 to 8 mm). Conversely, 43 percent of all soft bodied organisms were collected live (30 of 70). These represent shallow infaunal worms with, presumably, high turnover rates. Overall, 7 percent of all organisms collected were live. Therefore, apparently few organisms are alive on the mobile sand ridges at any one time; those that are dominantly common soft bodied worms with short life spans.

There were few organisms collected per unit area of seafloor. A combined area of approximately 5.5 square ft was sampled for the 10 samples. This represents a total of 6.1 living organisms per square ft (ft^{-2}) (5.7 soft bodied ft^{-2} and 0.4 shelled organisms ft^{-2}). This is a low figure compared to some bay and mudflat environments (as reviewed in Powell and others, 1989). Short term fluctuations in organism abundance are also expected (Glemarec and Menesguen, 1980). An estimate of total living plus preserved "new" and "old" dead organisms present in the sampled area (1378 individuals, table 3) shows a density of approximately 262 individuals ft^{-2}.

None of the species collected, live or dead, is considered to be an endangered or even rare species. Most are common constituents of inner shelf to nearshore benthic assemblages in the Gulf of Mexico. Therefore, even if local populations were impacted by sand removal activities, recruitment from nearby populations would likely lead to a return to fluctuating background population levels within a few years. Most are common epifaunal to shallow infaunal species, which is to be expected in areas of mobile sand. Some species collected dead represent lower salinity nearshore to estuarine conditions; it is assumed that these are either very old shells, representing conditions long since absent, or abnormal low salinity excursions that would lead to only very temporary settlement. Only one economically valuable species was collected, *Crassostrea virginica* (the edible oyster); however, it was not common, and the oyster shell fragments were discolored and presumably very old. Therefore, no oyster reefs would be expected in this high salinity area, nor have any ever been documented.

Since most of the organisms collected were dead, it is important to evaluate whether these organisms died very recently (e.g., within the last few months), fairly recently (e.g., years to decades), or whether they represent a different fauna that may have lived under conditions no longer present (e.g., perhaps centuries or longer ago). One method of determining relative time since death is to look at attributes of shell preservation, for example whether bivalves are disarticulated; or whether shells are discolored, broken, or show other signs of postmortem alteration. In general, articulated bivalves are quite "new" (days to months since death); blackened or discolored shells are always "old" (a minimum of many decades since death); however, fresh looking shells may be either "new" or "old" (Powell and Davies, 1990). Few (2 percent) dead pelecypods are articulated (app. D) and thus must have died very recently. Fifty five percent of all dead shelled organisms look "old" (table 5); this is a minimum estimate of the relative abundance of "old" shells, as some of the "new" looking shells undoubtedly are also old. Therefore, well under half of the shelled individuals could have been alive recently. That is not true for the soft bodied organisms, however. Not surprisingly, these organisms are poorly preserved for long periods of time; none of these individuals showed any indication of being "old" (table 5). Overall, at least 48 percent of all individuals collected must be "old"; in fact, a much greater percentage probably is.

Most species collected may also have been alive in the near past. This study collected at least one individual that appeared to be "new" from 68 percent of all shelled species. By including the recently living soft bodied organisms, 72 percent of all species included at least one "new" looking individual (table 6). Therefore, even though most species were not collected alive in this study, there is a reasonable chance that a species has lived at that station within the last few decades, assuming at least some of its dead individuals still look "new".

A measure of whether most shell material is whole or fragmented may, possibly, give some indication of the time since death. The older the shell, the more likely that it has been broken. Certainly, the longer a shell sits near the sediment surface, subject to continual reworking, the more likely it will be broken (Davies and others, 1989a). Most shells analyzed for this study were whole shells (78 percent), rather than fragments (table 5). This is partly an artifact of the laboratory protocols (e.g., table 4), which ensures that only one fragment per individual will be counted, and thus one broken specimen cannot dominate the entire sample. Therefore, many species were abundant as fragments in the thanatocoenosis (for example, comminuted pieces of sand dollars); however, these were commonly not tabulated, as few whole specimens or complete mouths were present. Undoubtedly, the conservative nature of these protocols underestimated total species richness to some extent. It should be noted, however, that this likely will not significantly alter the overall results, as no shelled species were collected live but not dead.

Many fewer soft bodied organisms were collected whole (27 percent, table 5). This is not surprising, as the sea floor sampling and sieving procedures are very destructive for organisms containing no durable or hard parts. It is assumed that most disarticulation of these organisms occurred during sampling, not by natural processes. Therefore, for soft organisms the percentage of whole organisms is not an indication of the relative age of the deposit; all individuals are assumed to have died within the last few years (more likely, the last few months).

Overall, most organisms collected were small. The most common size class was 4 to 6 mm (8 of 10 samples, table 5), representing 165 organisms (table 14). This trend of small size dominance is produced by the much higher abundance of shelled organisms, which were on average much smaller than soft bodied organisms (table 5). Eighty five percent of all shelled organisms were less than 1 cm in size; fewer than 3 percent were larger than 2 cm. In contrast, only 13 percent of soft bodied organisms were less than 1 cm in size, and 44 percent were larger than 2 cm. Size frequency distributions of shells from most samples show a near exponential decrease in shell abundance with increasing size (figs. 55, 56); only sample SR-46 BG shows a near normal distribution (fig. 57). This exponential decrease is very obvious for combined

Table 14.--Shell and soft-bodied organism size frequency data

Sample	4 to 6 mm	6 to 8 mm	8 to 10 mm	10 to 15 mm	15 to 20 mm	20 to 30 mm	30 to 40 mm	40 or more mm
SHELLS								
SR-16 BG	13	10	8	11	0	0	0	0
SR-18 BG	22	9	5	5	0	0	0	0
SR-32 BG	16	9	4	1	0	0	2	0
SR-36 BG	19	16	3	1	0	0	0	0
SR-39 BG	17	10	0	1	0	0	0	0
SR-43 BG	14	14	1	2	1	1	0	0
SR-46 BG	9	14	21	19	1	0	0	0
SR-48 BG	22	14	11	3	0	0	0	0
SR-54 BG	17	9	7	5	2	1	0	0
SR-56 BG	16	12	9	4	1	0	0	0
Total	165	117	69	52	5	1	2	0
SOFT BODIED								
SR-16 BG	0	0	0	15	0	3	1	7
SR-18 BG	0	0	0	1	1	0	0	0
SR-32 BG	0	0	0	0	0	2	0	0
SR-36 BG	0	1	1	2	0	0	1	0
SR-39 BG	0	0	0	0	0	1	0	13
SR-43 BG	0	0	1	0	1	0	0	0
SR-46 BG	0	0	0	0	0	0	0	0
SR-48 BG	1	0	0	3	1	0	0	0
SR-54 BG	0	1	0	1	5	1	0	1
SR-56 BG	0	2	2	0	0	0	1	0
Total	1	4	4	22	8	7	3	21

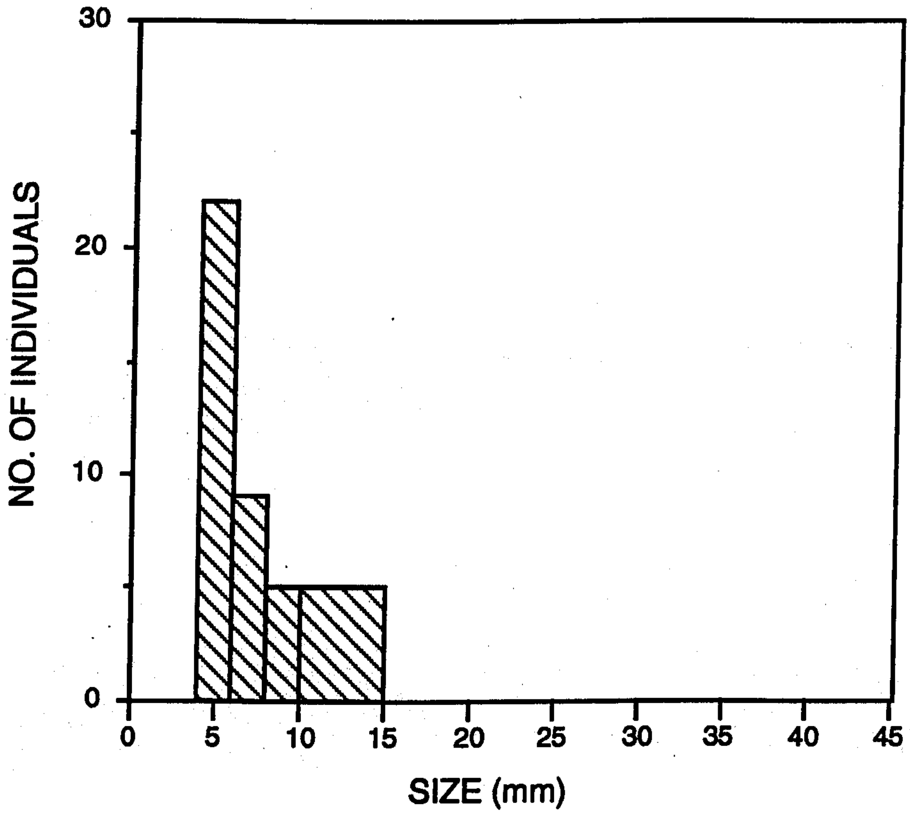


Figure 55.--Shell size frequency, SR-18 bottom grab.

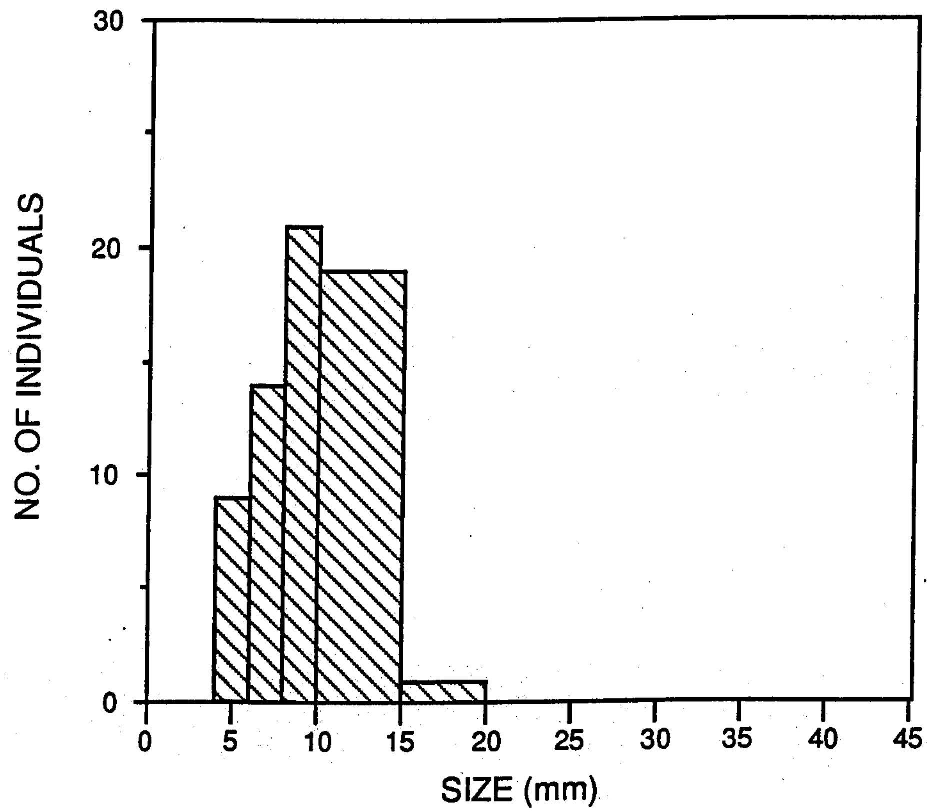


Figure 56.--Shell size frequency, SR-46 bottom grab.

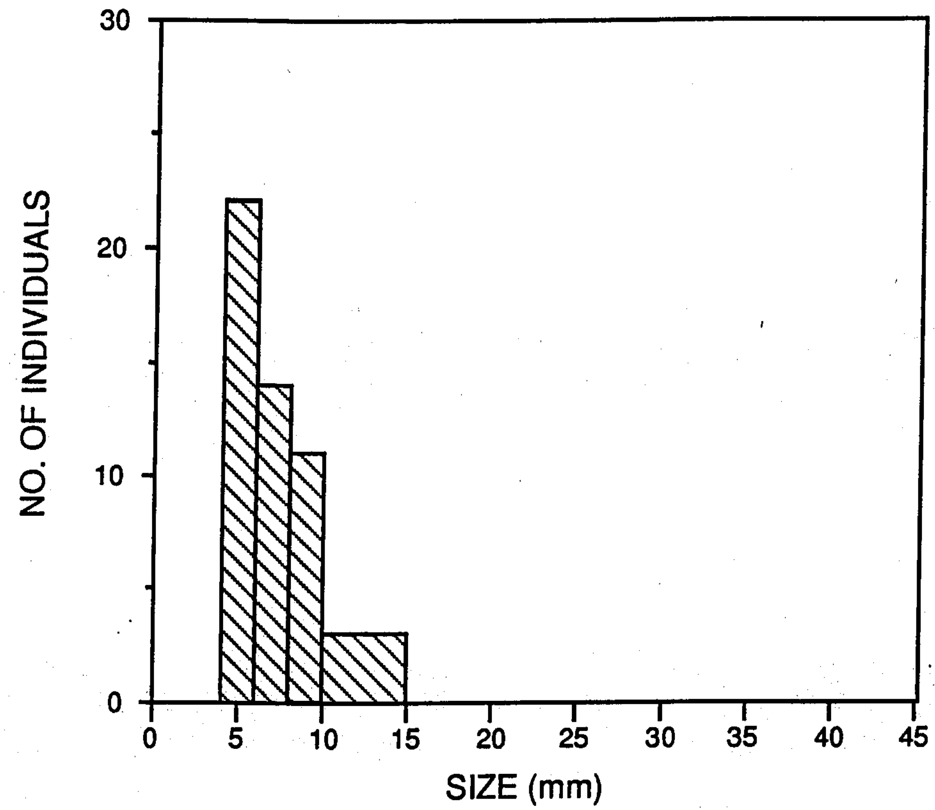


Figure 57.--Shell size frequency, SR-48 bottom grab.

shell samples (fig. 58). Such a pattern of decreasing abundance with increasing size indicates high juvenile mortality, typical of (among other things) unstable environments (Raup and Stanley, 1978; Mancini, 1978). The fine sand ridges of this study with their postulated high sediment mobility would certainly be classified as an unstable environment with a poor interstitial fauna from the standpoint of benthic community analysis (Webb and others, 1976). Therefore, it is reasonable to assume that many of the species present may not typically survive to adulthood, but are found in this unstable environment only as juveniles. Reproductive populations of these species would not be jeopardized by mining. Other common species are small, indicating the likelihood of a short life span, and thus the probability of rapid recovery of population levels following the conclusion of dredging.

BENTHIC FAUNAL TRENDS

This preliminary study indicates that there are relatively few living large benthic organisms in the areas of interest. Most living organisms are soft bodied worms; much of the shell material is "old". No endangered or economically important species were found alive or recently dead. Shell condition, species richness, and size frequency distributions all support the hypothesis that few adult organisms presently live in this postulated unstable substrate; therefore impacts on benthic species from dredging activities would appear to be limited. Nonetheless, this is a very preliminary pilot study; much additional work (including properly designed strategies of dredging, trawling for nektonic fishes, and box coring for deep infauna, Dayton and Oliver (1980),) would be necessary to confirm or contradict these findings prior to any commercial resource utilization.

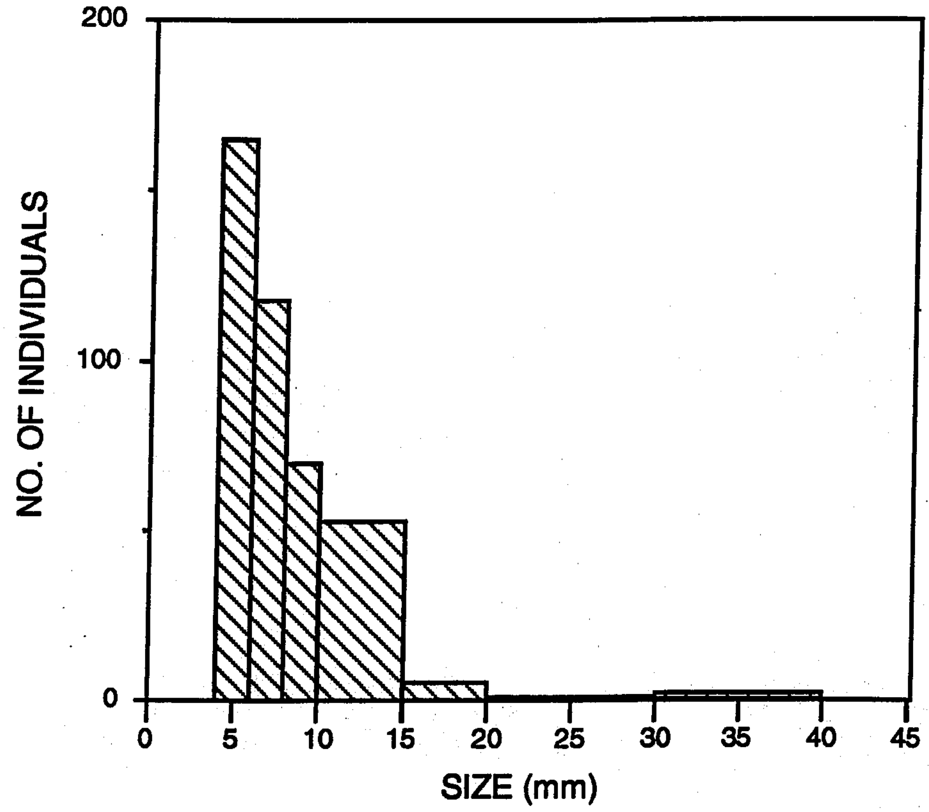


Figure 58.--Composite shell size frequency of EEZ bottom grabs.

ECONOMIC EVALUATION

To evaluate the feasibility of near-term leasing of offshore sand deposits, information from this report was used to define the geologic and engineering parameters needed to perform a detailed economic analysis of the three identified beach nourishment projects. Other required engineering and cost parameters were obtained from a report by the Louisiana Geological Survey entitled, "Characterization of the Development Potential of Ship Shoal Sand for Beach Replenishment of Isles Dernieres."

SAND SOURCE SITE SELECTION

In order to determine the geologic and engineering parameters needed as inputs for QUIKSAND, the first step was to compile data pertinent to each of the five identified sand source areas. This information is displayed in Table 15. All table entries, with the exception of "Over Fill Factor," are self explanatory. Simply stated for purposes of this report, the over fill factor is the estimated number of cubic meters of fill material required to produce one cubic meter of beach material when the beach is in a condition compatible with the native material (after the winnowing processes). In consideration of this and other factors, such as proximity to project sites, workable area outside of shipping fairways, etc., Source Areas 2 and 4 were chosen. This selection set some of the geologic parameters, and also established the distance from sand source site to project site. The latter was the basis for calculation of the dredge and deposit round trip sail time and hence the dredge rate parameter.

Table 15.--Sand source area

		Source Area 1	2	3	4	5
Water Depth Range (Feet)		28 - 48	32 - 60	28 - 60	36 - 60	40 - 60
Estimated Quantity of Sand (Million Cubic Yards)		164	139	198	143	79
Sand Thickness (Feet)	Range	4.0 - 13.0	0.3 - 17.2	2.4 - 18.9	0.7 - 25.0	4.9 - 9.5
	Average	10.0	6.2	10.2	10.1	7.2
Percent Sand		96.55%	97.39%	96.28%	96.91%	90.1%
Overfill Factor	Dauphin Island Project 1.85 Million Cubic Yards	1.47	1.41	1.42	1.30	1.65
	Little Lagoon Project 0.04 Million Cubic Yards	4.00	3.25	3.60	2.70	2.90
	Perdido Pass Project 0.12 Million Cubic Yards	1.75	1.68	1.90	1.45	2.40
Comments		Shipping fairway covers approx. 35% of area. Some cores with pre-Holocene material not good for beach replenishment.	Shipping fairway covers approx. 30% of area.	Shipping fairway covers approx. 30% of area. Some cores with pre-Holocene material not good for beach replenishment.	Shipping fairway covers approx. 60% of area.	Shipping fairway covers approx. 35% of area.

ECONOMIC ANALYSIS

The cost and engineering parameter value used in the model were derived from information contained in the Louisiana Geological Survey Report and applied to three dredging methods which are outlined as follows:

1. Utilize an existing 16,000-yd^3 hopper barge dredge using a direct pump-out discharge through a single-point mooring buoy and a submerged pipeline to transport the sand to shore.

2. Utilize two existing 1,300-yd^3 hopper dredges using a direct pump-out discharge through a single-point mooring buoy and a submerged pipeline to transport the sand to shore.

3. Utilize two existing 1,300-yd^3 hopper dredges to mine the sand and dump it close to shore where a pipeline dredge would rehandle the sand and transport it to shore through a pipeline.

These allocated cost parameters represent fixed cost and operating cost. In handling the fixed-cost parameters, each project site was assigned a prorated share based on the sand volume which must be mined in order to satisfy the sand volume requirements for the project site. Table 16 displays these fixed and operating costs for the above three mining methods.

For Method 1, the dredge operating cost is \$1.70/yd^3; the commodity transportation cost is \$0.41/yd^3; and the prorated share of the fixed cost (in \$/yd^3) is approximately as follows: Barge and pipeline cost \$0.25/yd^3, dredge

Table 16.--Fixed cost and operating cost

Method	Sand Source Area	Project Site	Number of Dredges	Project Volume Prorated Share of Fixed Cost Parameters in Dollars			Operating Cost $ / cu. yd.	
				Dredge Transportation and Storage	Barge/ Pipeline	Mobilization Cost	Dredge	Transportation Range of Values Min, ML, Max
1 16,000 Cubic Yard Hopper Dredge with Direct Pumpout Discharge	2	Dauphin Island	1	90,000	720,000	450,000	1.70	0.31, 0.41, 0.51
		Little Lagoon	1	4,000	32,000	20,000	1.70	0.31, 0.41, 0.51
		Perdido Pass	1	6,000	48,000	30,000	1.70	0.31, 0.41, 0.51
	4	Dauphin Island	1	90,000	720,000	450,000	1.70	0.31, 0.41, 0.51
		Little Lagoon	1	4,000	32,000	20,000	1.70	0.31, 0.41, 0.51
		Perdido Pass	1	6,000	48,000	30,000	1.70	0.31, 0.41, 0.51
2 Two 1,300 Cubic Yard Dredges with Direct Pumpout Discharge	2	Dauphin Island	2	90,000	720,000	81,000	2.04	0.32, 0.42, 0.52
		Little Lagoon	2	4,000	32,000	3,600	2.04	0.32, 0.42, 0.52
		Perdido Pass	2	6,000	48,000	5,400	2.04	0.32, 0.42, 0.52
	4	Dauphin Island	2	90,000	720,000	81,000	2.04	0.32, 0.42, 0.52
		Little Lagoon	2	4,000	32,000	3,600	2.04	0.32, 0.42, 0.52
		Perdido Pass	2	6,000	48,000	5,400	2.04	0.32, 0.42, 0.52
3 Two 1,300 Cubic Yard Dredges with Dump Discharge and Pipeline Dredge Rehandling	2	Dauphin Island	2	90,000	720,000	612,000	2.04	2.47, 2.77, 3.07
		Little Lagoon	2	4,000	32,000	27,200	2.04	2.47, 2.77, 3.07
		Perdido Pass	2	6,000	48,000	40,800	2.04	2.47, 2.77, 3.07
	4	Dauphin Island	2	90,000	720,000	612,000	2.04	2.47, 2.77, 3.07
		Little Lagoon	2	4,000	32,000	27,200	2.04	2.47, 2.77, 3.07
		Perdido Pass	2	6,000	48,000	40,800	2.04	2.47, 2.77, 3.07

towing and storage cost \$0.03/yd^3, and the mobilization of 1-16,000 yd^3 hopper barge dredge \$0.15/yd^3.

For Method 2, the dredge operating cost is \$2.04/yd^3; the commodity transportation cost is \$0.42/yd^3; and the prorated share of the fixed cost is approximately as follows: Barge and pipeline cost \$0.25/yd^3, dredge towing and storage cost \$0.03/yd^3, and the mobilization of 2-1,300 yd^3 hopper barge dredges \$0.03/yd^3.

For Method 3, the dredge operating cost is \$2.04/yd^3; the commodity transportation cost is \$2.77/yd^3; and the prorated share of the fixed cost is approximately as follows: Barge and pipeline cost \$0.25/yd^3, dredge towing and storage cost \$0.03/yd^3, and the mobilization of 2-1,300 yd^3 hopper barge dredges and 1 pipeline dredge \$0.24/yd^3.

Certain other engineering and geologic parameters were also defined for use in the QUIKSAND model. These parameters (expressed as a range of values) are: (1) Sand body area (110-116-332 acres), (2) sand body thickness (5-10-15 ft.), (3) sand recovery factor (0.96-0.97-0.98), (4) dilution factor (1.00-1.02-1.04), (5) operating days (165-185-200 days per year), (6) sand fraction (0.66-0.71-0.76) and (7) dredge rate (Method 1 - sand source area 2, 12,000-14,000-16,000 yd^3/day). Of the above parameters, sand body thickness and operating days are not tabulated. The sand body area was determined by calculating the acres required at the given thickness to yield the required project sand volume. The dredge rate also was determined by calculations which included consideration of distance from sand source area to project site, dredge capability of equipment, travel rate and pipeline connection, and pump-out times. The value of these parameters is displayed in Table 17.

Pertinent economic parameters not included with the cost and engineering parameters are those related to the discount and inflation factors. The model includes a two-tier scenario for the inflation and real-price increase factors. The two-tier approach allows more flexibility in the use of these factors. Instead of being limited to one range of projected values, two different scenarios (near-term and long-term projection) may be introduced. The timing of the introduction of these second value sets in the yearly cash flow calculations is determined by an input parameter identified as the time to second scenario. Due to the relatively short duration of the projects involved in these economic analyses, the second scenario (long-term projection) did not enter into the calculations. The economic parameters (and range of values) are: (1) interest rate (0.06-0.08-0.10), (2) time to second scenario (3 years), (3) real-price increase for first scenario (0.005-0.01-0.015), (4) real-price increase for second scenario (0.01-0.015-0.02), and (5) and (6) inflation rates for first and second scenarios (0.04-0.05-0.06).

Once input values for all of the above parameters were established, the model was run using various values of commodity price in dollars per cubic yard. The purpose of this reiteration with a varying commodity price is to establish a commodity price at which the present worth or the MROV of the mined mineral is approximately equal to zero. As explained previously, the model arrives at the MROV for a particular set of engineering, geologic, economic, and cost conditions by random independent sampling to determine a discrete value for each of the ranged input parameters for each trial calculation of the 1,000 trial set from which the MROV is determined. In doing each of these trials, a discounted cash flow analysis is calculated such that the revenues and costs are determined yearly using appropriate discount and inflation factors.

RESULTS

When the commodity price is valued for any particular set of conditions, the MROV calculated represents a present worth value either above or below the economic break, even point of zero MROV. In this way, the model is not used to establish a present worth for a certain commodity price but is used to establish the minimum commodity price at which the dredging project is economically feasible. In other words, because the operating cost parameters include plant ownership cost, all personnel and machinery cost, and contractor overhead and profit, the commodity price that yields a zero MROV represents the cost of dredging, transporting, and placement of a cubic yard of sand onto the project site.

The economic analysis for each of the three dredge methods for placement of sand onto the three project sites was performed for the two previously identified sand source areas. The cost per cubic yard and the dredge time in months for each project site and sand source area are displayed in Table 18.

It is apparent from this table that utilization of Sand Source Area 4 yields the lowest cost per cubic yard regardless of the mining method. This is explained by the reduced volume requirements associated with Sand Source Area 4 (smaller overfill factor reference Table 15) for each of the project sites. This difference was sufficient in the case of the Little Lagoon and Perdido Pass sites to overcome the increased sail time required by utilizing Sand Source Area 4 versus Sand Source Area 2. It is also apparent from Table 16 that Dredge Method 1 is the most cost effective, both from the standpoint of cost per cubic yard and total project time; particularly, for the large volume requirements of the Dauphin Island project. The cost per cubic yard utilizing Sand Source Area 4 and Dredge Method 1 for the Dauphin Island project is $4.35, for the Little

Lagoon project $9.06, and for the Perdido Pass project $4.80. While there appears to be a great disparity in these cost figures, especially for the Little Lagoon project; this can be explained by consideration of the overfill factor (Table 15) for each of these projects. In this particular case, due to the overfill factor, 30 percent, 170 percent, and 45 percent more material than required in place at the project site must be handled respectively, for the Dauphin Island, Little Lagoon, and Perdido Pass projects. This factor has an even greater effect because all fixed costs were prorated based on the volume of mined material.

DISCUSSION

The economic analysis and modeling using the QUIKSAND model indicates that a commodity price of $4.35/yd^3 is associated with the Dauphin Island project utilizing Sand Source Area 4 and Dredge Method 1 (one 16,000 cubic yard hopper barge dredge and direct pump-out through submerged pipeline). As previously mentioned, the cost of the other two projects is higher mainly due to the overfill requirement. However, if the three project volumes and costs are summed together, the average cost per cubic yard would be $4.47. Even though this analysis shows dredge Method 1 to be the most economical for each project when compared to the other two dredge methods, a more detailed and knowledgeable consideration of the dredging aspects might recommend utilization of a dredge method with a direct stream discharge for the Little Lagoon and Perdido Pass projects. For these low-volume projects, smaller sized dredge equipment could complete the project within a reasonable time and, presumably, with much less fixed cost accountability.

6. Geologic data and resource characterization were analyzed in terms of areal extent, volume, sediment size, and compatibility for beach nourishment. Six lithofacies comprised of thirteen microfacies were delineated based on sediment characterization, spatial extent, and environment of deposition. Two lithofacies (Clean Sands and Graded Shelly Sands) were determined to have highest potential for beach nourishment sources. The offshore target areas were evaluated to determine their sand compatibility for beach nourishment, sand volume, and surface sand distributions. These target areas all contain sufficient appropriate sand to serve as potential sources for beach replenishment projects.

7. An analysis of sand samples from onshore sites was performed to evaluate the potential of onshore sand resources. Ten sediment samples from active and inactive sand pits in Mobile and Baldwin County were evaluated with respect to grain size, sand extent, and color to determine if they would be appropriate for beach replenishment. In addition, production figures for sand mining in coastal Alabama were evaluated to determine if sufficient sand is available for beach replenishment. It was determined there is insufficient clean white sand available from onshore sources for beach replenishment.

8. An economic analysis based on information in this draft report was completed by the MMS using a mathematical model referred to as QUIKSAND. The economic analysis was accomplished for three identified beach replenishment projects; Dauphin Island, Little Lagoon Pass, and Perdido Pass utilizing two of the sand resource areas, 2 and 4, identified in this report. The economic analysis and modeling using the QUIKSAND model indicates that a commodity price of $\$4.35/yd^3$ is associated with the Dauphin Island project

utilizing Sand Source Area 4 and Dredge Method 1 (one 16,000 cubic yard hopper barge dredge and direct pump-out through submerged pipeline). As previously mentioned, the cost of the other two projects is higher mainly due to the overfill requirement. However, if the three project volumes and costs are summed together, the average cost per cubic yard would be $4.47. Even though this analysis shows dredge Method 1 to be the most economical for each project when compared to the other two dredge methods, a more detailed and knowledgeable consideration of the dredging aspects might recommend utilization of a dredge method with a direct stream discharge for the Little Lagoon and Perdido Pass projects. For these low-volume projects, smaller sized dredge equipment could complete the project within a reasonable time and, presumably, with much less fixed cost accountability.

9. An assessment of heavy minerals was to be completed. No concentrations of heavy minerals were identified in bottom samples or cores. Therefore, it was not possible to accomplish this task.

10. The physical and biological environmental impacts of sand dredging in resource areas were determined from existing wave and current data and benthic samples taken for this study. Three types of preliminary environmental analyses were accomplished for this study: Impacts of offshore sand dredging on shelf circulation; on ongoing human marine activities; and on local benthic biota. It was determined that dredging may not significantly alter background wave regimes, and thus should not lead to shoreline change, except, possibly, during major storms. Data are insufficient to model major storm effects. Any dredging activities would need to avoid identified types of structures and shipping fairways. Preliminary evidence from 10 of 59 samples collected for

this study indicates that there would likely be little long-term impact on benthic biota, assuming hard bottoms are avoided. Additional work is required to confirm or refute these preliminary findings.

Several important general conclusions may therefore be drawn from this study. Much of the Alabama shoreline, both facing the Gulf of Mexico and in the bay system, is undergoing significant, long-term erosion. If the political and regulatory decisions are made to attempt to temporarily alleviate this pattern, critical threatened shorelines will need to have ongoing programs of replenishment. Sources of appropriate sand must be identified, and economic and environmental evaluations completed to determine the cost effectiveness and environmental impacts of such a program. For the Alabama coastal zone, there are no local onshore volumes of appropriate sand available for any large scale program.

This study has delineated several target areas that appear to hold sufficient reserves of appropriate sand resource material in the Alabama EEZ. Sand distribution within these target areas, however, is complex, based on a patchy facies pattern. Detailed geological evaluation of these sites prior to initiation of dredging would be needed to ensure a cost-effective program. A thorough economic analysis for such a program is essential for proper management decisions. While preliminary environmental analyses seem to indicate that such an offshore mining program could be conducted with limited impact to the benthic biota and coastal erosion patterns, nonetheless a thorough environmental study is needed. This would involve evaluating trends in both the benthos and nekton, as well as obtaining and modeling a long-term data set coupling local water dynamics with bathymetry and weather patterns. It is strongly recommended that these additional studies be accomplished prior to initiation of any serious discussion on utilization of sand resources from the Alabama EEZ.

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