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BOTTOM SEDIMENT TYPES OF THE NORTHERN INSULAR SHELF OF PUERTO RICO; PUNTA PEÑÓN TO PUNTA SALINAS

By

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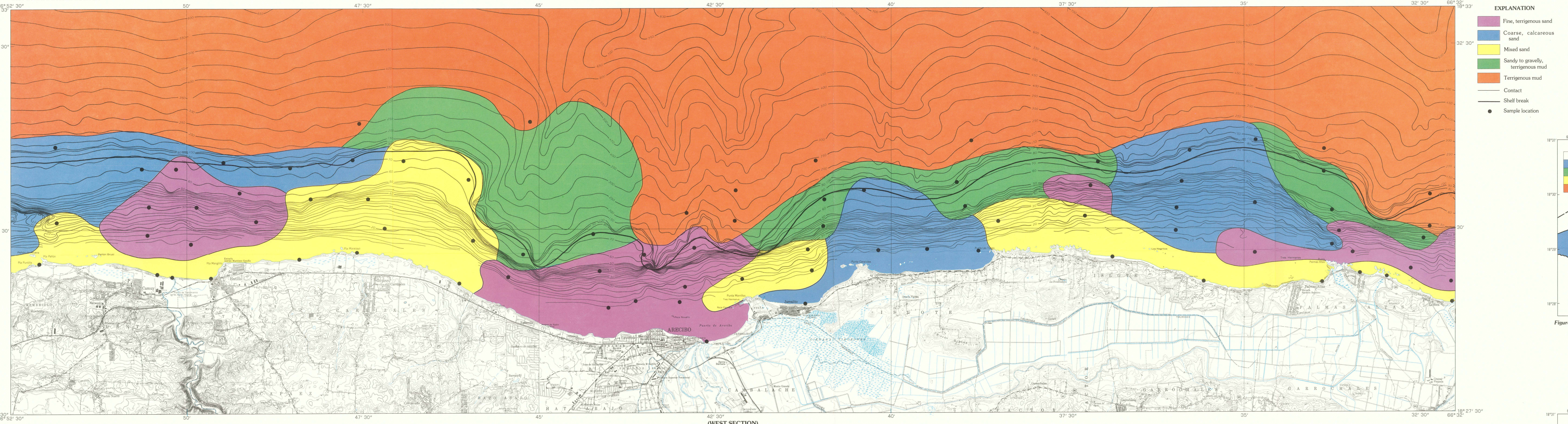

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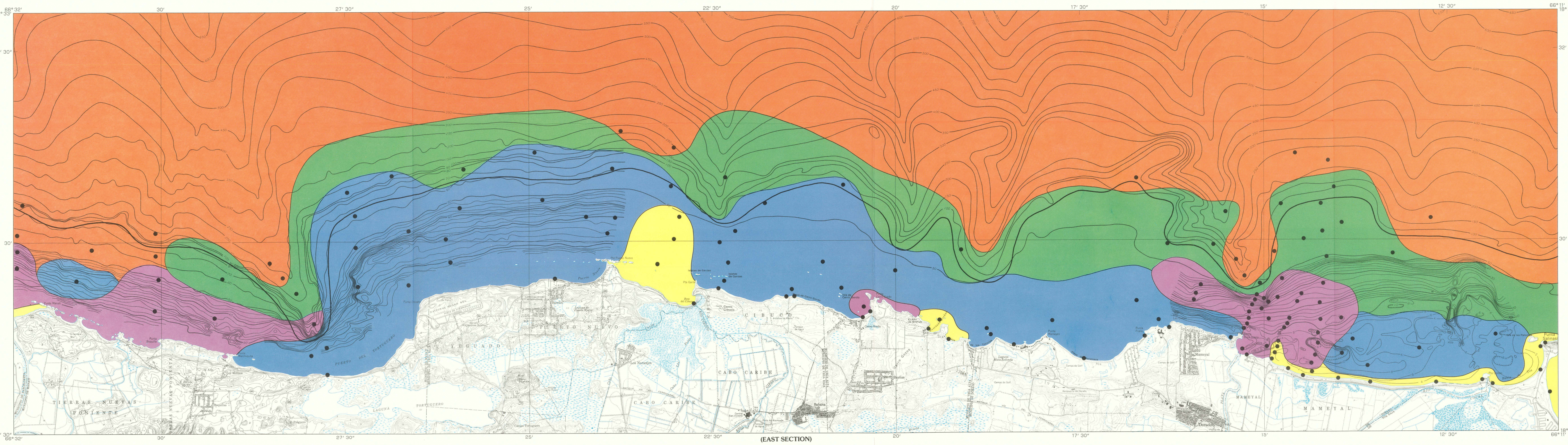

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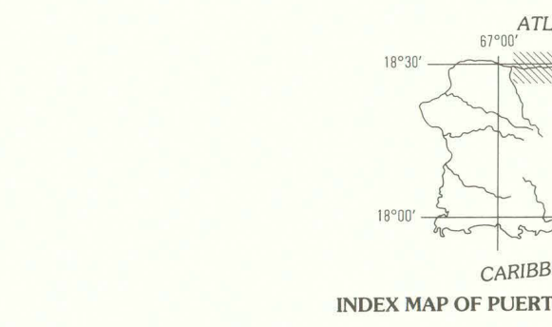

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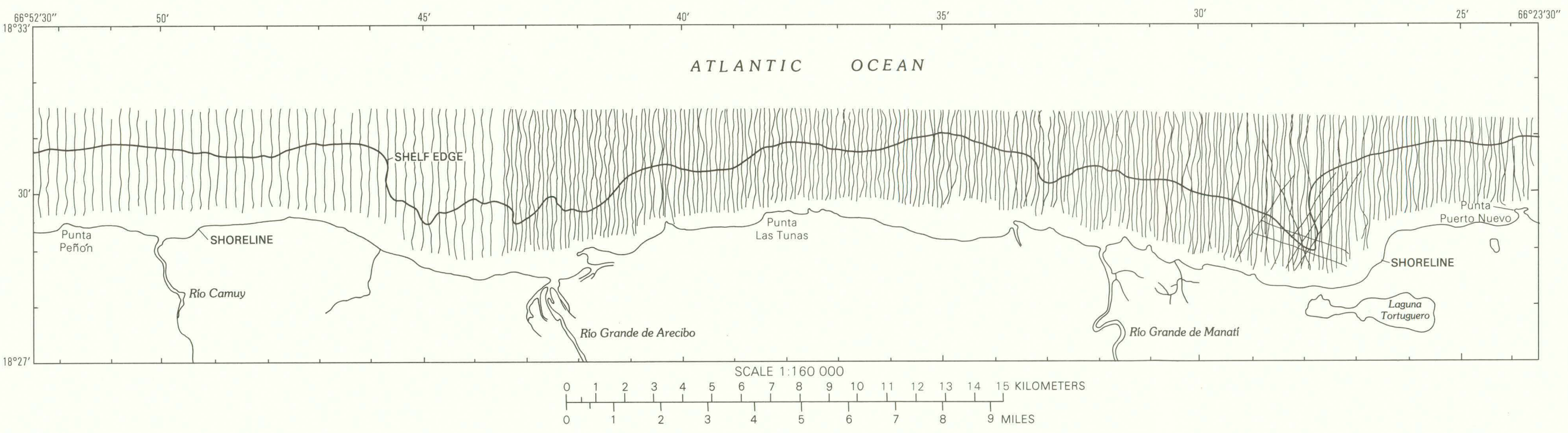
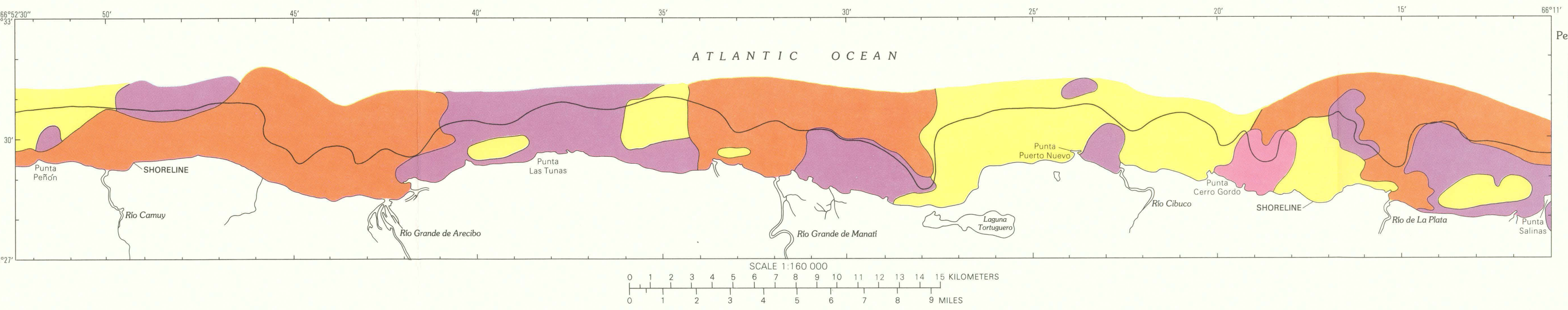


Figure 1—Tracklines of seismic-reflection profiles obtained by Western Geophysical Company of America (1974), Punta Peñón to Punta Puerto Nuevo. Tracklines are at 200-m spacing.



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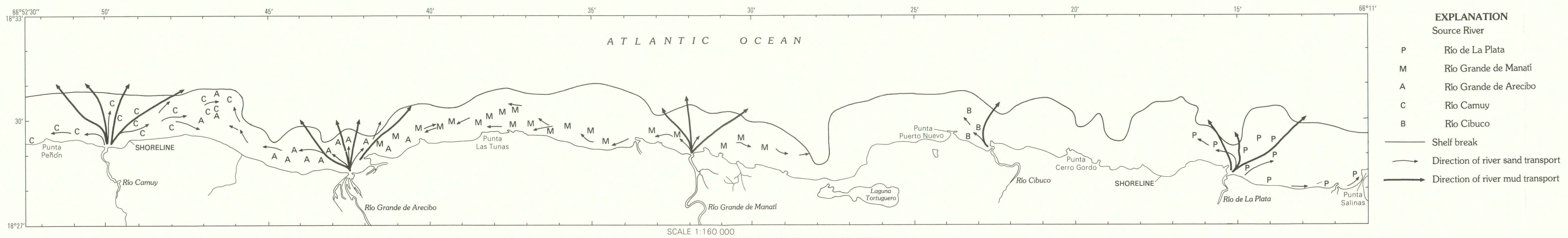

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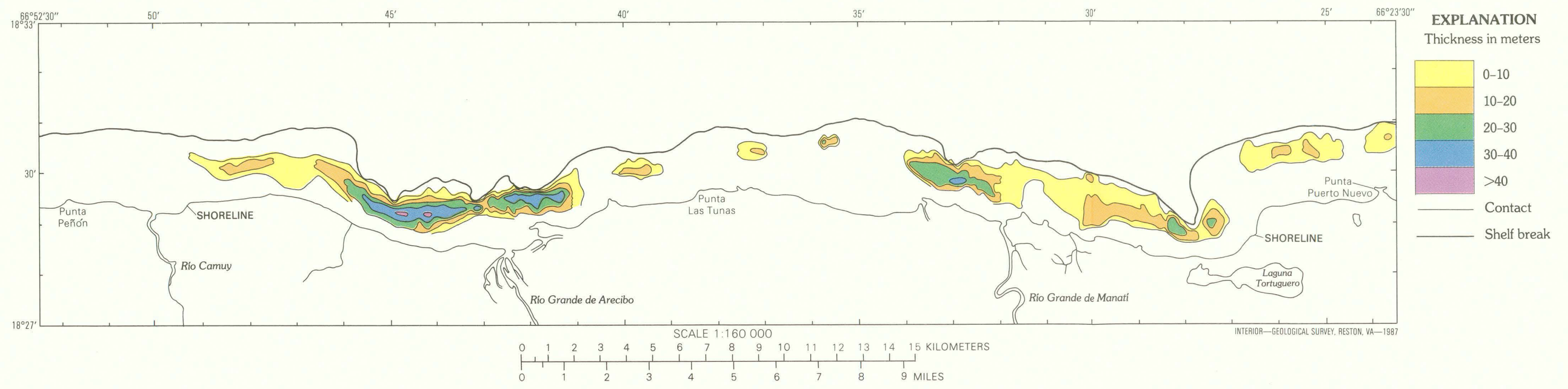

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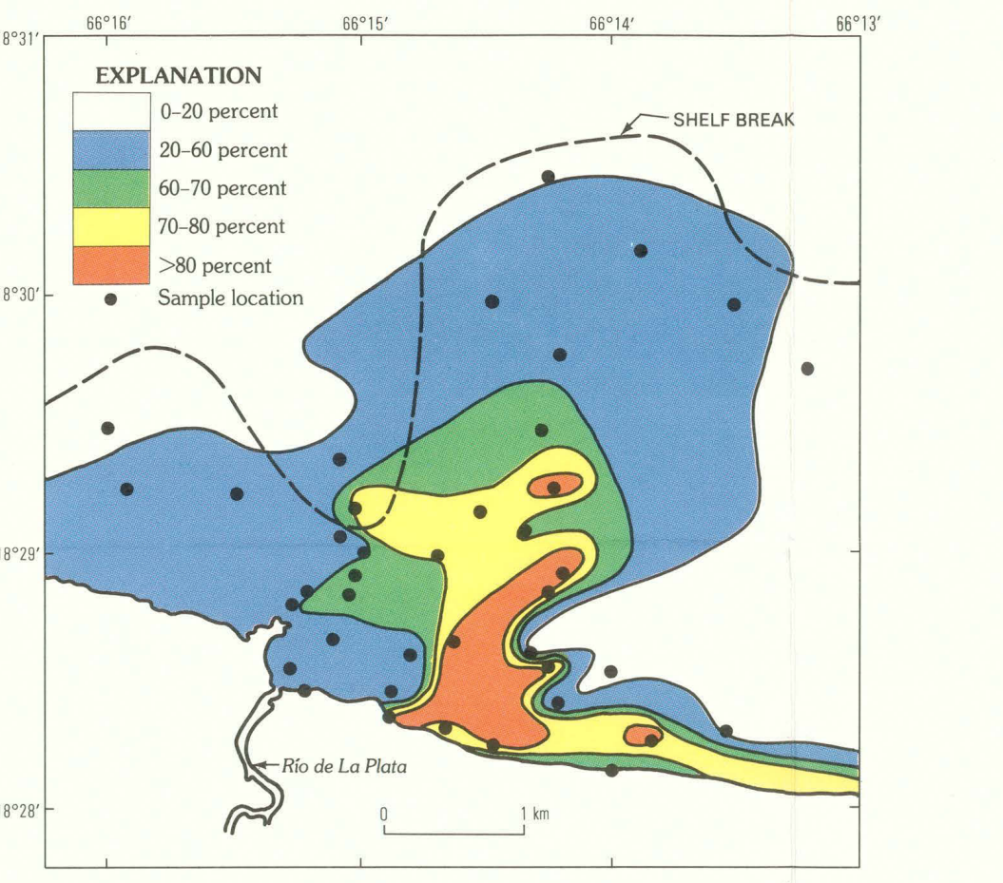

Figure 2—The abundance of fine sand (0.125–0.25 mm) on the Río de La Plata shelf.

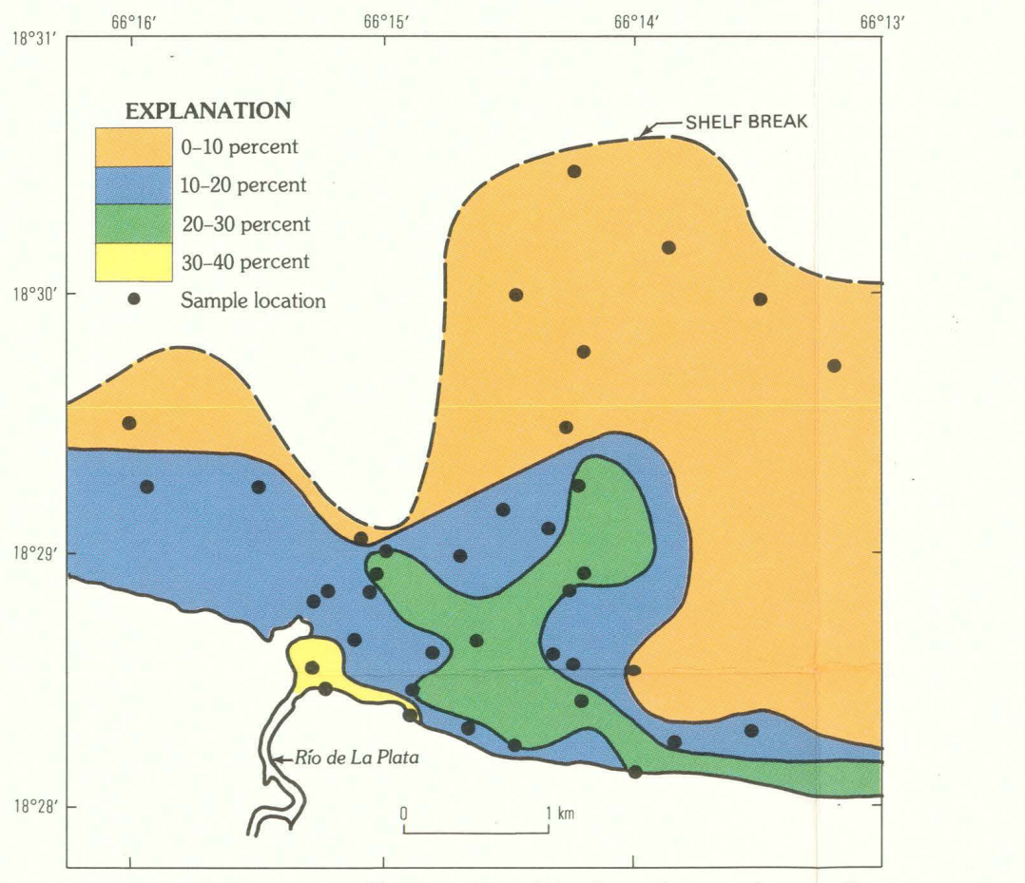

Figure 5—The abundance of heavy minerals in the carbonate-free, medium sand (0.25–0.5 mm) fraction of Río de La Plata shelf sediments.

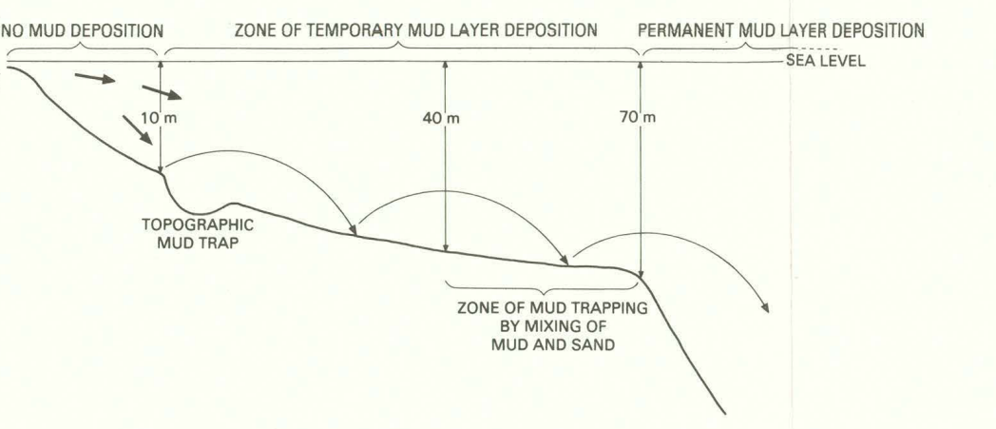

Figure 6—The "mud hopping" mechanism for dispersal of fines across the northern shelf of Puerto Rico after river floods have contributed a blanket of shelf mud (after Grove and others, 1982).

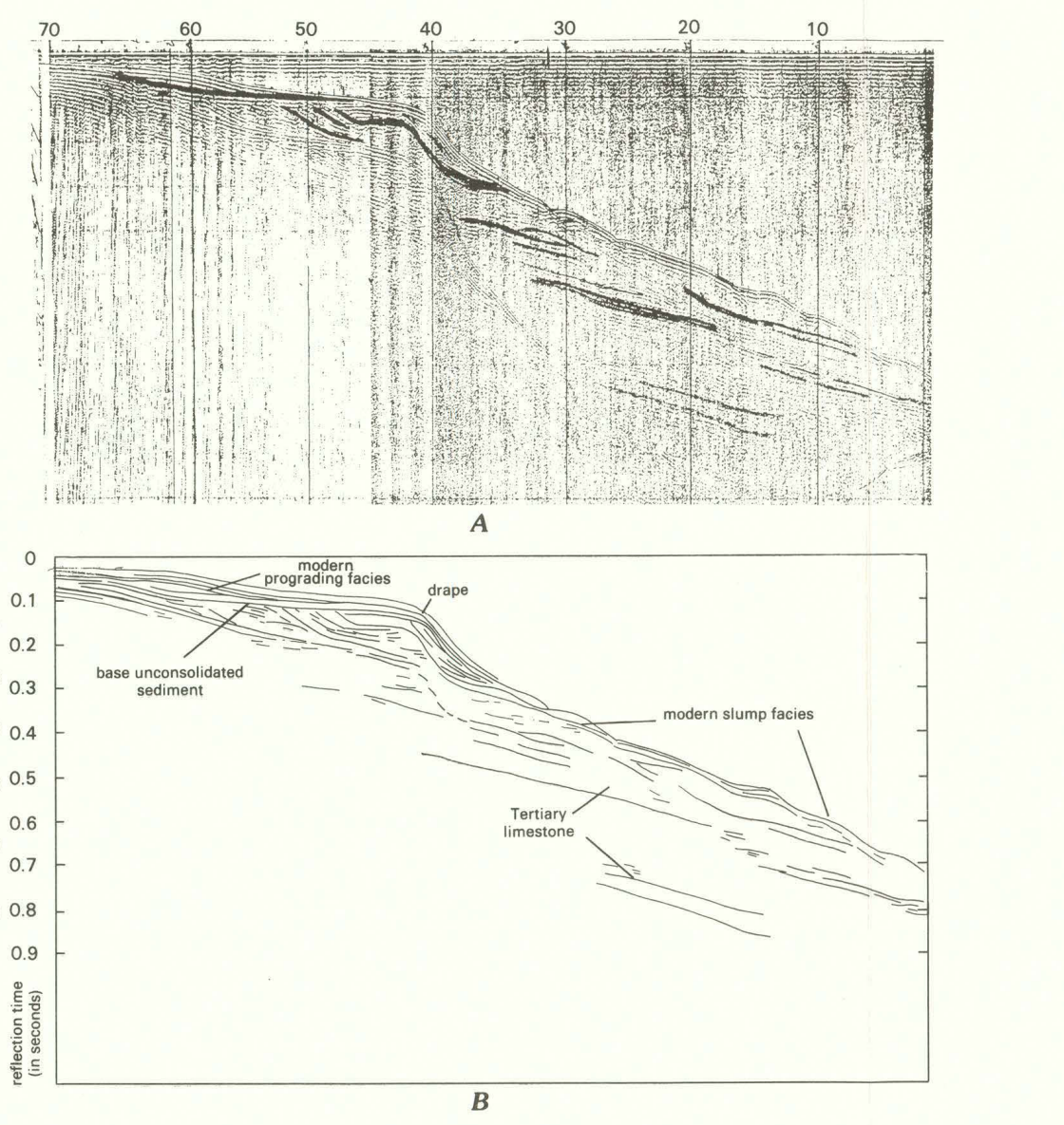

Figure 8—*A,* Cross-shelf seismic profile off the Río Grande de Arecibo. *B,* An interpretation of the seismic profile shown in *A.*

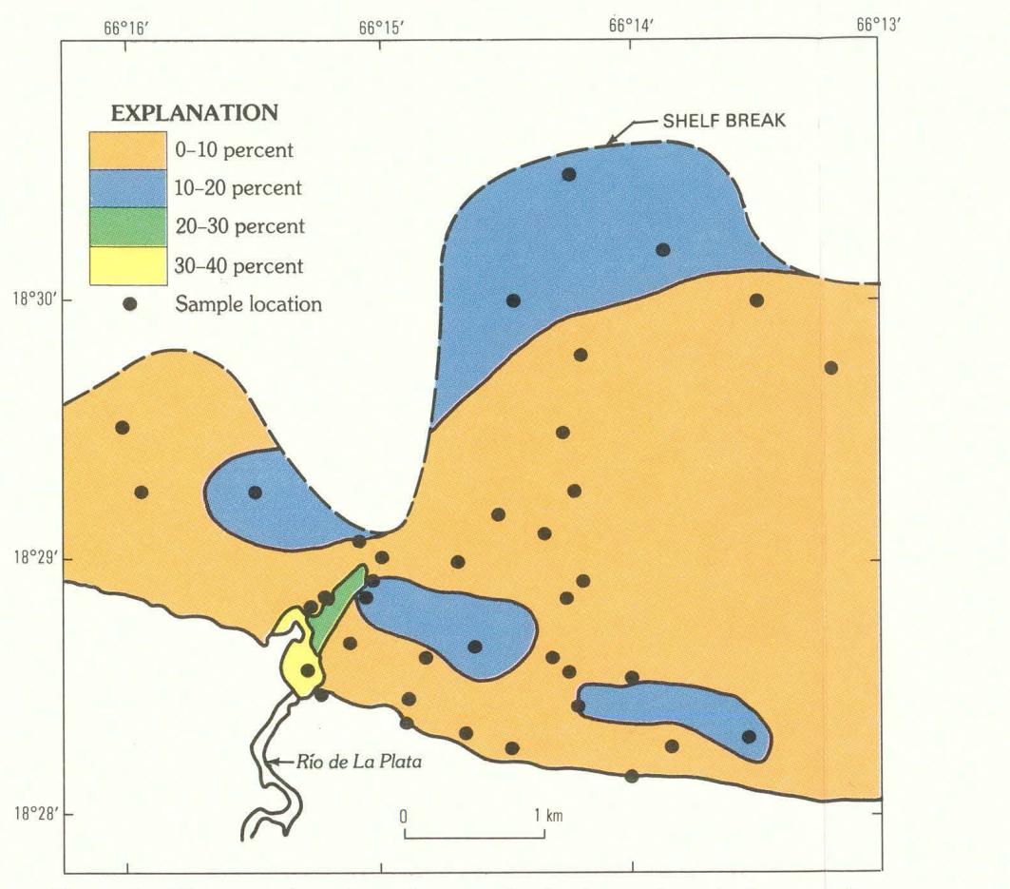

Figure 9—The concentration of magnetite in the carbonate-free, medium sand (0.25–0.5 mm) fraction of Río de La Plata shelf sediments.

INTRODUCTION

Sediment cover on the narrow insular shelf around Puerto Rico is patchy and diverse with little lateral continuity. This sediment-cover variability is a reflection of the wide range of physical and biological factors affecting shallow sedimentation in this area (Schneidermann and others, 1976). The most important of these variables are shelf bathymetry, wave energy, reefs, mangrove distribution, and the proximity of river mouths. Reefs and mangroves are important controls of sedimentation of the southern shelf of Puerto Rico which is subject to lower wave energy. The northern shelf is subjected to wave systems influenced by trade winds, to storm-driven swells from North Atlantic storms, and to wave energy conditions much higher than along other Puerto Rican shelf segments. Fluvial sediment contribution is a more important factor in northern shelf sedimentation than contributions from either mangroves or coral reefs.

The dominant sediment type on the entire Puerto Rican shelf is calcareous skeletal sand (Schneidermann and others, 1976). Major constituents include coral, molluscs, calcareous algae, and foraminifera. The northern shelf has a less calcareous sediment cover than the remainder of the Puerto Rican shelf and is typically muddier because of the effect of fluvial sediment.

Most continental shelves of the world are covered by relict sediments deposited under conditions unrelated to those of the present (Emery, 1968). However, the sediments of the northern shelf, at least those at river mouths, are being deposited in equilibrium with the physical conditions of the shelf environment. This is due to the steep and narrow nature of the northern shelf, the exposure to high-energy wave conditions, and the numerous rivers which supply both sand and mud directly to the shelf. The steepness and narrowness of the shelf also promote rapid cross-shelf transportation of sediment, particularly under the prevailing high-energy wave conditions. Because there are no well-developed estuaries to trap sediments, much of the fluvial load is transported directly to the shelf during floods.

Study of the northern shelf thus affords an unusual opportunity to observe sediment deposition in equilibrium with the physical environment, presumably like that of most shelf deposits found in the geologic record. There are also a number of practical reasons why the study of the northern shelf is important. An understanding of shelf processes is needed to evaluate the potential environmental impact of offshore sand mining, dumping, waste water outfalls, and offshore drilling. An understanding of the origin of the shelf sediment cover is a first step in exploration for heavy minerals and sand for construction uses. Recent studies suggest that present-day shelf processes on the northern shelf may be responsible for the formation of deposits of heaviest of the heavy minerals such as monazite and magnetite which are of possible economic value (Pilkey and Lincoln, 1984).

The study concerns a portion of the northern insular shelf extending from Punta Peñón to Punta Salinas and offshore to the upper insular slope. Several important rivers drain to this shelf area including, from east to west, Río de La Plata, Río Cibuco, Río Grande de Manatí, Río Grande de Arecibo, and Río Camuy (see map). Fluvial sediments dominate the northern shelf because the greatest rainfall occurs on the northern side of Puerto Rico and because most of the island's land area drains to the north.

The insular shelf break occurs at a water depth of about 70 m and borders the landward slope of the Puerto Rico trench. The insular shelf, which ranges in width from 1.5 to 5 km, has a slope that is very steep relative to typical continental shelves. Shelf bathymetry between 15 and 70 m water depth is generally smooth and has only minor local relief. At depths shallower than 15 m, the bathymetry is often highly irregular due to resistant outcrops of the Pleistocene eolianite described by Kaye (1959). Coral reefs are not present in the study area.

Three well-developed submarine canyon systems extend far onto the shelf off the mouths of Río Grande de Arecibo and Río de La Plata and off Laguna Tortuguero. The canyon off Laguna Tortuguero is the only one of the three that heads where no river is present; however, Laguna Tortuguero is believed to be the former channel and mouth of the Río Cibuco (Jose Muníz, Puerto Rico Department of Natural Resources, oral commun.) The largest canyon is off Arecibo. This canyon was described by Gardner and others (1980) on the basis of dives with the nuclear research submarine, NR-1. They note that four channels at the canyon's head merge into a single canyon at a water depth of 900 m. The canyon is cut into lithified Tertiary deposits that form benches which are covered by varying amounts of unconsolidated sediment. Shepard and others (1979, p. 124–129), who measured currents in the Río de la Plata canyon, observed strong current activity both up-canyon and down-canyon. They recorded what is interpreted to be the beginning of a small turbidity current formed after a minor Río de La Plata flood.

The shoreline and beach sediments adjacent to the study area were described by Guillou and Glass (1957), Kaye (1959), and the Puerto Rico Department of Natural Resources (1978). Schneidermann and others (1976) described the sediment cover of the entire Puerto Rican insular shelf based on about 300 grab samples. Detailed studies of other segments of the Puerto Rican shelf include those of Pilkey and others (1978), Shideler (1980), Beach and Trumbull (1981), and Grove (1982).

Western Geophysical Company of America carried out detailed seismic (both high-resolution and deep-penetration), side-scan sonar, and bathymetric surveys as part of a nuclear power plant siting study (Puerto Rico Water Resources Authority, 1975). Cross-shelf seismic profiles at 200-m spacing were obtained over most of the present study area as far east as Punta Puerto Nuevo (fig. 1).

Most published studies of the northern shelf area deal with the Río de La Plata part of the shelf. The sedimentary processes observed there are considered to be a model for processes at the river mouths in the study area. Pilkey and others (1978) found that sand and mud from the Río de La Plata is deposited across the shelf in a distinct, dark-colored band. Lateral boundaries of this band with calcareous, light-colored, authochthonous shelf sediments are very sharp. The fine fraction of the fluvial sediments is continually removed to deeper water. Cross-shelf mud blankets are eventually transported to the shelf edge. This process takes several weeks. Sand is transported across the shelf to a depth of about 20 m and is then moved laterally, both to the east and west (Grove and others, 1982).

According to Swift's (1976) classification, the sedimentation regime of the Río de La Plata shelf (and of the entire study area) is allochthonous. Most sediments arrive via river-mouth bypassing. Estuaries are not well developed and most do not trap much fluvial sediment during floods.

METHODOLOGY

Over 1,000 grab samples, representing all of the beach, shelf, and upper-slope environments were utilized in this study. Samples were collected at various times over the past 10 years utilizing several methods. River samples were taken by hand. Mid-shelf, outer-shelf, upper-slope, and submarine-canyon samples were obtained using either a Shipek[1] grab or a box dredge from research vessels Jean A and Cape Hatteras. Nearshore areas where navigational hazards existed were sampled from small boats using a VanVeen grab. Navigation was conducted by: (1) location on U.S. Geological Survey topographic maps, (2) navigation with transit and plane tables, (3) dead reckoning, (4) hand-bearing compass, or (5) radar. Sample locations were chosen with great care to aid in delineation of sediment boundaries.

Standard laboratory techniques were used to analyze the samples. Granulometry was done either mechanically using standardized sieves or settling tubes, complemented with some pipette analysis of fines. Usually, percent mud (<63 μm) was determined by wet sieving. Percent calcium carbonate was determined by digestion with 10 percent HCl. The nature and physical condition of the sediment was determined by observation of various size fractions under a binocular microscope. A limited number of selected thin sections of epoxy-impregnated sand samples were observed with a petrographic microscope primarily for mineral-grain identification. Heavy-mineral separation was done using tetrabromoethane. Studies of heavy-minerals were done by X-ray diffraction on some samples, the results of which will be discussed further in a subsequent section.

Our study also included the preliminary examination of 30 vibracores and piston cores obtained mostly off the Río Grande de Arecibo and the Río de La Plata mouths. However, sediment-type boundaries, inferred dispersal paths, and processes are determined solely from grab-sample data.

SURFICIAL SEDIMENT TYPES

The sediment cover of the northern shelf is divided into five groups: (1) terrigenous sand, (2) calcareous sand, (3) mixed sand, (4) sandy to gravelly mud, and (5) mud. The distinction between these sediment types is particularly useful to a study of the area since it can be done on a purely visual basis.

Terrigenous sand.—The fine-grained, river-derived sand on the northern shelf is generally black to brown (due to abundant rock fragments and heavy minerals). The mean grain size is 0.177 mm. This sediment type commonly contains about 10 percent mud. The average calcium carbonate content is about 28 percent but varies from 6 to 77 percent. Noncalcareous constituents are mainly quartz with some metamorphic and igneous rock fragments. The calcareous constituents are largely contributed by present-day organisms, although some detrital limestone grains are present. Calcareous skeletal grains tend to be fresh in appearance, coarser than the noncalcareous components, and highly angular.

Terrigenous sand is concentrated on shelf segments adjacent to river mouths. Such sand is dispersed in lobes that extend across the shelf and both east and west across the river mouths. Terrigenous sand from the Río Grande de Arecibo, Río Cibuco, and Río de La Plata has moved farther to the west than to the east.

Calcareous sand.—The coarse-grained calcareous sand is generally light brown, although some samples contain black- or brown-stained fragments. The black-stained shell fragments make it possible to confuse this sediment type with the mixed sand type. Mollusc-shell fragments are the dominant calcareous component but Halimeda plates, foraminifera, coral fragments, bryozoans, and other coralline algae fragments are present in varying proportions. Although calcareous beach sand tends to be highly polished, the calcareous components of shelf sand are usually dull and weathered. The calcareous sand has a mean grain size of 0.60 mm, although there is a wide range of mean grain size within the sediment type. Calcium carbonate content averages 83 percent.

A few samples contain rhodoliths (red algae nodules) which have a combination of columnar and laminar growth forms (Bosellini and Ginsburg, 1971). The rhodolith-bearing sand is the coarsest sand in the study area. This sand is restricted to those segments of the insular shelf at water depths greater than 30 m, away from river mouths, although the sand is relict material which probably originated at shallower depths and during lower sea levels.

Mixed sand.—This sediment type has a distinctive salt-and-pepper appearance reflecting a true mix of light-colored carbonate sands and dark-colored terrigenous sand. Most of the calcareous grains are well rounded and polished. This is the most common beach-sediment type in the area and covers large areas of the nearshore shelf environment. The average grain size is 0.5 mm (medium sand). This sediment type is generally located in high-energy nearshore zones and is completely devoid of mud. A small gravel fraction (2-4 mm), 6 percent or less, is commonly present. The calcium carbonate content is highly variable (2–69 percent) and averages 28 percent.

The megascopic distinction between terrigenous sands and mixed sands is subjective. Overall, mixed sands are coarser grained because the calcareous fragments are usually larger than the terrigenous sand grains typically contributed by rivers.

Mud.—Two fairly distinct types of mud characterize the outer shelf and slope. Both contain 40 percent or more silt- and clay-size grains. One has little sand or gravel with an average grain size of 0.0050 mm; the other contains a sandy to gravelly component and has a mean grain size of 0.037 mm. The gravel fraction of the latter consists almost entirely of weathered calcareous skeletal material, but is, in a few cases, composed of igneous and metamorphic rock fragments. The average calcium carbonate content is about 30 percent.

Several lines of evidence indicate that the surficial terrigenous sand and mud are recent in origin. The sediment texture, the abundance of terrigenous grains, and the geographic location of the patches of terrigenous sand all point to nearby rivers as sources of the material. The distribution of the fine-grained sand fraction on the Río de La Plata shelf (fig. 2) is a clear indication of textural equilibrium with modern processes. Figure 2 shows that fine sand ranges from greater than 80 percent in abundance near the Río de La Plata mouth to less than 20 percent of the total sediment on the outer shelf. A simple seaward gradation in the abundance of the fine sand fraction would not be expected if the material were relict rather than recent.

The less weathered physical condition of the carbonate grains in the terrigenous sand is strongly indicative of a recent origin. This is especially evident when compared to the more weathered physical condition of the carbonate grains of the calcareous sands which are concentrated away from river mouths and have been accumulating more slowly (Pilkey and others, 1979). The highly worn nature of the carbonate fraction of the calcareous sand also points to a longer history of exposure to the physical and biological environment on the sea floor, an indication of probable original deposition during the last sea-level rise.

The recent origin for the shelf's terrigenous sand and mud was documented following Hurricanes David and Frederick in 1979 on the Río de La Plata shelf. A sandy mud layer was deposited on the shelf by these storms and associated floods. Over the next five months, most of the mud was washed out of this layer, leaving behind the newly contributed sand-size material (Grove and others, 1982).

The distribution of the abundance of calcium carbonate, studied by Bush (1977) (fig. 3), is strongly controlled by the fluvial contribution of different sections of the shelf. Seaward of river mouths, the carbonate content is always less than 30 percent. Between river mouths, one half of all sediment samples usually contains over 70 percent calcareous material and almost one fifth of the samples contains over 90 percent. The carbonate content of upper slope muds closely reflects that of the adjacent shelf.

SEDIMENT DISPERSAL

During major floods, the numerous small rivers that empty onto the shelf deliver sediment with a wide range of sizes. For instance, Reed and Kiser (1972) report that during five floods in 1970, suspended-sediment loads contained between 20 and 40 percent sand-size material. Once this load reaches the shelf, the sand and the mud follow different paths of dispersal on the shelf (fig. 4). Mud generally moves straight offshore from the river mouths and then disperses laterally once it reaches the outer shelf-upper slope region. Sand exhibits a significant degree of lateral dispersal on the middle to inner shelf. A significant portion of the load contributed to the shelf by river floods is probably lost immediately to the deep sea via the submarine canyons indenting the shelf.

The two largest rivers in the study area, the Río Grande de Arecibo and the Río Grande de Manatí, form an almost continuous belt of river-derived or mixed terrigenous-carbonate sand (see map). In a study of sand dispersal, heavy minerals of the fine sand (0.125–0.25 mm) fraction of samples from this area are described by Grossman (1978). The most common heavy minerals from the study are dark-green hornblende and opaque minerals that are believed to be mostly magnetite, tourmaline, and hypersthene. Augite and epidote are also present. Zircon and rutile, which Guillou and Glass (1957) observed in abundance in beach sediments adjacent to the study area, are minor components on the shelf. Heavy-mineral analyses of the two studies are difficult to compare because different size fractions were studied.

Dispersal patterns for each of these rivers can be determined by X-ray diffraction of heavy-mineral fractions. This technique, which amounts to "finger-printing" of river sands, is particularly successful in distinguishing Río Grande de Arecibo and Río Grande de Manatí sand (Grossman, 1978). Fluor-tremolite, which is an important constituent of Río Grande de Arecibo sand, is very rare in Río Grande de Manatí sands. Thus, the height of the fluor-tremolite X-ray diffraction peak could be used to measure the mixing of sand from the two rivers. Zones of mixing were identified for the Río Grande de Arecibo-Rio Grande de Manatí systems and the Río Grande de Arecibo-Río Camuy systems (fig. 4). In both cases, the mixing zone is about 2 km wide. The Grossman (1978) model, and observations of the farthest shore-parallel and shore-normal distribution of muddy river sand from riverine point sources allows us to infer dispersal paths of sand and mud for all river systems (fig. 4).

Sand is dispersed on the shelf both east and west of the river mouths, with greatest dispersal to the west. A large percentage of the fluvial sand is probably lost over the edge of the shelf. The exact percentage of loss cannot be quantified from available data, but slope samples often contain significant sand-size fractions.

The abundance of fine sand in the total sediment on the Río de La Plata shelf (fig. 2) exhibits a clear pattern of decreasing concentration in a seaward direction. The surficial sediment cover nearshore and to the west of the river mouths is 80 percent fine sand, whereas near the shelf break fine sand is 20 percent or less. This represents a very strong sorting trend occurring within 2 or 3 km. The abundance of heavy minerals in the fine sand fraction also decreases offshore (fig. 5) with maximum concentrations just to the west of the river mouth. The same general trends in size and heavy-mineral distribution probably exist on the shelf just seaward of all river mouths.

The mechanism by which mud crosses the shelf (fig. 6) has been termed "mud hopping" (Pilkey and others, 1978). The mud which blankets the shelf immediately after floods is removed, probably in a series of hops, by minor storms and current activity. The mud deposited off the Río de La Plata from Hurricanes David and Frederick was moved to the shelf break within a period of five months (Grove and others, 1982).

SEDIMENT THICKNESS

Three major lenses of unconsolidated sediment on the northern shelf were covered by a detailed high-resolution seismic survey (Puerto Rico Water Resources Authority, 1975). The survey shows that the lenses are elongate and parallel the adjacent east-trending shoreline. All are on the central to outer shelf and each appears to be associated with a present or former river mouth. The thickness of these lenses has been estimated from the seismic-survey data (fig. 7). The detailed seismic study ended on the shelf area off Punta Puerto Nuevo (fig. 1) and did not include the shelf off Río Cibuco or Río de La Plata. Near the mouth of the Río Grande de Arecibo (fig. 8), a lens of unconsolidated sediment thins gradually seaward from a maximum thickness of about 40 m on the central to outer shelf. In other sections of the insular shelf, not shown here, the lenses extend all the way to its edge.

West of Laguna Tortuguero is a 5-km-long lens whose maximum thickness exceeds 20 m (fig. 7); this lens contains about 71 million m³ of sediment. Laguna Tortuguero is probably near the former mouth of the Río Cibuco and the shelf lens of terrigenous sediment was deposited before the river mouth shifted to the east.

On the central shelf, a second 5-km-long unconsolidated sediment pod more than 30 m thick extends westward from the mouth of the Río Grande de Manatí. The volume of this lens is estimated to be about 66 million m³. The largest lens of unconsolidated sediment exists off the Río Grande de Arecibo. The lens extends both eastward and westward from the river mouth, is almost 10 km long, and contains at least 211 million m³ of sediment.

The total volume of sediment in these deposits is about 348 million m³. No detailed information is available on the textural and mineralogic characteristics of these deposits. They are assumed to consist of fine to very fine sand. The age of the sediment in the lenses is unknown. However, they probably are almost entirely of Holocene age and were deposited after sea level reached its present position. On a very steep, narrow shelf such as this one, the landward migrating shoreface during a cross-shelf transgression would probably disperse much of the unconsolidated shelf-sediment cover, causing its removal from the shelf. A vibracore study presently underway may give insight to some of the details of the textural and mineralogic characteristics of these sediment lenses as well as details on their ages and exact modes of deposition.

EXPLORATION TARGETS

The lenses of unconsolidated material on the northern shelf are considered to be potential sources of sand for construction purposes, although additional sampling is needed to confirm its suitability for such uses. As previously mentioned, the volume of sediment in these northern shelf deposits is about 348 million m³. Because sand deposits onshore have been depleted to a large extent, evaluating a potential offshore source is important. Three other submerged deposits have been discovered on the Puerto Rican shelf with a total volume of sand exceeding 200 million m³ (Trumbull and Trias, 1982; Rodríguez, 1984).

Several factors must be considered in evaluation of the economic potential of these offshore sand deposits. The cost of sand extraction will be relatively high on the northern shelf of Puerto Rico. Mining operations on this shelf would be exposed to trade winds and thus require heavier equipment than a similar operation in sheltered waters. A northern shelf sand mining operation could experience a substantial amount of weather "downtime". Wave energy also plays an important role in determining economic potential.

The sorting of material during cross-shelf transport may also be responsible for the formation of placer deposits on the shelf. Most of the world's economic placer deposits on continental shelves are found in stranded beach deposits left behind by a rising sea level. The sorting of heavy minerals is the surficial sands of the Puerto Rican shelf suggests a strategy for exploration of the heaviest of heavy minerals based on the assumption that significant sorting and concentration of minerals may occur in response to shelf rather than beach processes.

Several of the minerals that are present in northern Puerto Rico rivers offer promise in this regard. Magnetite, monazite, and native gold may be concentrated very close to present or ancient shorelines. Figure 9 shows the concentration of magnetite in the heavy-mineral fraction of the carbonate-free, medium-sand-size fractions from Río de La Plata. Again, it is assumed that the Río de La Plata example would be similar to the other river mouth shelf segments. This figure illustrates that separation by sorting of the heaviest of the heavy minerals from the lightest of the heavy minerals, such as the pyroxenes and amphiboles, is occurring in the immediate vicinity of the shoreline. Monazite is a minor but consistent constituent in most river-sediment heavy-mineral fractions. Because it is one of the heaviest of the heavy minerals, it could be expected to concentrate very close to river mouths.

Puerto Rico's rivers were once mined extensively for gold by the early Spanish settlers. Because the rivers are short, native gold may have reached the shelf as relatively coarse particles and may also be concentrated very close to river mouths.

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