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U.S. GEOLOGICAL SURVEY

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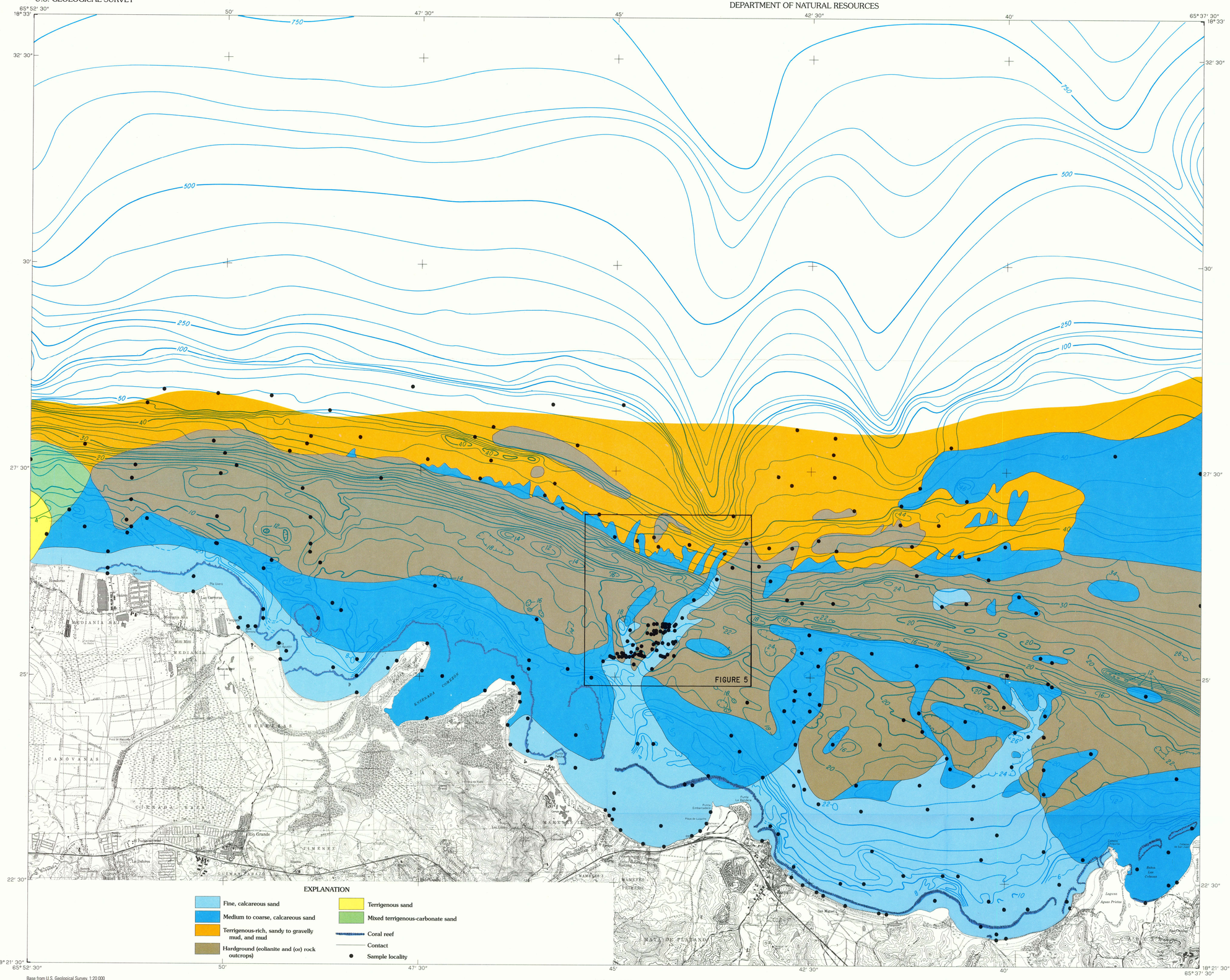
GEOLOGIC INVESTIGATIONS SERIES
I–2612



EXPLANATION

- Fine, calcareous sand
- Medium to coarse, calcareous sand
- Terrigenous-rich, sandy to gravelly mud, and mud
- Hardground (eolianite and (or) rock outcrops)
- Terrigenous sand
- Mixed terrigenous-carbonate sand
- Coral reef
- Contact
- Sample locality

Base from U.S. Geological Survey, 1:20 000
Cayo Icacos, 1958; Fajardo, 1962; Río Grande, 1963
1000-m Universal Transverse Mercator grid based on Puerto Rico Coordinate System

SCALE 1:40 000

1 0 1 2 3 MILES
1 0 1 2 3 4 5 KILOMETERS
1 0 1 2 3 NAUTICAL MILES

BATHYMETRIC CONTOUR INTERVALS: 2 METERS TO DEPTH OF 50 METERS; 10 METERS FROM 50 TO 100 METERS DEPTH; AND 50 METERS FROM 100 METERS DEPTH TO MAXIMUM DEPTH.
DATUM: MEAN LOW WATER
TOPOGRAPHIC CONTOUR INTERVAL: 10 METERS; DOTTED LINES REPRESENT SUPPLEMENTARY 1-METER CONTOURS; DASHED LINES REPRESENT 5-METER CONTOURS.
DATUM: MEAN SEA LEVEL
SHORELINE REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER

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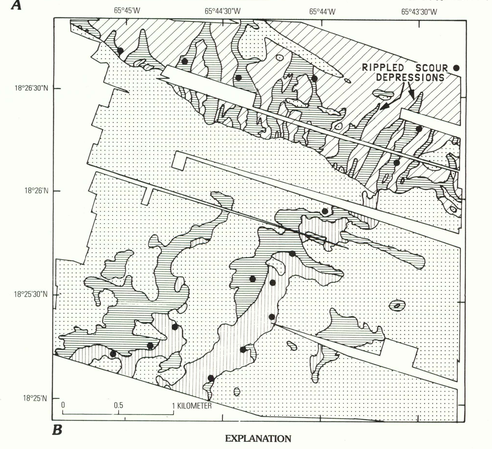

EXPLANATION

- Eolianite and hardground
- Medium to coarse sand
- Fine sand
- Terrigenous-rich mud
- Sediment sample locality

Figure 5. Representative sidescan-sonar image (*A*) and interpretative sketch (*B*) of a segment of the Luquillo insular shelf showing the distribution of sediment types. Area of this image is shown on the map. In this image, sea-floor areas of high acoustic backscatter are displayed as white and areas of low backscatter as black. Figure modified from Gowen and others (1993).

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DISCUSSION

INTRODUCTION

This map shows the areal distribution and thickness of sediment types on the insular shelf off the northeast coast of Puerto Rico (fig. 1). The sediment distribution is primarily a function of in-situ organic production and redistribution by hydrodynamic processes. Patterns of transported sediment are the result of the prevailing transport mechanisms and thus are useful in studies of pollutant transport, the impact of residential and commercial development along the coast, and the utilization of marine resources.

Terrigenous input from rivers in the Luquillo area is minimal except during unusual periods of river flooding (Haire, 1975). This contrasts sharply with the shelf west of the study area, where major rivers contribute significant amounts of terrigenous material particularly during storm-generated floods (Pilkey and others, 1978; Grove and others, 1982; Pilkey and others, 1987; Rodriguez and others, 1992). The lack of significant discharge and sediment influx from rivers in the study area has permitted the formation of coral reefs and associated biologic communities. Coralline buildup occurs nearshore as linear-trending patch reefs and continuous fringing reefs. Further offshore, corals grow on outcropping eolianite ridges and hardgrounds that predominate in the mid-shelf area. These biologic communities are the principal sources of sediment production in the study area.

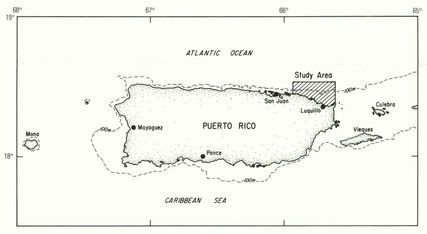

Figure 1. Index map showing location of study area.

METHODOLOGY

Marine geologic surveys were carried out in April and May of 1991 aboard the RV *Jean A*, owned and operated by the Puerto Rico Department of Natural Resources. Additional sampling and SCUBA observations were carried out in June 1992 aboard RV *Boriken*, owned and operated by the U.S. Geological Survey.

A total of 342 surface sediment samples were collected from the beach, insular shelf, and insular slope of the study area. Of these, 170 samples were recovered and analyzed by Stout (1979). Beach samples were collected by hand at the swash zone and offshore samples with a Shipek or Van Veen grab sampler. Textural analyses were completed at the Puerto Rico Department of Natural Resources Sedimentology Laboratory. Samples were initially wet-sieved to separate coarse (gravel and sand) and fine (silt and clay) fractions, then dry sieved and pipetted in accordance with the procedure outlined by Folk (1974). Percent calcium carbonate was determined following the procedures outlined in Carver (1971). The samples were described and their constituents identified by means of a binocular microscope and point-count techniques.

Approximately 650 km of high-resolution seismic-reflection data and sidescan-sonar imagery were obtained in the study area by means of Huntec Sea Otter boomer and Klein 100 kHz sidescan systems (fig. 2). The sidescan imagery was presented in Schwab and others (1996b). A shore-based mininranger system was used for navigation on the RV *Jean A*, whereas the Global Positioning System (GPS) was used on the RV *Boriken*. Position error was approximately ± 5 m for geophysical and sampling operations on the RV *Jean A* and ±100 m for sampling conducted using the RV *Boriken*.

PHYSICAL SETTING

The shelf along the Luquillo coast is narrowest to the west (about 3 km) and becomes progressively wider to the east, where it reaches a maximum width of 10 km. The head of a large submarine canyon is approximately 5 km north of Punta Embarcadero and a smaller canyon is 2 km to the east. The shore in the study area is composed of sandy beaches and mangrove swamps. Several headlands and small peninsulas dot the shoreline. The major rivers of Puerto Rico drain toward the northern insular shelf. Rivers and small streams discharging into the Luquillo area originate in the Caribbean National Forest (El Yunque), a tropical rainforest located 15 km inland. Annual rainfall there approaches 500 cm (Brown and others, 1983), the highest value for the island. Regardless of this vast amount of rainfall, the abundance of vegetation inhibits erosion, resulting in an insignificant amount of terrigenous sediment transport by rivers to the shelf (Goenaga and Cintrón, 1979). As a result, coral reefs and associated biologic communities flourish in many parts of the study area and are the major source of sediment production.

In contrast, the shelf west of the study area exhibits a patchy and diverse sediment cover resulting from the mixing of river-derived siliciclastic sediment and in-situ production of carbonate grains (Grove, 1982; Pilkey and others, 1987; Rodriguez and others, 1992). Here, during storm-flood events fluvial sediments are deposited directly on the shelf because the north coast lacks sediment-trapping estuaries. Transportation and deposition of fluvial sediments on the shelf west of the study area have increased significantly in the last century due to deforestation and urbanization (Goenaga and Cintrón, 1979). Thus, most coral reefs west of the Luquillo shelf have been degraded considerably as a result of siltation.

The nearshore zone of the study area is dominated by patch and fringing reefs. Subaerially exposed, scattered patch and fringing reefs are found between Punta Iglesia and Punta San Agustin. These reefs effectively absorb wave energy and thus allow flourishing growth of marine grasses and calcareous algae within the lagoons and tidal flats behind them.

Farther east, on the north and west side of Punta Miquillo and on the north and east side of Punta Picúa, are fringing reefs that average about 400 m wide. Goenaga and Cintrón (1979) reported that these two reefs are in poor health, having little living coral and a low diversity of coral types as a result of the dredging of a channel parallel to the shoreline. This channel affected the structural integrity of the reef framework and created an environment rich in silt, which is resuspended into the water column by periodic storm-wave action. The same reef system exhibits a slightly higher living coral cover at Punta Percha (Goenaga and Cintrón, 1979).

Patch reefs are ubiquitous from Ensenada Comezón to Río Mameyes. Corals present include *Acropora palmata*, *Montastrea annularis*, *Montastrea cavernosa*, and *Diploria strigosa* (Goenaga and Cintrón, 1979; Stout, 1979). East of this reef system, a complex of barrier, fringing, and patch reefs form a buffer to wave energy making Playa de Luquillo one of the most popular recreational beaches in Puerto Rico.

East of Luquillo is a series of patch and fringing reefs (Torres, 1973) where water clarity increases but coral species diversity is low; *Acropora palmata*, *Diploria strigosa*, and *Montastrea cavernosa* are the most common species (Goenaga and Cintrón, 1979).

The mid-shelf region (from 10 to 30 m water depth) is characterized by rock outcrops and ridges of eolianite. These submerged, lithified sand dunes are part of a series of Pleistocene-age eolianite ridges that occur along the entire north coast of Puerto Rico (Kaye, 1959). They trend roughly east-west and have a relief of about 5–8 m. Corals and other marine invertebrates have encrusted these outcrops. Head corals, including *Montastrea spp* and *Diploria spp* are present along with soft corals, sponges, echinoderms, and other sessile and free-moving benthic organisms.

The outer-shelf region (from the 30-m isobath to the shelf edge) is mostly flat, minor local variations in relief being outcropping rock. The insular shelf break occurs at a water depth of about 70 m.

SURFICIAL SEDIMENT TYPES

We have divided the sediment cover on the shelf and upper slope of the Luquillo area into three principal types on the basis of textural and compositional parameters (table 1): (1) fine, calcareous sand; (2) medium to coarse, calcareous sand; and (3) terrigenous-rich mud intermixed with minor occurrences of gravelly mud along the shelfbreak. In addition to the three principal sediment types, a small deposit of fine, terrigenous sand and mixed terrigenous-carbonate sand is found nearshore at the western edge of the study area (table 1). This small sedimentary deposit is part of a larger deposit of river-derived siliciclastics from the Río Grande de Loíza, about 200 m west of the Luquillo study area boundary (Rodriguez and others, 1992). The areal distribution of sediment types shown on the map was derived from textural and compositional sediment sample analyses and sidescan-sonar imagery (Schwab and others, 1996a).

Fine, Calcareous Sand

Samples of this sediment type are composed of >90 percent calcium carbonate (table 1); grains include a wide variety of biologically produced material, coralline algae, coral fragments, Mollusca, and *Foraminifera* being the most common (fig. 3). The mean grain size is 0.180 mm and the sediment is moderately sorted. This sediment type is similar to that found on most beaches (fig. 3 and table 1) except those around Ensenada Comezón and Bahia las Cabezas, which are enclosed by patch and fringing reefs.

The fine, calcareous sand is widespread mainly on the inner shelf, landward of the eolianite ridges and hardgrounds. However, it also partially fills a series of northeast-southwest-trending "channels," most likely subaerially formed, that cut across the eolianite.

Medium to Coarse, Calcareous Sand

This sediment type contains a mixed assemblage of virtually clastic-free calcium carbonate; calcium carbonate averages 97 percent (table 1). Grain components are similar to the fine, calcareous sand (fig. 3). The mean grain size is 0.550 mm, and the sediment is moderately sorted.

Where sediment is present in the mid-shelf region, it is predominantly of this type. This sediment type is also found in reef-protected areas and beaches between Ensenada Comezon and Bahia las Cabezas. In the mid-shelf area, this sediment type infills channels and depressions that cut across the eolianite ridges and hardgrounds. Immediately seaward of the eolianite ridges and hardgrounds, elongate deposits of this sediment type overlie the mud deposit of the outer shelf. The orientation of these deposits suggests that sediment is being transported offshore across the shelf, possibly in response to storms (see discussion under "Sediment Transport").

Terrigenous-rich Mud

This sediment type contains an average concentration of 56 percent silt- and clay-size grains and is very poorly sorted (table 1). Calcium carbonate particles average 60 percent of the sediment. Some have a sandy to gravelly component of calcareous material. Constituents of this sandy to gravelly component include terrigenous material and a variety of biologically produced material, coralline algae, Porifera, Mollusca, and *Foraminifera* being the most common (fig. 3). In other areas of the terrigenous-rich mud deposit, particularly in the deepest part of the study area, little sand and gravel is present. Mud is present in the outer shelf and upper slope of the study area.

SEDIMENT THICKNESS

Analysis of seismic-reflection profiles and sidescan-sonar imagery show that the hardgrounds and eolianite ridges that predominate in the mid-shelf region have little or no sediment cover (figs. 4 and 5). Only in channels that cut across them or in troughs between individual ridges is there a measurable amount of sediment. In contrast, sediment in the beach and nearshore region ranges between 4 and 12 m thick but exceeds 20 m at one location (near lat 18° 23.5′ N., long 65° 40.0′ W). This nearshore deposit, about 3 km long (parallel to the shoreline) and 2 km wide contains about 30 million m^3 of sediment. Although detailed information on the subsurface textural and mineralogic characteristics of this deposit is unavailable, we assume that it consists of fine, calcareous sand, similar to the surficial material recorded in grab samples collected from the sea floor (table 1). This deposit is considered to be a potential source of sand for the construction industry and for beach nourishment projects, but cores will be needed to confirm its suitability for such use. Other submerged deposits in which the total volume of sand and gravel exceeds 200 million m^3 have been discovered elsewhere on the Puerto Rico shelf (Trumbull and Trias, 1982; Rodríguez, 1984; Trias, 1990). Elsewhere south of the hardgrounds, the sediment commonly thickens to about 8 m and in some places to 12 m in a shoreward direction. Seismic-reflection data are not available close to shore to determine the thickness of the sediment.

Seaward of the hardgrounds and eolianite ridges the sediment is thickest near the head of the largest submarine canyon in the study area (lat 18° 27.0′ N., long 65° 43.5′ W.), 12–16 m thick around the head of the canyon and less than 4 m thick within the canyon itself (fig. 4). Sediment is lost off the shelf to the deep sea by way of submarine canyons that indent all of the northern shelf of Puerto Rico (Shepard and others, 1979; EEZ–SCAN 85 Scientific Staff, 1987; Pilkey and others, 1987; Scanlon and others, 1996). However, sidescan imagery shows that mass movement has not occurred recently at the head of the submarine canyons in the study area (Schwab and others, 1996a).

Elsewhere seaward of the eolianite ridges and hardgrounds, the sediment is about 4–8 m thick except near the western boundary of the study area, where a 12- to 16-m-thick lens of mixed terrigenous-biogenic sand has been deposited near the mouth of the Río Grande de Loíza. This lens extends about 1 km to the west of the study area (Rodriguez and others, 1992).

SEDIMENT TRANSPORT

Physical oceanographic data are not available for this region. However, sediment transport directions can be inferred from the geophysical and sedimentologic data. The steep, narrow northern insular shelf is exposed to high-energy wave conditions that promote rapid cross-shelf sediment transport (Pilkey and others, 1978; Grove and others, 1982; Pilkey and others, 1984). A site-specific study using high-resolution sidescan-sonar surveying techniques was conducted in the study area to document the effect of major storms on the nearshore sand supply and the fate of the sand eroded from the coast (Schwab and others, 1996a).

The medium to coarse, calcareous sand shown on the map is closely associated with, and probably originates from, the eolianite ridges and hardground outcrops. A series of elongate areas of the medium to coarse, calcareous sand seaward of the eolianite ridges and hardgrounds are oriented northeast-southwest, roughly perpendicular to the shoreline (fig. 5). The sidescan-sonar imagery shows that pathways that this medium- to coarse sand followed from the eolianite ridges, around individual topographic highs (coral heads), before being deposited over the adjacent terrigenous-rich mud (fig. 6). Although sediment cores are not available for ground-truth information, seismic-reflection profiles suggest that these coarse-grained deposits are relatively thin and form the floor of elongate furrows generally <1 m deep in the surrounding mud (Schwab and others, 1996b). These medium- to coarse-grained sand deposits, which are covered by large, long-crested ripples having wavelengths of approximately 1–2 m (fig. 6), are oriented approximately perpendicular or slightly oblique to the northeast-southwest orientation of the furrows.

Interpretation of the geophysical and sedimentologic data suggests that the series of elongate deposits of medium- to coarse, calcareous sand seaward of the eolianite ridges and hardgrounds are indicative of net sediment transport to the northeast, roughly perpendicular to the shoreline (Schwab and others, 1996a). Similar features (termed "rippled scour depressions") have been described in a variety of shelf and nearshore settings (for example, Cacchione and others, 1984). Exactly how these furrows form is unknown. However, Schwab and others (1996a) inferred that the enhanced bottom stresses associated with storms result in an intensified quasi-steady current (downwelling current due to storm "set-up") and oscillatory flows (waves) capable of transporting medium- to coarse sand seaward from the eolianite onto the terrigenous-rich mud deposit in waters >30 m deep. The lack of fine-grained, calcareous sand deposits seaward of the eolianite ridges and hardgrounds suggests that during storms the same currents that transport medium to coarse, calcareous sand offshore, forming the rippled scour depressions, either do not act on the inner-shelf fine-grained, calcareous sand deposits or are not capable of transporting the fine sand to the outer shelf because it is effectively trapped in the nearshore zone by the eolianite ridges.

SHORELINE CHANGE

Historical shoreline rate-of-change data for the study area presented by Thieler and Danforth (1993) are based on analyses of historical maps and photographs spanning the period 1936–87, using the Digital Shoreline Mapping and Digital Shoreline Analysis Systems (Thieler and Danforth, 1994). The period of record embraces an average of 33 yrs, but commonly includes only two or three historical shoreline positions. The shoreline rate-of-change in the study area ranges from 3.15 m/yr of accretion to 3.10 m/yr of erosion (fig. 4). The average rate-of-change is approximately zero, which implies the area is regionally stable. There is, however, more erosion on the northwest side of the headlands and more accretion on the southeast side. This trend is present at Punta Miquillo, Punta Picúa, and to a lesser extent at Punta Embarcadero. The shoreline of the embayment between Punta Percha and Punta Embarcadero is eroding at rates as high as 2 m/yr.

Based on geomorphic indicators of net longshore transport (river-mouth spits), Morelock and others (1985) suggested that the net transport near the study area undergoes seasonal reversals from east-to-west during summer, changing to west-to-east in the winter. Rodríguez and others (1994) reported observing similar effects of seasonal reversal in longshore transport direction along a groin-protected beach west of the study area, in the San Juan metropolitan area. This process may be responsible for the trend of shoreline changes in the embayments between Punta Miquillo and Punta Embarcadero. Winter storms, which cause much of the beach erosion on the northeastern coast of Puerto Rico, generally impact the coast from the north-northwest. Subsequent fair-weather, westward longshore drift may enhance beach recovery on the west sides of the embayments.

The shoreline embayment between the town of Luquillo and Cabeza Chiquita, in general, is eroding at rates of 1–2 m/yr on the west side and accreting at similar rates on the east side. This trend may represent the net result of seasonal changes in longshore drift or the local influence of nearshore bathymetry on wave refraction.

Schwab and others (1996a) found evidence of cross-shelf sediment transport in the study area. Net offshore sand transport could also explain some of the high erosion rates at the headlands. However, the relative importance of the longshore versus offshore components of sediment transport here is unknown.

ACKNOWLEDGMENTS

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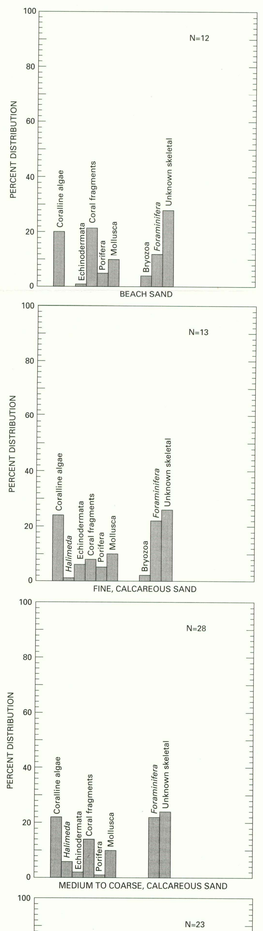

Figure 3. Average composition of the sand fraction for sediment samples collected in the Luquillo study area. N, number of samples. Figure modified from Schwab and others (1996a).

CONVERSION FACTORS

Multiply	By	To obtain
centimeters (cm)	0.3937	inches (in.)
meters (m)	3.281	feet (ft)
kilometers (km)	0.6214	miles (mi)

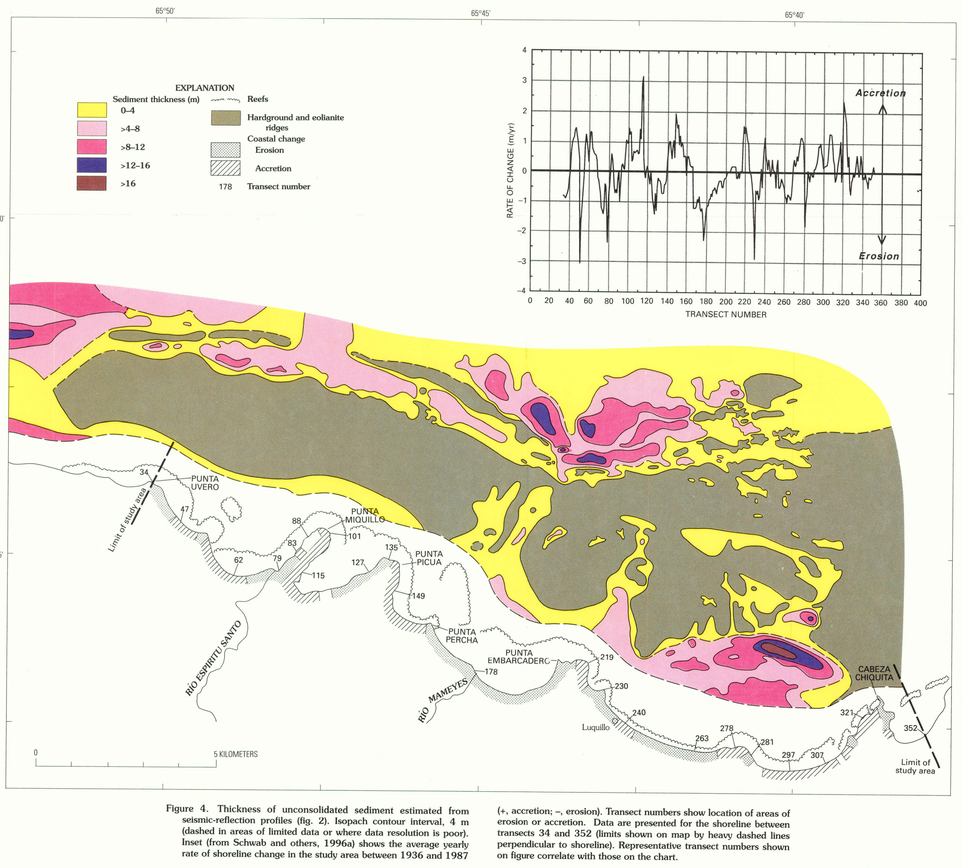

Figure 4. Thickness of unconsolidated sediment estimated from seismic-reflection profiles (fig. 2). Isopach contour interval, 4 m (dashed in areas of limited data or where data resolution is poor). Inset (from Schwab and others, 1996a) shows the average yearly rate of shoreline change in the study area between 1936 and 1987 (+, accretion; –, erosion). Transect numbers show location of areas of erosion or accretion. Data are presented for the shoreline between transects 34 and 352 (limits shown on map by heavy dashed lines perpendicular to shoreline). Representative transect numbers shown on figure correlate with those on the chart.

Figure 6. Digitally processed sidescan sonograph showing a rippled scour depression seaward of an eolianite ridge. This image is displayed at full resolution but is not geometrically correct. Figure modified from Gowen and others (1992).

Table 1. *Tabulation of sediment characteristics*

Sediment type	Mean grain size (millimeters)	Sorting[2]	Gravel (%)	Sand (%)	Silt + clay (%)	Calcium carbonate (%)
Fine, calcareous sand	0.180 (0.070–0.260)	0.94 (0.62–1.09)	0	96 (82–100)	4 (0–18)	96 (90–100)
Medium to coarse, calcareous sand	0.550 (0.030–3.000)	0.85 (0.68–1.26)	8 (0–49)	92 (51–100)	0	97 (92–100)
Terrigenous-rich mud	0.035 (0.063–2.000)	2.46 (1.36–340)	3 (0–8)	41 (4–62)	56 (43–100)	60 (23–86)
Fine, terrigenous sand	0.085 (0.029–0.150)	1.27 (0.60–2.10)	0	92 (80–100)	8 (0–15)	20 (7–25)
Mixed terrigenous-carbonate sand	0.260 (0.135–0.790)	0.90 (0.50–2.20)	2 (0–15)	07 (85–100)	1 (0–15)	45 (17–90)
Beach sand	0.238 (0.138–0.339)	0.98 (0.45–2.20)	3 (0–17)	97 (82–100)	1 (0–3)	93 (17–90)

[1]The top value in each group is the average value; values in parentheses are the range of values.
[2]Sorting values less than 0.35 are very well sorted; 0.35–0.50, well sorted; 0.50–0.71, moderately well sorted; 0.71–1.00, moderately sorted; 1.00–2.00, poorly sorted; 2.00–4.00, very poorly sorted; greater than 4.00, extremely poorly sorted.

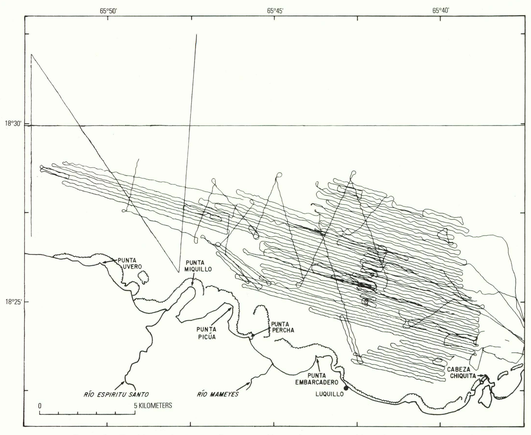

Figure 2. Tracklines of seismic-reflection profiles and area covered by sidescan-sonar imagery.

MARINE GEOLOGIC MAP OF THE NORTHEASTERN INSULAR SHELF OF PUERTO RICO—LUQUILLO AREA

By

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