Physical and Environmental Assessment of Sand Resources—Texas Continental Shelf

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SUMMARY

A recent inventory of nonfuel minerals in the northwestern Gulf of Mexico demonstrated that potentially economic deposits of sand, gravel, and heavy minerals occur on the Texas continental shelf. Particularly promising for leasing and commercialization in the near term are deposits of sand that form shoals on the inner continental shelf. Preliminary analyses indicate that these sand deposits are suitable for beach replenishment because sediment textures of the shoals are generally compatible with those of native beach sand. Offshore sand extraction may become attractive economically if onshore sources of beach-quality sand are volumetrically limited. Offshore mining of sand could also reduce the degradation of wetlands caused by onshore mining activities.

Demand for beach replenishment sand along the northwestern Gulf of Mexico is increasing as the combined effects of rising sea level and land subsidence are manifested as rapid beach erosion. In Texas, Sabine and Heald Banks are two offshore sand deposits that have the greatest economic potential for near-term exploitation because they are (1) suitable for beach replenishment, (2) the largest sand deposits located offshore of some of the most rapidly eroding developed shores, (3) relatively close to potential markets in both southeastern Texas and western Louisiana, and (4) relatively close to major ports that can support offshore mining activities.

The principal efforts of this study were directed toward assessing the quality and volume of Sabine and Heald Bank sediments and evaluating the composition and thickness of overburden materials. To accomplish this, the banks were cored, sediment textures and mineralogy were determined, and volumes of the sand deposits were estimated using bathymetry, seismic profiles, and lithologic information. Geographic locations and attributes of all the pertinent offshore data sources were incorporated into ARC/INFO, a widely used geographic information system (GIS). An additional task evaluated the potential environmental impact of mining the sand deposits by examining the overburden. Another task reviewed the available extraction technologies and determined which are likely to be most appropriate for developing the identified sand resources on

the Texas continental shelf. We also conducted a preliminary investigation of potential obstructions to extraction operations such as production platforms and offshore pipelines.

The preliminary findings of this study indicate that Sabine and Heald Banks may each contain nearly 2 billion m^3 of sand and muddy sand. Most of that material would be suitable for beach replenishment and other applications that can use well-sorted fine sand with some shell and some sediments finer than sand. The sand deposits are located in water depths ranging from 4.5 m to about 17 m with the greatest thickness of sand coinciding with the shallowest water depths. Several petroleum pipelines, production platforms, and a lighthouse are located within the trend of high-quality sand deposits. Although these structures would locally interfere with sand extraction, they would not necessarily preclude the dredging of sand from the banks. Equipment designed for open-water dredging (moderate wave climate) would be required to extract the sand resources. Because of the distances between the sand deposits and their potential market, it is anticipated that dredging and sand transportation would be separate operations. On the basis of current technology, costs, and efficiencies, it appears that a hydraulic sidecast dredge or bucket dredge would be appropriate for sand extraction and a system of tugs and scows would be needed to move the sand between the Banks and beach fill sites.

INTRODUCTION

Statement of the Issue

Potentially economic concentrations of sand, shell, and heavy minerals have been identified in the northwestern Gulf of Mexico during decades of exploration and research on the continental shelf. On the Texas portion of the continental shelf, significant sand accumulations at or near the sea floor occur as shore-aligned sand bodies and a patchy accumulation of transgressive sands that were deposited during the most recent rise in sea level (Paine et al., 1988; Table 1). Fluvial sand and gravel occur within late Wisconsinan stream courses that extend across the continental shelf, but these valley-fill deposits may be covered by tens of meters of overburden.

Potential markets for offshore sand exist along the northwestern Gulf of Mexico. Sand contained in drowned shoreline and nearshore deposits has the greatest near-term economic potential because it can be used for beach-replenishment projects. Beach replenishment can be justified where large recreational, residential, and industrial investments would be damaged or destroyed by continued coastal erosion and storm impacts. Long-term erosion of Texas beaches and heavy beach use near population centers make beach replenishment an attractive alternative to other methods of shoreline stabilization.

Purpose of the Study

One of the primary objectives of this study is to determine the suitability of offshore sand for replenishment of beaches along the southeastern Texas and western Louisiana coasts. To reach this objective, the following physical attributes were determined for each of the priority offshore sites: (1) the three-dimensional geometry of the deposits and their approximate volumes; (2) the mineralogy and textural characteristics of the deposits, including grain size, sorting, and lateral and vertical variation; and (3) the degree to which the mineralogical and textural characteristics of the banks match characteristics of nearby beaches. The detailed sedimentological data provided a basis for calculating sand volume, determining its suitability for beach replenishment, and providing a basis for assessing the economics of extracting sand from these deposits.

Another objective of the study was a preliminary assessment of the potential environmental impact of offshore dredging near Sabine and Heald Banks. Some of the most important environmental issues related to offshore mining involve disposal of the overburden

Table 1. Attributes of prospect types on the Texas continental shelf. BN = beach nourishment; Ind = industrial uses; Con = construction. From Paine et al. (1988).

Prospect Type	Resource	Best Example	Time of Formation	Suitable for BN	Suitable for Ind	Suitable for Con	Comments
Shore-parallel sands	sand	Sabine and Heald Banks	post-Wisconsinan	yes	yes	yes	May contain some shell
Stream courses	sand, gravel	Mustang Island Area	late Wisconsinan to early Holocene	no	yes	yes	May be covered by several meters of overburden
Shelf-margin deltas	sand	Rio Grande Delta	Wisconsinan	no	?	?	May contain silt and clay
Transgressive sands	sand, heavy minerals	South Padre Island Area	post-Wisconsinan	yes	yes	yes	May contain shell; Rio Grande area promising

material, concentration and composition of the dredging plume, and potential alterations to the physical processes as a result of the mining activity. To address these issues, preliminary assessments were conducted of the thickness and composition of material other than sand covering the sand deposits.

REGIONAL SAND RESOURCE EVALUATION

Previous Work

Several earlier studies have investigated the distribution of surficial sediments on the Texas continental shelf including the sand shoals of Sabine and Heald Banks. Those studies, which were based mostly on widely spaced bottom samples, provide a regional depiction of surface sediment types, but they are one-dimensional in scope. Consequently, the published transects and sediment maps do not provide information regarding the thickness, geometry, and lateral extent of the lithologic units. Also, most of these studies did not report grain-size analyses so that sediment textures could be compared quantitatively.

Stetson (1953) conducted a regional survey of sediment textures that included the distal part of Heald Bank but not Sabine Bank. The Heald Bank transect, as well as adjacent transects off Galveston and southwestern Louisiana, showed that the shelf surface sediments are patchy, poorly sorted, and composed mostly of silt with some fine sand.

Curray (1960) used sediment textures and composition as well as radiocarbon dates to interpret the geologic history of the northwestern Gulf of Mexico during the Holocene rise in sea level. He reported that Holocene sediments of the shelf were composed of two facies, a basal sheet of transgressive nearshore sands overlain by shelf muds. According to Curray, this idealized facies succession is present over much of the shelf except where sedimentation rates are low and the basal sand facies is exposed at the seafloor. The sand deposits associated with Sabine and Heald Banks were considered to be part of the basal sand sheet.

Frazier (1974) presented a map showing extensive sand deposits blanketing the continental shelf of the southeastern and central Texas coast. Like Curray (1960), Frazier also used sediment textures and radiocarbon dates to interpret the sea-level history. He also concluded that the blanket sands are transgressive shelf and shoreline deposits that accumulated during the Holocene rise in sea level.

Williams et al. (1979) investigated the potential sand resources on the inner continental shelf between High Island and Freeport, Texas. An objective of the study was to locate sand deposits that could be used for beach replenishment projects on or near Galveston Island. Their work did not include Sabine and Heald Banks because they were considered too far offshore for commercial utilization. In their study, high-resolution seismic profiles and vibracores were used to conclude that the best nearshore sand deposits were associated with the ebb tidal deltas at Bolivar Roads and San Luis Pass.

White et al. (1985) collected and analyzed numerous surface sediment samples from the inner continental shelf along the upper Texas coast. Their sample sites came close to but did not include Sabine and Heald Banks. Nevertheless, the results of the study suggest that Sabine and Heald Banks are the only sand deposits in the area that are large enough to support offshore mining.

Nelson and Bray (1970) and Thomas (1990) both used high-resolution seismic profiles, cores, and radiocarbon dates to investigate the incised valley of the Sabine-Neches river system and the relationship of Sabine Bank and Heald Banks to sediments within the valley fill. Both studies concluded that the banks are accumulations of shoreline sands deposited during a stillstand in sea level and that the banks were submerged during a subsequent rapid rise in sea level. Neither of these studies specifically examined the sediment textures of the banks and their potential for beach replenishment.

Paine et al. (1988) conducted a regional synthesis of lithologic data for the continental shelf that included surface sediment samples, shallow cores, and foundation borings. An objective of this study was to identify the locations of non-fuel mineral deposits including beach-quality sand. Results of the study have shown that near-surface sand accumulations are generally thin, discontinuous, and not nearly as widespread as indicated by Curray (1960) or Frazier (1974). The study also identified Sabine and Heald Banks as favorable sites for beach-quality sand and recommended specific studies related to the volume and quality of sand within the Banks.

Potential Uses of the Sand Resource

In Texas, several beach replenishment projects have been recommended for Galveston Island (U.S. Army Corps of Engineers, 1983) to restore a beach that once existed seaward of the Galveston seawall, to offset high rates of erosion on beaches west of the seawall (Morton, 1974; Paine and Morton, 1989), and to replace contaminated sand removed from beaches after an oil spill (Morton and Paine, 1985). Some Galveston Island property owners have used muddy Pleistocene sediments for beach fill (Morton and Paine, 1985) because sand suitable for beach replenishment is locally unavailable.

Other segments of the southeastern Texas coast are also undergoing widespread and rapid beach erosion, including the eastern part of Bolivar Peninsula, much of the shore from High Island to Sabine Pass, and the western Louisiana coast. An investigation of historical trends of beach erosion in southeastern Texas and western Louisiana and their causes is being conducted as part of a cooperative program between the U.S. Geological Survey (USGS), the Bureau of Economic Geology (BEG), and the Louisiana Geological Survey (LGS).

Locations of the Sand Resource

The largest potential sources of beach-quality sand offshore of the southeastern Texas and western Louisiana coast are Sabine Bank and Heald Bank (Paine et al., 1988). These sand-rich shoals, interpreted as reworked nearshore and shallow marine sediments, are located 40 to 50 km offshore and in water depths of 4.5 to 17 m (Figure 1). Sand deposits associated with the banks cover more than 1,000 km^2 (Table 2) and are as much as 8 m thick. Widely-spaced cores, foundation borings, and seismic records indicate that average thickness of the sand is about 3 m.

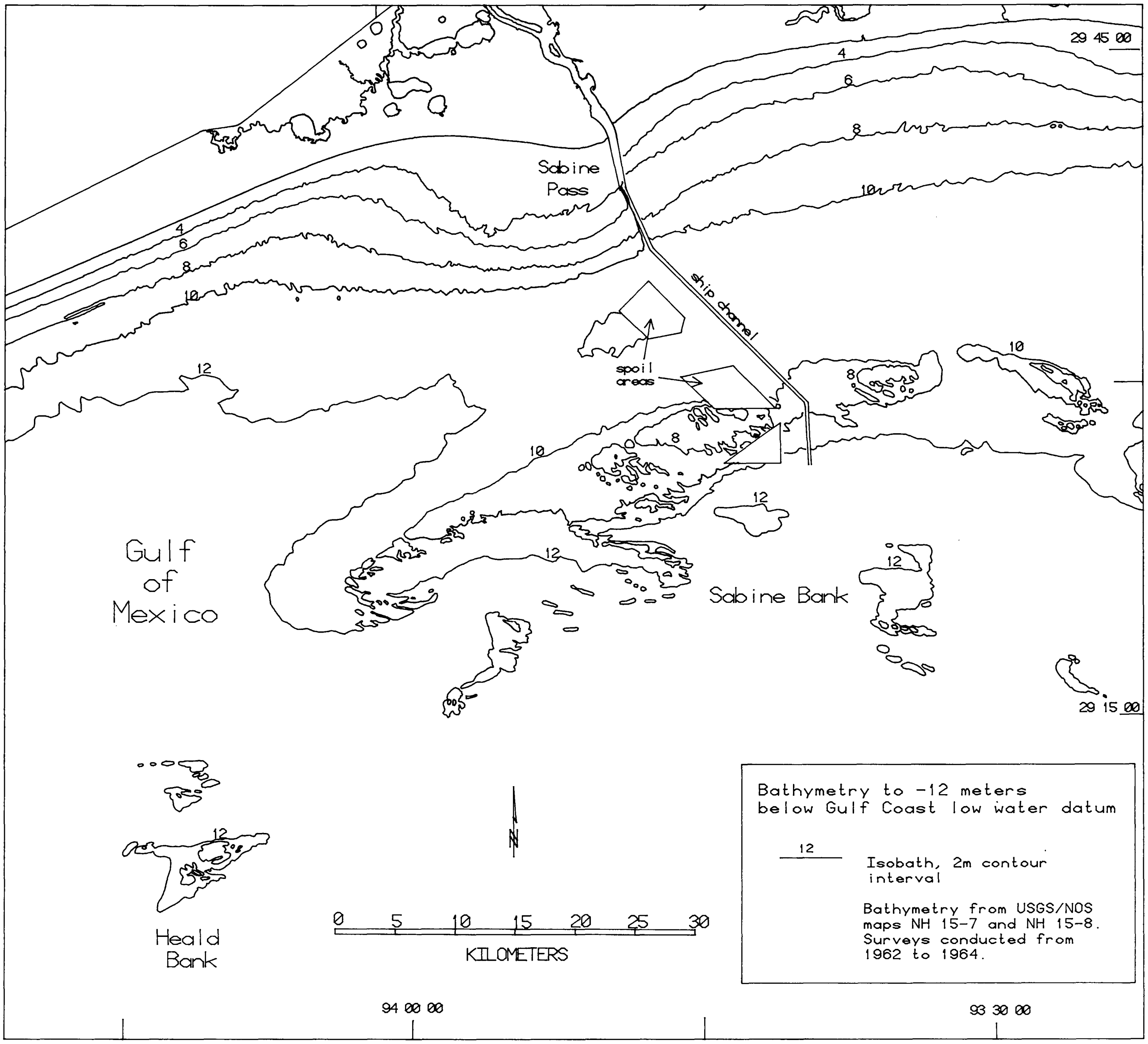

Figure 1. Location of Sabine and Heald Banks and related bathymetry of the continental shelf.

Table 2. Physical and environmental attributes of sand resources associated with Sabine and Heald Banks.

Bank	**Sabine**	**Heald**
Areal Extent	570 km^2	460 km^2
Sand and Muddy Sand	839 million m^3	945 million m^3
Sand Quality	88–92% sand	no textural data
Range of Water Depths	4.5–12 m	10–14 m
Existing Structures	At least 7 production platforms, 4 pipeline segments, and a permanent shoal marker (lighthouse)	At least 2 production platforms and 2 pipeline segments
Shipping Considerations	Sabine Ship channel at northeastern end	Galveston shipping fairway at southwestern end

Preliminary calculations suggest that sediment volume in the banks could be more than 3 billion m^3 (Paine et al., 1988). The bank deposits are composed dominantly of fine to very fine sand (Nelson and Bray, 1970), which is similar to the textures and composition of most Texas beaches (Bullard, 1942).

Sand deposits associated with Sabine and Heald Banks (Figure 1) offer several potential advantages for use in beach replenishment projects. They are the largest sand deposits offshore of some of the most rapidly eroding developed shores in the western Gulf of Mexico and therefore they are relatively close to potential markets in both southeastern Texas and western Louisiana. Also, the banks are far from sources of chemical contamination and thus are probably a better source of beach sand than is sediment dredged from nearby ship channels. Finally, Sabine Bank and Heald Bank sand deposits are likely to be suitable for replenishment of nearby beaches because the sand deposits formed from sediments and by processes similar to those that formed the adjacent Gulf beaches. Smaller sand deposits on the southeastern Texas continental shelf potentially suitable for beach replenishment have either already been evaluated (Williams et al., 1979; U.S. Army Corps of Engineers, 1983) or are being examined as part of the USGS, BEG, and LGS cooperative coastal geology program.

Potential onshore sources of sand in the general area include abundant fluvial sands and relatively scarce strandline deposits (Jackson et al., 1990). These onshore sand deposits would require greater transportation distances than the offshore deposits. Furthermore, the onshore sand deposits may not have size and sorting characteristics appropriate for beach replenishment, they may be limited in volume, and mining the onshore sand deposits may have negative environmental impacts. These impacts, such as degradation or loss of coastal wetlands, enhanced flooding, health and safety hazards, and reduction of sensitive wildlife habitat, are significant because they would occur in an area that is already undergoing alarming wetland losses resulting from land subsidence and a rise in relative sea level (Morton and Paine, 1990).

FIELD INVESTIGATION OF SABINE AND HEALD BANKS

Physical Setting

Sabine and Heald Banks are inner shelf shoals located off the southeastern coast of Texas (Figure 1). The shoals are aligned northeast-southwest and are parallel to the present shoreline trend. Sabine Bank, which is the eastern bank, lies on the Texas and Louisiana border 33 km (18 nautical miles (nm)) south of Sabine Pass, Texas, and about 91 km (50 nm) east of the Entrance to Galveston Harbor. About one-fourth of the eastern end of Sabine Bank lies in Louisiana. The federally maintained Sabine Bank ship channel cuts across a natural saddle on the eastern end of the Bank and is maintained at a depth of 12.8 m (42 ft) below mean lower low water (MLLW) and at a width of 244 m (800 ft) by periodic dredging (National Ocean Service, 1990; U.S. Army Corps of Engineers, 1992). Two dredge spoil areas, where sediment dredged from the channel is dumped, abut and partially cover the bank just west of the ship channel (Figure 1). Another spoil area used for channel maintenance is landward of the bank and just west of the ship channel (Figure 1).

Sabine Bank is delineated by the 10 m (33 ft) isobath. The Bank extends 49 km (27 nm) in a northeast-southwest orientation and is about 7.3 km (4 nm) wide at its widest section. A few small shoals detached from Sabine Bank exist to the east but are not considered in this study. The shallowest portions of Sabine Bank are on the eastern end between the spoil areas and west of the ship channel. This shoal area is marked by the Sabine Bank lighthouse. Depths are as shallow as 4.5 m (15 ft) but deepen to more than 9 m (30 ft) to the southwest.

The bathymetric map (Figure 1) shows that the 10 m (33 ft) and 8 m (26 ft) isobaths are smooth on the landward side of Sabine Bank relative to the seaward side, and on the eastern part of the bank, the landward side is steeper than the seaward side. On the seaward side, however, the 10 m (33 ft) and especially the 8 m (26 ft) isobaths display a digitate configuration oriented southeast-northwest, which is normal to the alignment of the long axis of the Bank. The 6 m (20 ft) isobath outlines small shoals, which are aligned normal to the axis of the Bank, on top of the eastern half of the Bank (Figure 1).

Heald Bank is 27 km (15 nm) southwest of Sabine Bank and 55 km (30 nm) southeast of the Entrance to Galveston Harbor (Figure 1). Heald Bank is not as well defined as Sabine Bank and has a relatively small area that is shallower than 10 m (33 ft). The 14 m (46 ft) isobath encloses a much larger area extending 30 km (16 nm) to the southwest from the eastern shallow areas. The 10 m (33 ft) isobath encloses two irregularly shaped areas with no particular orientation.

Physical Processes

The southeastern shore of Texas is a microtidal, wave-dominated coast in the classification of Hayes (1979). Tides are chiefly diurnal with a diurnal range of 0.85 m (2.8 ft) on Sabine Bank (National Ocean Service, 1979). Mean significant wave height (Hs), as determined from 20 years of hindcast data, is 1.0 m (3.3 ft) with a mean peak wave period of 5.4 seconds (Hubertz and Brooks, 1989, station number 13). The lowest monthly mean significant wave height occurs in July and August and is 0.8 m (2.6 ft). From November through March monthly mean Hs is 1.1 m (3.6 ft), and April has the largest mean Hs of 1.2 m (3.9 ft). According to the hindcast study, the highest waves approach from the south and southwest, but the most common wave approach direction is from the southeast.

The above hindcast study did not consider waves generated by tropical cyclones. The study area, however, is greatly affected by both tropical storms and hurricanes. Tide records from the bay side of Galveston Island show that water levels caused by storm surges exceeded 1.2 m (4 ft) about every 5 years from 1908 to 1983 (Morton and Paine, 1985). In a hindcast study that only included hurricanes occurring during the period from 1956 to 1975, the return interval for a significant wave height of 4.5 m (14.8 ft) was determined to be 5 years (Abel et al., 1989, station number 13).

An estimate of sediment mobility, including transport through and into the study area and resuspension and deposition of sediment within the area, may be approximated from dredging histories of the ship channel leading to Sabine Pass, formally referred to as the entrance to the Sabine-Neches Waterway. The U.S. Army Corps of Engineers dredged a portion of the channel, which starts at the landward 10 m (33 ft) isobath and runs seaward across the Bank (Figure 1), three times in the last 11 years (U.S. Army Corps of Engineers, 1992). From these data, the average annual shoaling rate is 32,000 m^3/km of channel dredged (67,000 yd^3/mi). The portion of the channel between the landward 4 m (13 ft) and 10 m (33 ft) isobaths and just seaward of the Sabine Pass jetties was dredged eight times over the same time period (U.S. Army Corps of Engineers, 1992) to yield an annual shoaling rate of 348,000 m^3/km of channel dredged (735,000 yd^3/mi). The sediment dredged from the channel was predominantly silt and clay with generally less than 50% sand (U.S. Army Corps of Engineers, 1992).

These dredging data indicate that muddy sediment is commonly transported in the study area. From these data, however, it is impossible to determine how much of the channel shoaling is caused by resuspension and deposition of sediment and how much is caused by sediment transport into or through the area. Slumping and erosion along the channel banks may also add to the shoaling rate. It is clear that sediment mobility is much greater between the landward 4 m (13 ft) and 10 m (33 ft) isobaths than farther seaward. The landward channel cuts across the former position of the ebb-tidal delta of Sabine Pass, which is a more dynamic environment than farther offshore.

Sources of Data

Bathymetry

Bathymetric data for the study were obtained from two 1:250,000 scale topographic-bathymetric maps produced jointly by the U.S. Geological Survey and the National Ocean Survey (U.S. Geological Survey/National Ocean Survey, 1977 and 1979). Hydrographic surveys for these maps were conducted from 1962 to 1964. Survey line spacing in the Sabine and Heald Bank area ranged from 9 m to 500 m (30 ft to 1,800 ft), and the bathymetry was originally mapped at a scale of 1:40,000. These maps show the locations, orientations, and external geometries of Sabine and Heald Banks.

Seismic Profiles

Three sets of high-resolution seismic profiles were used to establish the regional geologic framework of the Sabine-Heald Bank trend and to assist in mapping the lateral extent of the sand resource. The 1,141 km (615 nm) of seismic data used in the study (Figure 2) includes: (1) regional Uniboom lines over Sabine Bank collected in 1988 by Rice University; (2) regional Uniboom lines over Heald Bank and part of Sabine Bank collected in 1990 by the BEG, and (3) regional lines over Sabine Bank collected in 1992 by the BEG as part of the cooperative program with the USGS.

Three other sets of seismic profiles were examined but were judged unsuitable for either regional framework analysis or detailed mapping related to evaluation of the sand resource. The unused seismic profiles were: (1) regional mini-sparker lines obtained jointly in 1976 by the BEG and the USGS; (2) regional sparker lines obtained in 1980 by Intersea Research for the USGS., and (3) local geophysical profiles collected at various times by contractors for hazard surveys and obtained from the Minerals Management Service; 1988 seismic data.–During the late 1980's, Rice University collected about 1,000 km (547 nm) of Uniboom data in the study area (Thomas, 1990). Approximately 704 km (379 nm) of these seismic profiles, which are centered over Sabine and Heald Banks, were examined for this study. The sound source for these profiles was an EG&G Model 230 Uniboom. Frequency range of the outgoing pulse was from 400 to 14,000 hz and the energy level was between 500 and 700 joules. Data were recorded after filtering as paper analog profiles. LORAN C was used for navigation, and Thomas (1990) reported locational accuracy of the shot points to within 200 m. Great care was taken to collect the data during fair weather conditions.

1990 seismic data.–In August 1990, the Bureau of Economic Geology in cooperation with Rice University, collected 182 km (98 nm) of high-resolution seismic data on the eastern portion of Sabine Bank and on Heald Bank (Figure 2). These data were collected with an EG&G Uniboom sound source at an energy level of 500 joules. Data were digitally recorded using an Elics system and recorded after filtering as paper analog profiles on an EPC recorder. Filters were generally set at 350

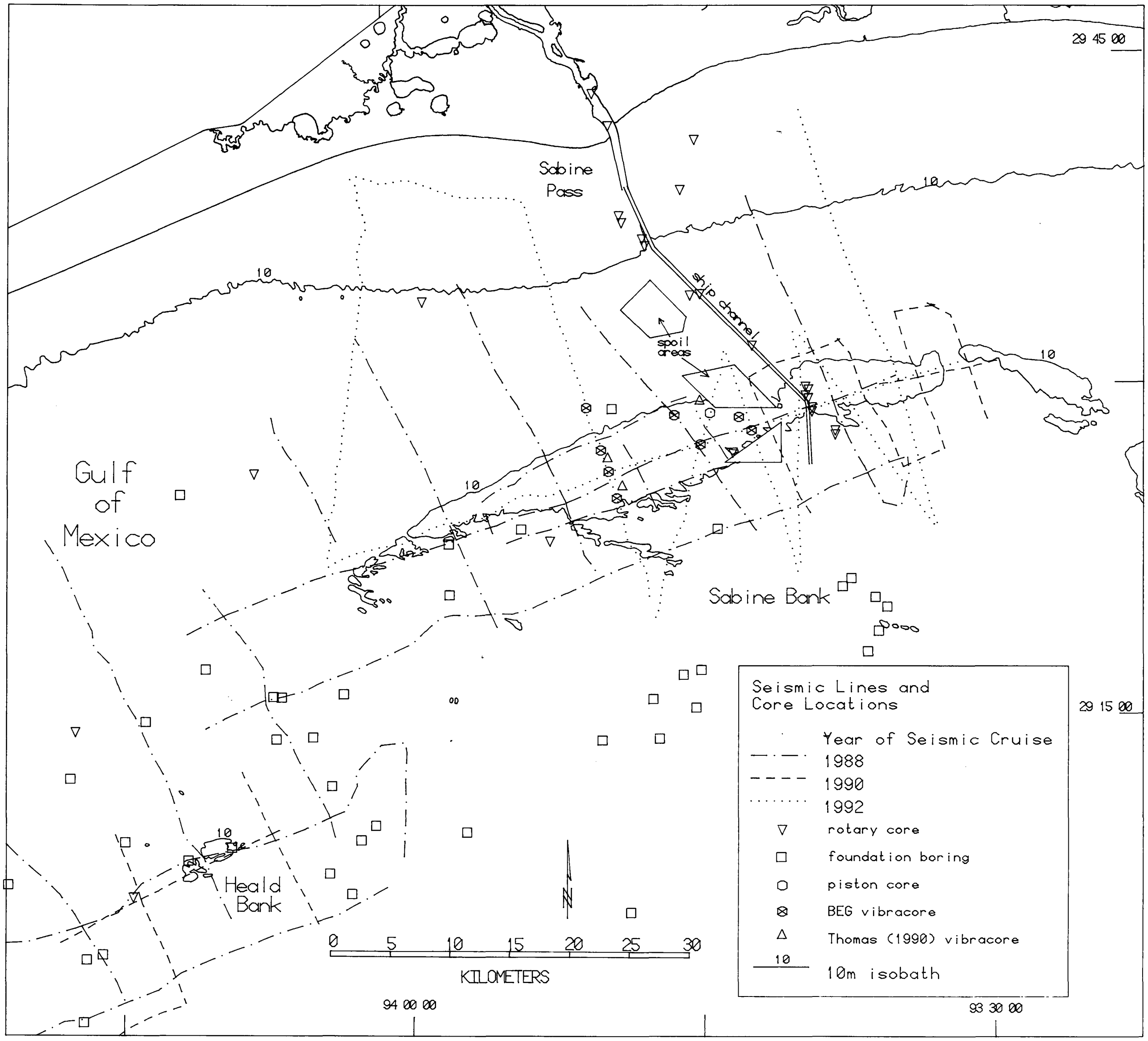

Figure 2. Locations of seismic profiles and subsurface lithologic data (borings and cores) used to evaluate the sand resources of Sabine and Heald Banks.

and 2,500 hz but adjusted depending on the character of the data. Navigation was by LORAN C and Global Positioning System (GPS) when available.

1992 seismic data.–During a joint cruise with the Bureau of Economic Geology and the U.S. Geological Survey in July 1992, an additional 255 km (137 nm) of high-resolution profiles were collected on Sabine Bank. An Elics system was used and data were recorded on optical disks and as analog paper profiles provided by the Elics' system printer. Data were also recorded as paper analog profiles on an EPC recorder with filters set at 240 and 2,400 hz. The sound source was an Ultrasonics bubble pulser that provided 60 joules at 1,200 hz. Navigation was provided by a Trimble Navigation Global Positioning System (GPS). The GPS automatically keyed the EPC recorder every 5 minutes, which provided shot point locations to within 100 m about every 600 m (2,000 ft) along the profile.

Foundation Borings

Numerous foundation borings within and near the Sabine and Heald Banks trend have been obtained in conjunction with siting of offshore production platforms and improvement of the Sabine Bank ship channel. Primary sources of the foundation boring descriptions are Fugro-McClelland Engineers and the Galveston District, U.S. Army Corps of Engineers.

More than 35 foundation borings were used to determine the lithologies of shallow subsurface sediments in the study area (Figure 2). Most of the borings penetrate at least 20 m below the sea floor, and they are the only records of sediment types that completely penetrate both Sabine and Heald Banks. When used with the vibracores, seismic profiles, and bathymetric maps, the foundation borings provide a supplementary basis for defining the geographic limits of the sand bodies and calculating sand volumes.

Detailed descriptions of foundation borings provide information regarding water depth, boring depth, sediment color, sediment composition, presence and concentration of accessories (organic matter, shells, calcareous nodules), sediment textures, engineering properties, and other sedimentological attributes that also can be used for lithostratigraphic correlations and interpretation of depositional environments. Although the lithologic descriptions are adequate for identifying the Banks as priority study sites, they are inadequate for characterizing the specific physical and chemical attributes of the sand deposits.

Vibracores

Vibracores were collected to determine the quality and suitability of the bank deposits for beach replenishment or other construction uses. Coring sites were selected by analyzing and integrating the bathymetric, seismic, and preliminary lithologic data. Selection criteria included anticipated thicknesses of the sand deposits, seismic characteristics of the sand bodies and underlying reflections, water depth, potential variable mining characteristics (presence or absence of hardgrounds), and any limitations imposed by the vibracoring equipment.

Vibracores were collected using standard aluminum irrigation tubes, which are 6 m long and 7.6 cm in diameter. Each tube is fitted with a core catcher and is attached to a pneumatic vibrator head that is part of a rigid steel frame. The frame is lowered by cable to the sea floor, where it rests on four pads. Compressed air rapidly vibrates the head, which drives the core tube into the sediment. A track on the frame guides the vibrator head and keeps the core tube vertical as it penetrates the sediments and is recovered. After the core is retrieved, it is sealed and marked for later processing. Geographic coordinates of the vibracores were provided by a dual-channel GPS navigation receiver.

A total of eight vibracores were collected from Sabine Bank, the larger of the two banks, and one vibracore was attempted on Heald Bank. High seas and failure of an anchor cable during coring operations prevented recovery of the core on Heald Bank. Penetration depths of the vibracores were controlled primarily by sediment composition. Soft mud with only a few scattered and broken shells allowed complete penetration of an entire 6 m core tube. In contrast, well-sorted sand or shelly sand was the most difficult sediment to penetrate. Core tubes encountering these sediments penetrated less than 2 m below the sea floor.

The vibracores were transported to the Core Research Center of the Bureau of Economic Geology in Austin, Texas, where they were inventoried, split into equal halves, trimmed with an osmotic knife, and physically described using standard core description sheets. Information recorded on the sheets included core depth, sediment color, sediment type, nature of contacts, textural trends, sedimentary structures, and presence of accessories (organic material, shells). The cores were then photographed (large-format color prints and 35 mm slides) and sampled for textural and compositional analyses. The photographed half and sampled half of the core were wrapped in plastic and placed in separate core boxes and are stored in a climate-controlled room. The archived core half serves as a permanent record of the sediment types encountered and the types of material sampled.

Sediment Textures

To assess beach compatibility, 43 samples from the vibracores were analyzed for gravel, sand, silt, and clay content. The gravel-size fraction is composed mostly of shell, but includes some rock fragments (Morton and Winker, 1979). Because shell dominates the gravel fraction, the two classifications (size and composition) are used interchangeably.

Textural analyses were performed at the Mineral Studies Laboratory at the Bureau of Economic Geology. Sieves and a rapid sediment analyzer (RSA) settling tube were used for the sand and gravel fractions, and pipette and Coulter counter techniques were used for the clay and silt fractions. The means and standard deviations (sorting) were calculated using the graphical methods of Folk (1980) as follows:

$$\text{Graphic mean} = (\phi16 + \phi50 + \phi84)/3$$

$$\text{Graphic standard deviation (sorting)} = (\phi84 - \phi16)/2$$

The mineralogy of the sand fraction, also an important parameter for assessing beach compatibility, was determined for several samples using optical methods. Results of the textural and mineralogical analyses were compared with sedimentological beach characteristics reported at selected sites along the southeastern Texas coast. These published and unpublished analyses of beach sediments have already been compiled for several proposed beach replenishment sites (references in Morton, 1974, 1975).

Data Management

Data generated in conjunction with the sand assessment project are being manipulated and stored in a geographic information system (ARC/INFO) so that archiving and future retrieval will be facilitated. Most Federal and State agencies use a GIS to store locational information and to create maps that superimpose several layers of information. The GIS component of this study anticipates the need for a digital data base so that information can be readily transferred to other users.

Major components of the sand assessment GIS include a digital base map with shoreline features and bathymetry, locations of seismic lines and shotpoints, values for the thickness between the sea floor and ravinement surface, locations of pipelines and platforms, and locations of subsurface lithologic information including foundation borings, cores, and rotary borings, which were compiled from several sources (unpublished data; Thomas, 1990; Nelson and Bray, 1970; this study).

SAND RESOURCES OF SABINE AND HEALD BANKS

Geologic Framework and Origin of the Banks

The general geologic framework of the Sabine and Heald Banks area has been established by previous offshore investigations that relied on seismic profiles and a few cores (Nelson and Bray, 1970; McGowen and Morton, 1979; Pearson et al., 1986; Thomas and Anderson, 1989). Five foundation borings from the area provide supplemental information on the thickness and other physical characteristics of the sand deposits. Descriptions of sediments encountered in these borings were obtained during an inventory of available information on nonfuel mineral occurrences on the Texas continental shelf (Paine et al., 1988). Since that inventory of borings was completed, high-resolution seismic data have been collected from the Sabine and Heald Banks area that are sufficient for construction of a preliminary geometric model.

Sea-Level Fluctuations

Like other continental shelves of the world, the Texas shelf partly owes its bathymetry and morphology to sea-level fluctuations. The alternating phases of rising and falling sea level were associated with expansion and contraction of continental ice masses during the late Pleistocene. Sea-level curves for the Gulf of Mexico consistently show that the last sea-level lowstand occurred about 18,000 yr BP and the rise in sea level slowed abruptly about 5,000 yr BP (Curray, 1960; Nelson and Bray, 1970; Frazier, 1974). Exact positions of sea level stages or rates of relative sea-level rise between 18,000 yr B.P. and 5,000 yr BP are uncertain. Nevertheless, it is clear that rates of shoreline retreat were so high during rising phases of sea level that barrier islands either were not well developed or were not widely preserved. Remnants of barriers preserved as shoals on the continental shelf, such as Sabine and Heald Banks (Nelson and Bray, 1970), probably formed during brief stillstands or minor reversals in sea level. The sand shoals of Sabine and Heald Banks lie along the southern margin of the entrenched valleys of the Sabine and Calcasieu Rivers and above the valley fill deposits (Nelson and Bray, 1970). Thus they postdate the valley fill and are related more to the late rising phase of sea level that caused transgression and submergence of the coastal plain.

Seafloor to Ravinement Surface Thickness

The grids of seismic profiles were combined to create an isopach map of the sediment between the most recently formed ravinement surface and the sea floor (Figure 3). The ravinement surface formed during the latest rise in sea level by the process of erosional shoreface retreat. Sediments deposited and preserved above the ravinement surface in the study area were transferred from the

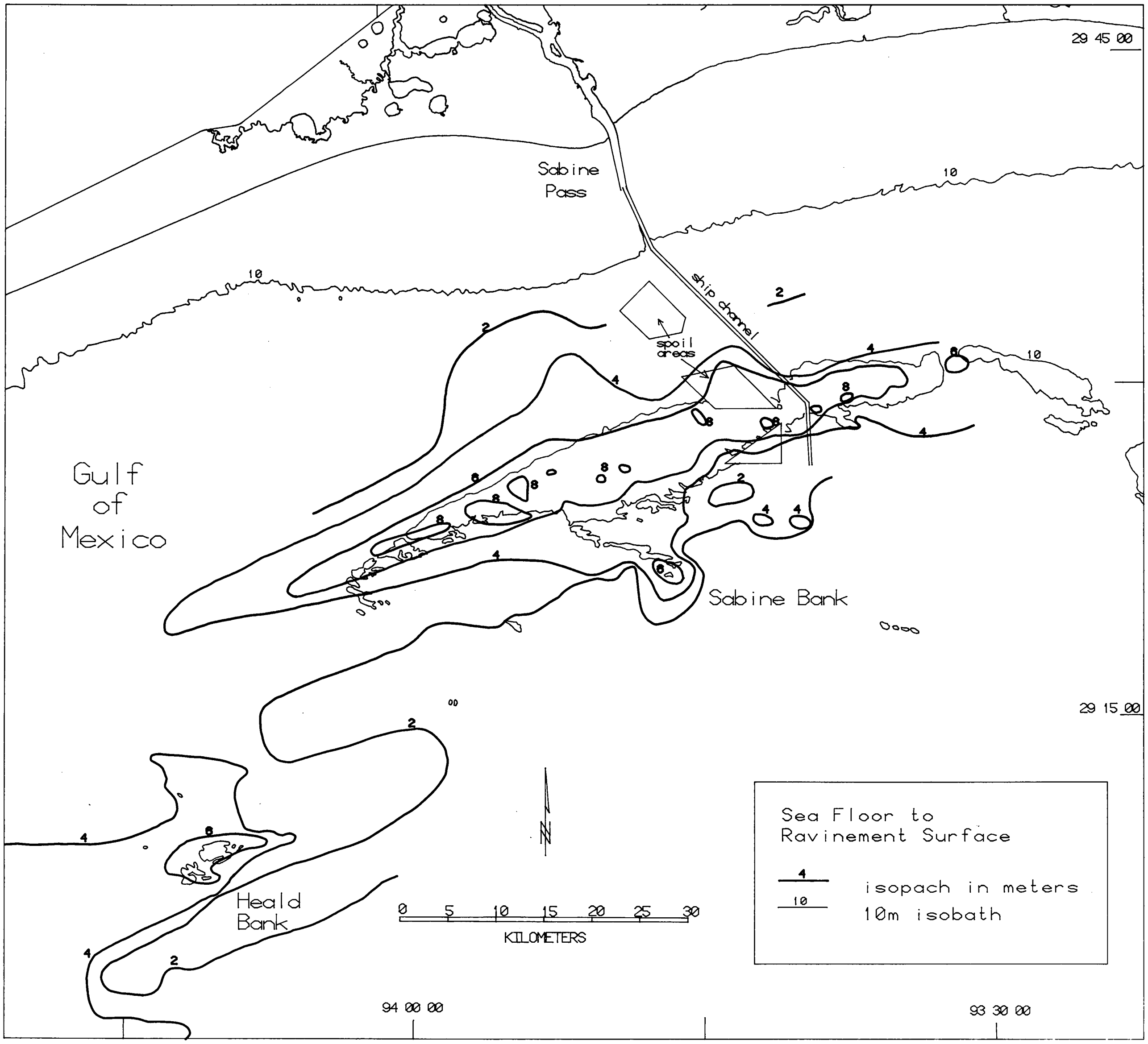

Figure 3. Isopach map showing the thickness of the interval between the sea floor and the youngest ravinement surface.

erosional shoreface to the inner shelf as the shoreline transgressed. More recent sedimentation above the ravinement surface has also occurred under present inner shelf conditions.

The ravinement surface was recognized in the seismic data primarily by truncation of underlying reflectors (Thomas, 1990). In vibracores VC-5 and VC-8 (Figure 4 and Appendix), the tops of the organic clay facies (facies F) correlate well with the depths of the ravinement surface determined from the seismic data. In both cores, the subsea depth of the clay facies and the interpreted ravinement surface are within 0.8 m of each other. Also the lithologic change between the organic clay and overlying facies is the most abrupt of the facies changes found in the vibracores. Because of this distinct lithologic change and the coinciding depth of the ravinement surface seismic reflector, the top of the clay facies is interpreted as the ravinement surface.

In general, the isopach contours parallel the trend of the Banks as delineated by the 10 m (33 ft) isobath (Figure 3). The thickness of the sediment above the ravinement surface ranges from 0 to 8 m (0 to 26 ft). Sediment thickness tends to increase over the banks, and there is a rough correspondence between greater thickness and shallower depths. Seaward of the Banks, the ravinement surface is exposed on the sea floor, and landward of the Banks, it comes to within 1 m of the sea floor. The southwest portion of Sabine Bank has relatively large areas of sediment thicknesses greater than 8 m (26 ft) (Figure 3).

It was originally thought that the isopach map of sediments between the ravinement surface and the sea floor could be used to determine the volume of beach quality sand. Discovery of the sandy mud facies above the ravinement surface in vibracores taken within the bank trend (Figure 4 and Appendix), however, revealed that such a determination would be an overestimation.

Shelf Erosion and Deposition

Since the highstand in relative sea level, the inner continental shelf of the upper Texas coast generally has been an area where sedimentation rates are low. It is far from any river mouth that empties directly into the Gulf of Mexico, and the nearest coastal plain rivers deposit their loads in

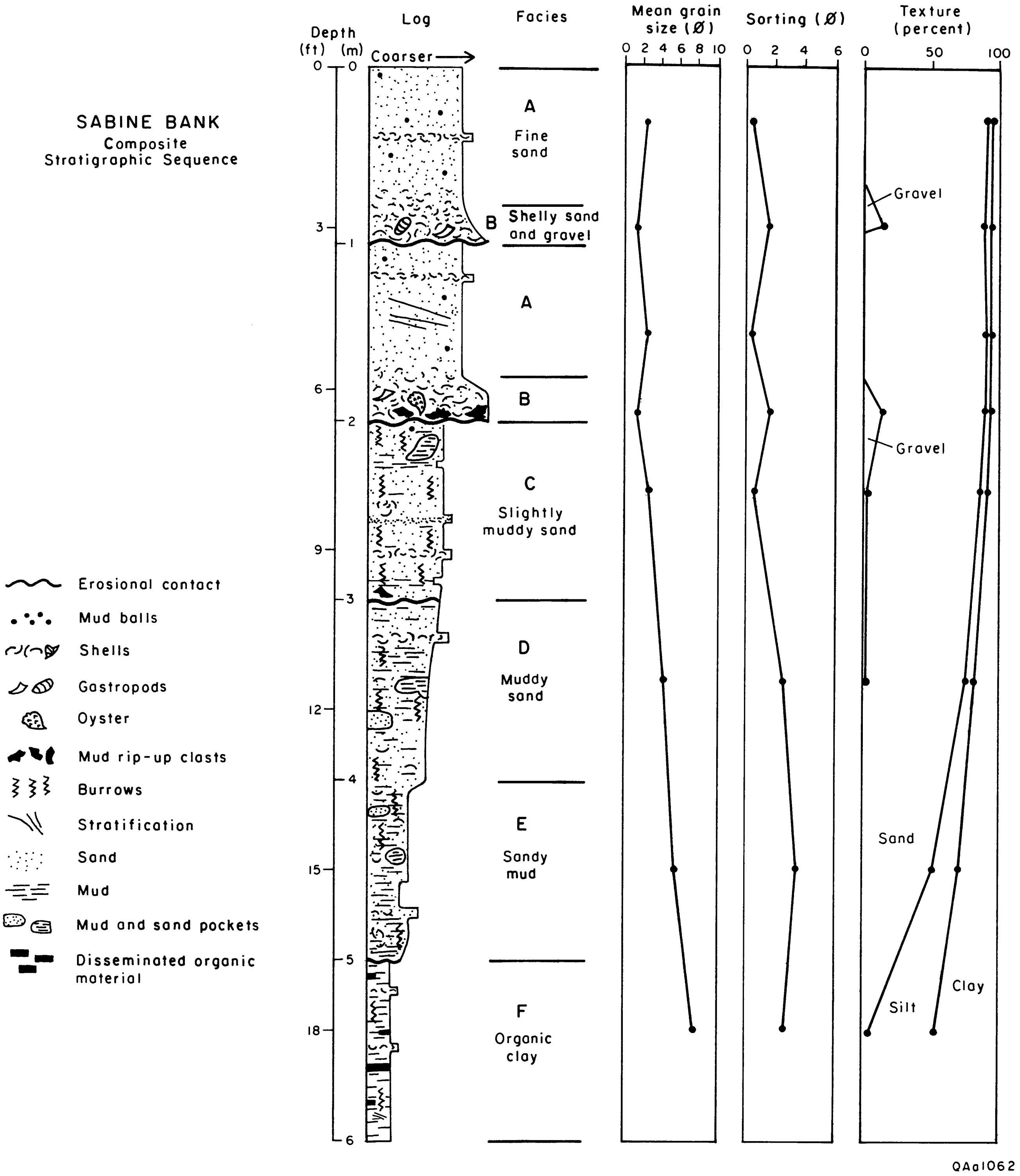

Figure 4. Composite stratigraphic column illustrating vertical succession of lithofacies. Plotted data are average values as presented in table 4.

small deltas at the heads of the major bays (Sabine Lake, Galveston Bay). The minor accumulations of fine-grained sediment deposited on the sea floor are mainly locally reworked and redistributed or imported from southwestern Louisiana by alongshelf currents.

The primary physical processes contributing to shelf sedimentation near Sabine and Heald Banks are (1) suspension and redistribution of preexisting shelf and shoreface sediments during storms and (2) transportation of suspended sediment from the adjacent shelf and bays (Sabine Lake and Galveston Bay). The latter sediments are transported as plumes through the dredged channels at Sabine Pass and Bolivar Roads, which are former tidal inlets. Suspended sediments derived from the bays may include fluvial sediment passing through the bay systems or sediment derived from erosion of the bay margin and bay center. What portion of the preexisting shelf or bay sediments contribute to shelf sedimentation is impossible to determine because of continuous physical and biological mixing. Storm-driven shelf currents and wave activity cause mechanical mixing, whereas burrowing organisms create additional heterogeneities after the sediments are deposited.

Current-meter records from production platforms (Forristall et al., 1977) and at brine diffuser sites for the Strategic Petroleum Reserve (Hann et al., 1985) provide a basis for estimating near-bottom current speeds and directions near Sabine and Heald Banks. These records indicate that there is strong coherence between wind vectors and shelf currents, indicating that neither the tidal component nor the river discharge (salinity gradient) component is large compared to wind stress. Although seasonal reversals in flow direction are recorded, the predominant direction of near-bottom shelf currents is to the southwest for most events that are capable of entraining and transporting significant volumes of sediment. This alongshelf transport direction is also maintained during high-energy events when peak velocities of nearly 2 m/s occur in water depths of 18 m (Morton, 1988).

Sediment transport on the Texas shelf has not been observed directly, but it can be inferred from moderately dense arrays of surface sediment samples collected after tropical storm Delia and Hurricane Alicia. Grain-size analyses of these samples indicate selective sorting parallel to flow directions that produce textural patterns resembling a longitudinal sand ridge system without topographic relief (Morton, 1988). The frequency and intensity of tropical cyclones in the Gulf of Mexico suggest that the near-surface sediments of Sabine and Heald Banks are repeatedly reworked and the near-surface sediments of the banks have been substantially modified since they were originally deposited.

Assessment of Sabine and Heald Banks

Primary Bank Lithofacies

Six lithofacies that characterize the sediments within and around Sabine and Heald Banks were identified from detailed descriptions of the vibracores. The lithofacies are fine sand, shelly sand and gravel, slightly muddy sand, muddy sand, sandy mud, and organic clay. Each lithofacies exhibits different sediment compositions, sediment textures, and preserved fauna. Also, each lithofacies occupies a predictable stratigraphic position within the vertical succession of lithofacies (Figure 4). The superposition of lithofacies describes an overall upward-coarsening facies architecture with progressively more sand and less mud from bottom to top. The attributes of each lithofacies are as follows.

A. Fine sand.

Lithology: very well sorted, subangular to subrounded, fine to very fine quartz sand. Some isolated small mud clasts and a few larger mud clasts. Trace amounts of granule-sized shell fragments, rounded phosphate grains, glauconitic grains and forams. Minor shelly layers less than 3 cm thick.

Sedimentary structures: Generally no observable structures present but occasional very obscure plane lamination.

Macrofauna: Polychaete worm tubes.

B. Shelly sand and gravel.

Lithology: Poorly sorted, shelly, sandy gravel and gravelly sand. The gravel fraction consist of whole shells and shell fragments. Mud ripup clasts may be present if the unit occurs above slightly muddy or muddy sand.

Sedimentary structures: Occurs as relatively thin beds (< 0.3 m) usually with an erosional lower contact and normal grading. Occurs within or at the base of facies A.

Macrofauna: Polychaete worm tubes, *Oliva sayana, Macoma tageliformis, Busycon, Anadara baughmani* (discolored and fresh), *Anadara brasiliana* (discolored and fresh), *Semele purpurescens, Macoma tageliformis, Mulinia lateralis* (discolored and fresh), Oyster fragments (discolored).

C. Slightly muddy sand.

Lithology: Poorly sorted, slightly muddy, fine sand with pockets and layers of mud, sand, and shelly, gravelly, muddy sand.

Sedimentary structures: Mostly bioturbated but some obscure muddy and sandy interbedding remains. May have erosional contact at base.

Macrofauna: *Mulinia lateralis* (discolored), *Argopecten irradians* (discolored), *Anadara baughmani* (discolored).

D. Muddy sand.

Lithology: Poorly sorted, muddy, fine sand with scattered shelly, muddy, sandy gravel pockets and thin layers. Some distinct pockets and layers of sand and mud throughout.

Sedimentary structures: Mostly bioturbated but some muddy and sandy interbedding remains. May coarsen upward with an increase in sandy interbeds.

Macrofauna: *Mulinia lateralis* (discolored and fresh), *Anadara baughmani* (discolored and fresh), *Noetia ponderosa* (discolored), *Crassostrea virginica* (discolored).

E. Sandy mud.

Lithology: Poorly sorted, sandy mud with isolated layers and pockets of shelly gravel, sand, and mud. Amount of shell material varies.

Sedimentary structures: Bioturbated with burrows filled with relatively coarser muddy sand and silt. Mud interbeds may be present. May coarsen upward, with mud layers becoming less distinct and less dominant. May have lower erosional contact.

Macrofauna: *Mulinia lateralis, Anadara baughmani, Trachycardium muricatum.*

F. Organic clay.

Lithology: Slightly organic clay with isolated layers and pockets of shelly, muddy gravel; muddy sand; and muddy silt. Pyrite is associated with burrows and organic material.

Sedimentary structures: Isolated burrows of muddy sand. Shelly, muddy gravel occurs as thin (<1 cm) layers. Silt/clay plane lamination is apparent in some sections. Organic material is disseminated but occurs in a few layers at higher concentrations. Clay is flocculated into silt-size particles. Distinct erosional upper contact.

Macrofauna: *Anadara baughmani.*

Sand Quality

Quantitative textural analyses of 43 samples taken from the 8 vibracores obtained for this study further define the facies described above. Table 3 provides data including sorting (standard deviation), mean grain size, and percent of gravel, sand, silt, and clay for each sample. These data are also plotted with the core descriptions in the Appendix. Table 4 provides the average textural values for each facies, and these values are plotted in Figure 4. It should be noted that the lithofacies described above were defined prior to and are independent of the quantitative textural analyses. There is, however, a good correspondence between the textural data and the qualitative facies descriptions, and the textural data confirm the upward-coarsening trends (Table 4).

The fine sand, shelly sand and gravel, and slightly muddy sand facies (facies A, B, and C) generally contain less than 15% mud and range in mean grain size from 0.75 ø to 2.98 ø (0.13 mm to 0.59 mm). One sample (SBV1C) taken from the shelly sand and gravel facies contains 22% mud. The fine sand and slightly muddy sand facies are moderately well to poorly sorted,

Table 3. Textures of individual samples.

Sample	Core	Facies	Depth in Core (m)	% Gravel	% Sand	% Silt	% Clay	Standard Deviation (ø)	Mean (ø)
SBV1A	VC-1	A	0.2	0.0	90.6	2.1	7.3	0.83	2.37
SBV1B	VC-1	A	1.2	0.0	91.4	1.6	7.0	0.50	2.50
SBV1C	VC-1	B	1.7	21.9	56.2	14.4	7.4	3.38	2.08
SBV1D	VC-1	C	1.9	2.9	85.5	2.4	9.2	0.75	2.67
SBV1E	VC-1	C	2.4	0.4	87.7	4.0	7.9	0.75	2.92
SBV2A	VC-2	A	0.3	0.0	90.9	1.7	7.4	0.38	2.08
SBV2B	VC-2	B	1.0	6.2	85.6	1.5	6.7	1.00	1.50
SBV2C	VC-2	B	1.5	32.8	59.2	1.5	6.4	2.00	0.75
SBV2D	VC-2	A	2.2	0.7	88.9	1.9	8.6	0.55	2.28
SBV3A	VC-3	A	0.2	0.1	93.3	2.4	4.2	0.58	2.60
SBV3B	VC-3	A	1.2	0.8	89.2	2.3	7.7	0.58	2.60
SBV3C	VC-3	B	1.7	10.2	81.0	1.6	7.2	0.98	2.02
SBV3D	VC-3	C	2.0	5.6	79.1	3.6	11.8	1.15	2.98
SBV4A	VC-4	A	0.2	0.7	90.4	2.1	6.7	0.45	2.41
SBV4B	VC-4	A	1.7	0.8	97.9	0.7	0.6	0.93	2.41
SBV4C	VC-4	C	2.1	2.2	87.0	3.9	7.0	0.75	2.67
SBV4D	VC-4	D	2.3	0.6	76.5	4.3	18.6	3.43	4.63
SBV4E	VC-4	D	3.4	0.8	75.0	6.3	15.8	3.25	4.80
SBV5A	VC-5	E	0.5	0.0	59.9	11.8	28.3	4.25	5.72
SBV5B	VC-5	E	0.7	0.0	33.5	19.9	46.6	4.68	7.20
SBV5C	VC-5	F	4.3	0.0	5.2	44.1	50.7	4.05	8.30
SBV6A	VC-6	A	0.3	0.1	93.3	3.0	3.7	0.55	2.38
SBV6B	VC-6	A	1.7	0.2	94.0	1.3	4.4	0.60	2.25
SBV6C	VC-6	B	2.0	2.1	89.7	1.6	6.5	2.23	2.18
SBV6D	VC-6	C	2.3	2.0	93.7	1.5	2.8	0.63	2.23
SBV6E	VC-6	D	2.8	0.9	76.2	8.6	14.3	2.55	3.80
SBV6F	VC-6	E	4.1	0.0	63.8	21.4	14.8	2.38	4.28
SBV6G	VC-6	E	5.4	0.0	39.5	32.0	28.5	3.35	5.48
SBV7A	VC-7	A	0.3	0.1	95.3	1.6	3.0	0.50	2.53
SBV7B	VC-7	B	0.8	26.2	69.9	0.6	3.3	2.20	1.13
SBV7C	VC-7	D	1.5	0.1	86.2	1.1	12.6	3.05	2.97
SBV7D	VC-7	D	2.0	0.4	85.3	2.2	12.2	0.98	3.03
SBV7E	VC-7	D	2.6	0.3	77.8	3.7	18.2	3.50	4.93
SBV7F	VC-7	E	2.9	0.3	75.9	5.9	18.0	3.35	4.76
SBV7G	VC-7	E	4.3	0.1	65.0	13.3	21.7	3.20	5.12
SBV7H	VC-7	E	5.3	0.3	28.3	22.3	49.1	4.63	7.31
SBV8A	VC-8	A	0.0	0.2	91.3	2.9	5.8	0.88	2.75
SBV8B	VC-8	C	0.6	0.7	84.6	7.3	7.4	1.05	2.95
SBV8C	VC-8	D	1.1	1.1	80.5	6.2	12.0	1.37	3.40
SBV8D	VC-8	D	2.3	0.5	67.5	9.1	19.5	2.49	4.95
SBV8E	VC-8	D	3.5	0.7	66.2	11.4	21.8	2.75	4.98
SBV8F	VC-8	D	4.0	2.3	66.8	9.4	24.4	4.13	5.42
SBV8G	VC-8	F	4.9	0.0	8.7	47.0	44.3	1.55	7.42

Table 4. Average textural values.

Facies	% Gravel	% Sand	% Silt	% Clay	% Mud (Clay+Silt)	Standard Deviation (ø)	Mean (ø)
A	0.3	92.2	2.0	5.5	7.5	0.61	2.43
B	16.6	73.6	3.5	6.2	9.7	1.97	1.61
C	2.3	86.3	3.8	7.7	11.5	0.85	2.74
D	0.8	75.8	6.2	16.9	23.2	2.75	4.29
E	0.1	52.3	18.1	29.6	47.6	3.69	5.70
F	0.0	6.9	45.5	47.5	93.0	2.80	7.86

whereas the shelly sand and gravel is poorly to very poorly sorted. These are the coarsest facies in the Sabine Bank area, and mean grain size within and between these facies is primarily a function of the relative amounts of coarse shell material and mud.

The muddy sand and sandy mud facies (facies D and E) contain considerably more mud than overlying facies. The muddy sand averages 23% mud and ranges from 14 to 34% mud, whereas the sandy mud facies averages 48% mud and ranges from 24 to 71% mud. The mud fraction in both facies is dominated by clay-size material (Tables 3 and 4). The average mean grain sizes of the muddy sand and sandy mud are 4.29 ø (0.05 mm) and 5.70 ø (0.02 mm), respectively. Both facies are very poorly sorted partly because the sediments are highly bioturbated.

The finest grained facies is the organic clay (facies F), which occurs at the bottom of the sedimentary sequence. Two samples from different cores were analyzed for this facies (Table 3). The two samples yielded very similar textural values with 91 to 95% mud with the silt and clay making up equal portions of the mud fraction.

Eroding beaches of the southeastern Texas coast that are candidates for beach replenishment have variable compositions and textures. The beaches between Sabine Pass and High Island locally can contain as much as 85% shell and other gravel-sized clasts composed of caliche nodules and rock fragments. The sand fraction is composed of well-sorted, fine to very fine sand (Bullard, 1942; U.S. Army Corps of Engineers, 1958; Bridges, 1959; Hsu, 1960; Prather and Sorensen, 1972) and has a mean grain size of 0.13 mm (Garner, 1967). The sand is composed mostly of quartz with some feldspar and minor amounts of heavy minerals. The beaches of Galveston Island also are composed of well-sorted, fine to very fine sand (Bullard, 1942; U.S. Army Corps of Engineers, 1953; Hsu, 1960) that have a mean grain size between 0.13 and 0.16 mm (Garner, 1967). Heavy minerals make up only a minor fraction of the sediments and shell content is generally low (<2%) except near San Luis Pass, where it can be as much as 15% of the sediment volume (U.S. Army Corps of Engineers, 1953).

Available compositional and textural data indicate that the sand deposits associated with Sabine Bank are compatible with the beach sediments of the southeastern Texas coast. Beach replenishment using the fine sand, shelly sand and gravel, slightly muddy sand, and muddy sand facies (facies A, B, C, and D) would require only a modest overfill ratio. The sandy mud and organic clay facies (facies E and F), however, are not appropriate for beach replenishment.

Sand Quantity

The three-dimensional geometry and volumetric estimates of sand deposits associated with Sabine and Heald Banks were determined using a combination of nearsurface lithology, bathymetry, and seismic profiles. Nearsurface lithology, provided by the cores and foundation borings, delineated the lateral extent of sand as well as the thickness of sand and any overburden (Figures 5–9). Bathymetry also was used to help define the lateral extent of sand, and the seismic profiles provided a crosscheck on subsurface correlation of the nearsurface lithofacies.

Both Sabine and Heald Banks are lenticular sand bodies that cover large areas (Figures 5–9). Together the banks contain about 1.8 billion m^3 of sand and muddy sand nearly equally distributed between the two banks (Sabine, 839 million m^3 and Heald, 945 million m^3, Table 2). Within the overall trends of sand deposits are elongate lenses where sand and muddy sand deposits more than 3 m thick are concentrated (Figure 5). These elongate lenses would be the optimum sites for sand extraction because of the relatively high sand concentrations. For Sabine Bank, the northern and southern elongate lenses contain about 252 million m^3 and 264 million m^3, respectively. The distribution of sand associated with Heald Bank is not well defined and it does not coincide solely with the bathymetric highs, but it extends far beyond the small irregular shoals defined by the 10 m isobath (Figure 5). The large area of sand less than 3 m thick accounts for slightly less than half of the total sand in Heald Banks and about 544 million m^3 is located in the elongate lens where thicknesses are greater than 3 m.

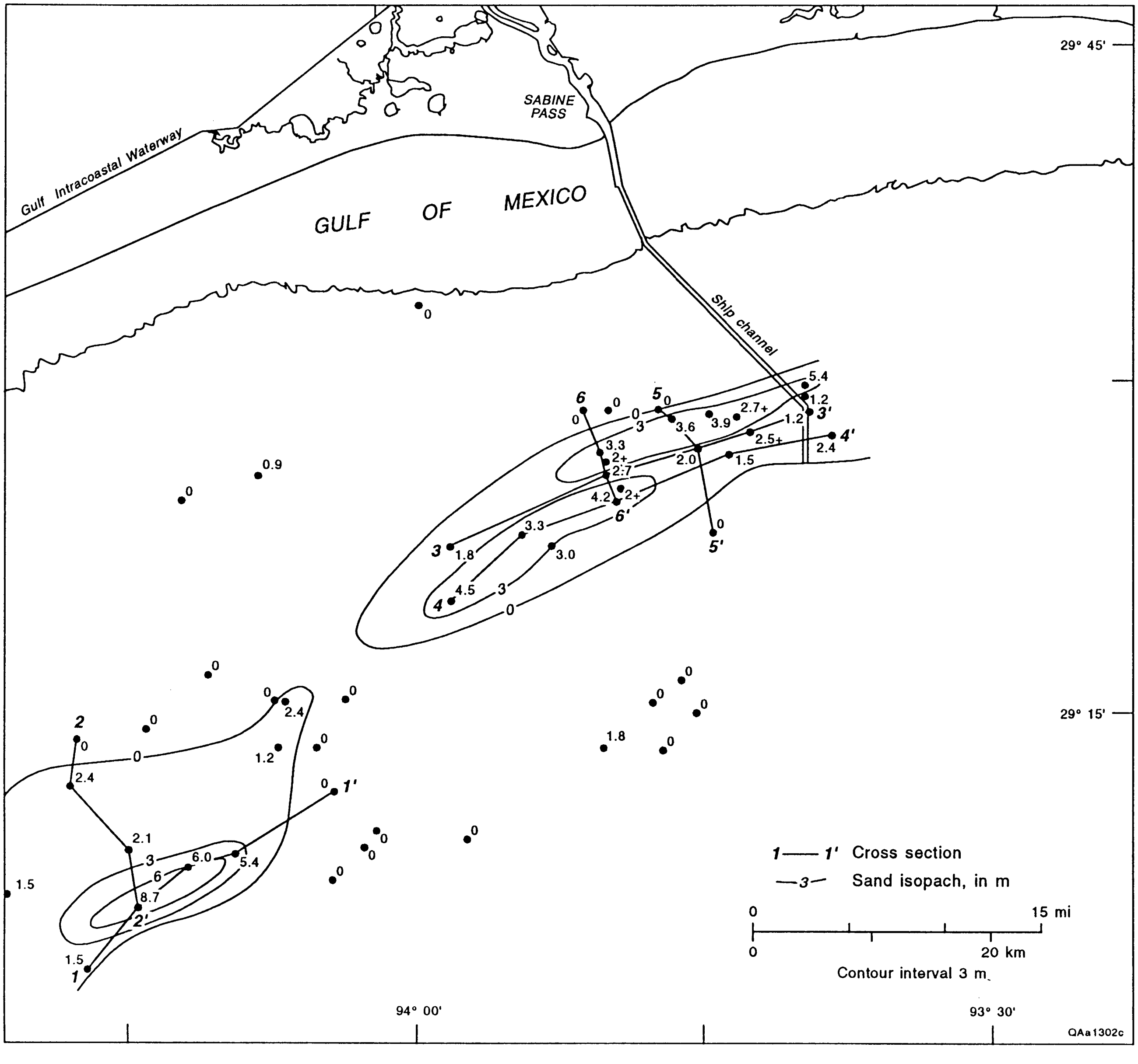

Figure 5. Locations of stratigraphic cross sections illustrating lithofacies associated with Sabine and Heald Banks. Isopach map of sand and muddy sand lithofacies based on foundation borings, vibracores (from this study and Thomas, 1990) and rotary borings (Nelson and Bray, 1970).

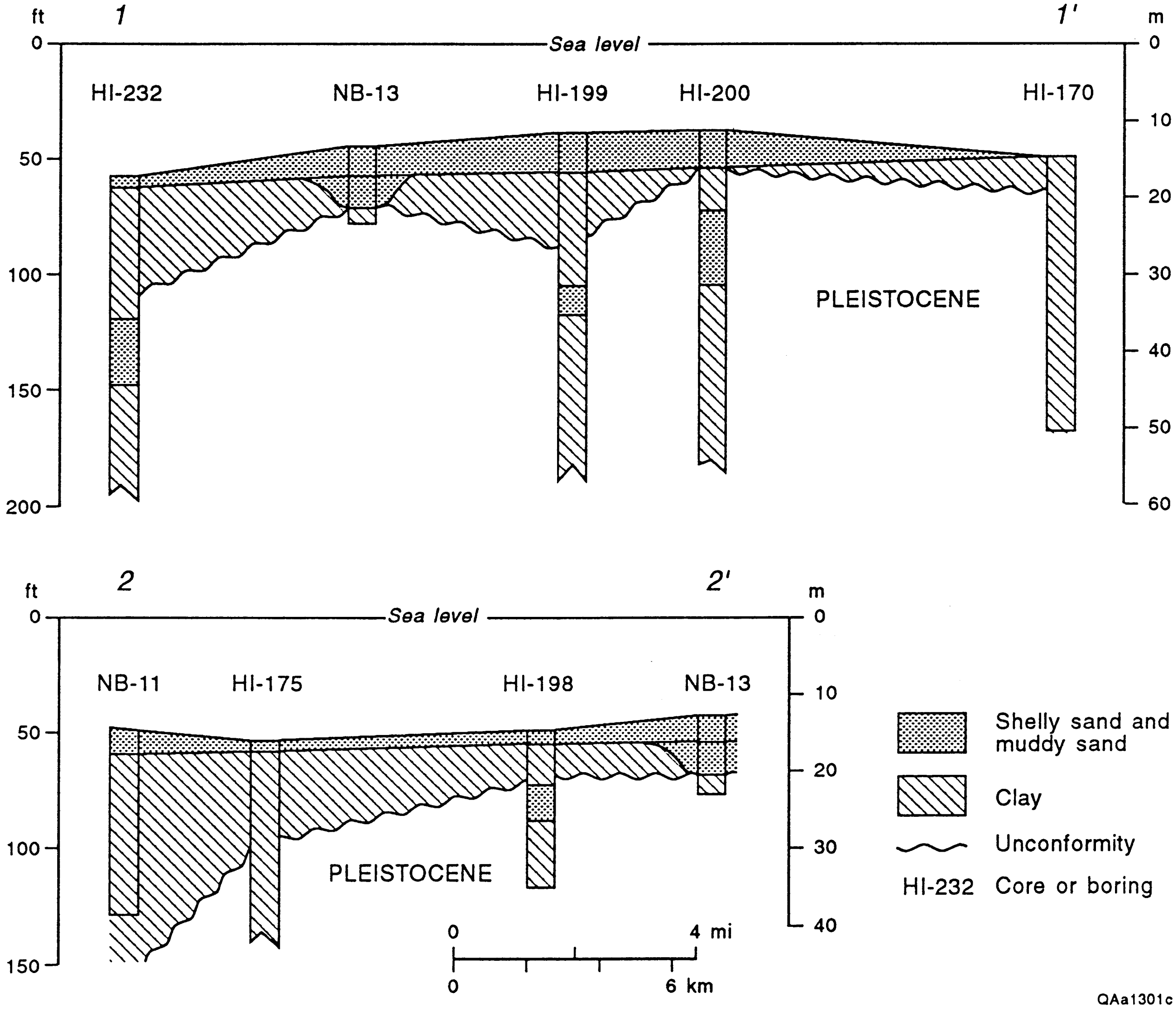

Figure 6. Stratigraphic strike and dip sections across Heald Bank.

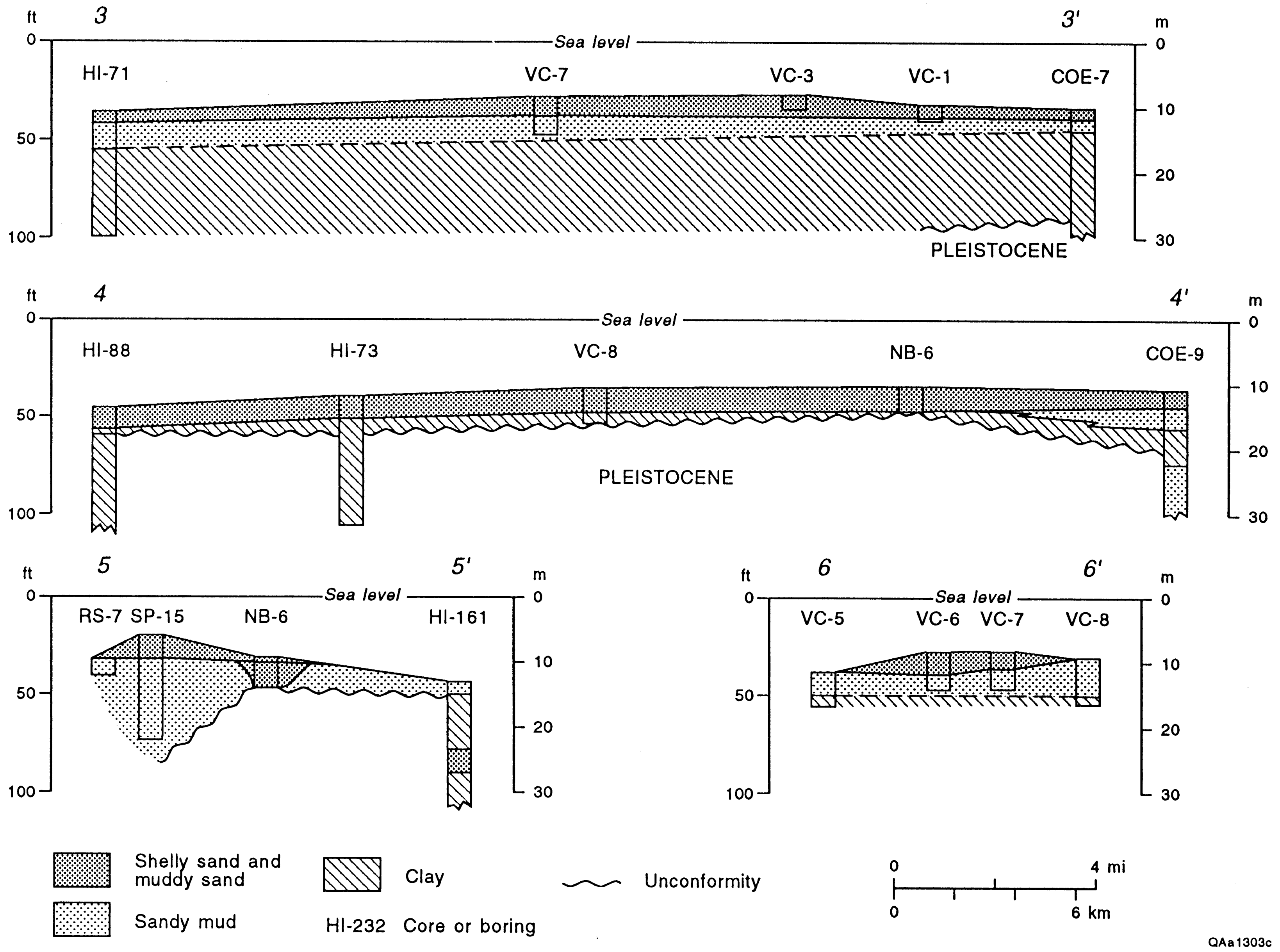

Figure 7. Stratigraphic strike and dip sections across Sabine Bank.

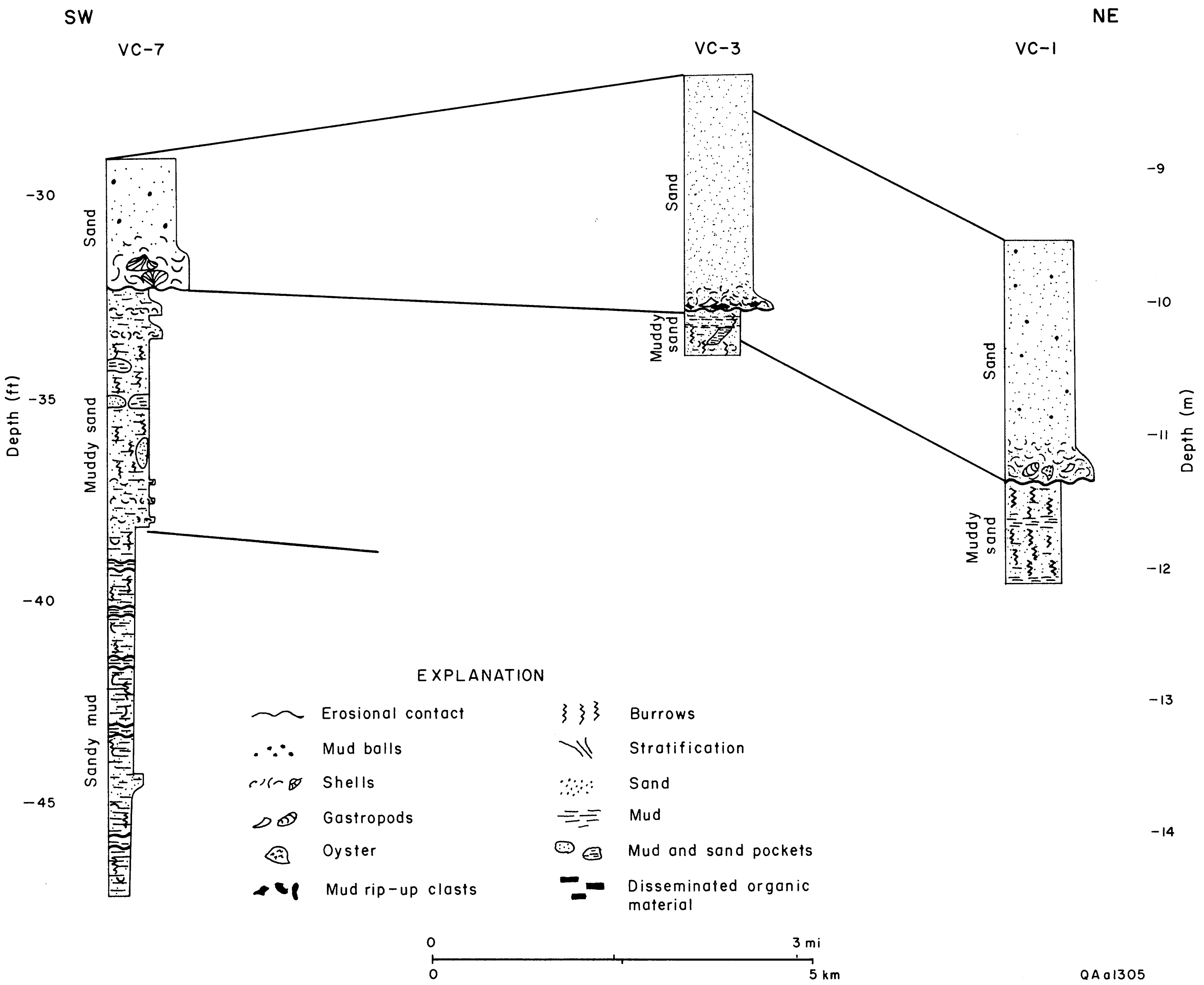

Figure 8. Detailed vibracore strike section across Sabine Bank.

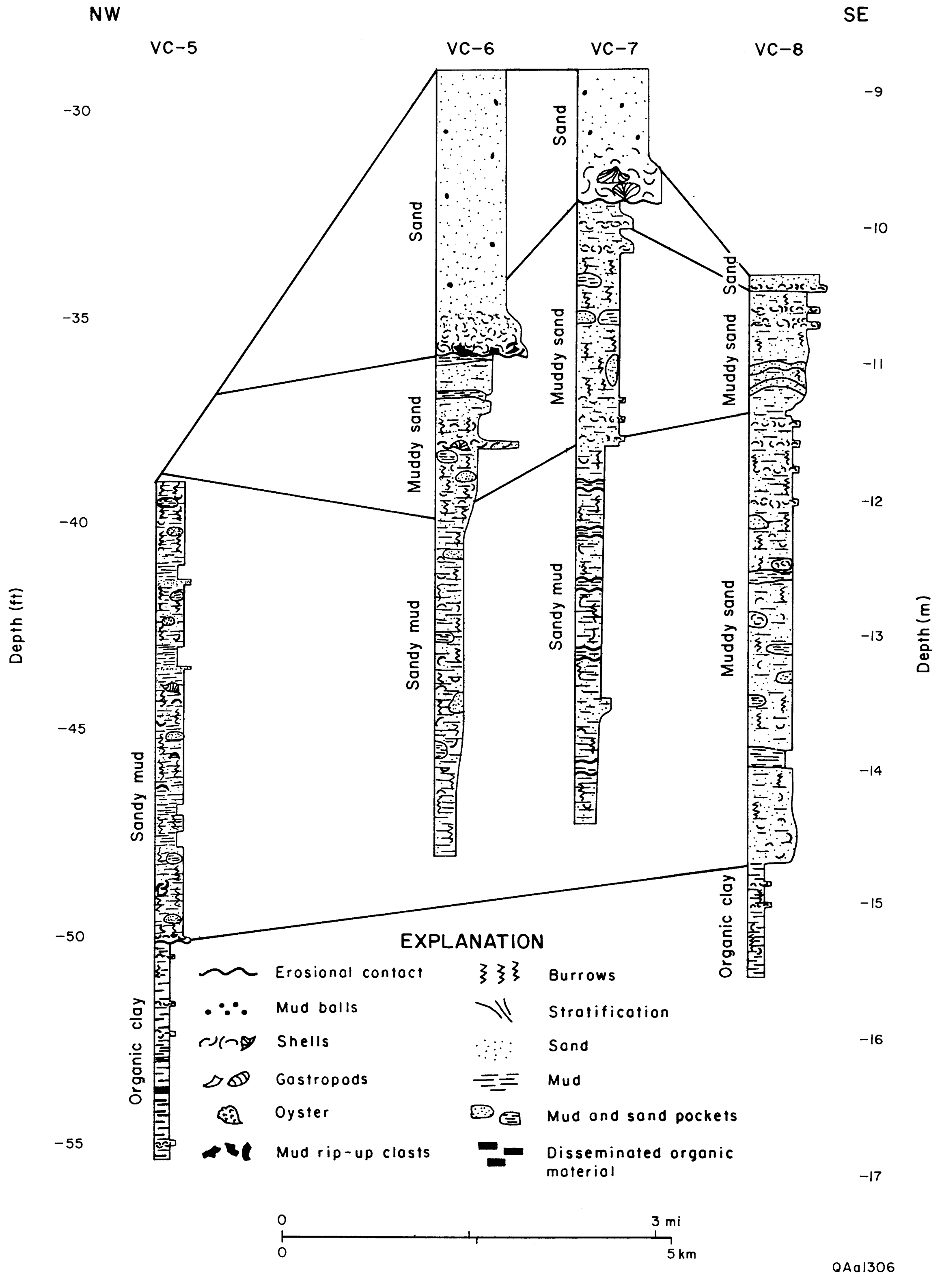

Figure 9. Detailed vibracore dip section across Sabine Bank. The top of the organic clay facies is interpreted as the ravinement surface.

ENVIRONMENTAL CONSIDERATIONS

Overburden Conditions

The initial work plan anticipated determining the volume, composition, and physical properties of the overburden material so that basic questions regarding magnitude of the overburden and alternative placement of the noneconomic material could be addressed. Furthermore, we expected to conduct preliminary analyses of clay mineralogy and heavy metal concentrations of the overburden because the dredging plume would include fine-grained sediments suspended while the sand deposits were being extracted.

Textural analyses of the vibracores and inspection of the foundation borings demonstrate that sand is exposed at the sea floor and overburden is not present where the high-quality sand deposits are located either on Sabine or Heald Banks (Figures 7–9). Therefore, the geochemical analyses of overburden material could not be conducted.

Shoal Stability

Plans to extract sand from the offshore banks could be influenced by their stability and whether or not they are (1) dormant features, (2) still actively forming or migrating, or (3) are being reworked in place. The stability of the banks could best be addressed by monitoring patterns of erosion and deposition and relating those patterns to the physical oceanography of water masses moving over and around the banks. These issues were not specifically addressed in the study, but preliminary inferences regarding shelf currents and bank stability can be made on the basis of historical bathymetric changes, existing oceanographic data, and sedimentological characteristics of the vibracores.

Each of the three potential states of stability has its own criteria that can be compared with the evidence derived from bathymetric maps and vibracores. (1) Relatively unchanged bathymetric contours and preserved internal stratification would suggest that the banks are inactive relict features that have not been subsequently modified by shelf processes. (2) If the banks are still actively growing, then sand accumulation would result in shallower water depths above or on the flanks of the banks, whereas bank migration would result in the displacement of shallower and deeper bathymetric contours in the direction of migration. Confirmation of these bathymetric changes would also require identifying a local source of sand supply and determining if the directions of bank enlargement or migration were compatible with directions of shelf sediment transport. (3) In situ reworking of the banks would be indicated if the bathymetric contours remained unchanged, but the vibracores encountered several erosion surfaces near the top of the cores separating the sediments that are characterized by physical structures from the underlying intervals where biogenic structures are predominant.

Preliminary comparison of digitized shelf bathymetry near Sabine and Heald Banks by the USGS suggests that the Banks are relatively stable and have not been migrating at least since the 1930's (Jeff List, personal communication, 1992). However, the vibracores show several reactivation surfaces within 2 m of the sea floor (Figure 4, Table 5, and Appendix). The similarity of scour depth regardless of water depth (Table 5) indicates that the extant waves and currents of the shelf are capable of reworking the upper 2 m of sediment. Additional evidence that the banks are being reworked in place is provided by Thomas (1990), who reported that the surface of Sabine Bank is characterized by large asymmetrical sand waves having crests that are oriented NW-SE, which is at a high angle to the long axis of the bank.

The available bathymetric and sedimentological data indicate that the banks are relatively stable and surrounded by marine mud (Figure 5). Therefore, it is expected that sediment motion on the banks would not interfere with sand extraction operations and extraction of sand from the banks would not interfere with sand supply to beaches of the southeastern Texas coast.

Table 5. Comparison of water depth and scour depth in sand and shelly sand facies.

Core	Water Depth (m)	Scour Depth (m)
1	9.5	1.8
2	6.0	2.1
3	8.2	1.8
4	7.9	2.0
5	11.7	mud
6	8.7	2.1
7	8.7	0.9
8	10.4	0.15

Other Environmental Concerns

Other environmental concerns regarding offshore sand extraction would be addressed in the future if the physical assessment studies demonstrate that Sabine and Heald Banks contain large deposits of sand suitable for beach replenishment and if economic analyses indicate that offshore deposits are competitive with onshore supplies. Additional environmental issues that could be addressed in subsequent years include analyzing coastal erosion potential resulting from changes in wave refraction patterns, predicting composition of the dredging plume, determining the geochemistry of the mud within the sand deposits (especially the form and stability of heavy metals in the mud fraction), and assessing the potential impacts of altered bathymetry on the fisheries industry.

SUITABLE EXTRACTION TECHNOLOGIES

The limitations and advantages of dredging equipment suitable for extracting sand resources from the continental shelf in the Gulf of Mexico have been reviewed and summarized by Chisholm (1991). The following discussion examines the summary by Chisholm (1991), describes the dredging equipment currently operating along the Texas coast, and determines the most likely technologies that could be used to develop sand resources from Sabine and Heald Banks. Field conditions and equipment parameters considered for this evaluation included water depths over the banks and at the placement sites, anticipated wave characteristics at the dredging and placement sites, haul distances, and potential rates of production for the various types of equipment. Results of this evaluation are necessary so that an econometric model, such as QUIKSAND, can be used to estimate costs of sand extraction.

Combined Dredging and Sand-Transferring Systems

Pipeline Dredges

Pipeline dredges are readily available throughout the northwestern Gulf of Mexico where they are commonly observed working in protected waters. Their principal use is for maintenance and improvement of navigation channels including the interior channels to major harbors and ports, the Gulf Intracoastal Waterway, and in numerous smaller channels and marinas. Pipeline dredges are self-contained units that simultaneously perform both excavation and disposal operations. The dredges use attached pipelines to transfer the dredged material usually to upland disposal sites.

Pipeline dredges are relatively small, efficient, and economical to operate. Despite these attractive features, they are not self propelled and are not designed to operate where exposed to ocean waves. Because of these limitations, pipeline dredges are not suitable for sand extraction from Sabine and Heald Banks.

Hopper Dredges

Ocean-going hopper dredges are also readily available throughout the northern Gulf Coast, where they are commonly used to maintain and deepen the Gulf entrance channels to the major harbors and ports. These hopper dredges are designed to operate when exposed to ocean waves and they commonly work between the jetties and in the Gulf of Mexico where the entrance channels crossing the continental shelf are unprotected. Hopper dredges are commonly observed operating in the approaches to Sabine Pass or Galveston Harbor. These entrance channels and associated fairways cross Sabine and Heald Banks, respectively.

Hopper dredges are relatively large and therefore require relatively deep water (>8 m [26 ft]) to operate. Along the Texas coast, a hopper dredge used to transfer sand from a navigation channel to the beach on South Padre Island was unable to get in closer than about 8 m of water (McLellan, 1990). Hopper dredges are also expensive to operate not only because of their size but also because they are self-propelled ships that perform both extraction and disposal as separate operations. As the name implies, these dredges store the dredged material in hoppers that are emptied over predetermined open-water disposal sites. The disposal sites are near but downcurrent of the navigation channel being maintained. Examples are the two spoil disposal sites flanking the northeastern end of Sabine Bank (Figure 1) that receive material dredged from the Sabine Bank Channel.

The advantages of a shallow-draft hopper dredge with direct pump-out capabilities have been summarized by Bruun and Willekes (1992). Even when fully loaded these dredges can operate in 3 to 4 m of water, which allows them to get near enough to the shore so that they can be directly emptied onto the beach. Bruun and Willekes (1992) reported that transferring several hundred thousand cubic meters of sand each year could be accomplished for about \$4 to \$5/m^3 (\$3 to \$4/yd^3) if the dredging site and disposal site were close to one another. These conditions commonly exist where tidal inlets are dredged and the dredged material is placed on the adjacent beach for beach replenishment. Bruun and Willekes (1992) also showed how the unit price of sand substantially increases as the haul distance between the dredging site and disposal site increases. Because haul distances to all potential replenishment sites on the upper Texas coast exceed 30 km, it is unlikely that a shallow-draft hopper dredge would be economical because much of the time it would be running to or returning from the beach fill site.

Separate Dredging and Sand-Transferring Systems

Some dredging operations are more economical if the dredging and sand transferring activities are conducted separately by different types of equipment. Potential combinations of equipment that optimize dredging and transportation would be the use of bucket or sidecast dredges to mine the sand and scows or hopper barges to transport it to the beach. The use of scows or barges can actually be a more efficient operation by reducing transportation costs and allowing the dredge to continuously mine the sand.

A mechanical bucket dredge mounted on a self-propelled jack-up barge could be used to load scows. However, the dredge would need to be moved after only a limited area around the dredge was mined. The jack-up capability would protect the dredge from high waves but it also imposes a disadvantage, which is the lack of complete mobility.

Hydraulic sidecast dredges are mobile and able to work in exposed marine environments. They are relatively small, can operate in shallow water, and normally are used to maintain small channels or inlets. Considering the offshore sand mining application, sidecast dredges are more mobile than jack-up barges and sidecast dredges also can be used to load scows or hopper barges. A severe limitation is that sidecast dredges in the U.S. are owned by the Corps of Engineers and would be unavailable for commercial extraction of sand resources (Chisholm, 1991).

Optimum Extraction Operations

Water depths over the Sabine and Heald Banks range from about 4.5 to 17 m and the thickest concentrations of beach-quality sand occur in water depths of 4.5 to 10 m. Furthermore, the shoreface profiles along the upper Texas coast are gentle and the 8 m isobath can be from 2 to 4 km seaward of the beach. These shallow water depths generally preclude the use of hopper dredges working in the navigation channels because they would not be able to work over the crest of Sabine Bank or get near the beach to discharge the sand. This latter limitation would require the use of an intermediate handling system that would transfer sand from the dredge to the beach. High equipment costs and inefficiencies of operation would probably preclude the use of this dual-transfer system.

Extraction of sand from Heald and Sabine Banks would require a dredge that is mobile and able to withstand moderate wave-energy conditions. A secondary desirable feature would be a system that eliminates the need to rehandle the sand. These criteria suggest that a shallow-draft hopper dredge with direct pump-out capabilities might be the optimum equipment for extraction of sand at Sabine and Heald Bank if the beach replenishment site is within 20 km of the banks. Unfortunately, all the potential sites exceed this distance and therefore it appears that separate mining and transportation activities would provide the greatest efficiency at the lowest cost.

Beach replenishment projects with haul distances greater than 20 km would probably employ a hydraulic sidecast dredge or mechanical bucket dredge and a system of tugs and scows that would move the sand between the Banks and the beach fill site.

POTENTIAL OBSTRUCTIONS TO SAND EXTRACTION

Numerous wells have encountered hydrocarbons along the Sabine-Heald Bank trend, and the existing infrastructure that supports the offshore oil and gas industry would need to be considered before any sand extraction plan was adopted. In the area of interest, there are production platforms, oil and gas pipelines, obstructions on the sea floor, a deep-draft navigation channel, and navigation aids that might interfere with sand-extraction activities (Figure 10). The following discussion is only a preliminary identification of the more obvious exposed and buried obstructions shown on navigation charts and generalized pipeline maps. It is not intended as an exhaustive inventory of all potential impediments to extraction of the sand resource, and additional field and laboratory work would need to be conducted before all the obstacles and their influence on dredging are known.

Platforms

In this report, "platform" is a generic term that refers to a variety of offshore oil and gas production facilities ranging from single-well caissons to multiple-well platforms. These steel structures that extend above sea level may occur in clusters around large fields (High Island Blocks 135, 136, 160, 161) or as isolated platforms (High Island Block 199). The locations of platforms are easily identified from government sources (Minerals Management Service, Coast Guard) as well as by visual observation.

The platforms represent potential obstructions to navigation as well as physical impediments to mining that would preclude extraction of sand within a prescribed distance around the structure.

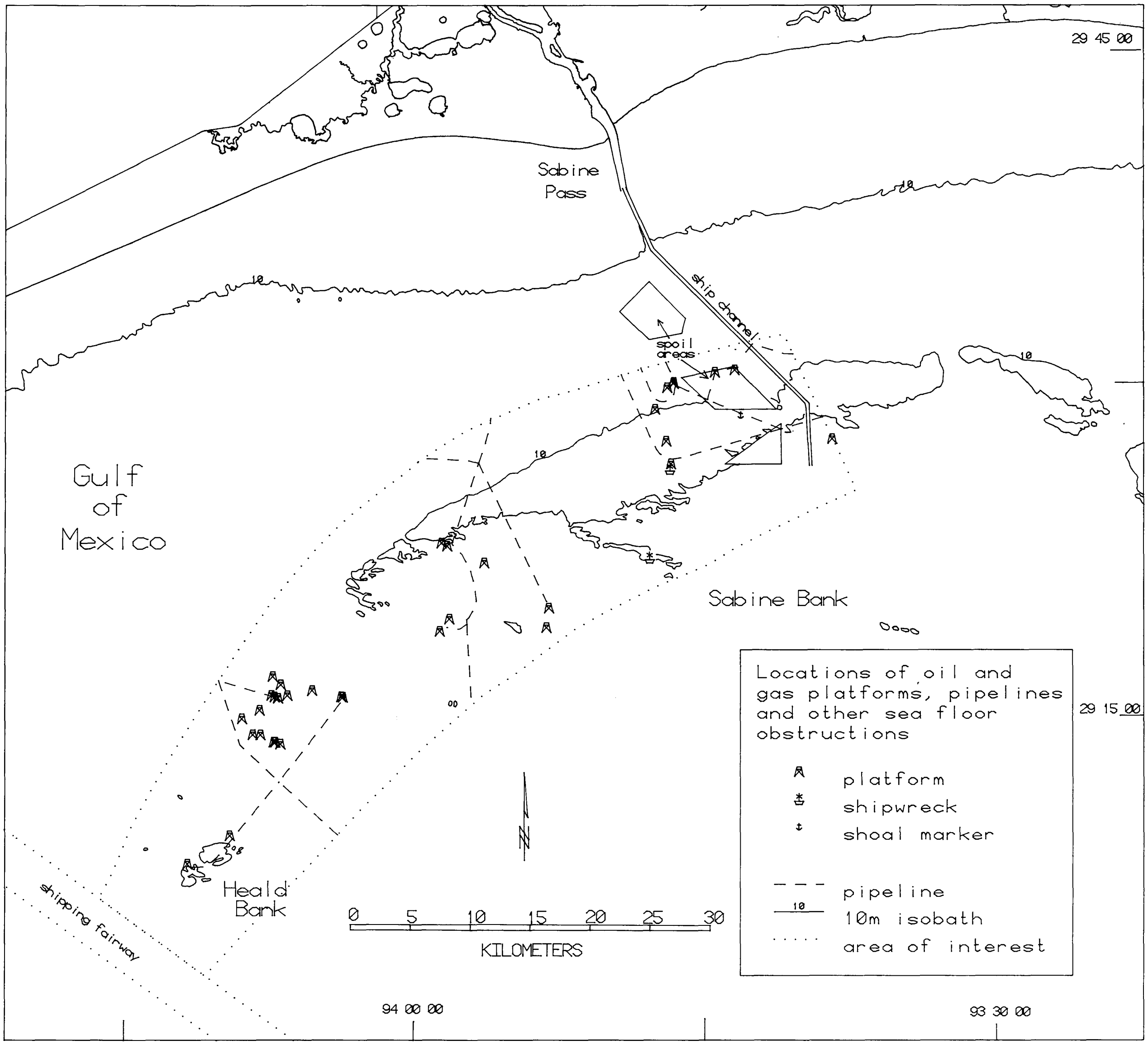

Figure 10. Locations of pipelines, production platforms, and other mapped obstructions with respect to thick sand deposits near Sabine and Heald Banks.

Pipelines

An elaborate network of pipelines collects the oil and gas produced from the platforms and transports the fluids onshore. The pipeline network consists of a hierarchy that ranges from small diameter intrafield gathering systems that merge with larger interfield pipelines. These pipelines of intermediate size then merge with larger diameter regional transmission pipelines that transport the fluids to refineries or marketing systems. Pipelines within the area of interest can be located using industry sources and previous compilations for pipeline impact studies.

Pipelines are long linear features that would prevent sand extraction or anchoring within a band parallel to the pipeline. Although the route of the pipeline is accurately known, the depth of burial may be uncertain because of changes in the sea floor or pipeline position after the pipeline survey was conducted. Most pipelines are initially buried as much as 3 m (10 ft) below the sea floor. The depth of pipeline burial can change by sediment deposition or erosion or by the pipeline moving up through the overburden.

Other Obstructions

Navigation charts published by the National Oceanic Service show the locations of a few shipwrecks and other obstructions on the sea floor (Figure 10) that might influence sand extraction from Sabine and Heald Banks. These obstructions are generally small features that could possibly prevent mining in their immediate vicinity, but would not impact a large area. A problem of greater magnitude is the accurate location and identification of uncharted snags and steel debris that are remnants of hydrocarbon exploitation or a result of illegal ocean dumping. These unrecorded obstructions would require magnetometer and diver-assisted surveys to determine how they would influence sand extraction.

The bathymetric high of Sabine Bank is disrupted at its northeastern end by a natural low that was deepened as part of the Sabine Bank Ship Channel. This deep-draft channel that crosses the Sabine Bank trend (Figure 10) is the main transportation route for large vessels destined for Sabine

Pass, Port Arthur, and Beaumont. Hopper dredges routinely operate in the channel to maintain safe navigation depths, but mining operations that interfered with safe navigation would be prohibited. At the southwestern end of the sand trend is the shipping fairway to the Galveston–Houston Ship Channel. Similarly, any sand extraction activities at Heald Bank that interfered with shipping would be prohibited.

A tall, lighthouse-like navigation aid marks the crest of Sabine Bank at its northeastern end near the Sabine Bank Channel (Figure 10). Sand extraction would be prevented within a relatively large radius around this shoal marker so that the marker foundation would not be undercut and exposed to marine erosion.

CONCLUSIONS AND RECOMMENDATIONS

The present geological investigation of the inner continental shelf of the upper Texas coast has demonstrated that a large volume of sand-rich sediments are associated with Sabine and Heald Banks. The total volume of sandy sediments, estimated at more than 1.7 billion m^3, constitutes a large hard-mineral resource suitable for uses such as beach replenishment and other construction activities. Compared to Sabine Bank, Heald Bank is in deeper water, contains more sand, and is closer to potential markets such as Galveston Island where projects requiring beach quality sand are currently being conducted or planned.

The sand deposits are located in water depths ranging from 4.5 m to about 17 m, and the greatest thickness of beach-quality sand coincides with the shallowest water depths on Sabine Bank. Several petroleum pipelines, production platforms, and a lighthouse are located within the trend of high-quality sand deposits, but they would not necessarily prevent mining of sand from either of the banks. Offshore mining of the sand resource would require equipment designed for open-water dredging (moderate wave climate). Also it is anticipated that dredging and sand transportation would be separate operations because of the distances between the sand deposits and their potential market. On the basis of current offshore mining technology, costs of operation, and mining efficiencies, it appears that a hydraulic sidecast dredge or bucket dredge would be appropriate for sand extraction and a system of tugs and scows would be needed to move the sand between the Banks and beach fill sites.

Although the scientific objectives of the first year of study were achieved, some work remains to be done so that leasing of the offshore sand resources can become a reality. The following recommendations for additional work are based on the findings of the preliminary study and on identifying information needs that still exist.

The 1992 vibracoring cruise was successful in obtaining cores for Sabine Bank. However, additional vibracores are needed to extend the textural control westward on Sabine Bank, to delineate the vertical and lateral limits of sand around Heald Bank, and to quantify the sediment composition and textures of Heald Bank. This work would finish the geological characterization of the entire trend and complement the sedimentological work on Sabine Bank that is presented in this report.

Further work is also needed to understand the physical processes in the Gulf of Mexico near the Banks and the potential influence of those processes on sand-extraction operations. In this report we only address average conditions for waves and tides. Those statistical averages provide some limited information about wave heights and periods, but they are inadequate with regard to planning a sand-extraction operation. More important than averages are the distributions of wave heights, wave periods, wave directions, current speeds, and current directions as well as the seasonality of all these processes. A spectral analysis of inner shelf processes is needed to determine if dredging equipment would be able to operate uninterrupted throughout the year or if mining operations would be suspended during certain months when wave energy is greatest. It would also be useful to know how the mining operations might be affected by weather patterns and meteorological factors (wind, barometric pressure, rain, and fog) and how offshore physical oceanographic conditions are linked to meteorological forces. Another application of the physical processes analysis has to do with predicting the direction and distance that suspended sediment will be transported away from the mining site. Movement and dispersion of the suspended sediment plume will depend on the sea state and shelf currents.

The preceding paragraph discusses the possible impacts of the environment on mining operations. Also needed are studies of the possible impacts of mining on the environment. One area of environmental concern is the possible changes in wave refraction patterns if large volumes of sand were removed from the sea floor. Altered refraction patterns could focus wave energy and accelerate erosion of beaches downstream of the refracted waves. Another area of environmental concern deals with the possible impacts of mining on the benthic fauna near the mining operation. Biological baseline studies of the infauna and the expected impacts of dredging on the mortality and recovery of the infauna will need to be investigated before leasing and mining begin.

Before leasing of offshore sand resources in the western Gulf commences, an economic analysis of offshore mining will need to be conducted. An economic analysis of offshore sand extraction has not been conducted for the Sabine-Heald Bank trend for several reasons. First, the physical and environmental issues regarding quality of the sand resource and possible environmental impacts need to be resolved before an economic analysis is conducted. Second, economic analyses are ephemeral because of the transient nature of supply and demand as well as externalities that determine economic climate. An economic analysis would need to be conducted before the near-term leasing phase is achieved but after specific mining objectives have been determined. A third reason why an economic analysis of Sabine and Heald Banks has been postponed is that an economic analysis of mining sand in the Gulf of Mexico at Ship Shoal was favorable (Kelly and Crawford, 1991). Furthermore, mining of sand off the Atlantic coast and along the west coast of Florida for beach replenishment are currently economical, and the economics of offshore sand mining in the Gulf of Mexico should improve as demand increases.

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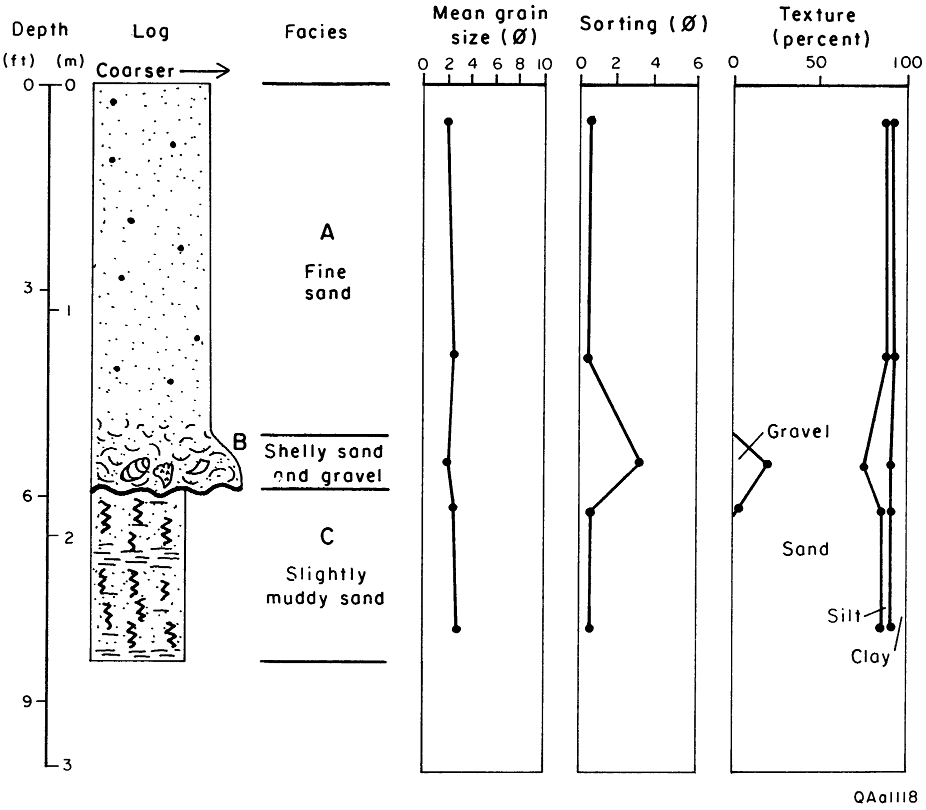
APPENDIX



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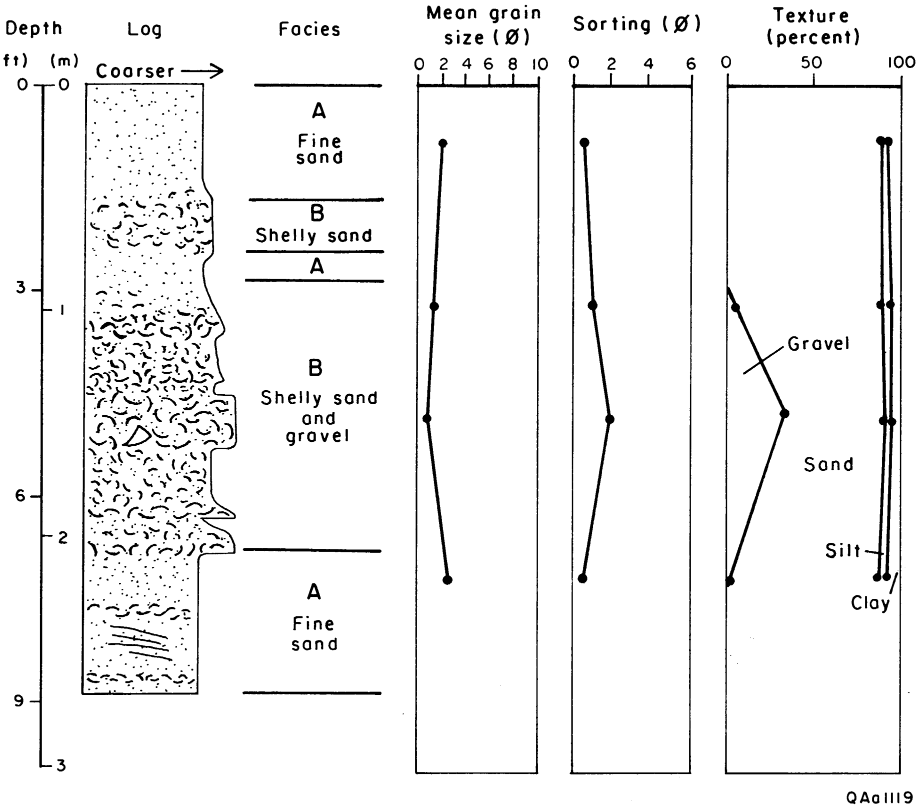

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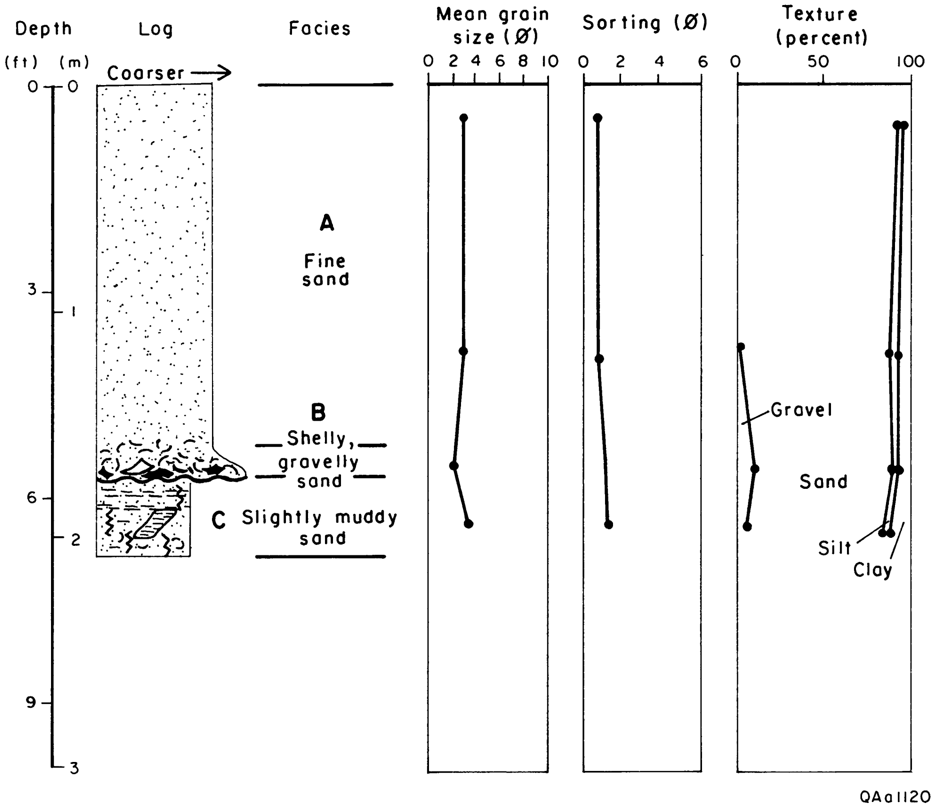

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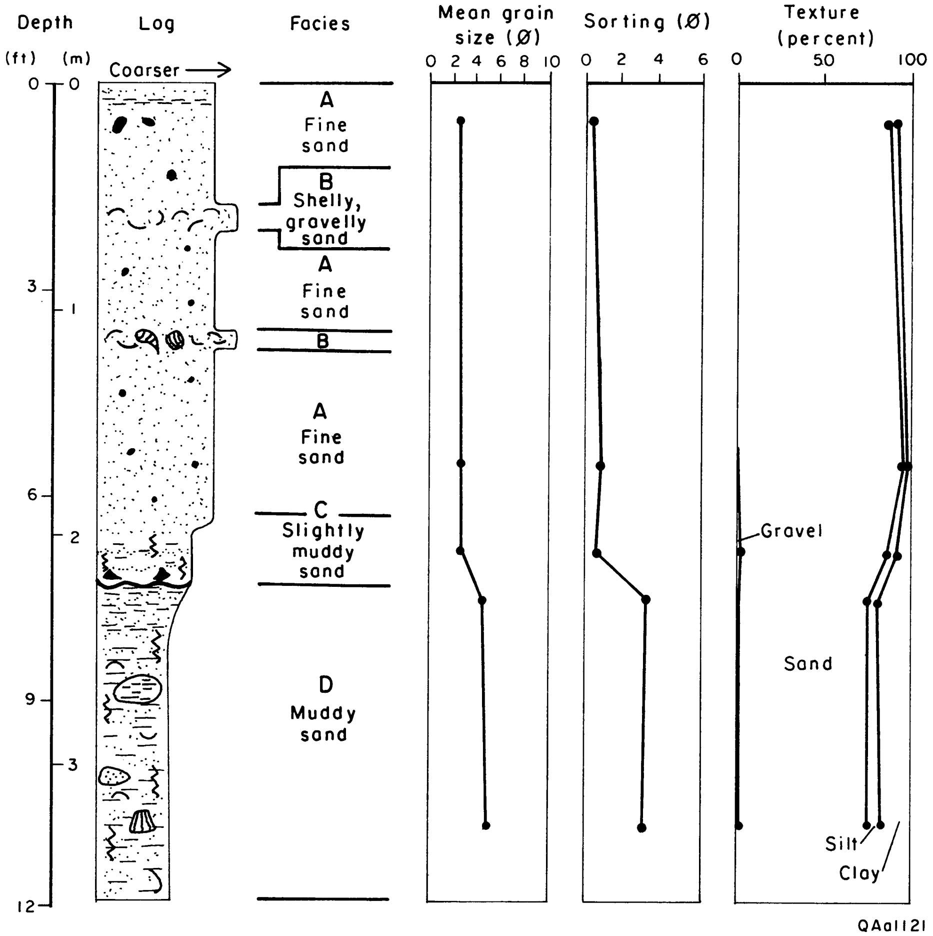

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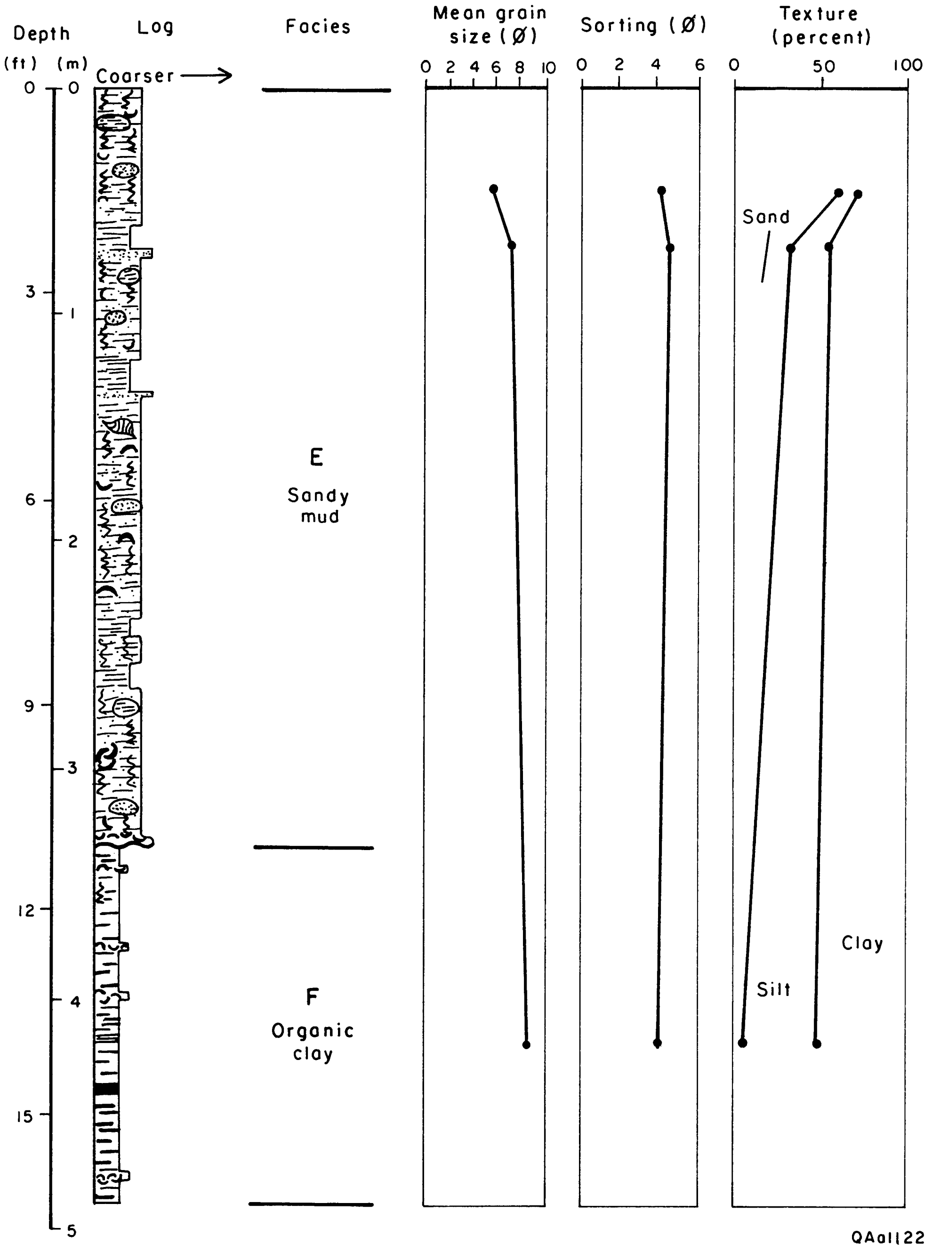

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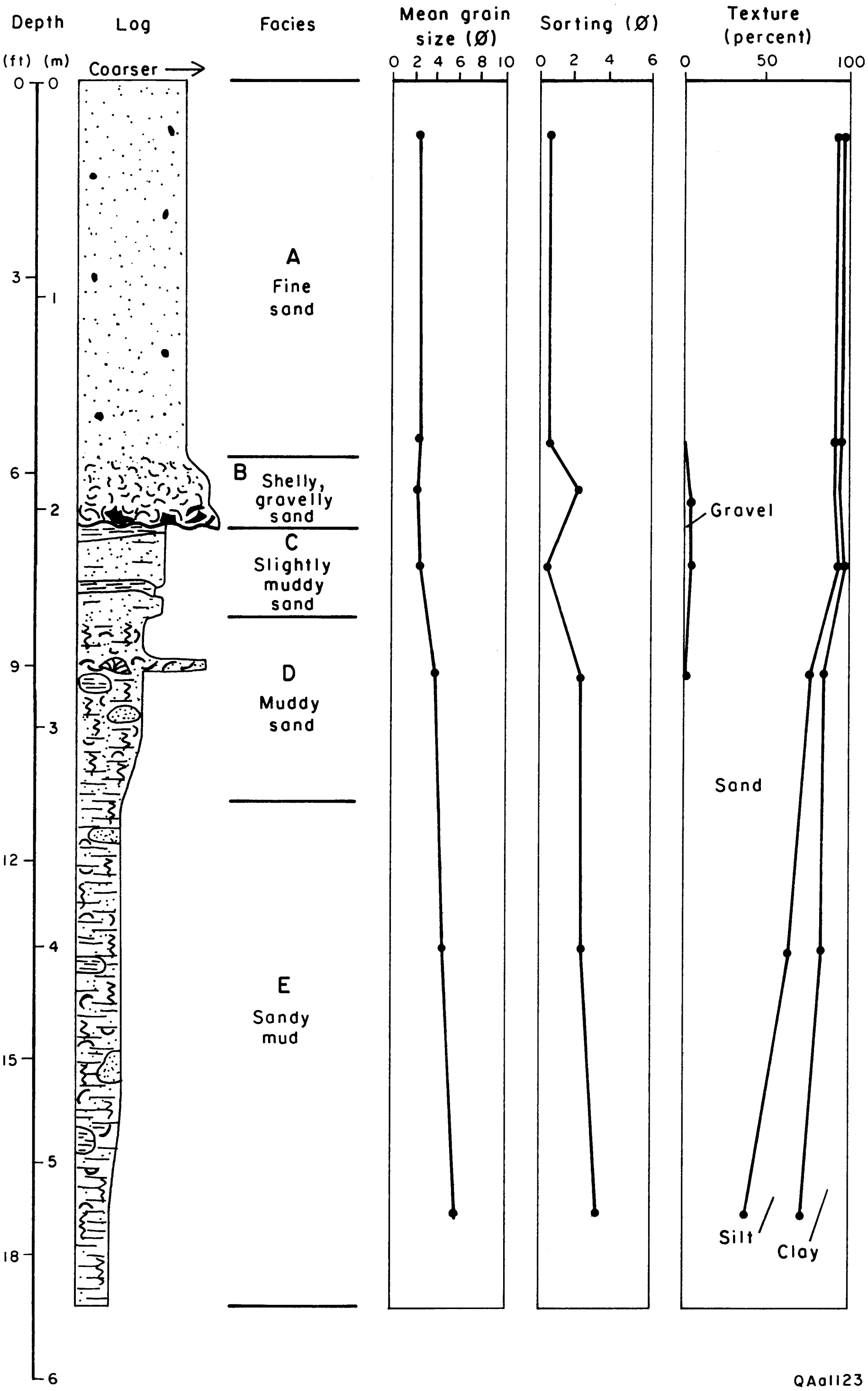

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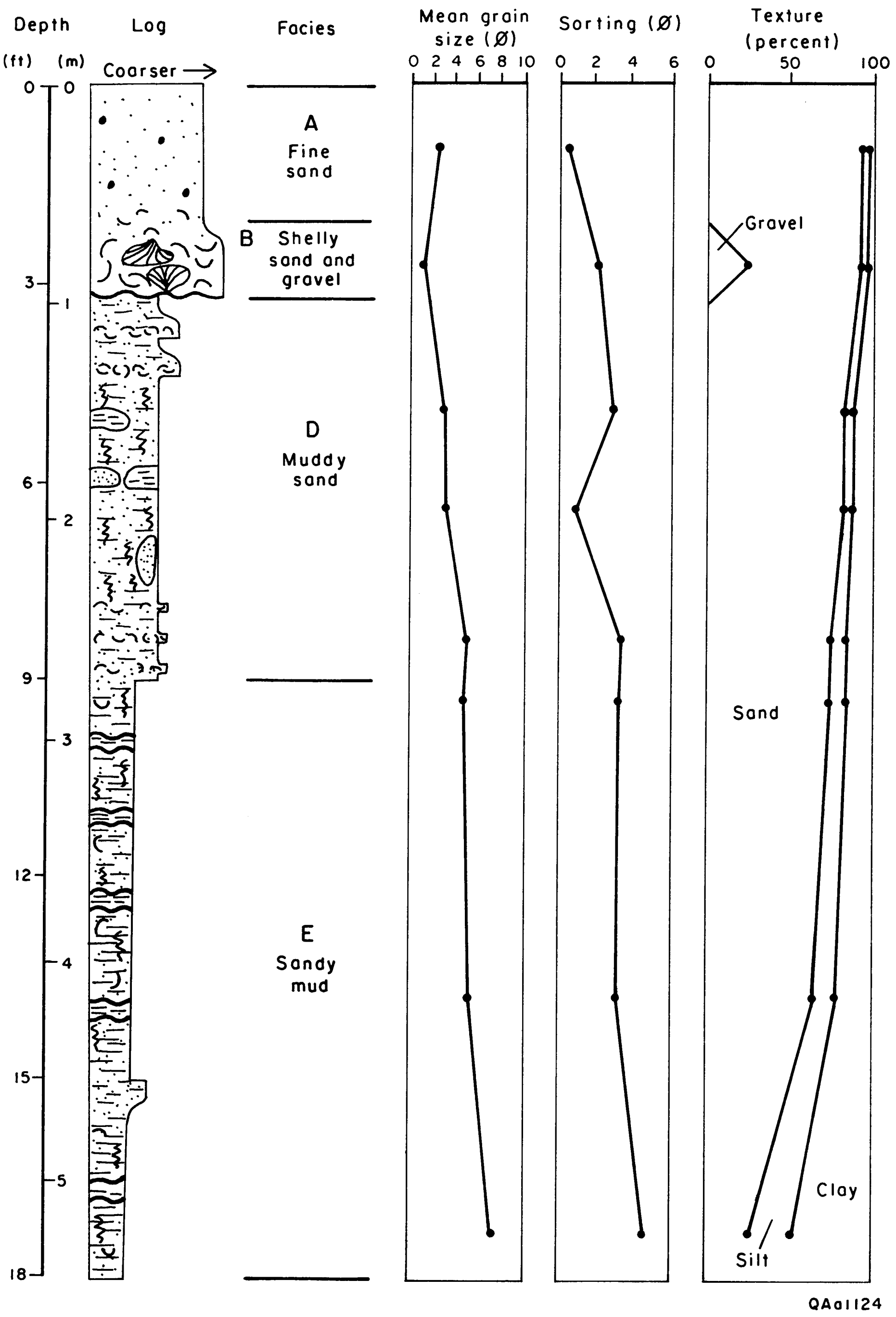

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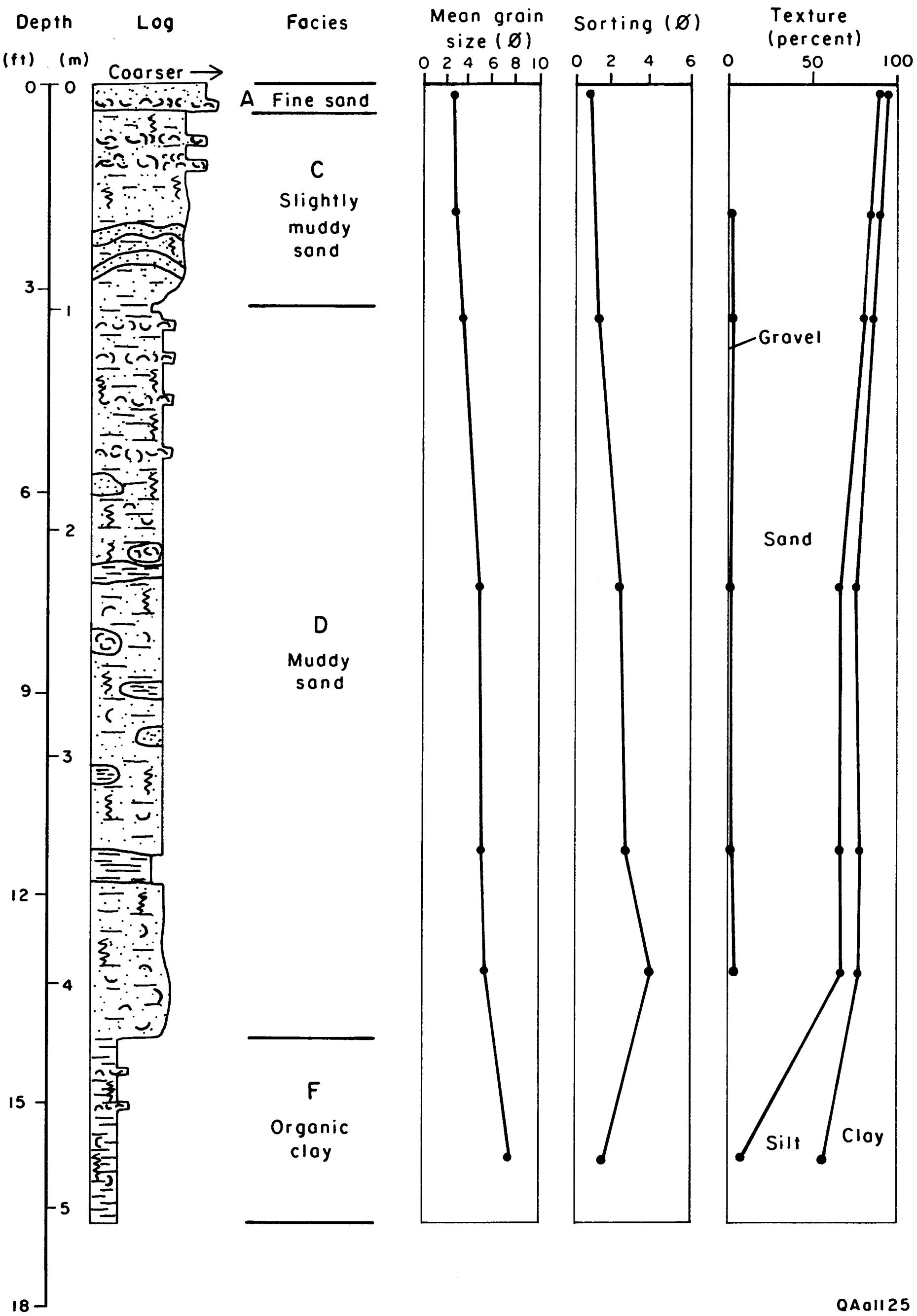

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