Shoreline Features and Quaternary Shoreline Changes Puerto Rico

GEOLOGICAL SURVEY PROFESSIONAL PAPER 317-B

Prepared in cooperation with the Puerto Rico Water Resources Authority, Puerto Rico Economic Development Administration, Puerto Rico Aqueduct and Sewer Authority, and Puerto Rico Department of the Interior

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By CLIFFORD A. KAYE

COASTAL GEOLOGY OF PUERTO RICO

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A study of shore forms resulting from deposition and solution of calcium carbonate in tropical seas and from oceanographic and geologic differences between the island's several coasts. Prepared in cooperation with the Puerto Rico Water Resources Authority, Puerto Rico Economic Development Administration, Puerto Rico Aqueduct and Sewer Authority, and Puerto Rico Department of the Interior

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By Clifford A. Kaye

ABSTRACT

Shoreline.—The coast of Puerto Rico is divisible into five types of shoreline in six separate stretches. Each type has a distinctive form and, presumably, history. Between Punta La Bandera and Playa de Naguabo, on the northeastern corner of island, the coast is highly indented and there are many small offshore islands. It has the outline of a drowned coast, although the offshore bathymetry does not readily substantiate this origin. From Playa de Naguabo to Puerto Patillas, on the southeastern corner of the island, the coast is characterized by several lengthy stretches of alluvial lowlands (fronted by long arcuate beaches) and rocky headlands. This coast gives some indication that faulting has been largely responsible for its morphology. Between Puerto Patillas and Punta Cuchara, on the south coast, the coast is a broad alluvial plain, and the shore consists of alternate swamps and gravelly beaches. Between Punta Cuchara and Aguadilla, on the west coast, the coast is similar to that between Playa de Naguabo and Punta Patillas, consisting of lengthy stretches of rock or of alluvium and gives indications of the importance of faults in the separation of alluvial basins from rocky uplands. The western part of the north coast, from Aguadilla to Arecibo, is a nearly uninterrupted limestone cliff with a narrow sandy bench at its foot. Some cemented dunes occur along part of this shore. The central part of the north coast is low lying and fronts an alluvial coastal plain that is marked by lagoons and swamps. The shore itself comprises both sand beaches and cemented dunes, which in places form rocky headlands and small offshore rocks.

Tides.—Tides in Puerto Rican waters are small, averaging about a foot, and are semidiurnal, except on the south coast where they tend to be diurnal.

Currents.—Currents are dominated by the northwesterly drift of the North Equatorial current. This means dominantly westerly coastal currents on the north and south coasts and northerly currents on the east and west coasts, although reversals, due in part to tides and also to other and largely undetermined causes, occur. The dominant current has imparted a serrated westerly grain to the shoreline of the north coast.

Temperature.—Temperature of Puerto Rican coastal waters normally ranges between about 28°C in March to about 30°C in September. Inshore temperatures are slightly above and below this.

Salinity.—From water samples tested for chlorinity, it seems that the waters of the south coast have a slightly lower salinity than waters of the other coasts. This may be due to the greater persistence of dilution by land drainage on the rather shoal and relatively calm south coast, even though the runoff from the south slope of the island is much less than that from the north slope.

Winds.—The northeast trade winds dominate the island and winds blowing from westerly azimuths are negligible in frequency and velocity (except for rare cyclonic storms). Winds on parts of the south coast are influenced by the nearby mountain front and deviate more frequently from the direction of the trades.

Waves.—The windward, or north, coast of Puerto Rico is exposed to more wave action than the other coasts. Not only is it exposed to the North Atlantic storm waves but it also lacks the protection of the broad shoals that front the other coasts.

Lunate embayments.—The several large lunate embayments of the north shore are apparently the result of the direct molding action of arcuate wave fronts. The arcuate wave pattern is produced by diffraction and later refraction, largely the effect of offshore obstacles. The progressive change of a straight shore to a lunate shore and then to a straight shore again is indicated in several places on the north coast where two or more lines of cemented dunes occur. The breaching of the outermost dune ridge allows the excavation by wave action of a lunate embayment in the uncemented sands on the landward side of the dune. As the breach widens the lunate embayment enlarges, coalesces with others, and finally is backed up against the second line of cemented dunes, where the shore tends to straighten out again.

Beachrock.—Beachrock occurs along much of the north coast and in a few places on the south coast. It is limited to limestone coasts, although a genetic relationship between beachrock and coastal rock has not been established. Beachrock is beach sand or gravel that is cemented by $CaCO_3$, and more rarely by iron oxides, in approximately the intertidal range. It typically forms a hard pavement with a surface that is cambered seaward and which is broken by small steps whose risers face landward. In cross section the beachrock pavement is wedge shaped with a thick landward edge. Cementation occurs in both silicate sands and gravel as well as in shell sands. In Puerto Rico beachrock is found overlying uncemented sand, dense limestone, and compact loamy soil. Calcite (rather than aragonite, which is widely reported from other localities) was the cementing mineral in the samples of Puerto Rican beachrock that were studied. One interesting occurrence of ferruginous beachrock was cemented, in part at least, by magnetite(?). The cause of beachrock cementation is not known. The principal hypotheses of the origin of beachrock are examined in light of the Puerto Rican data; and because

of various objections to alternate hypotheses, the importance of biochemical action in the cementing process is favored.

Cemented dunes.—Cemented foredunes also occur widely on the north coast. Here, too, the cementing mineral is calcite and the rock (eolianite) resembles beachrock in hand specimens. The cemented dune complex of the north coast is made up of dunes of different ages. Some dunes are compounded, and include some reef rock and littoral marine deposits as well as dune sand of several generations of accumulation. In places the cemented dunes form rocky headlands and, where they are partly submerged, small offshore rocks. Cementation of dune sand is apparently taking place at the present time, for a contemporary foredune showed spotty cementation of the interior. The $CaCO_3$ cement is probably leached from carbonate sands in the upper part of the dune by downard percolating rainwater. It may precipitate at depth because of evaporation, or organic agencies, or a combination of both. Curious geomorphic features are produced by the wastage of cemented dunes.

Pitting.—In the spray zone eolianite is intensely pitted, and the depth and diameter of the pits vary roughly inversely with the altitude of the pit. Pits of three forms occur: cylindrical, flat-floored, and round-bottomed. Cylindrical pits may be true pot holes ground out by the surf. Flat-floored pits occur only in the spray zone and, beside their flat floors, are characterized by deeply undercut sides and pronounced narrow overflow channels. Round-bottomed pits generally occur outside the spray zone. The pits are thought to be due mostly to rainwater solution rather than to solution by spray or by organic agencies. The peculiar form of the flat-floored pit is explained by solution by thin layers of rainwater overlying spray pools in density stratification. The frequency distribution of fluctuating levels of the spray pool are shown by geometric construction to offer an explanation for the form of the flat-floored pit.

Tidal terraces.—Tidal terraces are characteristic of eolianite shores, particularly in exposed locations. The surfaces of these terraces lie at about mean high tide and commonly are broken by low curved steps. Tidal terraces are thought to form in two ways: (a) as a base level of pitting, and (b) by the recession of the nip, which flanks it both above and below. The tidal terrace is not involved in the solution of the nip because the thick coat of encrusting coralline algae, which thrives in the intertidal zone, forms an armor against the solutional attack which is responsible for the nip.

Nip.—The nip is a deep groove in carbonate coastal rocks between the levels of about mean high wave-crest and mean low wave-trough. It is suggested that the nip is due to occasional solution by surface marine waters, which is very much enhanced in the wave zone by the pronounced agitation. Commonly the nip appears poorly developed on exposed coasts simply because the upper visor has been torn off by wave action.

Wave destruction of cemented dunes.—Some cemented dunes have suffered massive collapse by the removal of their loose sand foundations by the action of strong surf.

Sandstone reef.—What appears to be a narrow barrier reef extending east from San Juan is probably a line of submerged cemented dunes that is capped by thin coral growth.

Oolite.—Off the northeast tip of Puerto Rico a chain of small islands consists entirely of oolite and geologically resembles, on a small scale, the Bahama Islands. Probably no ooids are forming at the present time in Puerto Rican waters. A lowering of sea level, however, by about five fathoms, such as very probably occurred in the late Pleistocene, would produce a broad very shallow bank off the northeast coast, which by its similarity to the Bahama Bank today would possibly be conducive to the formation of carbonate muds and ooids.

Algal deposits.—Several examples of laminated deposits in coastal situations are described as due to the lime-depositing activity of the blue-green algae. These are (a) "beach varnish," (b) a white encrustation on rocks in the spray zone that appears rarely and then rapidly disappears, (c) a brownish surface crust on oolite, (d) an algal breccia from the south coast, and (e) a cream-colored deposit on reef rock from Mona Island.

Coral reefs.—The coral reefs of the Puerto Rican coast are briefly described. Fringing reefs occur off much of the east, south, and west coast, and ribbon reefs with accompanying sand cays occur off parts of the south coast. Except in the eastern part, the north coast is free of well-developed reefs. This may be due to the large discharge of turbid river water on this coast and to the frequent large waves which keep bottom sediment stirred up and thus smother coral growth.

Protected river mouths.—Many of the rivers on the north coast have mouths that are sheltered by rocky headlands. The advantage of this position for maintaining an open outlet is evident in the reduced sand accumulation that characterizes it. Steps of development in the protected position are described.

Beach-faceted pebbles.—The faceting of pebbles on a beach may occur from the grinding action of sand as it is washed back and forth by wave swash over coarse-grained beachrock. Beach-faceted pebbles differ from wind-faceted pebbles because of the more uniform and massive nature of the grinding process in the former. Beach-faceted pebbles should therefore be recognizable in a geologic section by broader facets and by the absence of fluting and delicate secondary pitting that typifies ventifacts.

There is evidence that the present sea level (defined herein as present sea level plus or minus about 2 feet) is at least 2,000 years old, and that it was probably preceded for an additional 2,000 years by a sea level perhaps as much as 12 feet (2 fathoms) lower. These figures are derived from a study of three Puerto Rican coastal areas that have had a long history of shore advance apparently controlled by present sea level and a slightly lower sea level. The width of these belts of prograded shore is divided by several kinds of time-distance measuring rods, such as the distances of early historical and archaeological sites from the shore, or measurements of shore advance on aerial photos taken about 15 years apart. Further indications of the antiquity of present sea level, although only qualitative, are given by shores that have evidently been extensively eroded, presumably during present sea level. Deep nips and wide tidal terraces formed by the sea surface at the present level offer additional qualitative evidence for sea level stability. From these data and from the close agreement of the altitudes of some Puerto Rican Pleistocene marine terraces and marine deposits with the altitudes of similar features on many coasts of the world, it is concluded that positive or negative crustal movement has been negligible in the coastal areas of Puerto Rico since at least the late Pleistocene. The stratigraphy of the complex of cemented dunes on the north coast of Puerto Rico is described. Four generations of eolianite are recognized, several or all of which may occur in the older dunes, where they are generally separated by paleosols. Cropping out below the eolianite in the older dunes are Pleistocene marine deposits, which in many places rest on pedestals of lower Miocene rock. Apparently ridges and knobs of Miocene rock provided platforms for the deposition of marine sediments during higher sea levels of Pleistocene time. These were later buried by wind-blown sand as sea level dropped. All four eolianites (E_1–E_4) were deposited when sea level was lower than at present. The youngest eolianite (E_4) is thought to date from early post-Mankato time, when sea level probably stood at about −30 feet (5 fathoms). The E_3 eolianite may date from early Wisconsin time or even Illinoian time and the two oldest from Illinoian time. Other Pleistocene marine deposits and marine terraces are described from Puerto Rican coastal areas. Positive sea levels at 5 feet, 15 feet, 25 feet, 50 feet, and perhaps 120 feet are indicated. Negative sea levels may have occurred at depths of 2, 5, 10, 22, and 50 fathoms, although there is much uncertainty as to the significance of data from the deeper levels. An attempt is made to correlate some of the sea levels with the standard glacial section.

SOME SHORELINE FEATURES AND THEIR DEVELOPMENT

Puerto Rico is exceptionally well suited for the study of a variety of shoreline features, particularly those forms that result from the deposition and solution of calcium carbonate and that characterize tropical seas. Some of these features, such as beachrock, cemented coastal sand dunes, shoreline nips, and tidal terraces, are probably nowhere so excellently developed within comparable range of continental United States. The island exemplifies, in addition, a variety of coastal types, which are the result partly of oceanographic differences between the several coasts and partly of differences in the geological structure and history of the coastal sections of the island.

The following notes on some shoreline features and their origins are arranged as to consider first the nature of the fundamental factors—the sea and air—and then to discuss several of the more interesting shoreline features themselves.

PUERTO RICAN SHORELINE TYPES

The coast of Puerto Rico is readily divisible into five types of shoreline in six separate stretches. Each type has a distinctive form and, presumably, history (fig. 6). The types will not be assigned names, principally because existing coastal classifications are either too restrictive in their morphologic implications or too insistent on the distinction about which there is least certainty—the origin of the coast. The shoreline types will be described in order, starting at the northeastern corner of the island and proceeding about the island in a clockwise direction.

PUNTA LA BANDERA TO PLAYA DE NAGUABO

The northeast coast (type A, fig. 6; pl. 1) is characteristically highly indented and dotted with small offshore islands. The rocky headlands and islands are formed by the long spurs that fan out from the flanks of the Sierra de Luquillo, and the islands generally have the same well-rounded form as the hills on the mainland. Except for low wave-cut cliffs and a certain amount of alluviation between headlands, the shoreline shows few effects of sculpting by the sea at its present level.

The coast presents an appearance of mature topography that has undergone fairly recent drowning. The offshore hydrography, however, is that of a shallow, nearly level bank and does not show the dissections expected of a recently drowned topography. Fringing coral reefs are common.

PLAYA DE NAGUABO TO PUERTO PATILLAS

The southeast coast (type B, fig. 6) is characterized by large rocky headlands and broad alluviated valleys. The valleys are fronted by long arcuate beaches consisting of siliceous[1] sand (beaches of the north coast, for example, are commonly shell sand or mixtures of siliceous and shell saand). Morphologically this stretch of coast differs from the coast to the north in being less indented and having broader elements—both headlands and alluvial stretches. The headlands drop off with steeper slopes and, in general, to deeper water than do those to the north, and wave-eroded cliffs, 100 or more feet high, are not uncommon. West of the Cabo Mala Pascua headland, the shore, which is formed by a low sandy apron that lies at the foot of the Sierra de Guadarraya, is fronted by a narrow fringing reef.

The coastline here gives indications of fault control. The broad alluvial plains on which the towns of Naguabo, Humacao, and Yabucoa are located and which are very much like the alluvial embayments on the west coast of the island, may be bounded by faults. The lowlands about Humacao and Naguabo are probably structurally related to the line of topographic depressions that extends as far west as Caguas (Kaye, 1957a), and the bold straight scarp of the Cuchilla de Panduras, which bounds the Yabucoa plain on the south, is very probably the result of late (Pleistocene?) faulting. The line of this scarp continues westward as the straight valley of Quebrada Guayabo, and thence, inscribing a broad arc concave to the south, for another 12 miles to the southwest, where it is marked by a perfect topographic alinement of valleys and divides (Kaye, 1957a). The south side of the Cuchilla de Panduras also seems to be bounded by a fault. Some indication of late fault displacement is provided by Chart 920 of the U. S. Coast and Geodetic Survey, which shows a steep submarine scarp lying a

[1] "Siliceous" is used here to mean quartz plus silicate minerals. Shell sand consists mainly of fragments of lime-secreting marine organisms, including calcareous algae.

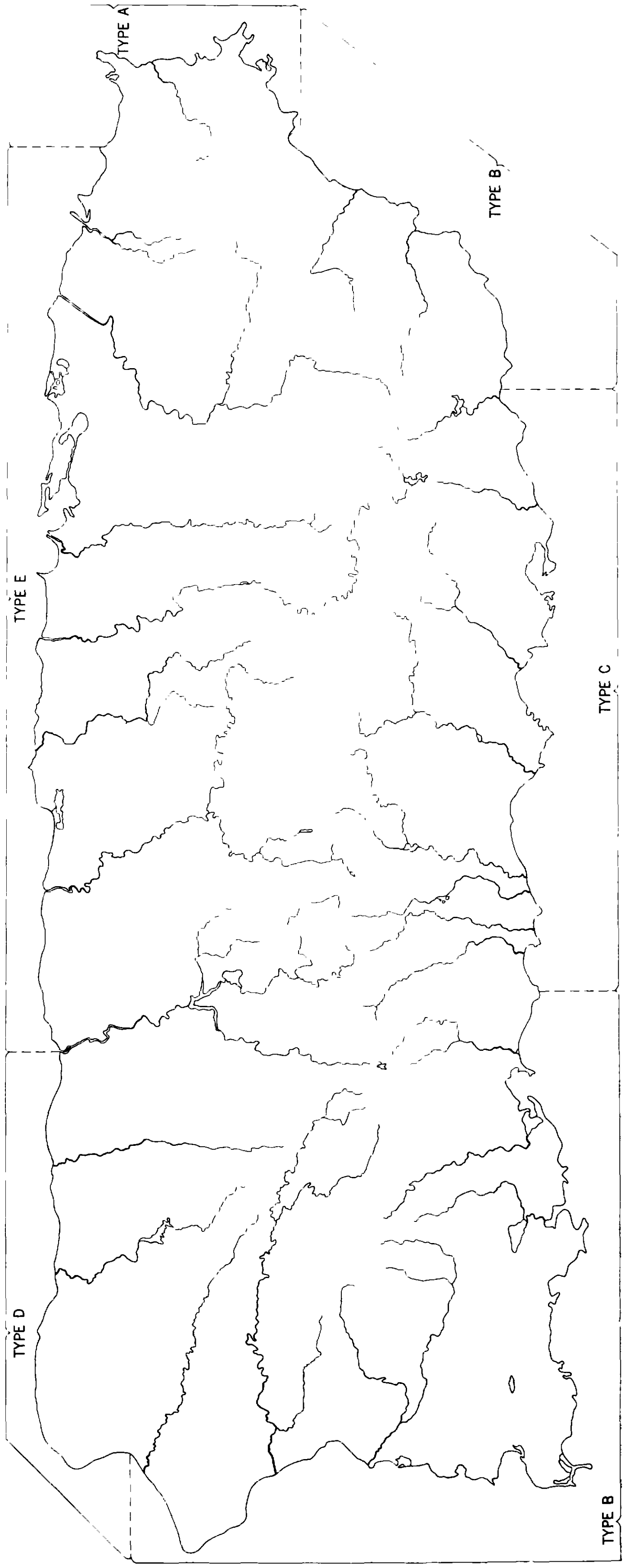

FIGURE 6.—Puerto Rican shoreline types.

mile off the Cuchilla de Panduras headland. On this chart the 100-fathom line is 1 mile off the coast, and a sounding of 709 fathoms (4,254 feet) occurs a little less than 2 miles from shore. This steep dropoff is apparently contiguous with the Maunabo depression; it is probably terminated on the north by the Cuchilla de Panduras fault block.

PUERTO PATILLAS TO PUNTA CUCHARA

This part of the south coast (type C, fig. 6) consists of a piedmont alluvial plain. The shore is formed by narrow beaches of dark-colored siliceous sand and andesitic gravel alternating with mangrove swamps. Fringing reefs occur along part of the shore, and farther out ribbon reefs and sand cays are strung out in a large east-west chain. There are no hard-rock outcrops. In back of the shore the featureless plain slopes gently to the foot of the steep mountain front, several miles to the north. The shore is strongly cuspate, with deep, somewhat asymmetrical embayments, and seems to reflect the contours of several very broad, poorly defined alluvial fans which have coalesced to form the piedmont plain. Longshore currents have somewhat altered the scalloped symmetry of these fans and have shifted sediment in a predominant westerly direction. In consequence, rivers emptying on this stretch of coast have deltaic accumulations mostly to the west of the river mouth.

In the eastern part of the south coast, in the vicinity of Arroyo, a low cliff has been eroded in the alluvial fan deposits. No signs of shore erosion of similar magnitude occur elsewhere along this coastal stretch. This general absence of erosion is probably the result of the protection provided by the broad offshore bank that fronts the coast west of Arroyo.

PUNTA CUCHARA TO AGUADILLA

The southwest coast (type B, fig. 6) consists of alternate rocky and alluvial stretches. The coastline is moderately indented. Punta Guayanilla, a recurved sand spit derived from sediment of the Río Tallaboa, and Punta Verraco, to the west, form two long arms across the mouth of the Bahía de Guayanilla, thereby protecting it from storm waves and making it possible for a broad tract of mangrove swamp to form along the shore in the lee of Punta Verraco.

The Bahía de Guánica is the only Puerto Rican example of a pouch-shaped harbor, a feature that is particularly common on the coast of Cuba. The origin of the Cuban pouch-shaped harbors has been discussed by Vaughan (1919, p. 280–291), among others, who suggested that they represented drowned river mouths. As at Punta Verraco, the well-protected nature of the Guánica harbor has made it possible for a swampy mangrove shore to develop.

Cabo Rojo, the southwest tip of Puerto Rico, is a double tombolo. It consists of two separate limestone knobs that are tied to the mainland by a forked tombolo and are also tied to each other by a narrow beach, thereby enclosing a small triangular lagoon.

Wave-cut cliffs are found at the tip of Cabo Rojo and for several miles to the east. From Cabo Rojo to Mayagüez, however, the coast is protected from severe wave erosion by a broad shallow bank (chap. *C* of this report, fig. 68) and as a result stretches of this shore are low and swampy. North of Mayagüez, where the bank narrows, wave sculpture is again evident.

Fringing reefs and sand cays are prominent off the south coast. On the west coast fringing reefs are found as far north as Mayagüez but sand cays are lacking.

In this stretch of coast structural control is apparent in the separation of some of the highlands and basins, as it is on the east coast of the island. Fault control seems particularly evident in the rectilinear nature of the northwest-trending shore of the Rincón peninsula (Kaye, 1957a).

AGUADILLA TO ARECIBO

The western part of the north coast (type D, fig. 6) is characterized by a nearly uninterrupted limestone cliff that either forms the shore or is separated from the shore by a narrow rocky or sandy bench. For most of its length the cliff varies from 150 to 200 feet in height, descending in altitude at both ends of the stretch and in places, between Hatillo and Arecibo, becoming barely discernible. The cliff is cut in limestone of early Miocene age and, in the vicinity of Arecibo, in sands and calcareous sandstones of early Miocene age. The narrow bench, or shelf, that lies at the foot of much of the cliff supports cemented dunes that in places form wave-eroded, rocky headlands. Because of the protection provided by the low shelf it is clear that at least part of the cliff owes its origin to former rather than contemporary wave erosion, associated perhaps with higher and perhaps with lower sea levels during Pleistocene time. However, the origin of this part of the shore remains obscure, as does the reason for its abrupt transition to the shoreline type adjoining it on the east. The cliffed shoreline as it now stands is clearly erosional. It may, however, have been originally initiated by displacement along east-west faults located well to the north of the present shoreline.

ARECIBO TO PUNTA LA BANDERA

This part of the coast (type E, fig. 6) is a low-lying alluvial plain broken by several large swamps and lagoons. The shore is marked in many places by cemented dunes and Pleistocene reef rock but for most of its length consists of narrow beaches and associated recent foredunes; it therefore alternates from rocky, where formed by the cemented dunes and reef rock, to sandy in character. Offshore islets and rocks, which mark the tops of submerged cemented dunes, are common and make navigation close to shore particularly hazardous. In the eastern part, this coast is indented by several large lunate embayments.

Some stretches of this shore are exceptionally mobile, either advancing and retreating rhythmically or showing a net retreat or a net advance; others seem relatively stable. The coast is exposed to severe buffeting by storm waves, although parts of it are protected by cemented dunes that form offshore islets or jut out as short rocky peninsulas. The slightly serrated form of the shore reflects both the trend of the cemented dunes and the effect of the predominantly westerly longshore current.

TIDES, CURRENTS, WINDS, AND WAVES

TIDES

The tidal range of these seas is comparatively slight. According to the 1951 edition of the "Tide Tables of the East Coast of North and South America" (U. S. Coast and Geod. Survey, Serial 731) the mean tidal range, which varied somewhat from point to point, was 1.1 feet at San Juan, 1.1 feet at Bahía de Fajardo on the east coast, 0.6 foot at Ponce on the south coast, and 0.8 foot at Puerto Real on the west coast. The same tables show that the maximum tidal range (highest spring to lowest spring) for 1951 at San Juan was 2.9 feet. This does not mean that any single tidal fluctuation attained this range, but rather that this represents the extreme limits that the year's tides attained. The tides on unprotected open shores are probably slightly less than those reported for the San Juan harbor.

The tides are normally semidiurnal (two tidal cycles daily) except on the south coast where, according to the "Sailing Directions of the West Indies" (U. S. Hydrog. Office, 1951, p. 331–332), the tides are more or less diurnal (one tidal cycle daily).

CURRENTS

The general currents of the northeast Caribbean region are discussed and figured in Chapter C of this report. The North Equatorial current, flowing in a west-northwesterly direction, dominates the entire Antilles. Close to shore, however, this general current may be very much deflected and local currents of entirely different kinds may be set up by the many influences that prevail along a shore. Thus, coastlines are generally marked by coastal currents (Shepard and Inman, 1950, p. 200; and Wiegel, 1953) that flow approximately parallel to the shore and are therefore divergent to the trend of the oceanic currents farther out. In some instances, coastal currents, which may extend out to sea for many miles, may operate as part of broad eddy circulations created by special hydrographic conditions. The coastal current is further modified in the breaker zone, where wave and surf characteristics, bottom irregularities, and the configuration of the shoreline itself—all tend to influence water movement and produce nearshore and particularly longshore currents (see Wiegel, 1953, p. 48, for definition of the nearshore current system).

Coastal, and particularly longshore currents, are factors of fundamental importance in the molding of shorelines. Off the north coast of Puerto Rico the oceanic current is westerly or northwesterly, and the prevailing coastal and longshore currents are westerly. This fact is clearly indicated by the westerly grain of the serrated north coastline (pl. 1).

However, there are also east-setting coastal currents on the north coast. These can be seen by observing the direction taken by the overflow of turbid river water about the mouths of the larger rivers following heavy rainfall (fig. 7). Although the majority of observations of this nature substantiate a prevailing westerly drift to the coastal currents of the north coast, many eastward-diverted trails of river water were noted by the writer throughout the year in unprotected situations along straight stretches of coast, like those east of the mouths of the Río Grande de Loíza, and Río de la Plata, and Bahía de San Juan.

Lobeck (1922, p. 361–362) hypothesized counterclockwise eddy currents in the lunate bays of the Puerto Rican north coast set up by the prevailing westerly coastal currents outside the embayments. Meyerhoff (1933, p. 183–185) reiterated this idea. But observations of currents made in September and early October by the U. S. Beach Erosion Board within one of the best formed of these bays—the bay between Punta Las Marías and Boca de Cangrejos (pl. 1)—showed only westerly drifts (fig. 15). Current velocities observed in these tests averaged approximately 13 feet per minute with a maximum velocity of 35.4 feet per minute. The westerly drift of the nearshore current in the lunate bays of the north coast was further confirmed by fluorescein dye tests and float observations, made by the writer early in the month of November in the Ensenada de Boca Vieja, a well-formed lunate bay just west of Bahía de San Juan. There are no confirmatory data therefore to support Lobeck's idea that

FIGURE 7.—Easterly coastal current on north coast. Turbid water is coming from mouth of Rio Grande de Loiza (lower left), which is nearly completely barricaded by a sand bar. Small patches of coral reef on right.

the water in the lunate bays circulates as a counterclockwise eddy.

There are several possible explanations for the occasional easterly set of the coastal currents. One of these is the possible existence of a large coastal eddy induced by the occasional northwesterly drift of the North Equatorial Current north of Puerto Rico. The "Current Chart of Central American Waters" for the months of September, November, and December (U. S. Hydrog. Office Misc. 10,690, Nos. 9, 11, 12) shows that off the north coast the mean current directions deviate during these months from the westerly set that generally prevails to the northwest. Such an oblique set to the offshore oceanic currents might produce a large counter current along the Puerto Rican north coast (fig. 8). The occurrence of easterly coastal currents at other times of the year might be the result of occasional reversions to this general current condition throughout the year. A second and perhaps more likely hypothesis to explain at least some of the easterly drift is the effect of the Coriolis force on river water as it enters the ocean (Harvey, 1945, p. 3). On the north coast

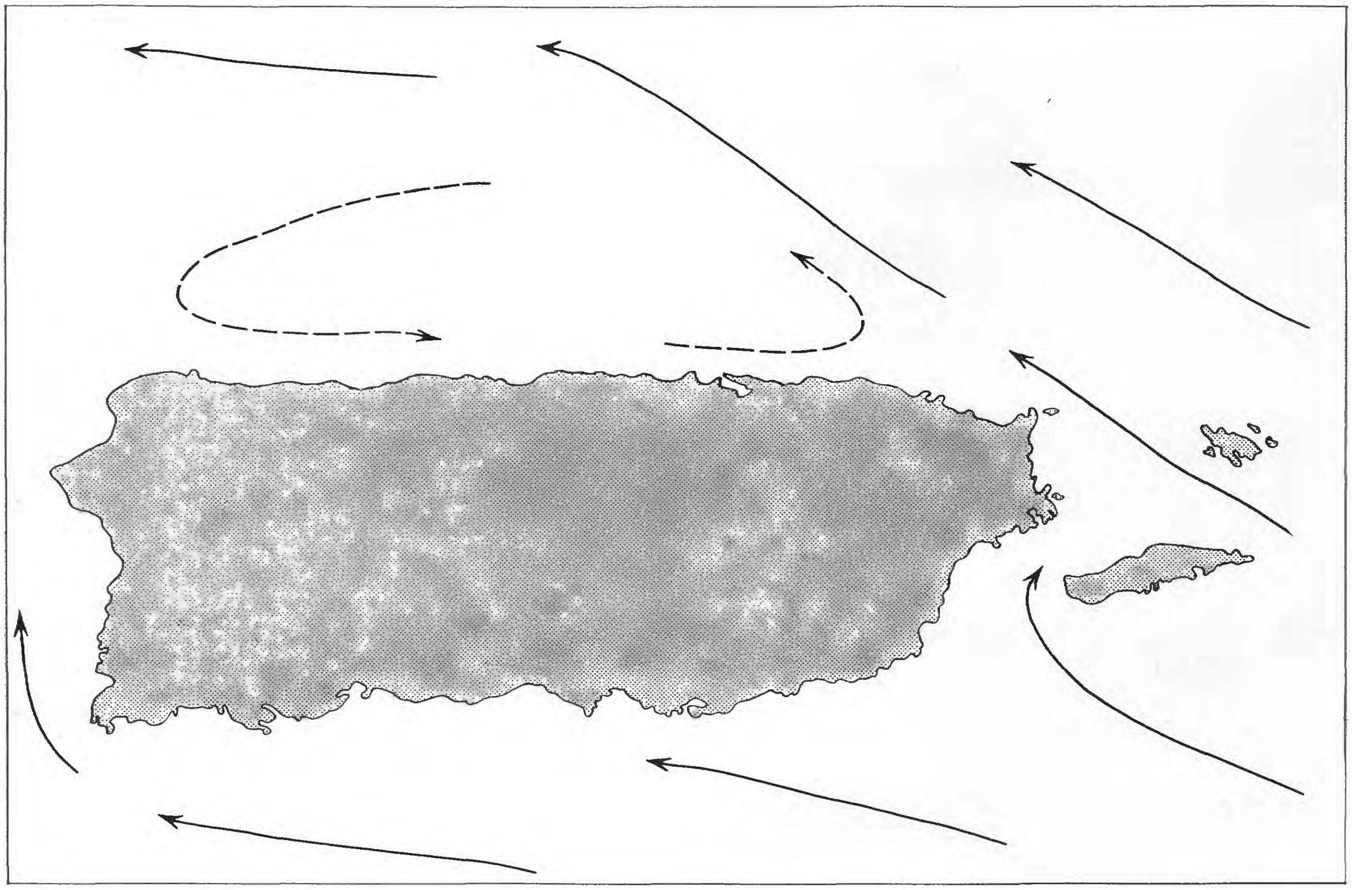

FIGURE 8.—Principal oceanic currents of Puerto Rico, showing hypothetical eddy off north coast during certain times of the year.

of Puerto Rico, a right-hand deflection in response to this force would direct the course of the muddy fresh-water layer eastward. This force should be effective, however, only in relatively calm seas, when the density stratification between the light river water and the denser salt water can be maintained for a considerable period. Even under optimum conditions, the eastward drift of the muddy water under the effect of the Coriolis force should not be very extensive, for the effectiveness of the Coriolis force should be rapidly dissipated by the frictional drag of the underlying marine waters on the superficial layer of river water.

Under the influence of the North Equatorial current the coastal and nearshore currents of the east coast of Puerto Rico flow mostly north, though occasional tidal currents set to the south. Topographic expression of the dominant northerly current occurs east of the town of Humacao, where a small rocky headland, El Morrillo, has acted as a natural groin against the longshore drift of sand. In consequence, the sandy beach to the south of this point is built out several hundred yards beyond the position of the beach to the north (fig. 9).

The coastal currents of the south coast set strongly to the west. They have imparted a serrated grain to the eastern half of the shoreline, which is similar to, though less well developed than, the westerly grain of the north shore.

On the west coast, the longshore coastal currents south of Punta Higuero, the tip of the Rincón peninsula, generally set northward. North of the peninsula there commonly is a southerly set, which is reenforced by tidal currents.

SEA TEMPERATURES

According to the "Current Charts of Central American Waters" (U. S. Hydrog. Office Misc. 10,690), the open sea temperatures about Puerto Rico range from a minimum of about 25°C in March to a maximum of about 28°C in September. The range of shore temperatures, however, is normally somewhat greater because of such factors as the temperature effect of admixed river waters, diurnal temperature changes in shallow and protected bodies of water, and radiation from shallow bottoms. The temperatures of coastal waters

FIGURE 9.—Natural groin, demonstrating northerly drift of sand by longshore currents on east coast. The small rocky headland acting as a groin here is El Morrillo, due east of Humacao.

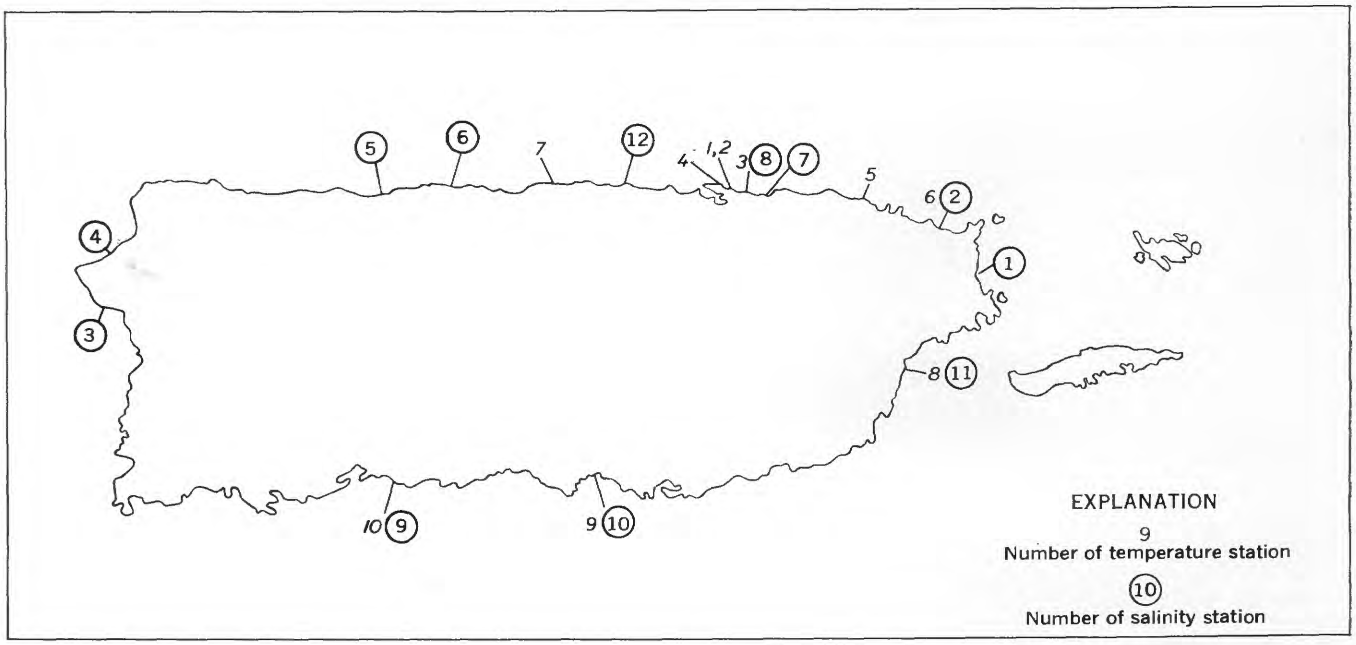

FIGURE 10.—Map showing location of sea-temperature and salinity measurement stations.

taken by the writer (see fig. 10) and tabulated below, however, are only slightly at variance with open sea temperatures. It will be seen from these data that the late summer temperatures are from 1° to 2°C higher than the early spring temperatures, which agree with open sea observations.

Temperature measurements of coastal water

[Location of measurement stations, fig. 10]

Station	Location	Date	Temperature (°C)	Remarks
	North coast:			
1	Santurce, mouth of Laguna del Condado.	Apr. 13, 1951	26.6	8:40 a. m.; probably reflects diurnal variations.
2	----do	Sept. 5, 1952	29.5	
3	Santa Teresita, San Juan	-----do	29.5	
4	Punta Escambrón, San Juan.	Mar. 27, 1951	27.8	
5	Poblado Medianía Alta	Sept. 6, 1952	28.5	
6	Luquillo	-----do	28.5	
7	Vega Baja beach	Sept. 9, 1952	29.5	Somewhat protected location.
8	East coast: Playa Humacao	Sept. 6, 1952	28.5	
	South coast:			
9	West of Salinas	Apr. 6, 1951	27.6	9 a. m.
10	West of Ponce	-----do	27.8	10 a. m.; from surface of coral reef.

SALINITY

There is a direct relation in normal sea water between the chlorine content (chlorinity, per thousand) and the content of total dissolved salts (salinity, per thousand). The formula is given by Harvey (1945) as:

$$\text{Salinity } (^{\circ}/_{\circ\circ}) = 0.030 + 1.8050 \text{ chlorinity } (^{\circ}/_{\circ\circ})$$

Twelve samples of coastal waters of Puerto Rico were collected on February 21, 1951, and tested in the chemical laboratory of the U. S. Geological Survey, Washington, D. C., for their chlorine content. The following table converts these data into expressions of salinity according to the above formula.

Salinity of samples of coastal water

[Analyst, W. W. Brannock. Location of measurement stations, fig. 10]

Station	Location	Salinity (°/₀₀)	Remarks
	North coast:		
2	Luquillo	36.11	
8	Santa Teresita	36.78	
7	Isla Verde	36.80	
5	Arecibo, east	36.20	
6	Barceloneta, west	36.67	
12	Punta Fraile	36.84	
	East coast:		
1	Bahía Demajagua	35.75	
11	Playa de Humacao	35.39	
	South coast:		
10	Salinas, west	35.82	
9	Ponce, west	29.76	A fresh-water spring was later found to be discharging close by.
	West coast:		
3	Punta, Cadena	36.35	
4	Aguada, west	36.20	

The above data indicate a somewhat lower salinity for the Caribbean sea waters of the south coast than for the waters of the north coast. This may possibly be accounted for by the admixture of land drainage in the nearshore zone of the south coast even though the runoff from the south slope of the island is much less than on the north. The stirring action of waves is responsible for the mixing of river water and sea water along a coast and where wave action is slight, as it is on the south coast, salinity may be sharply reduced in the shore zone.

FIGURE 11.—Northeast trade winds; a tree near Punta Manatí showing effect of dominant northeast winds.

WINDS

Puerto Rican waters are dominated throughout the entire year by the northeast trade winds (fig. 11). At San Juan the greatest percentage of winds observed are easterly, with frequency of winds decreasing progressively as they deviate from east. Winds blowing from westerly azimuths are negligible in frequency and velocities. Winds are more consistently easterly in the summer months, attaining a maximum frequency in July when the east winds blow 68 percent of the time. The greatest deviation from the pattern of east wind dominance is in October, when the east wind blows only 34 percent of the time. Minimum average wind velocities for the year, 8.2 miles per hour, are also recorded in October.

Wind data for San Juan, Puerto Rico, 1899–1930

[From U. S. Hydrog. Office Pub. 128, table 13; source, U. S. Weather Bureau]

Month	Wind									
	Mean velocity (miles per hour)	Percent of observations from—								
		North	Northeast	East	Southeast	South	Southwest	West	Northwest	Calm
January	13.3	2	12	54	16	10	4	(1)	1	0
February	12.0	3	13	49	15	13	6	(1)	1	0
March	12.9	4	15	47	13	15	4	1	1	(1)
April	12.4	2	15	45	17	16	3	1	(1)	(1)
May	11.5	1	8	48	23	18	1	1	(1)	(1)
June	12.4	(1)	3	61	25	10	(1)	1	(1)	(1)
July	13.7	(1)	3	68	19	9	1	0	0	(1)
August	12.6	1	8	61	17	11	1	(1)	(1)	(1)
September	9.7	2	8	40	20	24	4	1	1	0
October	8.2	1	10	34	20	28	5	1	1	(1)
November	9.7	3	13	35	18	22	6	2	1	0
December	11.6	4	16	46	14	14	4	1	1	0
Mean	11.6	2	10	49	18	16	3	1	1	(1)

1 Less than 0.5 percent.

The effect of winds on the molding of the north shore of Puerto Rico is very important, particularly because cemented dunes provide one of the important shoreline elements. These dunes, which are actually old foredunes, do not reflect, however, the dominance of the east wind, suggested by the published wind data, as much as they do the dominance of northeasterly winds. The importance of northeasterly winds is further indicated by certain trees on the north coast whose trunks have been bent in a truly remarkable manner by the trade winds and which, in consequence, are elongated in a direction that is probably the resultant force of all the winds to which they have been exposed above a certain critical velocity (fig. 11). The orientation of several of these trees on a barren hilltop overlooking the ocean, north of the town of Manatí, was S. 58° W., presumably reflecting a N. 58° E. dominant wind direction.

The winds of the south coast, as shown in the observation record of Losey Field, about seven miles east of Ponce, differ somewhat from those of the north coast. The east wind is less dominant and an appreciable percentage of orographic winds blowing from the island highlands to the north occur. These data probably also pertain to winds at the nearby coast, several miles to the south, although there one could expect the northern winds to be less marked.

Wind data for Losey Field, east of Ponce, Puerto Rico, April 1941–April 1944

[Source: U. S. Weather Bureau]

Direction	Percentage of all observations	Average velocity (miles per hour)
North	11.1	4.6
North-northeast	6.0	5.1
Northeast	18.0	6.1
East-northeast	8.8	7.6
East	10.3	8.4
East-southeast	8.9	12.2
Southeast	16.8	13.6
South-southeast	2.8	10.9
South	1.3	8.2
South-southwest	.5	8.8
Southwest	.4	7.7
West-southwest	.1	7.3
West	.2	3.6
West-northwest	.2	4.3
Northwest	2.5	4.6
North-northwest	8.2	5.2
Calm	3.9	

The meteorologic factors responsible for the shifting of the winds to the north and south of the dominant easterly direction of the trades have only recently been appreciated. It has now been established (Riehl, 1945) that between spring and late autumn the atmosphere of the Caribbean region is periodically swept from east to west by large wavelike disturbances, called by the meteorologists "waves in the easterlies." The sequence of events that occur as one of these waves passes over a point has been described by McDowell (1950, p. 34) as follows:

Before the island comes under the influence of the wave, the wind flow is from the east, with scattered clouds and random local showers. As the forward part of the wave approaches, the wind turns into northeast and the sky becomes remarkably free from clouds and fine, clear weather results. This persists for 18 to 24 hours until the wave crest passes, at which time the wind shifts into southeast and the sky becomes full of towering cumulus clouds with frequent heavy showers. The bad weather continues for 24 hours or more and then gradually returns to normal as the disturbance moves away.

In the winter months, broad perturbations associated with cyclonic lows that have developed along cold fronts in more northern latitudes sweep the Caribbean from west to east. The sequence of winds, as such a disturbance passes over a point, is from the normal east to the southeast, shifting then through northeast and finally back to east again.

WAVES

Waves are the most important dynamic factor in the molding of shorelines. They are primarily responsible for beach erosion and beach deposition. Waves in turn are direct expressions of wind and its effect on the water surface over which it has blown. For discussion and bibliographies see Sverdrup, Johnson, and Fleming 1952; Haurwitz and others, 1949.

The monolithic character of the easterly winds in the Puerto Rican area dominates the wave systems of the surrounding waters. There is therefore an unequal distribution of wave work on the four coasts of the island. The northern one receives a disproportionate share of buffeting, whereas the east, south and west shores are generally relatively calm. The reason for the difference in wave activity between the coasts is readily apparent. The north coast is unique among the four coasts in the following ways: (a) There is an uninterrupted length of fetch across the entire Atlantic Ocean for the development of waves by northeast to northwest winds. (b) Unlike the east, south, and part of the west coast, the bottom off the north coast deepens rapidly and few shoals exist. As a result the surf is rougher, and large waves break against the shore instead of dissipating their energy against offshore banks and reefs. (c) The north shore is exposed to the heavy swells that originate with North Atlantic storms and which are particularly frequent in the winter. A rough idea of the energy of some of these swells can be had many times during the winter by watching them break against the cemented dunes. It is not un-

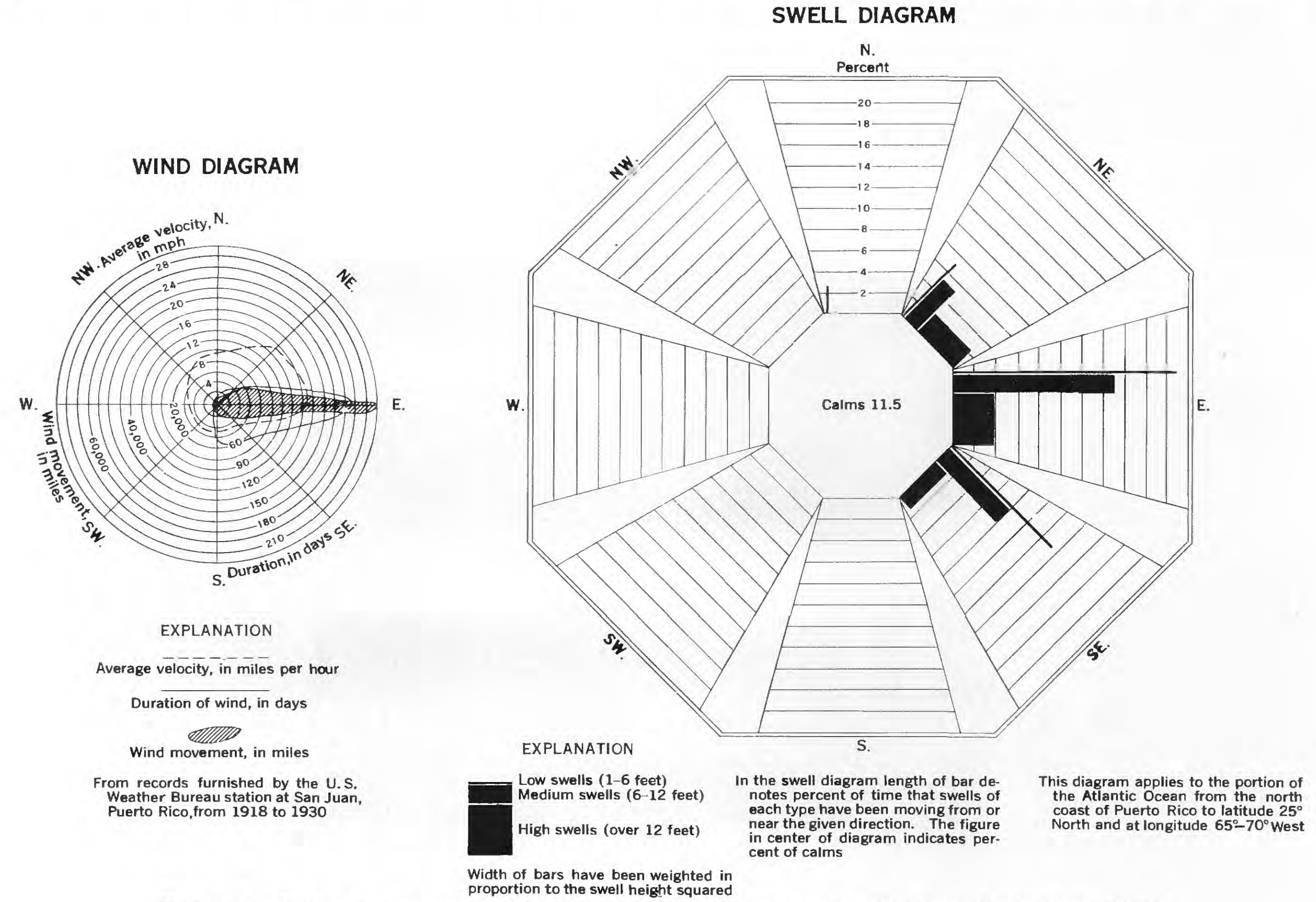

FIGURE 12.—Wind and swell diagrams from northern Puerto Rico. Source: U. S. Beach Erosion Board (1948).

usual, for example, on the shore north of Manatí to see white water shoot more than 100 feet into the air.

Figure 12, from the records of the U. S. Hydrographic Office, shows observations of swells made from vessels between the north coast of Puerto Rico and latitude 25° N. The swell diagram conforms very well with the wind diagram for San Juan. The distinction here between swell (in the strict sense of the term, see Wiegel, 1953) and wind wave was probably not carefully drawn in compiling these data, and the diagram very likely represents waves that were actively being formed as well as waves that were no longer under the influence of their generating winds.

A typical wave pattern of the open sea consists of two or more intersecting sets of waves, or wavetrains (fig. 13). Each wavetrain has been created by wind blowing from a different direction. The result is that there is generally more than one wave system approaching a shore, although one may clearly dominate. The multiple nature of the wave system can usually be seen from the air. Aerial photographs of Puerto Rican coastal waters usually show two or more wavetrains that generally, though not invariably, are directed from easterly azimuths. Usually it is only on the western, or lee, shore of Puerto Rico that wave directions are abnormal in this respect. Here waves are generally from a westerly azimuth, although these waves are commonly extreme refractions of easterly swells from the Caribbean Sea and the North Atlantic.

On approaching the shore, waves are generally subjected to considerable refraction (Munk and Taylor, 1947; Johnson and others, 1948; Shepard and Inman,

FIGURE 13.—Northwest wavetrain at Cayo Icacos, off northeast tip of Puerto Rico. The wave complex shows refracted, diffracted, and reflected elements. Island consists of cemented oolitic dunes.

1950; Pierson, 1951). Wavefronts strongly oblique to a shore are invariably refracted in shallow water so as to conform more nearly to the bottom contours. In this manner waves may reach the surf zone parallel to, or nearly parallel to, the shore, regardless of the angle of incidence between the wave train in the open sea and the coast (Sibul, 1954, gives good ripple-tank illustration of this effect). The large swells approaching the north shore of Puerto Rico from the east or northeast are therefore refracted in the nearshore zone to conform more or less to the prevailing easterly orientation of the beaches. Moreover, the usual compound wave pattern of the open sea tends to simplify in the surf zone where minor wave systems lose their identity in favor of the dominant wave train. Not only are ocean waves refracted by the topography of the bottom in the nearshore zone, but they are also diffracted around the ends of reefs, small islands, and jutting headlands (Putnam and Arthur, 1948; Blue and Johnson, 1949; and Sibul, 1954). Diffracted waves have in fact played an important role in molding some of the lunate embayments of the north coast.

Observation of several north-coast beaches indicates that erosion is mainly due to high (>5 feet), short-period (<8 seconds) waves and very high (>6 feet) long-period swells. Moderately high (3–6 feet), long-period swells may, on the other hand, be constructive rather than destructive. On the north coast, therefore, intervals of beach erosion occur most regularly in the winter months (with the very high North Atlantic swells) and less regularly throughout the rest of the year, depending on meteorologic conditions in the island's vicinity.

FORMATION OF THE LUNATE SHORELINE

Several particularly deep lunate embayments, whose origin has been the subject of some speculation, occur on the eastern part of the north coast in the vicinity of San Juan. One of these is the Ensenada de Boca Vieja, just west of San Juan; another, just east of San Juan, lies between Punta Las Marías and Boca de Cangrejos, and a third lies west of Punta Miquillo, north of the town of Río Grande. The second embayment, which lies east of Punta Las Marías, is compound, having a small median point.

Lobeck (1922, p. 361) explained the lunate bay of the Ensenada de Boca Vieja as the result of a large counterclockwise eddy that was a countercurrent to the westerly flowing longshore current without. This is essentially the same mechanism as that postulated by Abbe (1895) for the very much larger cusps of the North and South Carolina coast. Current observations made by the U. S. Beach Erosion Board (1948) in the lunate embayment east of Punta Las Marías give, however, no evidence of such an eddy (fig. 14); nor did current observations made with the aid of floats and fluorescein dye by the writer in the Ensenada de Boca Vieja.

Lunate shores, less well formed or smaller than the three just mentioned, occur at many places on the Puerto Rican coast (fig. 15). Both large and small embayments give evidence of having been molded by waves under rather similar circumstances. All of these shores illustrate the tendency for waves to mold shores, and particularly sandy shores, to conform to their pattern, or an average of their patterns. Thus, where waves are refracted or diffracted by offshore obstacles, the arcuate wave patterns touching shore tend to impress an arcuate shape on the shore.

This cause and effect relation between wave and shore may not, however, be entirely direct or simple. For example, as lunate embayments enlarge, the nearshore topography—and therefore the shoreline as well—tends to conform to the wave pattern. But the wave pattern will be controlled, insofar as refraction is concerned, by the nearshore bottom topography. Nevertheless, the Puerto Rican coast offers examples of lunate embayments in various stages of development (described below) which seem to show that starting with an initial diffracted wave pattern, there is a progressive enlargement of the bay in the form which preserves the initial arcuate wave pattern. While the movement of sediment necessary for the molding of a shore may be due largely to longshore currents, in the smaller and more youthful embayments sedimentary movement may be largely onshore and offshore, conforming with the wave pattern.

Various stages and conditions in the development of the lunate shore occur on the Puerto Rican north coast because of the many offshore reef patches in the eastern part and the cemented dune (eolianite) islands that abound in the central section. The eolianite islands are not uncommonly relicts of once large, cemented foredunes that have been broken up piecemeal by wave erosion. Initial gaps, in such a dune ridge allow the waves to work on the soft sediments on their landward side (fig. 16). The pattern taken by this erosion of the soft alluvial hinterland of the eolianite carapace is lunate. The curvature of the shore may be finally lost, however, when the gaps in the cemented dune have widened and the beach has receded to some older eolianite ridge to the south. At this stage the shore tends

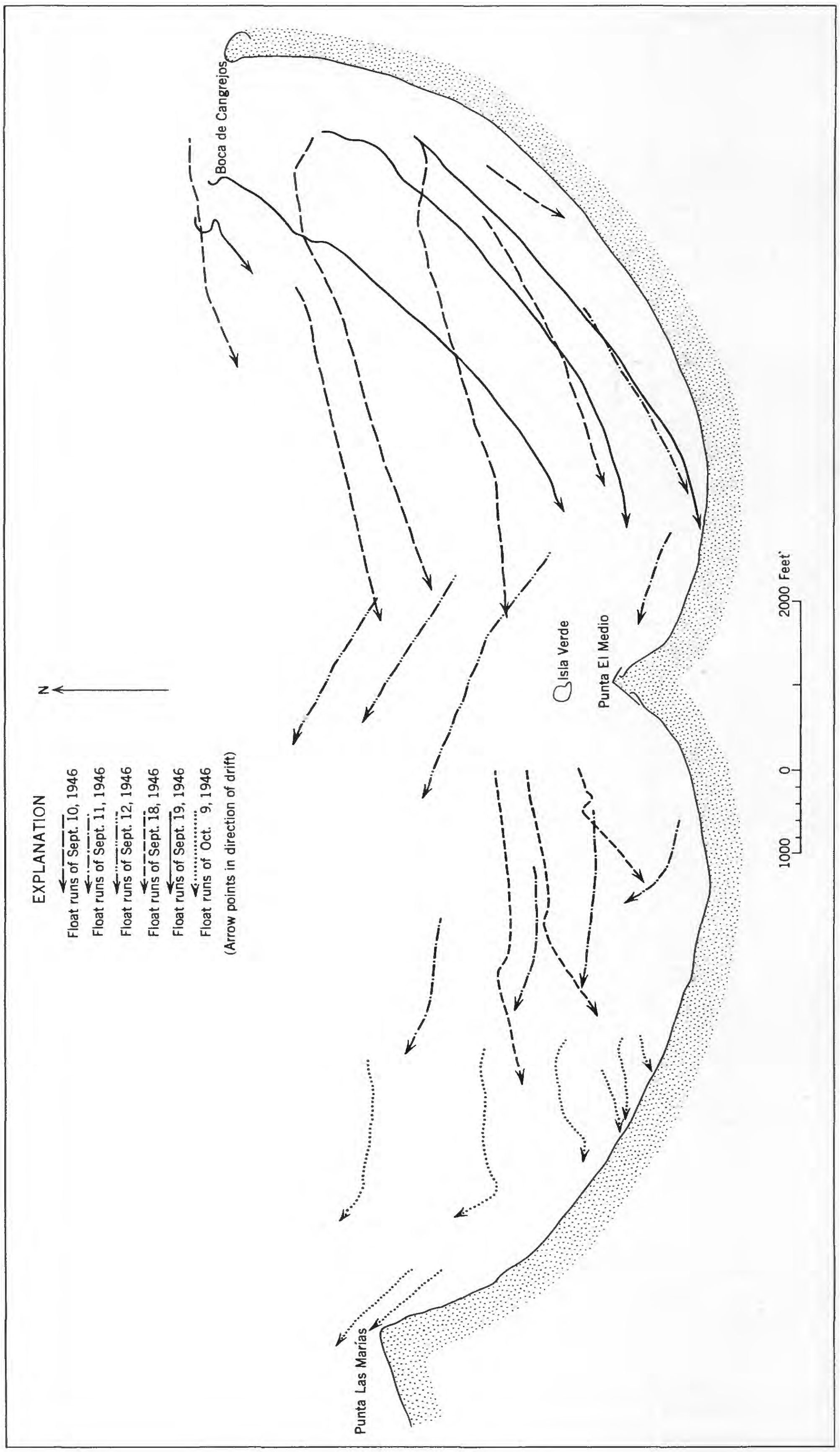

FIGURE 14.—Observations of currents in a lunate bay on the north coast of Puerto Rico, just east of San Juan (U. S. Beach Erosion Board, 1948).

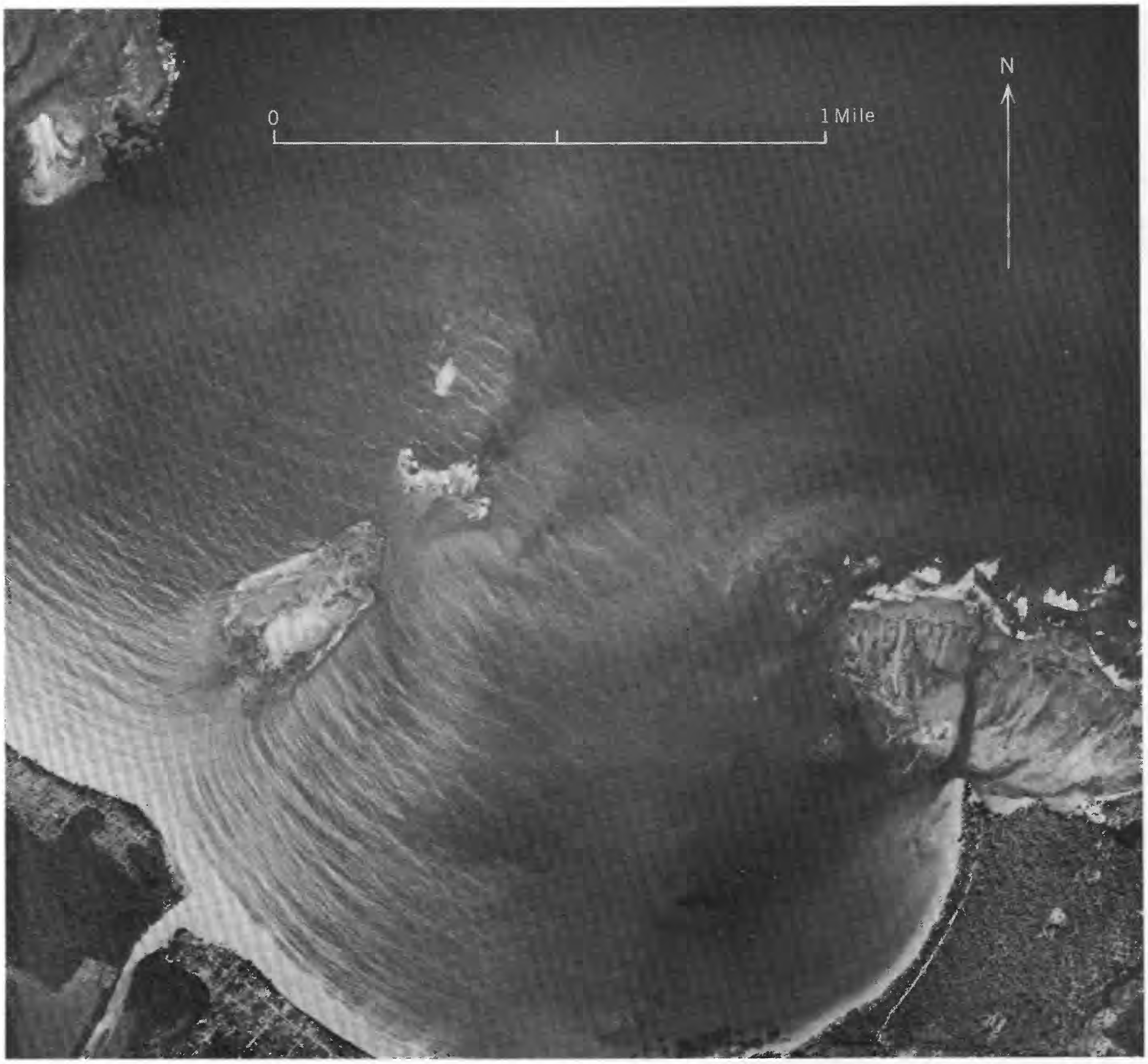

FIGURE 15.—Wave pattern, lunate shoreline, and coral reefs, at Punta La Bandera, west of Luquillo. A northeast swell is refracted by coral reefs into arcuate patterns. Note point in lee of large reef patch and how it conforms to wave pattern. Small fringing reef on right broken by a narrow channel that widens landward. Zone of lime mud occupies about one-half the width of the reef. This reef, and a similar one on the upper left, shows lateral growth by the accretion of small reef patches.

to straighten out against the flank of the older ridge (fig. 17).

An instructive example of an incipient lunate embayment occurs near the eastern end of the long, narrow eolianite ridge that forms the shore north of Manatí (figs. 18, 19). Here a gap about 25 feet wide has been eroded behind which a semicircular basin has been excavated by the waves in the sandy floor of a low valley. This small basin, which in form is a miniature lunate bay, has a radius of about 250 feet and appears to have been excavated solely by diffracted waves. It is, incidentally, interesting from another standpoint for in its present form its wave agitation is in resonance. At all times and irrespective of the height of waves outside the eolianite ridge, the waves inside the basin are of considerable height. This results from the fact that the dimensions and shape of the basin are such that the backwash of breaking waves, as it rushes down the steep beach face, always meets the oncoming wave at the breaking point. This sudden addition of backwash

FIGURE 16.—Dissected eolianite ridge north of Manatí, showing development of lunate (scalloped) shoreline.

therefore builds up the height of the onrushing wave to a size quite extraordinary for diffracted waves in a small protected basin.

About a mile to the west of the resonating basin, the eolianite ridge terminates and a second and possibly older ridge, oriented slightly more to the northwest, fronts the coast (fig. 16). The latter ridge is in an advanced state of piecemeal destruction by wave attack, and the several breaks are so wide that less than half the length of the original ridge remains. The lunate embayments behind these breaks are correspondingly larger than the resonating basin to the east. Moreover, some of the embayments have coalesced to form a scalloped shore. The recession of this shore is limited by an older eolianite ridge to the south.

The essential condition therefore for the formation of the lunate shore of the type under discussion is that offshore obstacles exist, as small islands, reefs, or shoals, to impress an arcuate form on approaching wave fronts (fig. 6). If the openings between the islands or reefs are narrow, waves will be diffracted (Putnam and Arthur, 1948; Blue and Johnson, 1949; Sibul, 1954) and their patterns will approximate circular arcs with centers at the midpoint of the gap (Blue and Johnson, 1949). If the spaces between the offshore obstacles are wide, the wave pattern will be curved according to the laws of refraction (Munk and Taylor, 1947; Johnson, O'Brien, and Isaacs, 1948; Pierson, 1951) and this curvature depends entirely on the shape of the bottom and the angle of approach of the incident wave train. Since the azimuth of incident wavetrains varies widely, the pattern of refracted waves touching the lunate shore generally does not fit the shore in any simple hand-in-glove fashion. However, what does occur in the large embayments, like that of the Ensenada de Boca Vieja, is that the shore assumes a sort of average outline of all the wave patterns striking it, and in effect, the shore is an envelope of all the diffracted and refracted wave fronts that lap against its sides.

Whether the lunate embayment will progressively enlarge by beach erosion or steadily shrink by beach advance seems, for the Puerto Rican coast, to be largely

FIGURE 17.—Dissected eolianite ridge at Punta Puerto Nuevo, north of Vega Baja, showing development of straight shoreline.

a matter of whether or not river-borne sediment is being supplied. Lunate bays that show a long history of beach advance (for example, Ensenada de Boca Vieja) invariably have a river mouth within their confines or immediately adjacent. Lunate shores showing a net retreat, on the other hand, are invariably remote from major drainage outlets. But regardless of whether there is a net gain or loss of beach sand, the influence of the waves on the direct molding of the shore is retained.

COASTAL FEATURES ASSOCIATED WITH NONCORALLINE DEPOSITION OF CALCIUM CARBONATE

The activity of reef-building corals in secreting calcium carbonate is well known. There are other types of coastal calcium carbonate deposition, however, both organic and inorganic, which produce rather distinctive physiographic features and to which comparatively little systematic study has been given. Included in this category are cemented beach sand (beachrock), cemented dune sand (eolianite), offshore sandstone reefs (rock reefs), oolitic limestone, deposits of the lime-secreting algae, and deposits of the lime-secreting annelids.

Except for calcareous algae, which can build fairly large deposits in colder waters, all the features are limited to warm-water coasts. The Puerto Rican north coast is particularly rich in examples of these deposits. The factors affecting the origin of each type deposit will be discussed separately.

BEACHROCK

Beachrock is beach sand or shingle that is cemented by calcium carbonate and, more rarely, iron oxides, within approximately the intertidal zone. It is limited to warm-water seas and its world distribution is similar to that of corals. The upper limit of cementation in many places is not precisely at the level of the highest spring tide but on Puerto Rico has been measured as much as three feet above (as at 199,330 m, 69,550 m). The upper limit of cementation is therefore possibly controlled by either the top of the capillary fringe at high spring tide or by the upper limit of wave swash.

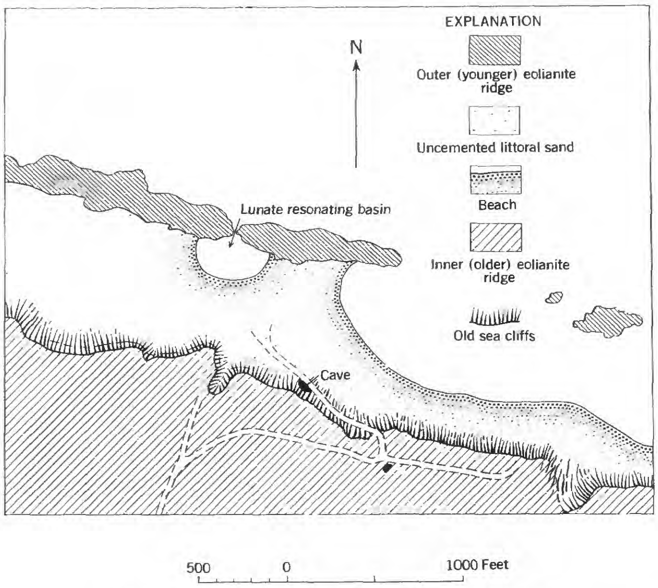

FIGURE 18.—Coastal geology north of Manatí.

The lower limit of beach-sand cementation is more difficult to determine but in general seems to lie slightly below low spring tide. It may be controlled by the lowest level of wave troughs at low spring tide.

Beachrock, the world over, characteristically forms a hard pavement,[2] the surface of which is generally cambered gently seaward (figs. 20, 21). The writer does not find a real basis for considering the less typical horizontally bedded beachrock as essentially different from the inclined, or dipping, variety. Beachrock is well stratified in thin beds which apparently are inherited from the stratification of the original beach sand, or shingle. It is the usual seaward dip of these beds, generally at angles of 6° to 8°, that imparts the seaward camber to the typical pavement surface (fig. 20). In addition, the broad dip slope of the pavement surface is broken by small escarpment slopes formed by the landward edge of beachrock strata (fig. 21). This makes the typical beachrock pavement resemble a flight of very low steps of broad tread that has been tilted seaward.

The pavement usually conforms rigorously to the shore, following all of its bends and curves (fig. 21). Where it deviates, we can assume that changes in the shoreline have occurred since the pavement was formed.

Besides the typical steplike form of a beachrock

[2] "Beachrock pavement" is used in this report for the typical morphological expression of beachrock, while the term "beachrock" alone is used only as a material term in the same sense that "concrete" and "concrete pavement" are distinguished. Daly (1924) used the term "beachrock plate," but "pavement" seems to be morphologically more descriptive.

FIGURE 19.—Lunate resonating basin at Punta Tortuguero. Pitted eolianite ridge in foreground.

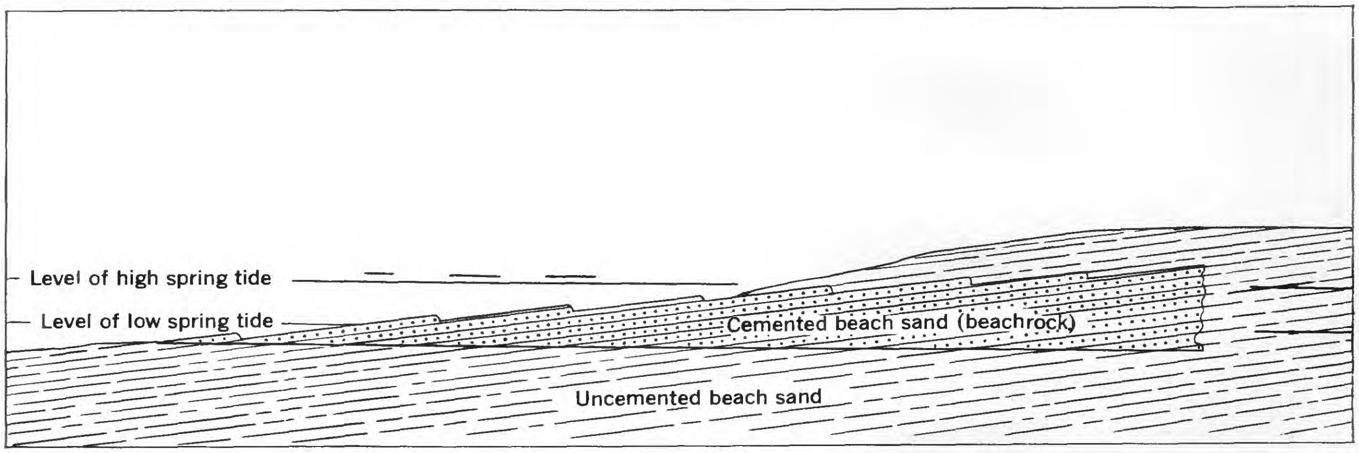

FIGURE 20.—Cross section of beach with partly exposed beachrock pavement.

FIGURE 21.—Very wide beachrock pavement east of Punta Puerto Nuevo, showing typical steplike form and curvature with the shore.

pavement, the surface is almost always pitted and shows signs of abrasion by the action of the waves that continually wash back and forth across its surface. The pits may be due to a combination of factors, destruction by organic agents (Ginsburg, 1953b), physicochemical solution, and abrasion and pothole grinding by loose sand and pebbles in the wave swash. Elongated rills normal to the strike of the pavement seem to result from abrasion by wave-transported sand. The pavement is rather commonly transected by joints, which

FIGURE 22.—Slab of beachrock pavement east of Punta Fraile, completely undermined, showing typical wedge-shaped cross section. Pavement rests on red loamy paleosol and dense lower Miocene limestone. Notice high-tide swash mark in background.

are usually oriented normal to the shore and are generally fairly widely spaced at intervals of 25 feet or more.

The width of beachrock pavements varies. In many places on the Puerto Rican coast the full width of the cemented zone is exposed, owing to the removal of the loose sand from the landside of the pavement, by either natural agencies or man (fig. 22). Most pavements that are totally exposed in this manner are well under 100 feet wide. There are exceptions as, for example, the arcuate pavement jutting out from shore at the Boca de Cangrejos, east of San Juan, which varies in width from about 100 feet where the pavement merges with the present coast to about 210 feet several hundred yards to the northwest.

Beachrock pavements may rest on almost any type of foundation—uncemented sand, clay, or rock—though the most common foundation is uncemented sand. The transition from beachrock to sand below is generally sharp and the base of the pavement seems to be a fairly horizontal surface. Beachrock on Puerto Rico has been found resting on dense to friable limestone (fig. 22), old loamy soils, cemented dune sand, and compact reef rock. In these cases the contact is commonly highly uneven as a result of the pitting in the upper surface of the underlying rock.

The landside edge of a pavement is generally buried beneath uncemented beach sand and is therefore lost to view. However, in places where it has been exposed by the removal of this sand it is seen to have a sharp vertical or nearly vertical contact with the uncemented sand behind. The vertical nature of the landside edge gives the pavement a wedge-shaped cross section, thickest on the landside, thin on the seaside, with an approximately horizontal base and a seaward sloping upper surface (fig. 20).

The sand and shingle that is cemented to form beachrock includes all lithologic types. On Puerto Rico one finds beachrock consisting of pure shell sand (called skeletal sand by Illing, 1954; it is a carbonate sand, rich in fragments of coral and calcareous algae besides shell fragments), practically pure siliceous sand, and

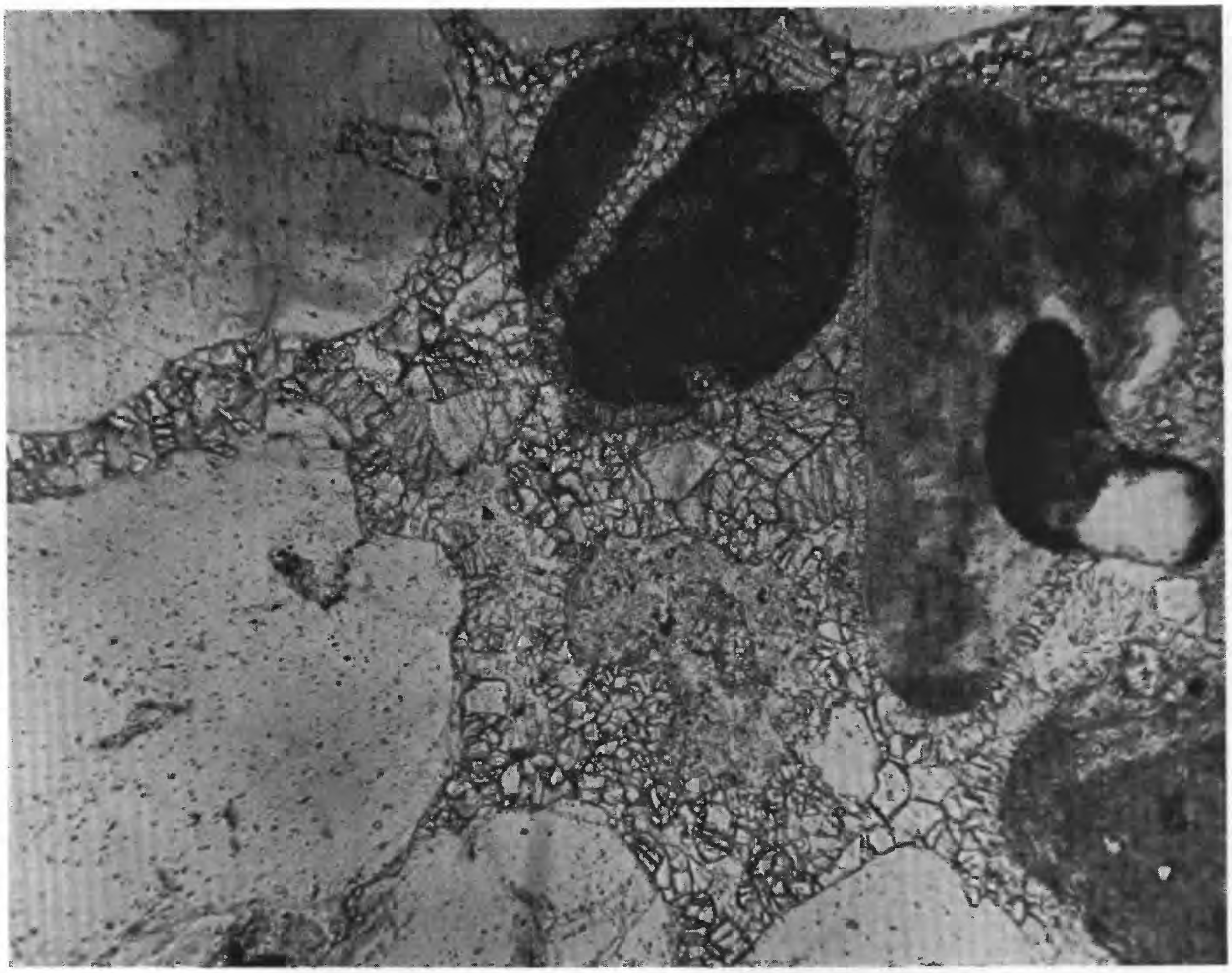

FIGURE 23.—Petrographic section of beachrock from Santa Teresita, San Juan. Light-colored grains are quartz; darker grains are *Halimeda* fragments, one of which exhibits slightly resorbed edges, but the other has its original sharp outline. Cement is granular calcite. Magnification, 120 ×; plane polarized light.

various mixtures of these two types. Beachrock conglomerate commonly consists of volcanic and tuffaceous rock types.

The cementing material of beachrock is generally $CaCO_3$, although under special conditions, principally where iron or steel is present in the beach deposit, iron oxides may form the cement (fig. 24). Several samples of Puerto Rican beachrock that were examined in thin section showed that the cement consisted of calcite. In one sample, a fine druse of acicular aragonite projected into pore cavities from the surface of the calcite cement. The crystals of calcite were large enough to be determined optically, and the uniaxial property of the mineral was readily established (fig. 23). The determination was confirmed by the cobalt nitrate stain test. The calcite cement tends to form a fringe of slightly elongated crystals—averaging about 0.03 mm in length, though there is considerable variation—around the sand grains. Where cementation is more advanced, equigranular and relatively coarse grained calcite occupies all the intergranular spaces.

The importance of calcite rather than aragonite as the cementing material in the Puerto Rican samples is in contrast to reports from other localities. Aragonite is given by Daly (1924) and Ginsburg (1953a) as the principal cement of Floridian beachrock, by Illing (1954), of Bahaman beachrock; and by Emery, Tracey, and Ladd (1954), of beachrock from Bikini Atoll. A possible explanation for the Puerto Rican anomaly is that the observed calcite is secondary after aragonite, as calcite is known to be the more stable polymorph of $CaCO_3$. One of the thin sections, however, was from a freshly exposed pavement that because of its friable cementation and unstained surface

FIGURE 24.—Very much eroded beachrock at San Juan, consisting of rubbish and sand cemented with iron oxide. This marks the toe of a late nineteenth or early twentieth century rubbish heap.

seemed of very recent origin. Illing suggests that calcite is precipitated from fresh water and aragonite from salt, thereby indicating a varied origin for the cement. As indicated below, however, the problem of beachrock origin is still in the stage of conjecture.

An exceptionally fine example of iron-cemented, or ferruginous, beachrock occurs on the north shore of San Juan, about 100 yards east of the Medical School, and consists of several relict patches of an eroded and once somewhat more extensive pavement (fig. 24). These patches of pavement probably aggregate several scores of square yards in area. The beachrock is nearly black in color, owing to the color of the cement. The pavement is about 2 feet thick, rises to an altitude of about 2 feet above high tide, and has the typical seaward camber. Besides much silicate sand and gravel, the beachrock includes an abundance of broken glass and crockery, iron objects (now completely corroded), copper wire and cable, wood, bones, paving bricks, broken roofing tile—in short, all the constituents of a refuse dump. This dump, which judging from the abundance of copper wire must date from either the 20th or the latter part of the 19th century, is no longer in evidence. The heterogenous assortment of jetsam and beach sand is well cemented into a hard puddingstone by black and brown iron oxides. The black cement is rather soft and by its magnetic properties and black streak seems to consist principally of the mineral magnetite.

The lithified rubbish points to the rapidity with which beachrock forms. Charles Darwin (1896, p. 15) implied in qualitative terms that the beachrock of Keeling Atoll in the Indian Ocean formed rapidly. Daly (1924) tells of the formation of calcareous beachrock on Tortugas in less than two years. Emery, Tracey, and Ladd (1954, p. 44) report finding shrapnel fragments in 1951 from World War II firmly cemented to the beachrock of Eniwetok Atoll. These

FIGURE 25.—Collapsing beachrock pavement. The tension fractures are partly sealed by spongy masses of agglutinated sand (dark tumerous forms in foreground) produced by polychaete worms.

authors also report finding a glass fishing-net float, a glass bottle and a brass cartridge case, the last two items also dating from World War II, embedded in beachrock. The writer has found Indian artifacts firmly embedded in calcareous beachrock at several points on the Puerto Rican coast.

Beachrock is somewhat sporadically distributed, commonly cropping out for a distance of several hundred yards or less along a beach. In many instances the pavement disappears beneath a cover of loose sand, and it seems quite clear that more beachrock exists along a coast than that which meets the eye. This was demonstrated at the eastern edge of Santurce, where exceptionally high waves eroded a beach back to a point that had not been attained in many years and exposed a beachrock pavement that, from its lack of surface stains and signs of erosion, appeared freshly formed. On the other hand, manmade borings and natural erosion reveal the fact that pavements are also sharply discontinuous and in some beaches occur only for relatively short stretches. In places, however, these short stretches of beachrock are clearly relicts of former lengthy pavements, which have since been partly destroyed by erosion.

The manner in which many beachrock pavements are destroyed, other than by surface pitting and abrasion, is highly characteristic. The uncemented sand foundation is sapped out by the turbulent surf; and the rigid pavement, which at first merely bridges the resulting hollow, ultimately collapses as large slabs (fig. 25) that either sink into the underlying sand or else move slowly out to sea by the progressive shifting of the sandy bottom. Where wave action is relatively slight and undermining is sufficiently gradual, the entire pavement may sink more or less intact, without any lateral movement. Stretches of beachrock pavement under several fathoms of water may therefore have originally formed at present sea level. Confirmation of this is furnished by a pavement off the eastern shore of San Juan, which is partly at the present beach level and partly submerged (fig. 54). Undermined pavements in a partial state of collapse are common on Puerto Rico. At one point, about 500 yards east of Punta El Medio, east of San Juan, the gaping joints that separate partly collapsed blocks of beachrock are sealed and overgrown by large tumerous masses of cemented sand built by polychaete worms (fig. 25). These colonies of worm tubes were also noted by Branner (1904) on Brazilian beachrock pavements. Their importance, however, in the lithification and maintenance of a typical pavement is probably negligible.

Beachrock acts as a deterrent to shore erosion, and, unless the flank of the pavement can be turned or the pavement undermined, it forms a natural rampart against the depredations of wave erosion on the uncemented sand behind. In places where the pavement cannot be sapped from below because of a solid foundation, wave erosion may eventually get a foothold behind the pavement by piercing some weak spot or by rounding the unprotected flank (due to the discontinuous nature of the pavement). As a result several places occur along the Puerto Rican north coast where beachrock pavements extend intact for considerable distances out from shore to mark the positions of former coastlines (fig. 53). The best example of this is the fine lunate pavement that extends over 1,000 feet out to sea from the Boca de Cangrejos, several miles east of San Juan. This feature seems similar, though smaller, to many of the Brazilian stone reefs described by Branner (1904).

DISTRIBUTION

Beachrock is found widely on the north coast of Puerto Rico (fig. 26) from Punta Vacía Talega on the east to Punta Higüero, at the tip of the Rincón peninsula, on the west. Along this coastline pavements are exposed intermittently in stretches ranging from several hundred yards to over a mile. Some of the longest stretches of continuous pavement are in the lunate bays in the eastern part of the north coast. Except for the above distribution, beachrock has been noted by the writer at only three other localities on the island: In the deep lunate bay, Bahía las Cabezas, just east of Cabo San Juan on the northeast tip of Puerto Rico; on a short stretch of coast about four miles west of Ponce; and in the vicinity of Cabo Rojo at the southwest tip of the island (this occurrence was not seen in the field but was interpreted from aerial photographs). No beachrock was seen on any other stretch of coast[3] although the possibility exists that it occurs buried beneath uncemented sand. Small detrital fragments of cemented beach sand were seen on the beach just west of Salinas on the south coast. These fragments of sandstone might conceivably have been torn from a beachrock pavement submerged offshore.

DISCUSSION OF ORIGIN

The problem of the origin of beachrock is a perennial one that still awaits experimental confirmation of any of the hypotheses thus far proposed. In its essence, the problem hinges more on an adequate explanation for the absence of beachrock from many beaches than on its presence in others. Hypotheses to explain the cementation of beach sand may be grouped as follows: (1) The $CaCO_3$ cement is derived from sea water in the pore spaces of the beach sand and is precipitated by physicochemical processes, principally through evaporation and a reduction of CO_2 partial pressure (Dana, 1849, p. 44; Branner, 1904; Daly, 1924; Kuenen, 1933; Ginsburg, 1953a; Emery, Tracy, and Ladd, 1954, p. 45–47). (2) The $CaCO_3$ cement is derived principally from fresh water that has leached either overlying calcareous beach sand or calcareous rocks to the hinterland and that is precipitated by a combination of evaporation and aeration (Kent, 1893; Branner, 1904; David, 1904; Crossland, 1905; Field, 1919; Umbgrove, 1928; Gardiner, 1930; Yonge, 1930; Stearns, 1935). (3) Cementation is biochemically induced, mainly by the activity of micro-organisms (either bacteria or algae) with a restricted ecologic range. This hypothesis has been suggested by Cloud (1952a) as a contributing factor. It, too, awaits the necessary field investigation.

In addition to the three hypothesized processes, opinions differ as to whether the total thickness of pavement is built up by accretion, stratum by stratum, or whether the entire pavement was cemented en bloc.

The difficulties inherent in a hypothesis advocating the precipitation of the $CaCO_3$ cement from sea water can be best demonstrated by a brief review of part of Daly's (1924) and Ginsburg's (1953a) discussions. Daly thought that beachrock cementation took place in two stages. An initial cementation from sea water was produced by the ammonifying action of decaying organic matter originally incorporated in bottom sediments and which had been piled onto the beach by storm waves. This well-known chemical reaction, described by Murray and Irvine (1891), consists of ammonia combining with CO_2 to form ammonium carbonate, which then reacts with calcium salts in solution to form calcium carbonate (Twenhofel, 1932, p. 317). According to Daly this is followed by a second stage

[3] The large islands off the east coast of Puerto Rico were not studied. A short stretch of beachrock occurs on the south shore of Cayo Icacos, off the northeast tip of Puerto Rico. A very short stretch of beachrock exists at Punta Oeste on the west side of Isla Mona. None was seen on Isla Caja de Muertos off the south coast of Puerto Rico.

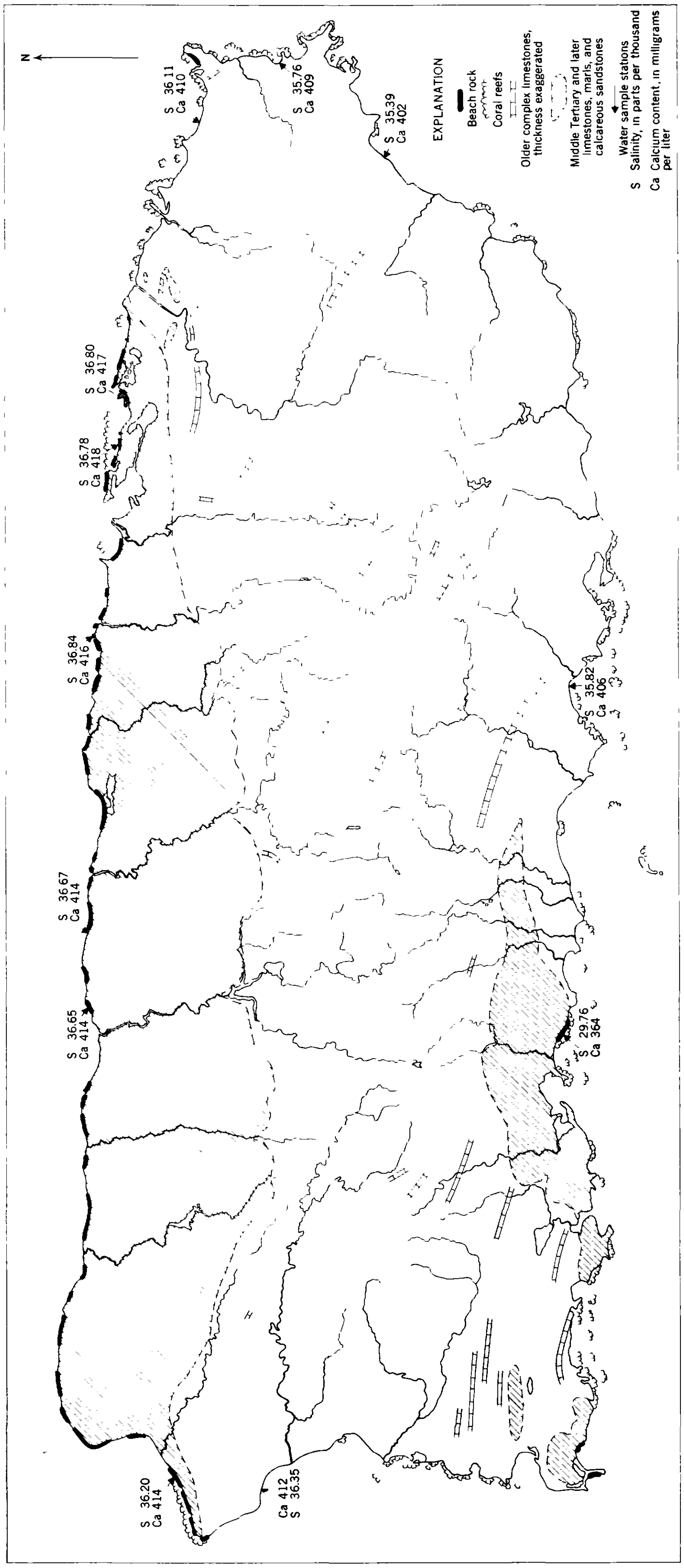

FIGURE 26.—Distribution of beachrock, coral reefs, and limestone in Puerto Rico. Coral colonies that do not reach tide level are not shown.

of cementation, where the precipitation of $CaCO_3$ from sea water results from the effect of aeration and surf agitation on the CO_2 partial pressure in the water. The first stage of cementation provides nuclei that are essential to the precipitation of $CaCO_3$ in the second stage. The localized distribution of beachrock was therefore explained by the fortuitous distribution of bottom sediments rich in organic matter that are cast onto the beach by storm waves; and since this would occur only on exposed stretches of coast subjected to full wave force, Daly suggested that beachrock is confined to only this type of coast. This is not exactly in agreement with Puerto Rican data. Some beachrock on Puerto Rico occurs on protected shores where reefs or offshore islets provide considerable shelter from strong wave action, as for example Bahía las Cabezas; west of Punta Fraile; and Puerto Neuvo beach north of Vega Baja. In addition there are exposed coasts—such as the beach south of Playa de Naguabo—where sand rich in organic matter is common but nevertheless lack beachrock. Beachrock has also been noticed, among others by Tayama (1952, p. 213), in the western Pacific on protected lagoonal coasts and on coasts with little wave action.

Ginsburg (1953a) thinks that the sporadic distribution of beachrock is due to the differences in beach permeability that is characteristic of storm-built beaches. The favorable environment, according to this author, is a beach that has (a) a steep slope and predominantly coarse grain size, allowing rapid drainage; (b) a pervious substratum, allowing complete drainage of the sands during low tide; (c) a certain stability to the beach, permitting the cementing process to develop; and (d) high temperatures, permitting the required evaporation of the pellicular water left in the drained sand. According to Ginsburg, the cement develops simply as an evaporite in these favorable circumstances, the critical difference between the beach of high permeability and that of somewhat lower permeability being that the rapid drainage of the former allows a larger period of time for evaporation to take place and for the sluggish equilibrium of sea water supersaturated with respect to $CaCO_3$ to become established.

While Ginsburg has gone farther than most in examining the physicochemical basis for beachrock cementation, his hypothesis does not fit all the data. For example, beachrock can form under conditions of poor to impeded drainage. At several places on the Puerto Rican shore beachrock rests directly on dense limestone, coral rock, sandstone and loamy paleosols, as at Punta Borinquen, Punta Maldonado, Punta Fraile, and at the mouth of the Río Grande de Manatí. On Punta Fraile, for example, well-cemented beachrock fills pits in dense coral limestone; at Punta Maldonado and east of Palmas Altas it rests on dense loamy soil of very low permeability. Perhaps the most convincing proof that drainage and evaporation are not always, or exclusively, essential to the cementing process is provided by an Indian stone mortar that the writer found firmly and nearly completely embedded in well-cemented beachrock just west of Punta Fraile. The mortar, of fresh hornblende diorite—measuring about 10½ inches by 9½ inches in its horizonal dimensions; 3 inches in height; and its shallow bowl, 1¼ inches in depth—had a very slight seaward tilt but was otherwise in a normal position, with its dished surface at the top. Except for a small area of the rim that was exposed at the time of discovery, the artifact was firmly encased in well-cemented beachrock. It seems clear that (a) there could have been little drainage above the mortar, certainly none at all in the shallow bowl, and (b) there was little if any evaporation from immediately beneath the mortar.

That permeability is a factor controlling the duration of the drained state in the upper part of the beach, as suggested by Ginsburg, is open to question. The fluctuation of the water table in a beach is controlled by the tidal interval. The interval between successive water-table fluctuations is therefore the same as the interval of the adjoining oceanic tides (although as Emery and Foster, 1948, demonstrate, there may be an appreciable time lag). Thus, while the water table of a highly pervious beach may respond more rapidly than a less pervious beach to the ebbing tide, by the same token it will respond more rapidly to the flooding tide. Although a pervious sand beach will drain more deeply during ebb tide than a less pervious beach—that is, the water-table fluctuation during the tidal cycle is greater—the sand in the uppermost part of the zone should be drained for about the same length of time, regardless of its permeability. In consequence, there is no net difference in the interval between successive high or low positions of the water tables for beaches of different permeability subjected to the same tidal interval.

Furthermore, if the duration of the drained state is a controlling factor, then shores subject to diurnal tides would be favored in beachrock development over those subject to semidiurnal tides. This is not supported by the data in Puerto Rico, where the south coast, with its diurnal tides, is nearly free of beachrock, whereas the north coast, with semidiurnal tides, is richly endowed.

Several aspects of the hypothesized role of evaporation in the formation of beachrock bear close scrutiny. We know that the greatest evaporation should occur at the surface of a beach and should diminish rapidly with depth below the surface. Emery and Foster (1948), for example, report negligible evaporation from several Southern California beaches below a depth of one foot. Concerning this observation, Ginsburg has suggested that evaporation may extend to greater depths in more tropical climates. Although evaporation data on beaches from different latitudes having similar permeability and granular properties are not available, observations and computations of the mean annual evaporation from the ocean surface at different latitudes have been made (Wüst, in Sverdrup and others, 1942, p. 120–124). Wüst has shown that the high humidity and the low prevailing wind velocities in equatorial latitudes reduce the mean annual evaporation to a figure that is comparable to that of latitude 30° to 35° north and that the evaporation maximum occurs at about latitude 20° north and south for all oceans of the world. Inasmuch as there are many beachrock localities in equatorial latitudes but few if any north of latitude 30° north, the primary importance of evaporation in the process of beachrock formation is brought into question.

Furthermore, if beachrock cementation were simply the result of supersaturation of beach water with respect to $CaCO_3$ brought on by evaporation, it is difficult to explain a thick beachrock pavement as having formed other than by the accretion of successive layers, starting with the lowermost. Such a construction would follow from the fact that the greatest evaporation would occur at or near the surface of the beach. The natural consequence of this would be the formation of a thin surface crust that would inhibit further evaporation from the underlying sand. In order to build up a pavement several feet thick it would therefore become necessary to have the beach very gradually prograde, stratum by stratum, each stratum becoming well cemented in turn before the deposition of the next stratum. A pavement built up in this manner, however, would tend to have a parallelogram cross section rather than the wedge-shaped cross section that seems so common on Puerto Rico. The sharp and nearly vertical landside edge of the pavement is difficult to explain if the pavement were formed by accretion. Moreover, such a layer-on-layer construction would seriously hinder the drainage of the thin surface layers of sand that would be essential for the building out of the pavement. In addition, the surfaces of nearly all exposed pavement show unmistakable signs of destruction (by solution and abrasion) rather than cementation and construction. Lastly, there is in fact some basis for thinking that the cementation process takes place at depth beneath a considerable cover of uncemented sand. For example, Daly (1924) estimated that the cementation of a pavement on Tortugas occurred beneath 25–100 cm of uncemented sand.

The same objections apply to the hypothesis that beach cementation is due to precipitation of $CaCO_3$ from nonsaline ground water by evaporation. Considering the fresh-water origin further, a type of beachrock that would seem particularly difficult to explain is that which occurs in settings not particularly conducive to the production of ground water high in dissolved $CaCO_3$, as, for example, beaches that are backed by nonlimestone hinterlands, like that at Samoa (Daly, 1924) and Oahu (Stearns, 1935); silicate sand beaches, like that in Brazil (Branner, 1904); and very narrow sand cays and other isolated settings (Kuenen, 1950; Fairbridge, 1950), where there is very little drainage area other than the beach itself.

THE SIGNIFICANCE OF THE PUERTO RICAN DATA

Beachrock on Puerto Rico is almost entirely limited to the shore fronting broad limestone outcrops, and still more specifically to the belts of middle Tertiary rocks of the north and south coasts (fig. 26). This distribution seems highly suggestive of the importance of a limestone hinterland to the formation of this rock, an idea already advanced by Gardiner (1930). The only exception to the limestone hinterland known to the writer is the stretch of beachrock on the small lunate bay west of Cabezas de San Juan. This beach, however, fronts a small drainage basin less than a square mile in area, in which limestone has been reported by T. W. Vaughan (unpublished notes on the geology of eastern Puerto Rico).

The striking correlation between limestone coastal areas and beachrock on Puerto Rico may conceivably be fortuitous, or else the result of a somewhat indirect relationship. For example, the distribution may result from differences in the sea-water composition of the several coasts which, in turn, may result from differences in the composition of river waters emptying on the respective coasts. The differences in wave action on the several coasts might also be a factor, although, since north-shore beachrock occurs in both sheltered and exposed locations, the importance of wave action on its formation seems unlikely.

An investigation of the difference in sea-water composition on the beachrock and nonbeachrock coasts shows that there are differences in salinity and Ca content on the several coasts, but that these differences point neither to a greater dilution of the north-coast waters by land drainage nor to an enrichment of these waters in Ca over the waters of the other coasts. Sea-water samples were collected from 12 beaches about the island (fig. 26) and tested in the laboratory of the Geological Survey in Washington for chlorinity, Ca content, HCO_3^-, and pH (table 1). The low pH of these water samples in comparison with field determinations of pH, made at a later date with a portable glass-electrode pH meter (Beckman model N–2), indicates that some postsampling changes occurred in the composition of the samples shipped to Washington. This was possibly brought on by plankton decomposition. In spite of these changes the chlorinity (Cl) and Ca values did not lose their proportionality nor, if we apply the findings of Thompson (1940) on postsampling changes in sea-water composition, is there reason to think that their absolute values changed. The salinity of the beachrock localities (with the exception of sample 22, whose low Cl content and abnormally high HCO_3^- content indicate dilution by a nearby fresh-water spring) are all close to or above the average salinity of Atlantic Ocean surface water of the latitude of Puerto Rico. According to Wüst, this value at latitude 18° N. is 36.30 percent (Sverdrup and others, 1942, p. 123). The Puerto Rican data therefore suggest that river-water dilution is often, if not usually, extremely slight. Only one sample, No. 7, by its high HCO_3^- content, indicates some admixing of river water (the HCO_3^- : Cl ratio of normal ocean water is 0.00735). The test data show a higher Ca content for samples from the north coast than from the other coasts. This, however, would be a natural consequence of the higher chlorinity of these waters (Sverdrup and others, 1942, p. 207). It is noteworthy, however, that the calcium: chlorine ratio of the Puerto Rican samples (close to an average value of 0.02047) is less than that for normal ocean water (0.02106; Sverdrup and others, 1942, p. 173) and indicates an improverishment in Ca. The cause of this relatively low Ca content is not known but may be connected with the high Ca extraction of lime-depositing organisms in Puerto Rican waters. It probably cannot be attributed to the extraction of Ca from sea water by the process of beachrock cementation, for the calcium : chlorine ratio is maintained fairly constant in all samples tested regardless of the presence or absence of beachrock.

The abnormally low salinity of sample 22, a south-coast beachrock locality, is particularly interesting because it shows that a high dilution of sea water by fresh water will not inhibit the formation of beachrock. The cause of this dilution was found to be a fresh-water spring located close to the sampling site.

The importance to the process of beachrock formation of the dilution of coastal waters by land drainage high in dissolved $CaCO_3$ has therefore not been dem-

TABLE 1.—*Chemical quality of Puerto Rican coastal waters*

[Analyses by W. W. Brannock, except as indicated. Cf. figs. 10, 26.]

Sample	Shore type [1]	Date	Location	Cl (mg per liter)	Salinity [2] (parts per thousand)	Ca (mg per liter)	H_2CO_3 (mg per liter)	pH	Remarks
1	BR	2/21/51	Aguada beach, NE. of Columbus Monument.	20,040	36.20	414	147	8.00	From surface of pavement; ebb tide; moderate wave height.
2	BR	9/9/52	do					[3] 8.12	From surf. Turbid river water off shore.
3	BR	2/21/51	Arecibo; 1 mile E. of Punta Morrillos	20,290	36.65	414	148	7.95	From tidal pool on pavement; ebb tide; weather protractedly clear.
4	BR	2/21/51	NW. of Barceloneta	20,300	36.67	414	148	7.85	From surf on pavement, low tide.
5	BR	9/9/52	do					[3] 8.20	From surf on pavement; ebb tide; weather protractedly clear.
6	BR	3/1/51	Punta Fraile	20,390	36.84	416	147	7.70	
7	BR	2/22/50	Santa Teresita housing development, E. of Santurce.	20,360	36.78	418	152	7.85	From surf on pavement; ebb tide; sample contains some kelp fragments and sand. Weather protractedly clear.
8	BR	9/5/52	do					[3] 8.00	
9	BR	9/5/52	Mouth of Laguna Condado; Santurce					[3] 8.08	High tide, weather clear; sea temperature 29½° C.
10	BR	2/25/50	E. of Punta El Medio	20,370	36.80	417	148	7.65	From surf on pavement; ebb tide.
11	BR	9/5/52	E. of Boca de Cangrejos					[3] 8.09	From surf on pavement; high tide.
12	X	9/6/52	Poblado Mediania Alta beach					[3] 7.8	Turbid river water about 100 yards off shore.
13	X	2/7/51	Luquillo	19,990	36.11	410	145	7.95	From surf on rocky point E. of beach; calcareous sand beach at this locality.
14	X	9/6/52	do					[3] 8.13	Water temperature 28½° C.
15	X	2/7/51	Bahía Demajagua, E. coast	19,790	35.75	409	145	7.90	High tide; from surf. Sample contained some organic matter.
16	X	2/25/51	1 mile N. of Playa de Humacao	19,590	35.39	402	144	8.05	Sea calm; weather protractedly clear.
17	X	9/6/52	do					[3] 8.00	Water slightly turbid; water temperature 28½° C.
18	X	9/6/52	3 miles W. of Punta Las Tunas					[3] 8.15	From surf; 20 min. after a shower.
19	X	9/6/52	Las Mareas, E. of Central Aguirre					[3] 8.08	High tide; sea choppy; water very turbid with some organic sediment.
20	X	9/6/52	W. of Salinas					[3] 8.13	Water slightly turbid.
21	[4] X	2/25/51	do	19,830	35.82	406	149	8.05	Sea calm, weather clear; small amount of white plankton in water.
22	BR	2/25/51	4 miles W. of Playa de Ponce	16,470	29.76	364	192	8.10	Low tide; protractedly clear; sea calm. A fresh water spring at tide level 50 yds away was noted. Others possibly present.
23	X	2/21/51	0.8 miles E. of Punta Cadena, W. coast.	20,120	36.35	412	147	7.90	Ebb tide; weather, protractedly clear.

[1] BR, beachrock; X, no beachrock.
[2] Salinity in parts per thousand (S ‰), computed from Cl according to formula: $S ‰ = 0.30 + 1.805\ Cl$.
[3] On-the-spot determinations by C. A. Kaye using a Beckman N–2 portable pH meter (glass electrode); each determination calibrated against a standard pH 7 buffer solution.
[4] Broken fragments of cemented beach sand were incorporated in the beach shingle and possibly indicate the existence of a beachrock pavement offshore.

onstrated by the Puerto Rican analytical data. Moreover, as already pointed out, in some parts of the world beachrock occurs where there is no limestone hinterland. In these places, however, the possibility exists that solution of the beach sand itself by rain falling directly on the beach (providing the sand has a significant carbonate content) may furnish all the dissolved $CaCO_3$ needed for the cementing process. This idea is essentially that of Branner (1904), Field (1919), and others. What it does not explain, however, is the patchy distribution of beachrock on long and seemingly homogeneous beaches, nor the exact nature of the physicochemical process that brings about precipitation.

In view of the objections to a purely physicochemical explanation of beachrock, one arrives by a process of elimination at the hypothesis that microbiological action may be largely responsible for its formation. The responsible organisms may be bacteria, whose role in $CaCO_3$ fixation in both marine and nonmarine waters has been rather extensively investigated (ZoBell, 1946, p. 100–103, also Harvey, 1945; Kuenen, 1950; Thiel, 1942; Thorp, 1935; Smith, 1926; Drew, 1914) : or algae, particularly the blue-green algae (Tilden, 1910; Bradley, 1929; Fritsch, 1945; Cloud, 1952a; Doty, 1954). The distribution of beachrock suggests very specific ecologic conditions for these organisms. The conditions indicated are: (a) brackish water, perhaps of a very narrow salinity range like that which develops at the salt water–fresh water interface beneath a beach: (b) water that is near saturation in $CaCO_3$; (c) a tidally fluctuating water table producing frequent aeration; (d) water temperatures above about 20° C; and (e) possibly enough organic matter to provide the necessary nutrients. These ecologic conditions accord with beachrock morphology and distribution. The sporadic distribution of beachrock on a beach, the real thorn to the problem, might then be attributed to the lack of one or more of the following requirements: (a) Waters of the proper salinity, (b) waters of the required saturation with respect to $CaCO_3$, (c) nutrients, (d) proper water temperature, and (e) innoculation with the specific micro-organisms. None of these conditions pose an ecologic range too restrictive for bacteria (ZoBell, 1946; Harvey, 1945).

Although the bacteriologic hypothesis lacks any experimental confirmation, there are good reasons for thinking it deserves serious investigation. It is reported by Harvey (1945, p. 99–102) in a description of the work of ZoBell and Anderson (1936) that bacteria proliferate particularly well in water between sand grains, and that bacteria in jar samples have been repeatedly reported to favor glass surfaces over the free water. It is also known that bacteria are very much more abundant in bottom sediments than in sea water that is directly in contact with these sediments. Some bacteria are so restrictive in their environment that they do not occur at all in the free water immediately overlying the bottom sediment in which they abound (ZoBell, 1946, p. 97–98). Smith (1926) pointed out the need for organic matter in the bacterial precipitate of calcite, and ZoBell (1946, p. 102) claims that "microbiological $CaCO_3$ precipitation is confined largely to sections where there is an abundance of organic matter." The amount of this organic matter in usual quantitative terms may not be large or noticeable to the eye, and it may take the form of adsorbed organic solution on the surface of the sand grains (Harvey, 1945, p. 101). The existence of a loose sand layer over the beachrock pavement during the course of its formation might therefore be necessary because of the injurious effect of sunlight, particularly ultraviolet rays, on the specific bacteria.

Cloud (1952a) has suggested that the blue-green algae may play a dominant role in beachrock cementation. On Onotoa Atoll, Gilbert Islands, these organisms were found to encrust newly formed beachrock ("bonded limesand") and to bind the surface sand of beaches and tide flats. The algae seemed to have the important function, according to Cloud, of holding the sands in place until they could be indurated. Doty (1954, p. 9) notes that on North Carolina beaches similar bonding of surface sands by blue-green algae occurs. Ginsburg (1953b) has described the presence of blue-green algae in Florida beachrock but described them simply as lime-borers. The bonding of loose beach sand by the filaments of blue-green algae was not noted on Puerto Rico. Blue-green algae are responsible, however, for a conspicuous type of seasonal lime deposit in the spray zone. For a short period in the spring of the year the rocks of the spray zone on the north coast of Puerto Rico are coated with a thin opaque white encrustation, presumably brought on by the blue-green algae: *Calothrix scopulorum* and *Entophysalis crustacea* (identified by F. Drouet). It remains to be determined, however, if blue-green algae thrive in loose sand at a depth of several feet below the surface and, if so, how much of the cementation is due to their activity.

Ferruginous beachrock, like the black pavement at San Juan that was described above, may also owe its origin to micro-organisms. The role played by bacteria in precipitating iron from salt water has been summarized by several writers (Glock, 1923; ZoBell, 1946, p. 103–104; Twenhofel, 1950, p. 419–421). The pertinence of this to beachrock cementation, however, also awaits field verification.

CEMENTED SAND DUNES (EOLIANITE)

Under this term will be discussed the distribution, origin, and special characteristics of cemented sand dunes and deposits of cemented windblown sand that are thin or lack the typical topographic form of the dune (lithified dunes from Bermuda have been described and figured by Agassiz, 1895; similar features from the Pacific have been described by Dana, 1849, p. 45–46, 253–256; and Hinds, 1930, p. 73). More recently McBurney and Hey, 1955, have described them from the coast of Libya. In the discussion of these features some sands will also be considered that show evidence of having been deposited in a littoral marine environment, either as beach deposits or as shallow offshore or lagoonal deposits, and that are too intimately interstratified with eolian sediments to be conveniently separated. Indeed, it is essential to note that the slight wind transportation necessary for the shifting of beach sand onto a foredune is not sufficient to give characteristics to the sand that will allow one to distinguish it readily in the field from the adjoining beach sand. Although the sand in a foredune has decidedly better sorting than beach sand, it has much the same texture, rounding, and composition. It is the topographic form of the dune and the occasional occurrence of the so-called eolian type of crossbedding that readily reveals the essentially eolian origin of these deposits. Nevertheless, in the basal parts of some cemented dunes (such as at Punta Fraile) we find beds that contain the heavy conch shell *Strombus gigas*, or coral heads (such as at San Juan, Punta Salinas, Punta Fraile, Punta Cerro Gordo, and most of the coastline east of Arecibo), thereby giving evidence of lagoonal or reef origin, or beds that contain coarse gravel and cobbles, which therefore might be of almost any origin except eolian.

Berkey (1915), Semmes (1919), Hubbard (1923), Meyerhoff (1933), and Meyerhoff and Smith (1931) called this cemented dune complex the San Juan formation. Because the complex includes rocks whose ages probably range from earlier Pleistocene to Recent and because the cementation of sand dunes is probably still an active process, there seems little reason to designate these features by a formational name. The name San Juan formation is therefore not used in this report.

EOLIANITE DISTINGUISHED FROM BEACHROCK

Beachrock forms a thin pavement that is limited essentially to the intertidal zone. Eolianite (lithified dune sand) on the other hand, ranges from well below sea level to altitudes of a 100 feet or more. Eolianite quite commonly exhibits eolian-type crossbedding and forms ridges whose shape is unmistakably that of a dune. There is little, however, to distinguish beachrock from eolianite in hand specimen and—as far as the Puerto Rican specimens are concerned—in thin section. Moreover, many cemented dunes have thick sections of strata dipping gently seaward; the dunes therefore are structurally similar to beachrock pavements. Here, except for position with respect to sea level, the only salient difference between eolianite and beachrock is the great thickness of one and the restricted thickness of the other. Despite the possibility that with a sinking coastline a beachrock pavement might grow unusually thick by successive accretions from above, there is little doubt that the thick section of seaward-dipping sandstones in the cemented dunes are true eolian accumulations (see discussion on origin and cementation that follows).

DESCRIPTION

Eolianite is wind-deposited sand with calcium carbonate cement. The mineralogic composition of the sand of the Puerto Rican cemented dunes is almost as variable as beachrock. However, all samples examined contained at least five percent carbonate (shell) grains. The cementing mineral as seen in several thin sections is calcite, similar to that of beachrock. The cementation ranges from slight to dense and the surface of the cemented dune is generally harder than the interior. The dense surface cementation is most marked in the spray zone on the ocean side and apparently is largely the result of the lime-depositing activity of blue-green algae that thrive in this zone. The degree of cementation seems to vary with age and the older deposits tend to be better cemented than younger deposits.

Macrofossils are rare in cemented dunes and consist principally of the shells of land snails. The shallow marine deposits that are included in the basal part of some of the dunes are, on the other hand, abundantly fossiliferous.

Except for ramifying tubular structures, which are particularly conspicuous on some eolianite surfaces and which may be root molds (possibly that of the sea grape, *Coccoloba uvifera*, fig. 28), plant fossils are entirely lacking. Hubbard (1923, p. 98) has suggested that the tubular structures are casts of coconut palm roots. But this tree, is neither endemic to the region nor does it have the simple sparse root system indicated.

Layers of red loamy fossil soils occur in the eolian sequence and separate dune accumulation of different ages. Typically these paleosols are uncemented red sandy loams that in some places still preserve a gray A (surface) horizon and attain a thickness of five or more feet, as in front of the Medical School, San Juan. Cemented unoxidized sand—that is to say, normal eolianite—occurs in places both above and below paleosol horizons.

FORM AND DISTRIBUTION

The cemented dunes preserve the elongated, whale-backed shape of the original foredune. In places, however, they are small low masses, which may indicate the small size of the original dune, or may represent erosional remnants of larger dunes. The eolianite ridges occur intermittently along the entire north coast of Puerto Rico and, as far as the writer knows, do not occur on the other coasts of the island (fig. 27). On the north coast the cemented dunes form all the offshore islets that lie west of the mouth of the Río Grande de Loíza and east of the town of Camuy. East of the Río Grande de Loíza only the small group of islets that lie off the northeast tip of Puerto Rico, La Cordillera, consist of eolianite. The ridge on which the city of San Juan is built is a cemented dune complex, as are all of the rocky headlands between Punta Borinquen, at the northwest tip of the island, and the Río Grande de Loíza.

The cemented dunes tend to be rectilinear or else follow slightly sinuous courses for distances of a mile or more (figs. 16, 17). The dunes are oriented from west to N. 80° W., with the large majority oriented at either of the extremes (fig. 27). This orientation is possibly controlled by the elongation of ridges and knobs of Miocene limestone and sand which form the foundation of many of the dunes (chap. C, this report).

In many places along the north coast there are two or more parallel rows of cemented dunes. The dunes on the north, or ocean side, are generally the most recently formed (Gleason and Cooke, 1927; also chap. C, this report). The bases of some of the younger dunes are now submerged, so that only their tops project above the sea in the form of small rocky islets. Younger dunes are devoid of soil and preserve fairly well the original form of the foredune. The older dunes lying to the south are generally soil covered and are broader at the base, somewhat eroded, and more gently rounded than the ridges to the north. Part of this difference in shape is due to the continuous accretion of sand by the older dunes throughout the long interval of dune formation (pl. 11). Older dunes therefore generally contain sand of several generations of dune construction with intervening paleosols. The platforms of reef rock and marine sediments, which underline many of the older dunes, rather commonly crop out on the south side (pl. 11). At San Juan, for example, four ages of dune construction and four lines of eolianite ridges are apparent (chap. A, pl. 2; pl. 11). The oldest is the area of broad ridges on which San Juan and Santurce are built. Two younger rows of dunes, oriented N. 83° W., are partly submerged and lie to the north. The youngest line of dunes is represented by the rocky island of the Peñon de San Jorge and four small rocks lying about 400 yards off San Cristóbal. Three lines of cemented dunes of different ages are particularly well developed for several miles to the east and west of the mouth of the Río Grande de Manatí. Off Cape San Juan the oolitic eolianite of La Cordillera forms 3 and possibly 4 separate dune ridges. The oldest ridge includes most of the islands of Cayo Icacos, Cayo Ratones, and Cayo Lobos. The youngest eolianite ridge of La Cordillera forms the chain of lesser islands to the north, including Las Cucarachas and Los Farallones (pl. 10).

STRUCTURE

Eolianite is well stratified, but eolian crossbedding may be of only secondary importance. This fact is evident where the interiors of cemented dunes have been exposed by erosion. Here the structure is seen to be compound and made up of several well-defined structural units, each characterized by different inclinations of the bedding. Thus the deepest part of the dune may consist of beds dipping steeply and fairly uniformally south. These may be overlain by a thick section of eolianite dipping gently to the north, and the dune may be capped by a relatively thin section of sandstone with eolian crossbedding. This relation is fairly common and characterizes many eolianite ridges, including that on which San Juan is built, the ridge north of Dorado, the ridges at Punta Cerro Gordo and Punta Puerto Nuevo, and the several large eolianite ridges east of Arecibo (fig. 43).

A particularly striking and rather common type of bedding resembles anticlinal or domal structures (fig. 28). These have been observed in most of the longer cemented dunes. These domal structures are generally circular in plan and symmetrical, with dips on the flanks as steep as 36° (which is also the maximum angle of repose measured in Puerto Rican uncemented dune sands). In plan the domes range up to 150 feet across. These structures are very probably depositional and were probably formed by the slow accumulation of drifting sand about some obstacle, such as an eroded knob of an older dune. Tayama (1952) figures a similar anticlinal structure from Pisief Island, Nomwin Atoll, the East Caroline group.

At the east end of the eolianite ridge north of Dorado (Punta Boca Juana), two eolianite domes of the type just described are separated from each other by a verti-

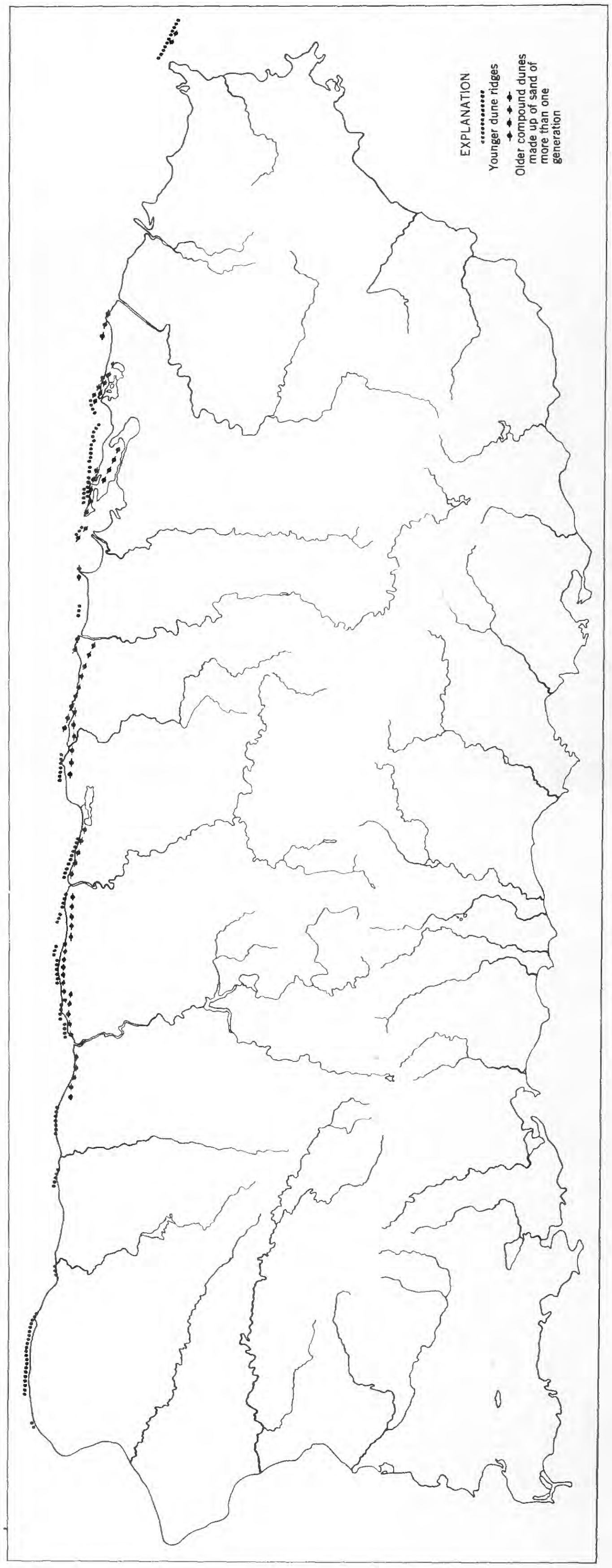

FIGURE 27.—Distribution of cemented sand dunes in Puerto Rico.

FIGURE 28.—Dome, arch, or anticlinal structure in eolianite; north of Manatí.

cal fault, while a second and parallel fault also cuts across the center of one of the domes. One hesitates to ascribe these faults to tectonic movement, and it is possible that they are due to prediagenetic slumping.

ORIGIN OF THE CEMENTING PROCESS

THE MODERN FOREDUNE

Large foredunes occur along much of the Puerto Rican shore. These dunes characteristically adjoin the beach and trend parallel to the shore. Nearly two miles of one of these dunes, that which extends between Punta Maldonado and Punta Vacía Talega, east of San Juan, was removed in 1951 to provide fill for the construction of the nearby International Airport. The excavation afforded an excellent opportunity to examine the interior of a modern foredune. This foredune consisted of shell sand in which elongated grain shapes were particularly abundant. Shells of both land and marine gastropods were rather common and were probably transported from the beach by hermit crabs. Part of the dune was moderately cemented in the interior. The reasons for the localization of the cementation were not evident. There seemed little doubt that the cemented sand was the same as adjoining uncemented sand in composition, texture, and apparently in date of deposition. The degree of cementation seemed to increase with depth and was decidedly more pronounced on the ocean side. In the cemented stretches of this foredune the surface was loose sand, beneath which was a zone, several feet thick, of very slight cementation by a deposit of white powdery calcium carbonate. This eolianite crushed readily between the fingers. At depth the white carbonate coating was replaced by a well-crystallized calcite cement, though it was possible to crush much of this rock between the fingers.

The stratification of this foredune was apparent only in the deeper cemented parts. At one place, where cementation was particularly prominent and the stratification very evident, the dune consisted of a series of crossbedded wedges with all beds dipping in some degree toward the ocean (north).

Other modern foredunes of the Puerto Rican north coast also show spotty cementation. Hubbard (1923) reported a core of cemented sand in the large foredunes at Camuy and west of Punta Jacinto. The dune lying north of the shore road between Arecibo and Barceloneta, however, is uncemented at the several places where its interior has been exposed by sand diggings. Likewise the interior of the dune between Hatillo and Arecibo was uncemented where it is exposed in small diggings. Both of these dunes, however, consist mainly of silicate sand.

CEMENTED DUNES

The essential differences between the cemented segments of modern foredunes and the older cemented dunes are that the former possess a loose sand cover and are clearly associated with modern dune construction, whereas the latter have cemented sand at the surface and mark the position of former shores. Hubbard (1923) considered the cemented core of modern foredunes as prima facie evidence of a greater age for the core, and he described the cemented core of several modern dunes as belonging to the San Juan formation. The modern foredune east of Punta Maldonado just described seems to indicate, however, that cementation is a continuous process and that the contact between cemented and noncemented sand is gradational.

The explanation for the cementation of dunes poses a somewhat simpler problem than that for beachrock. One thing seems certain and that is that the $CaCO_3$ cement of the eolianite is derived from the dune itself and that it is mainly precipitated from percolating rain water. This means that cementation will not take place in dunes with a negligible content of carbonate sand. Whether precipitation is brought about by evaporation of pore water in the interior of the dune, or by some organic agent, or by a combination of both processes remains to be adequately investigated. There is reason to think, for example, that blue-green algae are responsible for the deposition of $CaCO_3$ cement in at least the surface zone (p. 101). The reasons for the spotty cementation in modern dunes and the coincidence in distribution of eolianite and beachrock on Puerto Rico likewise remains to be explained.

WASTAGE

Some of the most curious geomorphic features of the Puerto Rican coast are forms produced by the wastage of eolianite. Cemented dunes exposed to ocean waves are subjected to multiple attack. They are destroyed from beneath by the removal of their uncemented sand foundation by the turbulent surf. They are destroyed frontally by the depredation of storm waves, and they are continually losing substance from their surface by a combination of chemical and organic activity. The fate of a cemented dune therefore is dependent on the direction of the most devastating attack. The variations in relative importance of the three destructional processes is richly illustrated by the many dunes on the north coast. Many of the features that are discussed below have already been studied on the Hawaiian coast by Wentworth (1938, 1939). The genetic processes revealed by the Puerto Rican material are, however, so clear that new light is cast on these shoreline forms and an extended discussion seems merited.

PITTING

Eolianite surfaces not covered by soil are generally pitted, and where cementation is advanced and the rock is relatively impervious the pitting may be intense (fig. 29). In the spray zone, which has a densely cemented veneer a few millimeters thick that is possibly the product of algal activity, the entire surface is generally covered with pits of all sizes, from 20 feet or more across down to the size of a pea, and with larger pits pocked with smaller ones. This intense pitting forms a highly characteristic jagged surface on which footing consists of the narrow, knife-like septa and delicate spikes that separate individual pits. The depth and diameter of pits tend to vary inversely with altitude, and on the crest and the landside of some of the higher dunes large pits are scarce. The progressive development of pits, as they widen and deepen, is readily apparent from a study of these features at different levels on the ocean side of the eolianite ridge. It is evident that as pits deepen they also widen and coalesce. The deep and wide pits are therefore compounded from many smaller pits.

There are notable differences in the form of pits. The most common type of pit outside the spray zone has a rounded bottom and resembles the typical solutional pit of limestones. In the spray zone, however, the most characteristic form taken by the larger pits is a broad, flat-floored depression with deeply undercut sides (figs. 19, 29, 30). On some low-lying terraces there is still a third type, a cylindrical pit with vertical axis (fig. 33).

The weathering, or reduction of an eolianite surface seems therefore to be largely a matter of pitting. From the standpoint of process, an explanation of these pits involves two major considerations: an explanation for the differences in form, and a mechanism for the removal of the residual noncalcareous sand that is left by the leaching of the pit. The second factor is by no means a minor consideration when it is realized that some eolianite contains relatively little carbonate in the sand fraction. In this regard it is noteworthy that in spite of great differences in carbonate content all eolianite seems to be marked by the same type and intensity of pitting.

The pitted surfaces of the younger cemented dunes, particularly in the spray zone, are generally free of loose sand. The noncarbonate sand as well as evap-

FIGURE 29.—Typical intense pitting of eolianite in the spray zone, north of Manati.

orite salts are thought to be regularly removed from pits by two agents, foraging animals and the flushing action of large waves. In the spray zone, including higher surfaces that are bathed only by storm waves, heavy spray may flush the pits clear of loose sand. Probably more important than this, however, is the work of the rock fauna, which continually forages on the dune surface. Of these animals the most abundant are several species of periwinkle, *Littorina ziczac* (Gmelin) and *Tectarius muricatus* (Linné). The rich accumulation of algae that thrives in the stagnant water of the pits not uncommonly contains a small quantity of loose sand enmeshed in the organic strands. The periwinkles and other animals eating the organic residue of the pit floor carry loose sand out of pits as it passes through their digestive tract (Emery, 1946, noted similar activity). The effectiveness of periwinkles as a surface cleanser is indicated by the vast numbers of these organisms that cling to all eolianite surfaces in the spray zone.

FIGURE 30.—Flat-floored pits in eolianite, showing undercut rims, shallow spillway notches, and standing pools of spray water.

Round-bottomed and flat-floored pits and their origin

Round-bottomed pits need little description. They occur mostly on the landward side of cemented dunes, and in higher dunes, above the spray zone where they tend to be narrow, deep, and irregular in cross section. They also occur in the spray zone, but here they are relatively rare and are much more symmetrical in shape. Outside the spray zone they rather commonly contain loose sand, but on the ocean side of eolianite ridges they are clean-floored.

Flat-floored pits, on the other hand, are limited to to the normal spray zone (fig. 30). They are not found on the landside of most dunes, nor on the crests of the very high ones. They make up the great majority of the larger pits in the spray zone and form the widest, if not always the deepest pits on the surface of the dune. In relation to their width they are shallow and a ratio of diameter to depth of about 7:2 was typical of many of the medium sized pits that were measured.

The undercut rim of the flat-floored pit is very pronounced. The sides of the pit are concave and widest slightly above the level of the floor. In larger pits, the undercut may amount to well over a foot. The floor of the flat-floored pit is level and remarkably smooth, a characteristic that is in complete contrast to the intensely pitted nature of all other eolianite surfaces. The flat floor is an eroded surface that bevels the eolianite and is not a surface of aggradation, such as would be produced by sand filling an initially round-bottomed pit. This is evident from the fact that the eolianite bedding commonly can be seen lightly marking the smooth surface of the pit floor.

Also typical of the flat-floored pit is a well-defined overflow channel in the pit rim, which may or may not be incised down to the level of the pit floor. These spillways commonly interconnect one pit to another, so that the flat-floored pits on a dune surface form a system of interconnected basins that drain from one to the other like an oldfashioned fountain (fig. 30).

The flat-floored pit in places exhibits two or more cycles of pitting. This is shown by smaller flat-floored pits that occur in the floors of older and larger pits (fig. 31). The inception of a new pit, or cycle of pitting, apparently is marked by the formation of small, shallow, round-bottomed pits in the bottom of a flat-floored pit. This secondary attack (the initiation of a second cycle) seems to occur only in flat-floored pits whose spillway channels have been cut down to floor level. There are many examples to show that as these secondary round-bottomed pits in the floors of the flat-bottomed pits deepen and widen they too start undercutting and developing flat floors of their own (fig. 31). Moreover, a new overflow channel leading from the secondary pit begins to develop, although its rate of downcutting seems to be slower than the rate of pit deepening. It is only when the new, second-cycle pit is well developed—that is to say deep, undercut and flat-floored—that the depth of the spillway catches up with the level of the pit floor. When this happens a third cycle of pitting may commence. As these pits finally reach the lower spray zone, just above tide level, they tend once again to revert to the round-bottomed form. The evolution, therefore, of a pit in the spray zone—as it grows and wastes away the eolianite surface—seems to consist of the following stages: (a) Small round-bottomed, (b) larger flat-floored, (c) two or more cycles of flat-floored pitting, and (d) round-bottomed (the last stage is not invariable). Throughout this process there is a continuous lateral merging, or coalescing, of pits.

Emery (1946), has explained intertidal pitting of calcareous sandstone at La Jolla, southern California, as essentially resulting from biochemical activity which affects the CO_2 partial pressure in tide pools. During the day photosynthesis by algae combined with high temperatures tends to decrease the CO_2 content of the pool. As a result the pools are saturated with $CaCO_3$ during daylight hours. At night, on the other hand, with the reduction of photosynethic activity and the lowering of water temperature a reversal of equilibrium occurs, and as a result the $CaCO_3$ element of the sandstone is dissolved. This hypothesis, although based on sound physical and biochemical reasoning, does not quite answer the most important facet of the problem of the Puerto Rican eolianite pits—namely, the distinction between round-bottomed and flat-floored pits and particularly the peculiar morphology of the latter. It is notable in this respect that the pits figured by Emery were not undercut nor did that author indicate whether they had smooth plane floors.

The round-bottomed pit is a common feature in most limestones regardless of proximity to the coast, and its origin can be readily explained. A graphic representation of the development of the round-bottomed pit from an initial depression is represented in figure 32. It is most probable that the pits in the eolianite are due to solution by rain waters. There seems little doubt that rain water is capable of dissolving $CaCO_3$. Miller (1952, p. 195), for example, has shown that the solvent action of fresh rain water, with an atmospheric partial pressure of CO_2 (3.5×10^{-4} bars), can amount to the dissolution of 0.044 gr $CaCO_3$ per liter at 25° C. The assumption can be made for purposes of the graphic analysis, that from time to time the pit will contain a rain water pool and that this pool will partly or entirely disappear by evaporation and (or) infiltration before the next rainfall. Furthermore, the assumption can be made that after the pit has reached a certain depth only an occasional heavy shower will fill it to the brim. Thus it can be seen that the level of the pool will continually fluctuate and, moreover, that the frequencies with which different levels of the pit will be wetted will vary. Thus the deepest point of the pit will be in contact with rain water with every rainfall and, furthermore, this point will be in contact with water longer than any other point on the pit side during the interval when the pool shrinks by infiltration and evaporation. The opposite extreme is the rim of the pit which, if the pit is deep enough, is rarely in contact with the rain-water pool. These two levels, then, the lowest and the highest points on the pit wall, represent the extremes in the frequency with which points on the walls of the round-bottomed pit are in contact with the solvent. Points at intermediate levels have intermediate frequency values. An approximation of the

FIGURE 31.—Two-cycle flat-floored pit, Punta Tortuguero. Pick and notebook rest on flat floor of first-cycle pit; broad spillway notch beyond. Present flat-floored pit is incised 3 feet below old floor.

relative frequency with which various levels of the pit are in contact with a pool of solvent rain water is shown by the curve to the right of the diagram of the round-bottomed pit in figure 32. Now if it is assumed that the amount of solution that occurs at various points on the pit wall is proportional to the relative frequency of contact with a solvent, the initial semicircular cross section of the pit can be modified to a new form on the basis of this frequency curve by geometrical construction. This is done by substituting the frequency values at various levels of the pit for the depth of solution at that level. For the sake of simplicity the depth is laid off normal to the tangent of the pit side of that level to produce the outline of the new pit. This is a deep and relatively narrow round-bottomed pit similar to those in the field. Needless to say this construction is a simplification of the natural process and, although there are factors affecting both the frequency curve and the direction of solution that are difficult to appraise, the construction illustrates the essential process in the development of the round-bottomed pit. Wetting of the pit sides—for example, by rain water during precipitation—regardless of the pool level will achieve a certain amount of solution not indicated in the analysis. The result of this probably is a slow widening of the pit.

The fundamental problem is an explanation of the flat-floored pits and why they are confined to the spray zone. The author proposes that the key to understanding the origin of these pits is furnished by a geometric construction much the same as that employed for the round-bottomed pit. However, the proposition must be made that the initial pit, which can be assumed to be hemispherical, is not eroded along its entire wetted surface, as in the round-bottomed pit, but is eroded by

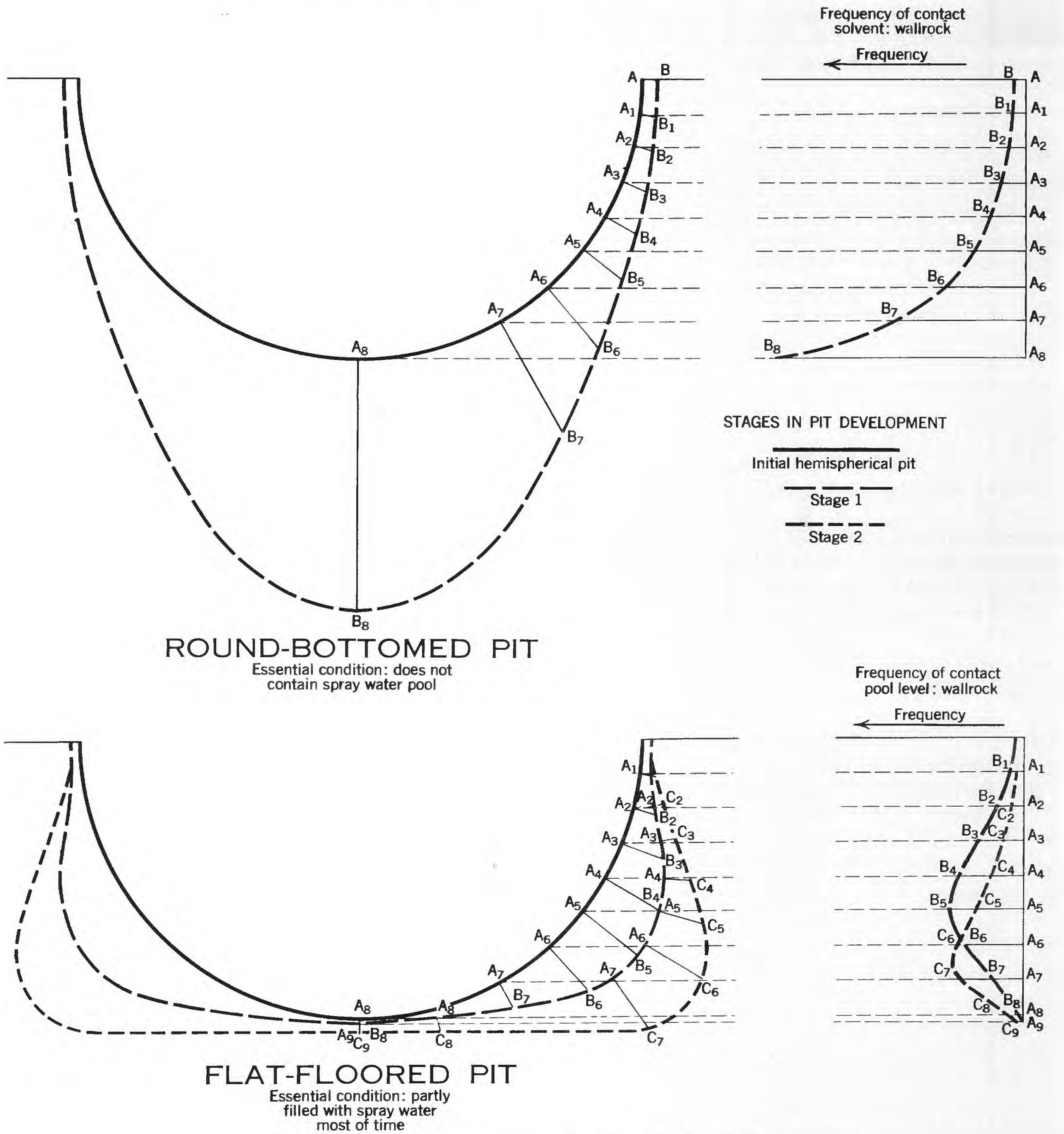

FIGURE 32.—Development of round-bottomed and flat-floored pits.

the surface of the pool—that is, only at the top of the wetted zone. The reasons for this kind of erosion, here called "pool level erosion," will be discussed later. Consideration is given first to the geometry of the alteration of pit shape produced by this type of erosion. Since erosion is restricted to the level of the pool surface, the frequency of pool level with respect to depth in the course of fluctuation is represented by an entirely different type of frequency curve from that shown for the round-bottomed pit in figure 32. Because the flat-floored pits are in the spray zone they are rarely without a spray-water pool. Thus the frequency curve (fig. 32, flat-floored pit) is at a minimum at the deepest level of the pit. Likewise it is relatively rare that the pool is filled to the brim. The fluctuations of pool level (depending largely on such factors as frequency of replenishment by rain and spray, and depletion by evaporation) therefore inscribe a normal frequency curve about some intermediate level. This curve is probably somewhat skewed because of the exponential relation of pool volume to depth. Two curves for the frequency of pool level, which are approximated to the right of the diagram of the flat-floored pit in figure 32, represent two successive stages in the enlargement of the initial hemispherical pit. The graphical construction is the same as for the round-bottomed pit. Values A–B, A_1–B_1, . . . A_8–B_8 are laid off along normals to the tangent of the initial pit at the respective levels. In stage 2 the surface used is that derived in stage 1. The effect of the downcutting of the overflow channel is taken into account in stage 2 because negligible solution can take place above the overflow level. In this stage it is assumed that the spillway has been dissolved down to level A_1. It will be seen that the pit profiles developed from this graphical construction are the same as those that occur in nature.

Two main factors bring about pool-level erosion in the spray zone. The first is a density stratification between rain water and spray-derived salt water. Because of evaporation, the salt water in the pit is normally more dense than ocean water. Rain water falling directly into the pool, or draining in from the surrounding surfaces, will therefore tend to float on top of the denser salt water. The ability of rain water to dissolve $CaCO_3$ has already been mentioned in the discussion of the round-bottomed pit. On the other hand, it seems certain that the salt water underlying the rain-water film is generally saturated with $CaCO_3$. The increase in temperature and the evaporation that take place in a pool must certainly alter the equilibrium of ocean water with respect to $CaCO_3$ in the direction of saturation. Therefore, it seems most likely that the solutional effect of the pool on the walls of the pit would be limited to the contact of the fresh-water layer at the surface.

Probably the sharp stratification between fresh and salt water (or even brine) is often very short lived. New spray falling into the pit will destroy the stratification (note, however, that only the very lowest part of the spray zone is frequently bathed in spray. The upper part is washed only when large waves, or swells, strike the coast). Furthermore, the normal diffusion of miscible liquids will in time destroy the density stratification and mix both types of water.

The second factor that probably contributes substantially to pool-level erosion is mechanical erosion by salt crystallization. As a spray pool evaporates and the level falls, it leaves behind a thin collar of salt on the pit walls. The crystallization of the salt in the fine pores of the eolianite most certainly dislodges the tenuously cemented sand grains of the eolianite. The erosion due to the fluctuations of the pool surface about some intermediate level in the pit is therefore appropriately expressed by the graphic analysis used in figure 32.

The origin of a second cycle of flat-floored pitting can now be explained. Once the overflow channel is cut to the depth of the pit floor, it eliminates the standing salt-water pool and thereby exposes the floor to direct pitting by rain water. This action, as we have seen, produces a round-bottomed pit. It is only when the new round-bottomed pit is deep enough to hold enough spray water to resist rapid evaporation that the process of flat-floored pitting begins over again.

Cylindrical pits

Cylindrical pits with vertical axes and diameters as large as one foot are found in eolianite on flat surfaces within or just above the tidal levels (fig. 33). They are also well formed on Punta Higüero on an elevated marine terrace of coarse sandstone. Hubbard (1923, p. 98, fig. 39) figured these pits and ascribed them to molds of coconut palm trunks. This tree, however, is a late arrival, having been introduced on the island in 1525 from the Cape Verde Islands (Roberts and others, 1942, p. 118). Moreover, the pits are too closely

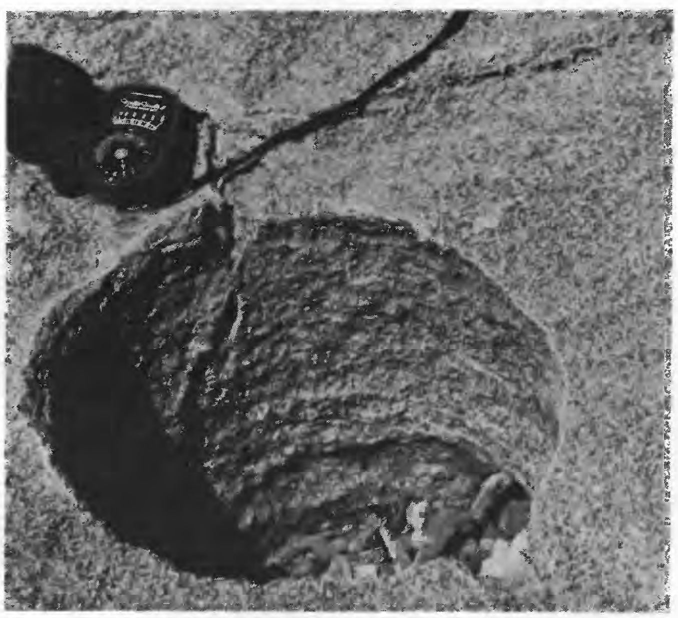

FIGURE 33.—Cylindrical pit. This is probably a true pot hole. Grinding pebbles(?) are visible in the bottom of the pit.

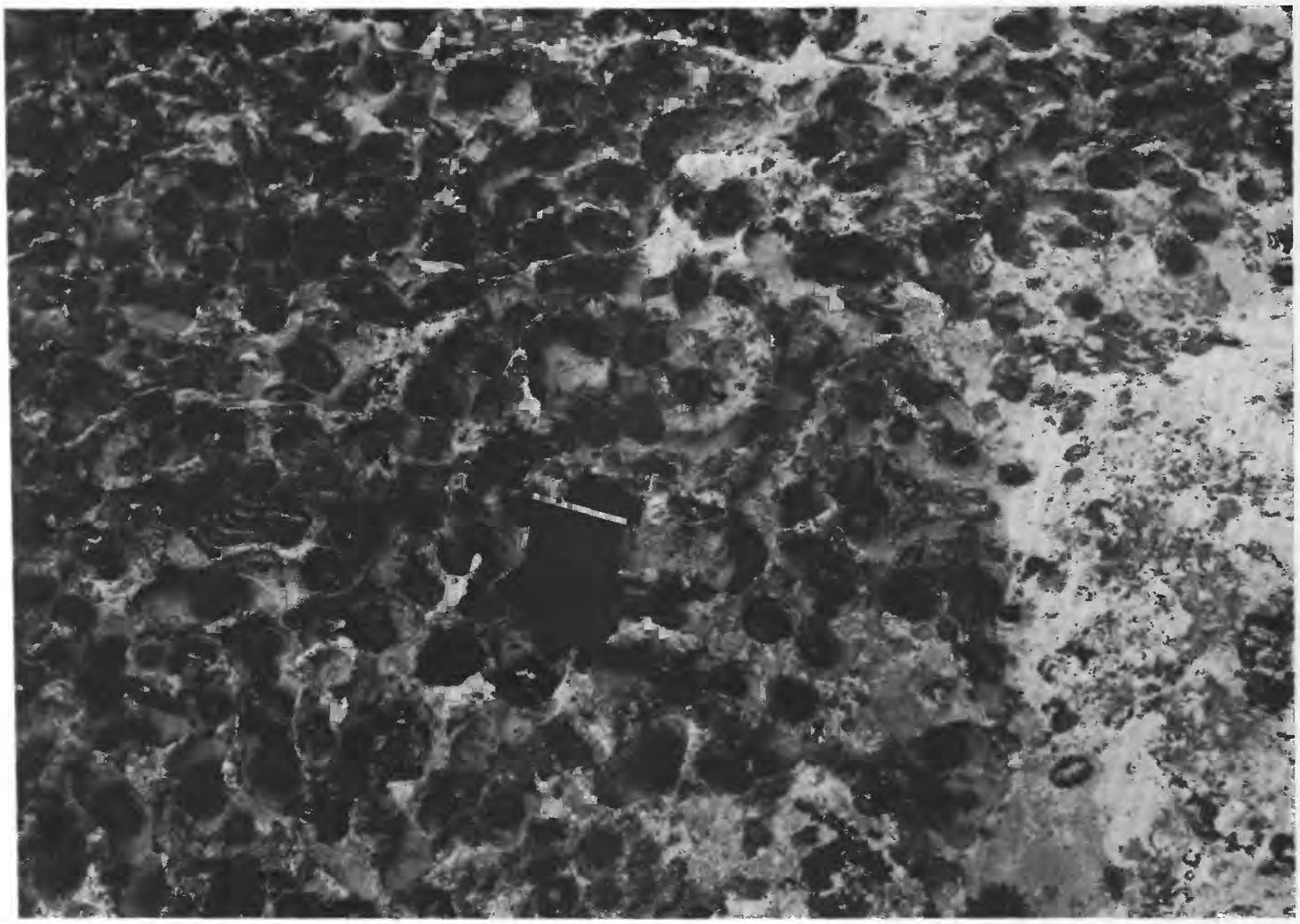

FIGURE 34.—Pitting by the sea urchin *Echinometra lacunter* on the surface of a tidal terrace. Several sausage-shaped holothurians and chitins are also visible. Camera plate is 4 x 5 inches.

spaced (not uncommonly nearly coalescing) to be the molds of trees that need room to develop leafy crowns.

Zotov (1941) has described pits of somewhat similar shape and has attributed them to solution by carbonic acid resulting from moss in the bottom of the pit.

Agassiz (1895, p. 269–270) has described similar pits from Bermuda under the term "pot-holes." The Puerto Rican pits give some indication of also being potholes, that is, pits ground out by the milling action of pebbles moved by a turbulent surf. Pebbles which could serve as grinding tools are generally found in the bottom of the pits. Pits above high tide, such as those about 100 yards east of the mouth of the Laguna del Condado (El Boquerón) in Santurce, could possibly owe their origin to storm waves or, as in the case of those on Punta Higüero, grinding associated with a higher sea level.

Pits by boring organisms

Within the intertidal zone horizontal or near-horizontal eolianite surfaces are attacked by boring organisms (Ginsburg, 1953b), of which the echinoid *Echinometra lacunter* (Linné) is by far the most important. These animals, commonly in large colonies, inhabit individual cup-shaped pits. They also may be responsible for elongated pits, commonly coalesced into a labyrinthic plexus of channels. Small holothurians, however, fit these channels nicely and convey the impression of having made them (fig. 34). Some shallow pitting is also accomplished by chitons.

TIDAL TERRACES

Eolianite shores that are exposed to strong wave action almost invariably have a conspicuous terrace whose surface has been variously estimated to lie between mean tide to high tide level (fig. 35). These occur along all the eolianite shores of the Puerto Rican north coast. A similar, though less conspicuously developed, terrace is also found in the dense Miocene limestone of Islas Mona and Monito, where it forms a sort of median shelf in the deep nip which marks the

FIGURE 35.—Tidal terrace in eolianite about four miles east of Arecibo, showing *Lithothamnium*-encrusted outer rim and steplike arrangement of higher terrace segments.

shoreline here. The tidal terraces are particularly conspicuous on the small eolianite islands off the north coast of Puerto Rico, and many of these offshore rocks have been entirely or nearly entirely reduced to this level (fig. 37).

Similar terraces were studied by Wentworth (1939) on Hawaii who called them "solution benches." This term seems somewhat less descriptive than "tidal terrace" since it does not specifically indicate the shoreline nature of the feature.

The tidal terrace is generally characterized by one or more very low steps whose risers are formed by sinuous septa on its surface. Each step rises to successfully higher elevation by increments as small as a fraction of an inch (figs. 35, 38). The steps generally, though not invariably, are highest on the landward side of the terrace. Because of the low, sinuous steps, tidal terraces resemble travertine and sinter terraces formed about hot springs (Lobeck, 1919, p. 364, compared the Puerto Rican tidal terraces to Mammoth Hot Spring, Yellowstone National Park; also Kuenen, 1950, p. 431–433, who notes that similar terraces are common on coral reefs). It is noteworthy that tidal terraces are not found on the lagoonal side of eolianite ridges or on well-protected shores. Where wave action is particularly strong the terraces may be 25 feet or more wide and may rise by successive steps to as much as 4 feet above high tide, though normally they do not rise much above high spring tide. Generally they are terminated above the solutional nip and are undercut at about mean low tide level (fig. 36).

The structure of tidal terraces are best examined at low tide or when the sea is calm (fig. 36). They are cut in eolianite and, unlike hot-spring terraces, are therefore essentially destructional rather than constructional features. The outer edge of the tidal terrace is a rim of eolianite, thickly coated with crustose coraline algae and a shaggy growth of brown algae. The intermediate rims, making up the risers of the steps, are also encrusted with coraline algae, although

FIGURE 36.—Tidal terrace on ocean side of eolianite ridge at low tide, showing heavy algal mat on outer rim and the nip both above and below the terrace. As is usual for the ocean side, the upper lip shows up poorly because the fragile visor has been broken off by storm waves. Note that the continuation of the profile of the dune ridge intersects the outer edge of the tidal terrace.

to a lesser thickness than the terrace edge. At several places west of Palmas Altas, near Barceloneta, the encrustation on the terrace rims consists of serpulid tubes and dense colonies of mussels (fig. 37). Similar serpulid encrustations were reported by Agassiz (1895) on Bermudan tidal terraces.

The processes leading to the formation of the tidal terrace are evident from a study of the shore at many points along the north coast. The essential prerequisite seems to be an environment favoring coralline algae encrustation (or, in exceptional cases, the proliferation of serpulids or mussels). The coralline algae thrive especially well in the intertidal zone, on rocky shores that are exposed to strong wave action or wherever there is a more or less continuous flow of aerated marine water. As long as the algae continue to thrive, the encrustation which they provide forms a protective armor against the solution of the underlying eolianite.

The tidal terrace seems to form in two ways: It can be a remnant left behind as a median shelf by the

FIGURE 37.—Pleistocene reef rock northwest of Barceloneta, entirely base leveled to tidal terraces. The rock rims of the individual pools are here encrusted with serpula tubes instead of the usual *Lithothamnium* encrustation. Low spring tide.

FIGURE 38.—Tidal terrace originating as the base level of pitting. Note relict eolianite pinnacles.

formation of the nip (fig. 36), or it can represent the base level of pitting of eolianite (fig. 35). It can also form by a combination of both processes. The solutional nip (described below), extends from approximately mean low to mean high wave level (the range represented by waves of mean height at mean low and high tides, respectively), and in places where the protective armor of the algal encrustation is lacking, such as on lagoonal shores, the nip occupies this entire range. On the other hand, where the armor of coralline algae occurs, the nip solution is confined to rock lying above and below the encrustation, which, as already mentioned, marks the zone between mean low and mean high tide. Rock protected behind the algal encrustation is therefore left behind in the form of a residual terrace as the nip develops.

The tidal terrace also may represent the base level of pitting. As we have seen, pits on the surface of an eolianite ridge enlarge, coalesce, and deepen until finally they reach the intertidal level, where they become encrusted with coralline algae. The stubby relicts of pit rims then become the sinuous septa on the surface of the tidal terrace (figs. 38, 39). The continuous flow of wave and spray water over these rims encourages the growth of coralline algae that allow these features to persist by protecting them from intertidal corrosion.

The surfaces of a tidal terrace are almost everywhere very much pitted by the echinoid *Echinometra lacunter* (Linné). These organisms seem to be mainly responsible for excavating basins a foot or more in depth in the flat surfaces of the terraces. In many places almost the entire surface of the tidal terrace is reduced by this kind of pitting and only the heavily encrusted outer lip and septa rise to the original terrace height (fig. 35).

FIGURE 39.—Development of pit rims into step risers on the tidal terrace surface of figure 38.

FIGURE 40.—Nip on lagoonal side of eolianite ridge on north coast, showing its upper limit at about high-tide wave crest (a level approximately marked here by the high-tide swash limit visible on photograph).

SEA-LEVEL NIP

Sea-level notches or nips, of striking depth and symmetry, whose origin can probably be attributed to solution rather than to mechanical erosion commonly occur on limestone and eolianite shores in tropical latitudes. On Puerto Rico nips are well developed in the eolianite of the north coast (fig. 40) and in the dense limestone of Miocene age of Islas Mona and Monito (Kaye, 1957b).

The upper level of the nip is at approximately mean high-wave level—that is to say, waves of about average height just fill the nip at high tide (whether mean high spring tide or mean high tide has not been determined). The lower level of the nip is the mirror image of this, and appears to be at approximately the altitude of the troughs of average waves at low tide. Nips are therefore 10 feet or more high, from floor to roof, on exposed coasts but only 3 or 4 feet high on protected shores. On protected shores, such as the lagoonal side of cemented dunes, the profile of the nip is a fairly symmetrical curve, deepest at approximately mean tide level. On exposed wave-swept shores, such as the ocean side of cemented dunes, the tidal terrace generally projects as a sort of median shelf from the center of the nip incision (fig. 36, 41).

The depth of the nip is variable. On the ocean side of cemented dunes nips may be 12 or more feet deep. Where the nip is absent or is not particularly well developed above the tidal terrace several reasons can be adduced: (a) wave erosion has torn off the fragile overhang, or visor, of the nip (fig. 36); or (b) rapid reduction of the eolianite ridge by pitting is taking place at a rate equal to, or exceeding that, of nip corrosion. On the lagoonal side of cemented dunes the depth of the nip not uncommonly exceeds 5 feet.

Some indication of the rate with which the sea-level nip is formed in eolianite is provided by a large boulder (one of several) near the east side of the entrance to the Laguna del Condado ("El Boquerón") in Santurce (Chap. A, pl. 2; figs. 57, 58). This somewhat rounded boulder is over 6 feet high and is perched on a much pitted tidal terrace. According to the Puerto Rican historian Angel Rivera (1922, p. 59), these large boulders were blasted from the adjoining eolianite shore in 1797 by the Spanish military engineers with a view to blocking the El Boquerón channel to English attackers under General Abercromby. A well-defined though relatively shallow nip girdles the base of one of the boulders. On the ocean side the nip measures 4 inches at its maximum depth while on the lagoonal side it is 10 inches deep at the deepest point. The nip is 29 inches high on the lagoonal side, which about corresponds to the maximum tidal range.

Many authors have expressed the opinion that the nip in carbonate rocks is caused by solution rather than mechanical abrasion by waves (Wentworth, 1939; Kuenen, 1947, 1950; Fairbridge, 1948). Solution rather than mechanical abrasion is indicated for the following reasons: (a) The nip is deeply incised on shores that are protected from strong wave action, such as the lagoonal side of cemented dunes (fig. 40, 41). (b) Cliffed shores of very pure limestone, like that of Islas Mona and Monito, lack the abrasive tools necessary for wave abrasion of the indicated order of magnitude. (c) Sea-level nips are not found on headlands of noncarbonate rocks on the east and west coasts of Puerto Rico, although they are well formed in soluble limestone and eolianite immediately adjacent.

Although it is often claimed that the surface water of the ocean is saturated and even supersaturated with respect to $CaCO_3$ (see Dole, 1914; Mayor, 1924b; Sverdrup and others, 1942, p. 206–207), the nip appears to provide empirical evidence that in coastal waters, at least, this may not be so at all times. Apparently because of this reported state of saturation, Wentworth (1939) felt obliged to attribute the nips on Hawaiian shores to the solvent action of fresh-water springs discharging at the levels of the nips. This specialized mechanism, however, could hardly explain the wide distribution of sea-level nips. Fairbridge (1948), on the other hand, suggests that the nip is due to the nightly drop in the temperature of the surface water of lagoons, which has the effect of increasing the CO_2 content of the water and causing an undersaturation

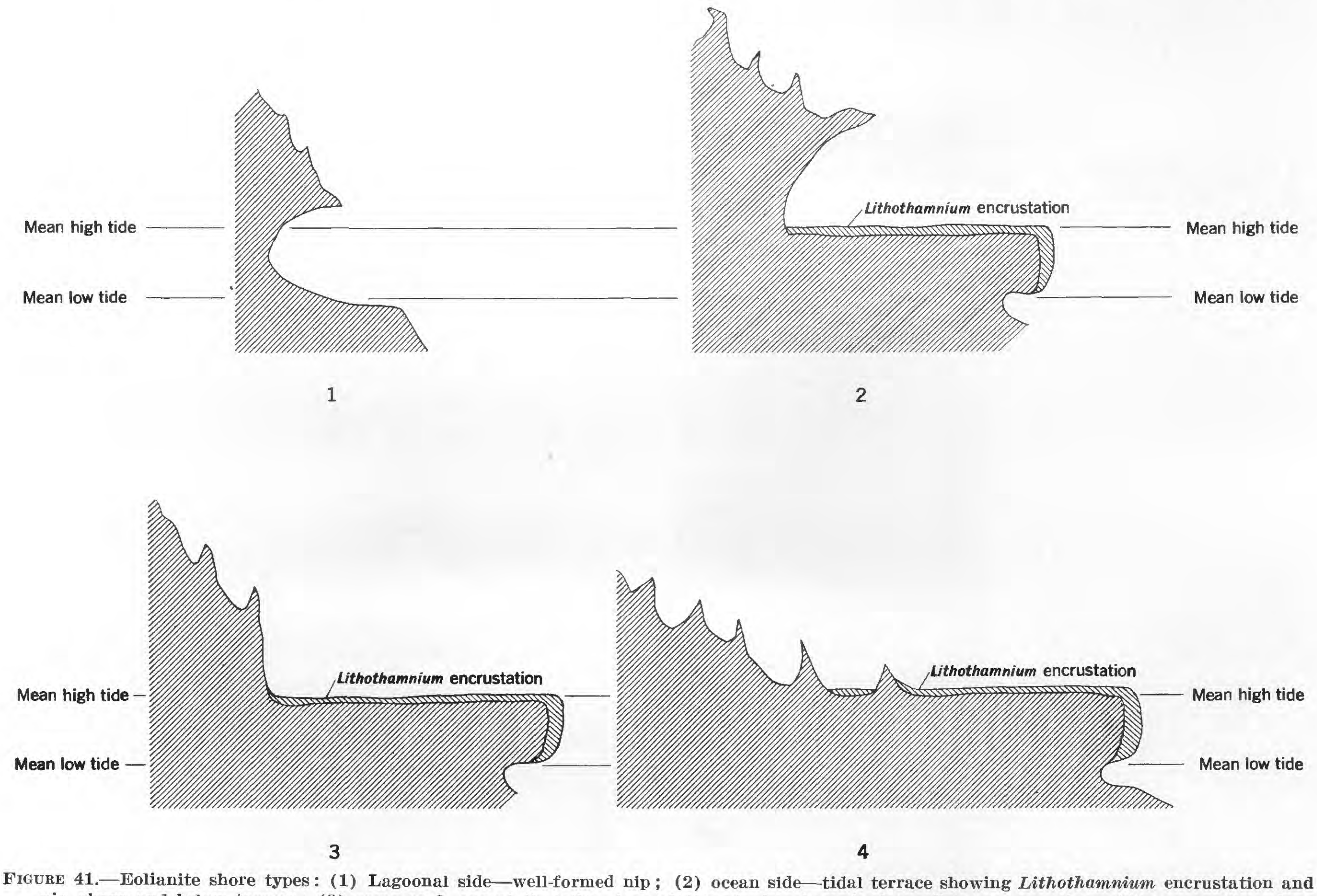

FIGURE 41.—Eolianite shore types: (1) Lagoonal side—well-formed nip; (2) ocean side—tidal terrace showing *Lithothamnium* encrustation and nip above and below terrace; (3) same as 2, except that the visor of the nip has been broken off by wave action; (4) ocean side—shore of low inclination with pits transforming into tidal terrace and only lower nip present.

with respect to $CaCO_3$ of the top few inches of water. Cloud (1952a) determined this diurnal variation by measurements of the water of the lagoon and reef flat of Onotoa Atoll. Nips on exposed coasts are continuous, however, with nips on protected shores. This is amply demonstrated on the Puerto Rican north coast where nips can be traced without any break in continuity from one type of shore to the other, as, for example, nips which entirely circumscribe cemented dunes. This suggests that the origin of nips facing deep coastal waters is the same as those facing lagoons. Occasional undersaturation of open coastal waters as well as lagoonal waters is thereby indicated.

In spite of much analytical work, speculation on the state of saturation of sea water with $CaCO_3$ is probably still permissible, inasmuch as the factors affecting the ionic product $Ca^{+2} \times CO^{-2}$ in sea water are not as yet thoroughly understood, nor has the value of the solubility product of $CaCO_3$ in sea water been unequivocally determined. It is postulated, therefore, that because of such factors as variation in salinity (resulting from land drainage and from heavy precipitation falling directly into the sea), organic generation of CO_2 in the ocean itself, and temperature changes, surface waters are occasionally undersaturated with $CaCO_3$. The solutional effect of this slight undersaturation is magnified, however, by the strong agitation of the waves. The writer has called attention elsewhere (Kaye, 1957b) to the importance of agitation on increasing the rate of limestone solution. Because the wave zone is preeminently a zone of strong agitation, it follows that the solutional effect of occasional undersaturation is magnified in this zone and that with time a profound solutional belt will mark the wave zone on limestone shores.

Ravelle and Emery (1957) have recently published a valuable study of limestone solution in tropical seas, in which they suggest that solution may, in spite of the apparent supersaturation of sea water with $CaCO_3$, result from the fact that much of the calcium may be complexed or hydrated. Solution could then occur when the carbonate concentration or temperature, or both, rapidly decreased, even though the product of the concentrations of total calcium and carbonate remain above the equilibrium saturation value.

WAVE EROSION

Storm waves occasionally break off large pieces of eolianite and toss them high onto the side of cemented dunes (fig. 42). At Punta Las Tunas, where frontal wave erosion and undermining have been particularly severe, large blocks of sandstone have been carried over the crest of the ridge (40 feet or more above sea level) and dropped into the narrow valley behind. The severity of wave action against the ocean side of the cemented dunes cannot be overemphasized.

FIGURE 42.—Large block of eolianite representing the visor of a deep nip, torn from ridge and tossed into present position by storm waves. Just west of mouth of Río de la Plata.

UNDERMINING

Many cemented dunes show partial destruction by massive collapse brought about by undermining. The high dunes that intermittently mark the shore for several miles east of Arecibo (Punta Morrillos, Punta Caracoles, Punta Las Tunas) illustrate this kind of destruction very well (fig. 43). These cemented dunes apparently rest on a loose sand foundation. The particularly strong wave action along this stretch of coast has apparently sapped much of the sand underlying these ridges, and as a result large segments of the eolianite have collapsed. Most of the eolianite that was affected in this way has disappeared from view, either by being broken up by the pounding waves or by sinking into the shifting bottom sands. Punta Las Tunas is a particularly good example of an undermined cemented dune, for in addition to large gaps in the ridge left by massive collapse, it is also broken by many gaping fractures along which differential settlement and shifting are actively taking place. The whole ridge trembles whenever a large wave strikes it, while from below comes the constant rumbling of the surf as it rushes through a network of caves and narrow openings. In several places collapse has been followed by wave attack of the more friable interiors of the cemented dunes, and in consequence large shell-like caves have been excavated (fig. 43).

Wastage of cemented dunes by undermining is probably the most rapid erosive process, but it seems limited to those dunes which rest on uncemented sand at shallow depth. Unquestionably many cemented dunes have

FIGURE 43.—Partly destroyed and eviscerated eolianite ridge. The large cavern has been slowly enlarged, except at the intertidal level where it has been protected by a *Lithothamnium* encrustation, which has resulted in the formation of a tidal terrace. The large segment of the ridge represented by the open water of the foreground has been destroyed by undermining. Punta Las Arenas area, east of Arecibo.

been entirely destroyed in this way, and it is reasonable to think therefore that at one time the bastion of eolianite ridges along the north coast of Puerto Rico was very much more extensive than it is today.

FACTORS AFFECTING THE BASE-LEVELING OF EOLIANITE ISLANDS

Some of the small eolianite islands, which are actually the tops of partly submerged cemented dunes, have been entirely reduced to tidal terraces. Others have been nearly reduced except for a few pinnacles projecting from the center of the terrace as relicts of pit sides. On the other hand, some of the larger islands still retain the general shape of the original dune and are only rimmed by a narrow tidal terrace.

Assuming that all of these dunes were submerged at the same time and that the base-leveling process—accomplished by pitting, and leading to the tidal terrace as the end stage—was initiated simultaneously, then the variations in the stage attained by different islands (more correctly islets, for some are not over 10 yards long) would appear to be simply a function of the original height of the island. The lower the original height of the island, the more completely it has been reduced to the tidal terrace platform. We have here, then, a crude means of establishing the original heights of these many rocks and islets.

SANDSTONE REEFS

Narrow linear reefs, which from their alinements apparently mark submerged eolianite ridges, occur off the north short of Puerto Rico. One such reef extends from Punta Escambrón, San Juan, due east to Isla La Cancora, a distance of a little under six miles (chap. A., pl. 2). Many eolianite headlands along the coast have similar submerged extensions. Although these reefs commonly support colonies of corals they are probably in the main rock rather than coral reefs. They represent either the submerged tops of foredunes whose initial height was lower than the present sea-level or else dunes that have been reduced to the tidal-terrace level of some lower sea level of the Pleistocene.

LA CORDILLERA: A MINIATURE BAHAMAN PROVINCE

Off the northeast tip of Puerto Rico a chain of small islands and rocks, La Cordillera, occurs. These are of especial interest because they consist entirely of oolitic eolianite, very much like that which makes up most of the Bahama Islands. This occurrence of oolite is unique for Puerto Rico and to the writer's knowledge similar rocks have not been reported as existing elsewhere in the Greater Antilles. Moreover, the physiography of La Cordillera is strikingly like that of the Bahamas and their banks (although on a much reduced scale), so that their geology is more than a matter of local interest. The writer visited the largest of these islands, Cayo Icacos, but did not land on the other islands. As viewed from a small boat, however, all the rocks and islets making up the La Cordillera chain appeared to be made of the same rock as Cayo Icacos.

The islands of La Cordillera are strung out along a west-northwest chain and rise from a narrow submarine ridge approximately 18 miles long (pl. 10). The islands and rocks are clearly cemented dunes like those described from the mainland and differ only in their oolitic composition. The topography of these islands suggests at least four generations of dune construction, the oldest and generally highest dunes being on the south and the youngest on the north. Cayo Icacos shows four successive dune alinements, equally spaced about 500 feet apart, the highest rising to an altitude of about 45 feet. The dunes, which are alined west-northwest, are cut by deep transverse grooves, oriented N. 68° E., that contain small saline lagoons (fig. 13). To the east these grooves are expressed by the northeasterly elongation of the individual islands. Topographically one is reminded of a sliced French loaf with the loaf alined west-northwest and the slices, N. 68° E. The northeasterly grooves probably show the dominant wind direction at the time the dunes were formed, and the west-northwest alinement of the dunes may have been controlled by the orientation of the shore.

Cayo Icacos consists entirely of oolite. The island has the elongated hummocky form of the eolianite ridge and the rock is crossbedded in the same manner as the eolianites on the mainland. The oolite is white when freshly exposed and turns light gray as the surface is weathered. It has the texture of a fine sandstone and is very friable when freshly exposed but hardens rapidly on exposure to air. Fairly large quarries on Cayo Icacos (the rock is used in sugar refining on the mainland) provide good exposures and reveal the internal structure of the dunes.

In thin section (fig. 44) the rock is seen to consist of light-brown rounded to subrounded grains that are cemented by granular calcite. The calcite cement consists of clear, rhombohedral crystals, with individual grain averaging about 0.06 mm in size. The degree of cementation is variable and intergranular porosity seems to be controlled by stratification. Where the cement does not entirely fill the pores it is not unusual to find the calcite assuming an acicular habit and forming a druse in the interior of the pore.

The granular component of the rock consists mainly of ooids—that is, grains possessing a massive micro-cryptocrystalline central core surrounded by a thin laminated shell (see Illing, 1954, for a very detailed description of identical Bahaman material). About a third of the grains, however, lack the laminated outer shell and consist simply of massive core material. The grains encompass a wide variety of shapes although all of them have rounded edges. While many of the grains are circular or nearly circular in section, a majority of them are ellipsoidal, ovoidal, bolster-shaped, elongate, lozenge, or rod-shaped in cross section. Grain sizes range for the most part from 0.07 mm to 0.25 mm, and 0.15 mm seems to be about the median diameter of the thin sections examined. This is finer grained than the Bahaman oolite described by Illing.

For descriptive purposes the grains can be divided into massive core and laminated shell. The shell laminae consist of very finely fibrous aragonite (aragonite was differentiated from calcite by staining with cobalt nitrate) averaging about 0.003 mm in thickness. Many shells are very thin, consisting of only one or two laminae, but some grains have a thick shell that makes up as much as three-quarters the diameter of the grain. In grains with somewhat angular cores, the laminae tend to be thinner at the angles and thicker on the sides, thereby rapidly modifying the initially angular core into a well-rounded ooid. Some grains show several concentric laminated zones separated by massive core material, and in places what appear to be bits of relict laminae occur embedded in massive core material. Compound grains, consisting of two or more laminated ooids that are entirely encased by micro-cryptocrystalline core material, are not unusual. Compound grains are usually larger in size, more angular or irregular in outline than the individual ooid. They too commonly have a thin laminated shell.

Volumetrically the core material exceeds the laminated encrustation of the shell. In thin section, between crossed nicols, typical core material is isotropic and from this fact would appear to be amorphous calcium carbonate. Illing (1954) states, however, that X-ray diffraction shows that the cores of the Bahaman ooids, which apparently have the same optical properties, are approximately 95 percent aragonite and five percent calcite. This composition may also hold true for the ooids of Cayo Icacos, although staining with cobalt nitrate does not produce a strong aragonite

FIGURE 44.—Oolite from Cayo Icacos, showing heteractinellid spicule, cryptocrystalline cores, laminated aragonite shells, and granular calcite cement. Several ooids are without any shell; one has six laminae; and the largest grain (lower center) is compound, having a thin zone of cryptocrystalline core material between shell laminae. In addition, several grains have ill-defined outlines indicating partial replacement by matrix calcite. Magnification 480 ×; plane polarized light.

reaction like that of the laminated shell. Most cores show a sparse sprinkling of minute points of birefringence and some have sizable patches of microcrystals in optical continuity.

Rare grains exhibit a spherulitic structure made up of radiating aragonite needles. Some of the cores have irregular patches of rather coarsely crystalline and seemingly secondary calcite and aragonite. Some cores, although these are relatively rare, contain minute fragments of shell or other skeletal material (spicules, fragments of calcareous algae, unidentifiable prismatic structure probably derived from mollusk shell, Foraminifera, and ostracodes). Foraminifera, ostracodes, and heteractinellid spicules are the only readily recognizable organic forms in the rock and may be found in as many as five percent of the grains. The Foraminifera and ostracodes range from very fresh tests, showing neither recrystallization nor solution, to tests entirely recrystallized and incorporated in microcryptocrystalline core. Occasionally one sees a test that is thinly encrusted with one or two oolitic laminae but otherwise contain no microcryptocrystalline core material. The interiors of such shells contain acicular, radiating aragonite. The most curious structures in the cores are the globular clusters and rosettes of minute calcite scalenahedra (fig. 44). These have been identified by Illing (1954, p. 28) as spicules of the heteractinellid *Calcarea*. The example he figured is identical with that of figure 44, a Cayo Icacos sample.

The contact of core with laminated shell and the contact of shell with the intergranular calcite cement is generally sharp. As mentioned previously, in thin section the grains, both core and shell, are light brown, though in reflected light both are pure white. The coloration in thin section is possibly the result of preferential wave-length absorption and diffraction by the surfaces of the many fine crystals composing this material. Traces of boring filamentous algae are found in the rock from Cayo Icacos, at considerable depth below the surface (for example, the floor of the quarry) suggesting thereby a predune date for the activity of these organisms. The algae are mostly long straight forms, rather than the short stubby or vermicular borings figured by Illing (1954, fig. 4). Many of the Cayo Icacos ooids are shattered by what appear to be radial shrinkage cracks, which may cut both core and shell though some are confined entirely to the core and stop at the contact with the shell.

The chemical composition of a sample of the oolitic eolianite from Cayo Icacos has been determined by semiquantitative spectrographic analysis (table 2, see table 3 for the threshold values of this analysis). An analysis of a sample of beach sand from the south shore of Cayo Icacos is given for comparison; this is a rather angular, medium-grained pure shell (carbonate) sand, white except for scattered pink Foraminifera, calcareous algae, and alcyonarian spicules. It consists principally of fragments of calcareous algae, Foraminifera, mollusk shells, echinoid spines, alcyonarian and sponge spicules and with sparse oolitic lumps and grains. It is not certain that ooids derived from the oolite can be distinguished from recently formed ooids (assuming that any exists) in the beach sand, for small derived fragments of bedrock are probably soon stripped of any calcite cement left adhering to them as they are rolled in the surf. In reflected light all the sand grains are a uniform porcelaneous white, and identification of individual grains is generally difficult. The high calcium carbonate content of both oolite and sand is apparent from the analyses. The oolite and the beach sand differ significantly only in the Mg, Fe, and Cu contents. The larger magnesium content of the sand is due to the higher content of skeletal grains, principally coralline algae detritus. The Fe is possibly due to scattered grains of detrital ferromagnesian minerals, mainly epidote, which have been washed to the island from the mainland and form only a very minor constituent of the beach sand. In any case, the analyses are sufficiently different to indicate that beach sand such as we find today did not form the parent material for the oolite.

TABLE 2.—*Percent concentration of minor elements in rocks from Cayo Icacos, P. R.*

[Semiquantitative spectrographic analyses by Janet D. Fletcher]

Description of sample	>10	10–1	1.0–0.1	0.1–0.01	0.01–0.001	0.001–0.0001
Oolitic eolianite from quarry	Ca	------	Sr, Mg	Fe, Ti, Ba, Al.	Cu, Mn, B.	Cr.
Laminated weathering crust on oolitic eolianite.	Ca	Fe	Ti, Mg, Al.	Mn, Sr, Ba.	Cu	Cr, B.
Modern beach sand; south shore.	Ca	Mg	Fe, Sr	Ti, Ba, Al.	Mn, B	Cr, Cu.

Looked for but not found: Ag, Au, Rh, Pd, Ir, Pt, Mo, W, Ge, Pb, Bi, Zn, Cd, Tl Co, Ni, Ga, In, Sn, V, Sc, Y, Yb, La, Zr, Th, Nb, Ta, U, P.

TABLE 3.—*Threshold values, in percent, of elements analyzed by semiquantitative spectrographic method*

Element	Sensitivity	Element	Sensitivity	Element	Sensitivity
Ag	0.0001	Gd	0.01	Re	0.005
Al	.001	Ge	.001	Sb	.01
As	.05	Hf	.05	Sc	.0001
Au	.003	Hg	.1	Si	.0001
B	.001	In	.001	Sm	.1
Ba	.001	K [1]	.1 (0.0001)	Sn	.002
Be	.0001	La	.003	Sr	.001
Bi	.001	Li [1]	.05 (0.0001)	Ta	.1
Ca	.0001	Mg	.0001	Tb	.1
Cd	.005	Mo	.001	Th	.05
Ce	.1	Mn	.001	Ti	.0005
Co	.0005	Na [1]	.1 (0.0001)	Tl	.005
Cr	.0001	Nb	.005	U	.1
Cs	1.0 (0.005)	Nd	.01	V	.001
Cu	.0001	Ni	.0005	W	.05
Dy	.01	P	.1	Y	.001
Er	.01	Pb	.001	Yb	.0001
F	.1 [2]	Pr	.01	Zn	.01
Fe	.001	Pt	.001	Zr	.001
Ga	.001	Rb [1]	.005 (10.0)		

[1] A second exposure is required for the high sensitivity listed.
[2] Fluorine is included when the second exposure is required for K, Li, Na.

DISCUSSION OF ORIGIN

The clear-cut separation of massive core material and laminated shell of the ooids from Cayo Icacos indicates a marked disconformity in the formation of the individual grain. Conditions responsible for the core material were clearly not the same as those that brought about the deposition of the laminated shell. The very fine grained nature of the core material suggests that it probably had its origin as fine-grained lime mud, possibly as a calcium carbonate gel (colloid) which coagulated into small pellets, entrapping in the process some minute shell particles. The precipitation of calcium carbonate as a gel has long been known. Rainey (cited in Vaughan, 1914b; Hunt, 1866; and Harting, 1871) were among early workers producing gelatinous precipitates of calcium carbonate from aqueous solutions. In these experiments crystals later developed from the gel. The tendency for gels to coagulate is also well known. This generally is a response of the charged colloids to similarly charged ions dispersed in the colloidal system. Thus Bradley (1929), making use of the studies of Schade (1909, 1910) on the formation of gall stones, postulated that the ferruginous oolite of the Green River formation was formed by the coagulation of colloidal ferric hydroxide dispersed in a line mud. Such coagulation may mechanically entrap particles of noncolloidal size and form alternate bands of colloidal and entrapped material, as was postulated by Bradley for the Wyoming oolites. Coagulation may also produce a massive structure if crystallization from the gel does not occur, or it may, with crystallization, produce a spherulitic structure. Both Rainey and Harting reported that calcium carbonate gel aggregated into spherulites. Under some conditions the initial crystallization of calcium carbonate has been observed in the laboratory to form spherulites of vaterite or one of the several hydrates of calcium carbonate (Brooks and others, 1950). While these minerals have not been identified in nature (vaterite is said to have been noted in some shells, Dana's "System of Mineralogy", v. 2, 1951) their instability and short life makes it possible that they have escaped detection during the little-known process of lime-mud precipitation of the Bahaman variety. The later conversion of these minerals to aragonite or calcite might effectively destroy the original spherulitic arrangement. We therefore have two possibilities to explain the massive core material of the oolites from Cayo Icacos: (1) There never was an ordered crystalline arrangement in most of them and they preserve fairly intact the vestiges of the original colloidal floccule, and (2) they went through a spherulitic stage which, except for a few rare grains, has been destroyed in the formation of a large number of somewhat differently oriented aragonite crystallites.

Unfortunately, there is little in the way of available field observations on the Bahaman lime muds to guide this speculation. Little is known of the actual equilibrium conditions of the Bahaman lime muds at the time of this formation and even less is known of their diagenetic changes. Vaughan's postulate on the formation of oolite was partly repudiated by him ten years later (Vaughan, 1924) with the recognition that more work had to be done on the subject. This has yet to be accomplished. The Bahaman lime muds have been described as a mixture of minute aragonite needles and calcite (Vaughan, 1914b), somewhat gelatinous when precipitated. Beyond this, little is known about their physical properties.

Much effort has, however, gone into deducing the origin of the lime mud of the Bahaman Banks and the Florida reef tract ever since the middle of the 19th Century, when Louis Agassiz (1851) first commented on these deposits (see Twenhofel, 1932; Thorp, 1935; Illing, 1954, for good reviews of the earlier investigations; also C. L. Smith, 1940; and Illing, 1954, for examples of more recent work in the area). The trend of current opinion is that most of the lime mud of the Bahaman Banks is a physicochemical precipitate from sea water that has become supersaturated with calcium carbonate by warming and evaporation as it passes over the broad, shallow banks. The Great Bahama Bank west of Andros Island, which has a width of 30 miles or more and a depth of less than 3 fathoms, is one of the most well known areas of lime mud deposition in the world. The environment is well suited for the physicochemical precipitation of calcium carbonate (C. L. Smith, 1940). Drew (1914), Kellerman and Smith, (1914), N. R. Smith (1926) and Bavendamm (1932) have demonstrated, however, that ammonifying and denitrifying bacteria are also responsible for some calcium carbonate precipitation on these banks.

Recently Illing (1954) has shown that ooids similar to those making up the rock of La Cordillera, are forming at the present time in a part of the Bahaman Banks that is characterized by lime sands rather than by lime muds. He reports sand-sized grains of microcryptocrystalline aragonite in various stages of induration from the area west of the Ragged Island cays, at the southern tip of the Great Bahama Bank. Furthermore, he finds these grains coated with laminated shells (that is, true ooids) in the sand bars that accumulate west of the several passages that separate the cays. Illing attributes the grains of massive core material to two origins: Fecal pellets and the agglutination by sticky organic materials (such as algal mucilage and Forminifera) of aragonite crystallites formed by physicochemical action. No observations, however, supporting this agglutination hypothesis are given, and the possibilty of flocculation—or even coagulation, like that just discussed for the lime muds—still pertains.

The part of the Bahama bank studied by Illing is sharply terminated on the east, where it drops off steeply to oceanic depths. The line of islands (or cays) parallels the windward (eastern) edge of the bank and is about a mile to the west. It is noteworthy that all the Bahama Islands are similarly elongated parallel to the bank edge and likewise crowd close to the windward, or prevailing current, edge. The depth of the bank in the Ragged Island area is, like most of the Great Bahama Bank, from 2 to 4 fathoms. Illing concludes (p. 85) that the formation of lime sediments

> . . . is most active within a border zone, a dozen or more miles wide, close to the periphery of the Banks. It is here that the cooler oceanic waters are first warmed by the shallow sea bottom, stirred up by the tidal currents, and brought into contact with marine algae which extract part of their dissolved carbon dioxide. All these factors contribute to the supersaturation of the water with respect to calcium carbonate, and

thus cause the change from skeletal to dominantly nonskeletal bottom deposits within a short distance of the ocean edge. Where currents are very strong, aragonite is precipitated on the rolling sand grains in the form of oölitic layers: where they are less powerful, accretion is shown by the formation of rounded grains of aragonite matrix from friable silt aggregates ["core"], and their subsequent cementation into grapestone. The sequence of changes is promoted by a shallow warm sea bottom, which in turn induces swifter tidal currents. The process is thus cumulative, as the shoals of sediment so formed serve to shallow the water still further, till finally the sea bottom is raised to sea level. At this stage the currents become much channelized, and, if sea level is stationary, vertical accumulation is replaced by lateral extension of the shifting shoals. Sea level acts as a base level of accumulation. Any downward movement of sea level would form an elongate island or a series of disconnected dry sand banks, on which wind action would pile up dunes alined approximately parallel with the ocean edge. The arcs of eolian-ridged cays have been formed in this way.

Lime muds are not known to be forming in the immediate vicinity of La Cordillera today. Lime muds do, however, cover the reef flat several miles to the west, at Punta La Bandera, and on some south-coast reefs, although these deposits may result from the attrition of reef material by wave action and biologic activity. The skeletal composition of the beach sand on Cayo Icacos suggests that ooids are not forming today on the bank south of La Cordillera, and that the conditions responsible for the formation of oolitic deposits must have prevailed in this area sometime in the past, probably in the late Pleistocene.

U. S. Coast and Geodetic Survey Hydrographic Chart 904 shows (pl. 10) that a drop in sea level of five fathoms would transform the western part of Sonda de Vieques into a broad bank whose depths generally would be less than three fathoms. A narrow neck of land would jut eastward from Punta Puerca on the mainland for a distance of five miles, and La Cordillera would therefore form the north boundary of a very shallow shoal which would be almost completely landlocked on three sides. Currents would probably enter this broad embayment from both the southeast and the north—those coming from the southeast passing first over the shallowed Sonda de Vieques between the islands of Culebra and Vieques, those coming from the north filtering through the passes between the developing cays along the northern edge of the bank. The hydrographic situation would therefore approach that of the present Bahaman Banks, though on a somewhat reduced scale.

DEPOSITS BY BLUE-GREEN ALGAE

Coastal deposition of $CaCO_3$ by some of the blue-green algae (Myxophyceae) occurs widely in Puerto Rico, particularly in the zone of ocean spray. Unlike the calcareous algae, these simple plants do not precipitate lime within their cell walls but induce encrustation on their surfaces, the precipitation occurring within the enveloping mucilage (Fritsch, 1945, p. 869) or even completely exterior to the organism. The precipitation is apparently the result of the absorption of CO_2 from the surrounding water by the photosynthetic activity of the organism.

Ginsburg (1953b), Mayor (1924a), and Fritsch (1945) among many others have documented the lime-boring activity of the filamentous blue-green algae. The algae, however, play a dual rôle insofar as $CaCO_3$ is concerned. On the one hand they dissolve lime; their method of attack is not known, but according to Fritsch (1945, p. 869) it may consist of solution by oxalic acid. On the other hand, the same organisms are capable of inducing $CaCO_3$ precipitation from surrounding water simply by absorbing CO_2 from the system. The dual rôle, lime dissolving and lime depositing, of these organisms has not been equally stressed in the geologic literature.

DARK BANDS AND EOLIANITE CEMENTATION

A feature of the soilless cemented dunes is the alternation of surface color, generally two shades of gray, disposed in broad, slightly sloping bands. In the higher cemented dunes lighter gray stripes commonly mark the base and the top of the dune, separated by a darker, brown to somewhat olive-gray stripe. This dark band is canted to the south, or landside; and its upper limit coincides with the upper limit of the spray zone. The dark discoloration is caused by blue-green algae of the spray zone. A sample of eolianite from the dark band was examined by Dr. Francis Drouet who identified *Calothrix scopulorum* Born. & Flah. and *Entophysalis crustacea* (J. Ag.) Drouet and Daily. Cross sections of surface eolianite show that these organisms penetrate at least several millimeters beneath the surface of the rock and that this distribution coincides with a thin crust of dense cementation. A causal relation between spray, algae, and cementation is therefore suggested.

The lime-depositing activity of the blue-green algae is prominently indicated by the occasional appearance in the spray zone of gleaming white encrustations on eolianite. This encrustation, which is quite remarkable in appearance, occurs only for relatively short periods and at irregular intervals. It does not seem to be a yearly occurrence. In the spring of 1951 it was widespread in the spray zone of the north-coast eolianite and was particularly thick along the spillway channels of the flat-bottomed pits (which normally have a very high population of blue-green algae). It appeared suddenly, although at different dates, on adjoining coastal localities but by midsummer had almost completely disappeared. Samples of the crust were sent to Dr. Drouet who identified *Plectonema terebrans*. Gom., *Entophysalis crustacea* (J. Ag.) Drouet and Daily, and *Brachytrichia quoyi* Born. & Flah., as the algae immediately underlying it and which are very probably responsible for the deposit.

The encrustation is a tough veneer, about 0.2 mm thick, white in color and porcelaneous in texture. The reason for its sudden appearance is not known; perhaps it is due to an epidemic or efflorescence of the responsible algae brought on by sudden and transitory changes in the composition and temperature of the sea water. Perhaps it is some change in the chemistry of the ocean water which makes it possible for the algae of the spray zone to precipitate lime. In any case, it demonstrates the ability of the blue-green algae of the spray zone to fix $CaCO_3$ in eolianite.

BEACH VARNISH

At two places on the north coast, one just west of Camuy and the other west of the mouth of the Río Grande de Manatí, a thin (0.4 mm) encrustation of slightly translucent lime of high varnishlike luster occurs, coating the beachrock pavement at about high tide level. This encrustation is closely analogous to the white encrustation just described. When leached in dilute hydrochloric acid it was seen to be underlain by blue-green algae, principally gelatinous clumps of the coccoid *Entophysalis crustacea* (J. Ag.) Drouet and Daily. Emery, Tracey, and Ladd (1954, p. 45) mention varnished beachrock on Bikini Atoll but did not investigate its origin.

LAMINATED CRUST ON REEF LIMESTONE, ISLA MONA

At Punta Oeste on the west coast of Isla Mona, about two-thirds of a mile south of the airplane landing strip, along the low shore fronting the section called La Sardinera (chap. C, pl. 12), a laminated algal deposit encrusts the rocky shore. The crust coats a much pitted bench formed at about high-tide level.

The underlying rock is a fairly dense, cemented shell sand and is part of an elevated Pleistocene reef. The crust is about an inch thick and consists of dense, aphanitic calcite, tan to cream in color and finely laminated. The algae responsible for the crust thrive as a thin mat on the surface. When seen in the field their filaments were lightly encrusted with fine calcite crystals. Momentary immersion in dilute hydrochloric acid was sufficient to remove this encrustation and expose the algal growth. This was done on a sample of the crust that had been in the writer's possession for 4 years, and the algae exposed were still completely viable. The algae were identified by Dr. Drouet as *Mastigoceleus testarum* and *Entophysalis crustacea* (J. Ag.) Drouet and Daily. The laminae are therefore built up by successive colonies of algae, and if one knew the frequency with which new colonies are established the age of the crust could easily be determined.

ALGAL BRECCIA WEST OF PONCE

About 4 miles west of Ponce on the south coast, Highway 2 cuts into the south slope of a hill of limestone of early Miocene age (the upper member of the Ponce limestone) and skirts the shore at an altitude of about 25 feet. On the north side of the road, in a small rock shelter, a layer of breccia forms the surface of the hill slope. Close inspection shows that the individual breccia fragments consist of embayed pieces of light cream colored limestone encrusted with a laminated deposit of terra-cotta colored carbonate. These are embedded in a pink dense carbonate deposit (fig. 45). Except for the cream-colored limestone fragments, which clearly come from the upper member of the Ponce limestone, the entire rock may be the result of algal activity. The laminated shell that surrounds the limestone fragments ranges in thickness from being barely visible to 5 mm. In some pebbles the shell is very much thicker on one side than another and there are marked unconformities in the laminae. Bradley (1929, pl. 46A) figures on algal cobble from the Green River formation that resembles these pebbles. He explains the unconformity in the laminations as resulting from the shifting about of the cobble during the course of algal encrustation, the cobble having rested first on one base then on another. The Puerto Rican pebbles on the other hand appear to be the result of the rifting of already encrusted pebbles which later received additional encrustation.

Although the pink matrix lacks laminations it, too, is probably algal. In thin section it is brown microcrystalline calcite with a dimly discernible texture of coalesced oval to rounded shapes, averaging about 0.25 mm in diameter. Scattered throughout are calcite-lined vugs and a "marbleized" pattern of medium-grained colorless calcite in curved and ramifying shapes that may represent casts of algal filaments. Also scattered throughout the matrix are many euhedral to subhedral calcite rhombohedra about 0.02 mm across. A few minute and nondiagnostic shell fragments make up the recognizable organic component.

Microscopically, the laminated shells of the pebbles are in many respects much like the surrounding matrix, although there are no vugs and the clear medium-grained calcite is arranged concentrically to form the

FIGURE 45.—Partly polished face of algal breccia from above highway, 4 miles west of Ponce. Small pebbles in lower right show rupture and the start of a second stage of encrustation.

thin white laminations. The main component of the typical laminated shell is microcrystalline calcite which is somewhat more even grained than in the matrix. Concentrations of iron oxide in poorly defined vermicular forms may represent the outline of algal filaments. Scattered throughout the laminated shell are euhedral to subhedral calcite rhombs similar to those in the matrix.

The contact of the shell with the limestone nucleus is not sharp and is characterized by tentacles and strings of the brown microcrystalline shell material projecting between the coarse calcite of the limestone. obviously destroying some of the crystals in the process but clearly isolating others. The calcite crystals isolated in this manner resemble somewhat the calcite rhombs scattered throughout the laminated shell or matrix, although scrutiny shows that the latter are more euhedral, clearer, and more uniform in size than the former. There is the possibility therefore that they are of different origin and that those in the matrix are the product of algal activity.

This deposit raises more problems than it elucidates. Is the laminated shell a replacement of the limestone nucleus or is it a true encrustration? Signs of replacement of the nuclear limestone by microcrystalline shell material points to a replacement origin for at least the inner part of the shell. This does not, however, eliminate the possibility that most of the shell was formed by encrustation. What is responsible for the cessation of laminar growth and the development of the massive matrix? Perhaps two algal species are indicated, the matrix specie appearing later on the scene, growing up and around the pebbles. Perhaps the pebbles were displaced from their original environment to that of the matrix algae. Moreover, the nature of the depositional environment is not clear. Did the algal breccia form in essentially the same environment that we find it in today—like the subaerial crust of Cayo Icacos, which will be described next? Or did it form in a marine environment, dating perhaps from a higher sea level of the Pleistocene? Or does it perhaps mark the site of a former fresh-water spring or drainage from such a spring?

SURFACE CRUST ON OOLITIC EOLIANITE, CAYO ICACOS

A thin brown crust coats much of the surface of the easternmost cemented dune on Cayo Icacos, including the highest point of this hill (altitude of about 45 feet). This crust is possibly the result of the lime-boring and lime-depositing activity of filamentous algae, although conclusive proof of this is lacking. The Cayo Icacos crust averages 5 mm thick, is rather crudely laminated, and consists of dense, exceedingly fine-grained calcite (determined by X-ray diffraction analysis). The surface is slightly pustulate and is light buff in color. Beneath the surface lamina, which is paper thin, is a dark brown layer, about 1 mm thick. The remainder of the crust, underlying the dark lamina, is cream colored, varying slightly from medium to light shades, in 2 or 3 wavy and somewhat discontinuous layers. A zone of small black flecks, which under the microscope are seen to be small subspherical grains and dendritic growths (manganese oxide?) occurs about midway in depth.

In thin section the entire crust is seen to consist predominantly of granular, submicrocrystalline calcite, with a grain size of 0.001 mm or less in diameter, distinctly brownish in plane polarized light and with aggregate high birefringence between crossed nicols. Irregular nests and elongated somewhat branching bodies of medium-grained clear calcite up to 0.2 mm in length and 0.02 mm in width are scattered throughout the microcrystalline groundmass. The groundmass itself exhibits an ill-defined, barely discernible mottled texture which is caused by slight differences in grain size. Sparsely scattered throughout the crust are ooids similar to those making up the underlying rock. Although some of these show various stages of transformation to the submicrocrystalline groundmass of the crust, many seem unaltered, preserving intact cryptocrystalline core and laminated aragonite shells.

The lamination of the crust is not particularly evident when studied in thin section. The dark-brown zone is slightly ruddier in color but otherwise is similar to the cream-colored material beneath. Dissolved in monochloracetic acid, the deep brown layer forms a large amount of iron oxide gel. Semiquantitative spectographic analysis of a cross-section sample of the entire thickness of the crust shows an iron content 100 times greater than that of the underlying oolitic limestone (table 4). Undoubtedly most of the iron reported for the crust is contained in the brown layer. Other differences in chemical composition between crust and underlying rock are a "ten-fold" increase in manganese, titanium, and aluminum, and a "ten-fold" decrease in strontium and boron in comparison with the oolite.

The contact of the crust with the underlying oolite is fairly sharp, although tentacles of the brown submicrocrystalline calcite of the crust project down into the fresh rock to a depth of about 5 mm. This encroachment is readily seen in plain polarized light because of the brown coloration of the crust material and the clear color of the calcite cement of the oolite. The tentacles of crust work into the oolite along the calcite cement, tend to keep to the interior of the cement and to eschew the bladed calcite prisms that are firmly attached to the ooid walls. Careful scrutiny shows that the initial development of submicrocrystalline calcite occurs at the interfaces of the interlocking calcite granules. Where the ooids are affected, however, it is the cryptocrystalline cores and not the oolitic laminations that are replaced by crustal material.

In one thin section the outlines of what may possibly have been filamentous algae are apparent. These are dark rodlike shapes, 0.0015 mm in diameter and generally between 0.015 and 0.020 mm in length, with some filaments as long as 0.040 mm. Each thread consists of a string of short rectangular to nearly spherical cells. These filaments are lacking from the upper part of the crust and are most numerous at the base of the crust and in the underlying oolite for a few millimeters beneath the crust, where they occur only in the ooids and not in the microcrystalline alteration of the cement.

It seems clear from the relict ooids scattered through the crust, as well as from the tentacles of crust material projecting into the underlying rock, that the crust has developed downward from the surface and has not been built up by accretion. If the crust is primarily due to algal activity, the difference in chemical composition between crust and parent rock may have resulted from the ability of the algae to fix certain elements selectively. The pronounced concentration of iron in the top millimeter of the crust is thus possibly due to the greater availability of iron at the surface, coming perhaps from soil, humus, the atmosphere, and sea spray. With depth this supply of iron is possibly cut off, and the deeper part of the crust by its faint coloration shows only a very slight iron enrichment over the composition of the parent rock. Many of the blue-green algae, such as the genera *Lyngbya*, *Microcoleus*, *Anabaena*, *Apanothece*, and *Chamaesiphon* (see Fritsch, 1945, p. 869), deposit iron hydroxide in or upon their sheaths and these may have been partly responsible for the crust.

The possibility that the Cayo Icacos crust formed in a marine environment is remote because of the lack of other evidence of marine inundation of the present topography; and there are scant geologic grounds for thinking that it formed other than subaerially, occurring as it does on the surface of the highest hill on a very young island. Although the crust is outside the normal spray zone, it is close enough to the ocean to receive fine spray and salt dust. The responsible algae may therefore belong, like others already discussed, to the salt-spray ecologic niche. The reader will note, however, that the possibility has not been eliminated that the crust is of a physiochemical origin. An explanation for this curious deposit, like all other coastal deposits of $CaCO_3$, awaits the necessary intensive study.

CORAL REEFS AND SAND CAYS

The following notes are the result of a cursory field study of several of the more accessible coral reefs on the Puerto Rican coast, supplemented by an interpretation of aerial photographs and hydrographic charts. The reefs of Isla Mona are discussed separately (see chap. C, this report). No study was made of the reefs in Sonda de Vieques except those along the east coast of Puerto Rico.

Corals grow in the waters of all four coasts of Puerto Rico (fig. 26). On the north coast coral colonies that are vigorous enough to raise reefs to intertidal levels are limited to approximately the eastern third of the coast. On the other three coasts, coral reefs, though spotty in occurrence, are widely distributed. The structure of the reefs is very similar to other reefs of the Caribbean as well as from other seas (for bibliographies and summary descriptions see: Vaughan, 1919; Kuenen, 1933 and 1950; Umbgrove, 1947; Fairbridge, 1950; Ladd and others, 1950; Pugh, 1950; Newell and others, 1951; Tayama, 1952; Cloud, 1952b; Emery and others, 1954). The Puerto Rican reefs will be summarily described, starting with the reefs on the north coast and proceeding systematically in a clockwise direction about the island.

A broken chain of poorly developed reefs, lying for the most part about a mile offshore, extend eastward from the city of San Juan to Punta Vacía Talega. This reef, or reefs, from its alinement with eolianite ridges, is interpreted to consist of relatively thin coral colonies growing on a shallow eolianite platform. At Isla Piedra the eolianite basement rises above tide level.

The writer has examined the reef closely at only two places, though he observed it several times from the air. Small shallow reef patches are readily accessible off Punta Escambrón, at the eastern tip of San Juan; a glass-bottomed boat makes regular visits to the reef northeast of Isla Verde. Here a typical shallow reef assemblage, dominated by *Acropora palmata*, hydrozoans, sponges, and gorgonians, rises to within a fathom of the surface. In slightly deeper waters large hemispheric corals and *Acropora cervicornis* occur.

From the mouth of the Río Grande de Loíza east to Punta Miquillo, scattered reef patches extend half a mile out from shore (fig. 51). On the west side of Punta Miquillo and on the east side of the adjoining Punta Picúa a well-formed fringing reef occurs that averages about a quarter of a mile in width. It is probable that both Punta Miquillo and Punta Picúa were formerly sand cays developed from these reefs, which since have been tied to the mainland by a broad marsh and narrow sand tombolos. Fringing reefs similar to those at Punta Miquillo and Punta Picúa occur at the ends of all north-coast promontories east of here. Some of these reefs probably rest on rock foundations, but those west of Luquillo (fig. 15) occur a considerable distance from rock outcrops and therefore may be built on sand or mud.

The fringing reef at the end of Punta La Bandera (better known as Luquillo beach) is one of the most accessible on the island. It is about 0.3 miles wide and is entirely exposed at low tide (fig. 15). It is highest at the outer margin, which rises to about mean tide level. The outer margin is broadly scalloped but not noticeably spurred. The edge is slightly serrated, or toothed. Only the outer margin of the reef, in a zone about 10 yards wide, contains living reef corals and *Lithothamnium*. Behind this marginal living zone is a reef flat (consisting of dead coral, dead calcareous algae, sand, and lime muds) that slopes very slightly landward. The reef flat exhibits a certain zoning, with a broad though irregular outer sandy zone—littered with broken fragments of *Porites porites*, a few living *Maendra areoleta* and holothurians in shallow pools, and sparse eel grass—that grades landward into a zone of soft lime mud and fine coral sand. In the latter zone there is a paper-thin surface layer of cream-colored lime mud overlying soft black lime mud smelling faintly of H_2S. A similar relation between light and dark mud was observed by Field (1932, p. 489) in the extensive lime-mud deposits of the Bahamas, where he noted that the organic mud was also high in $CaCO_3$.

A narrow channel cuts the reef near the west end. This widens shoreward and joins the lagoon at the southwest edge of the reef. The reef flat, when seen from the air, is broadly scarred by radial lines (the "trickle zone" of Fairbridge, 1950) that are formed by the drainage of the reef flat during low tide.

A short stretch of reef similar in every respect to that of Punta La Bandera except that it is separated from shore by a mile of open water occurs about a mile and a quarter to the northwest. Smaller reef patches rise from the sandy bottom between these two reefs.

Small reef patches and poorly developed fringing reefs characterize the rocky headland between Punta La Bandera and Cabezas de San Juan (Cape San Juan). A fringing reef several hundred yards wide marks the western end and part of the north shore of Cayo Icacos, lying a little over a mile east of Cabezas de San Juan.

Much of the east coast north of Punta Lima is bordered by fringing reefs. Some of these reefs, judging from their location at the edge of tidal swamps, probably rest on sand or mud foundations. These reefs generally have a well-formed *Lithothamnium* rim and spurs and seem to grow for the most part from

FIGURE 46.—Coral reefs off Central Aguirre, south coast. Cayos Caribes on right, Cayos de Barca on left; low tide. Note mangrove-covered sand cays and recurved ends of reefs. Turbid water in bay is flowing through passage during tidal ebb, causing rip-current eddy.

a 2- to 3-fathom platform. Many small patch reefs that do not reach intertidal level also occur off this stretch of coast.

On the south coast of Puerto Rico a fringing reef extends almost continuously for four miles along the coast between Cabo Mala Pascua to the bay called Puerto Patillas. This reef is exposed at low tide.

About a mile offshore between the Bahía de Jobos (Central Aguirre) and Isla Caja de Muertos lie a line of recurved ribbon reefs (Fairbridge, 1950) and associated sand cays. This alinement of reefs begins on the east at Punta Ola Grande, where for several miles it is merely a narrow fringing reef on the Caribbean side of a sinuous compound sand spit. From Punta Pozuelo, the southwest end of this spit, a reef which is about a quarter of a mile wide projects to the southwest for a distance of 1½ miles (fig. 46). On the lee side of this reef are a score of narrow sand cays (Cayos Caribes) oriented normal to the reef margin and separated from each other by drainage channels. These channels serve the purpose of draining to the bay behind the water that washes over the higher, outer margin of the reef. This reef alinement continues to the west, with the Cayos de Barca, Cayos de Pájaros, Cayo Morrillo, Cayos de Ratones, Arrecife Media Luna, Cayo Alfeñique, Cayos de Caracoles, Cayos Cabezazos, and Cayo Berbería. All the reefs have sand cays, for the most part covered by vegetation, on the north to west (lee) sides. Crescent-shaped Cayo Alfeñique, with its arms pointing to the northwest, shows the importance of the southeast winds and the northwest and westerly currents in the molding of these features. These recurved reefs and associated cays substantiate the thesis of Vaughan (1914a), Umbgrove (1947) and others that they represent the modifying work of wind and waves.

The western half of the south coast has several stretches of fringing reefs and many small recurved reefs with associated sand cays. A fringing reef is easily accessible from Highway 2 about 5 miles southwest of Ponce. This reef consists largely of *Lithothamnium* and has a deeply scalloped rimmed margin that rises to about mean tide level. The reef ranges from 100 yards to several hundred yards in width. West of Ponce reef patches and elongated or ribbon reefs become more numerous, and west of Punta Jorobado there is a veritable archipelago of these reefs and their accompanying sand cays. For the most part they lie a mile or more off the present coast and trend generally east-west. Off the small fishing village of Parguera these reefs have an arcuate arrangement, concave to the south, which matches the trend of a limestone cuesta along the coast at this point. This suggests that the reefs are founded on rock and their alinement reflects submerged bedrock highs. Many of the sand cays contain a dense mangrove cover, and local fishermen report that some of the cays have disappeared during storms. Undoubtedly the stability of these sand cays in the face of large waves is slight.

Between Cabo Rojo, the southwest tip of Puerto Rico, and Mayagüez on the west coast are many stretches of fringing reef from 100 to 200 yards wide. These reefs are not flourishing and appear to be suffering from a greater than average turbidity of the water and unusually slight wave action along this stretch of coast. Both of these characteristics are probably caused by the broad shallow bank that lies immediately offshore. The bank not only minimizes wave action against the shore by reducing wave energies but also limits the amount of ocean water available for diluting land drainage.

A poorly developed fringing reef occurs on the north side of the Rincón peninsula from Punta Higüero nearly to Punta del Boquerón, just south of the mouth of the Río Culebrinas. From this point north and then east along the north coast no coral reefs are found except for scattered small patches that for the most part do not attain intertidal levels.

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FACTORS AFFECTING THE DISTRIBUTION OF CORAL REEFS ON THE NORTH COAST

The lack of well-developed living coral reefs on much of the north coast is curious when one considers that this is the windward coast of the island and receives the most severe buffeting by the surf. There are several possible explanations for this:

1. The watershed of the north coast is the largest of the island, as to both area and discharge, and the large volume of silt-laden waters from the north-coast rivers may be the most important factor inhibiting coral growth. It is well known that corals have little tolerance for waters of low salinity. Likewise, it is recognized that light is essential for their growth. Turbidity reduces light transmission of water and thereby limits the depth of coral growth (Yonge, 1940; Kuenen, 1950, p. 417; Cloud, 1952b, p. 2131). Although the salinity of the north-coast water samples described earlier in this report (table 1) indicated no measurable dilution by river waters, there is no doubt that flood discharges from the several large rivers reduces the salinity of the marine waters about their mouths. After heavy rains the long plumes of muddy river water off the mouths of the rivers (generally diverted to the west) may interconnect one major river mouth with the next, and form a widespread apron of turbid, low-salinity water along much of the coast. The possibility that these turbid waters are responsible for inhibiting reef growth is given some support by the fact that well-formed reefs occur only east of the mouth of the easternmost major river—the Río Grande de Loíza.

2. Because of the large storm waves that rake the north coast from time to time, reefs growing on sandy or muddy bottoms in relatively shallow water have particularly unstable foundations. Most known reefs in Puerto Rican waters are in shallow water and a majority of them seem to rest on a 2½- to 5-fathom platform. These depths are within the range of large storm waves that would stir up the sand and mud and, in general, both destroy the foundation of young reefs that are struggling to establish themselves and smother them in the stirred-up sediment.

PROTECTED RIVER MOUTHS

The mouths of many Puerto Rican rivers that drain to the wave-swept east and north coasts exhibit a tendency to avoid sandy coastal stretches and to favor positions that hug close to the sides of rocky promontories. This type of river mouth, here termed protected river mouth, characterizes Ríos Guayanés, Humacao, Pitahaya, Sabana, Cocal, de la Plata, Cibuco, Manatí, and Arecibo.

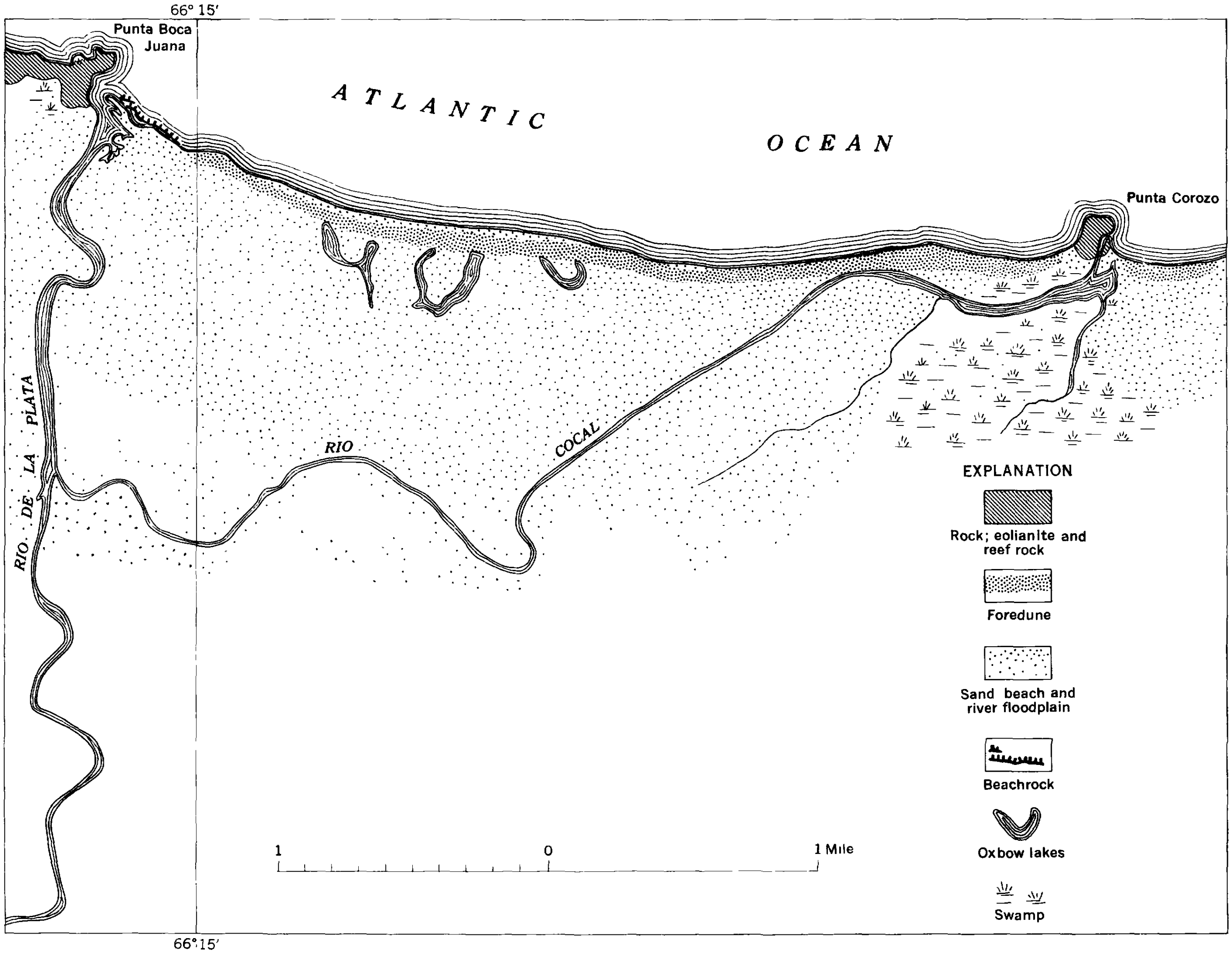


FIGURE 47.—Example of double river outlet, both mouths protected; west of San Juan.

The adjective "protected" seems appropriate because, in effect, the river seeks out the protection of a rocky shore in order to maintain an open, unencumbered outlet. Normally rivers that let out on sandy shores are clogged by sand bars built across their mouths by wave action, which in effect, are nothing more than the extensions of the flanking beach. Most of the Puerto Rican rivers emptying into the Carribbean Sea or the Mona Passage, and several on the north and east coasts that have not yet attained a protected position, are barred with beach material during most of the year. The permeabilities of the barriers are such, however, that the normal discharge of the rivers is able to seep through. With the rapid and substantial augmentation in river discharge that accompanies particularly heavy precipitation in the drainage basin, the bar may be overtopped and then swept away, thus permitting the river to empty unimpeded into the sea. Following this, the sand bar is rapidly rebuilt.

While this process of alternate clogging and clearing of the river mouth seems to provide an adequate system for the south and west-coast rivers, there are two factors which explain the contrasting prevalence of the rock-protected mouths on the north and east coasts. The first is that wave action is stronger on the north and east coasts, in consequence of which the construction of the mouth bar proceeds more rapidly and builds up to greater heights than on other coasts. The second factor is that the larger normal discharges of the north- and east-coast rivers generally exceeds the transmissibility of the fine sand barriers that plug their mouths. This means, then, that a north- or east-coast river will tend to overflow its low banks and form marshy sloughs in its lower reaches. These overflow channels and marshes extend roughly parallel to the shore in the low swale that is generally situated just behind the sandy beach ridge. At high water they overflow the barrier at the lowest point along the beach. This generally is at the point where the beach ridge meets a rocky headland, for it is here that waves are unable to pile up much sand. This dearth of sand is probably due mainly to the fact that some headlands project obliquely from the shore and thereby provide a shelter from sand deposition by waves and longshore currents. Once a river has attained a mouth having the advantage of such a protected position, it will retain this mouth as a stable outlet. Only with extremely large discharges or following serious beach erosion by large storm waves will the river re-establish a nonprotected outlet. Such an outlet, however, is of necessity short lived.

RÍO GRANDE DE LOÍZA

This river (fig. 7, 51) exhibits several essential conditions for the formation of the protected mouth, even though it has not yet attained this stage of development or has lost a protected mouth in the rapid prograding of the deltaic shoreline about its mouth. The river mouth, particularly during prolonged dry periods when river flow is much reduced, is subject to damming by a heavy beach bar. This, in turn, brings about widespread flooding of the coastal plain. Because of the economic seriousness of these floods the sand-bar barrier must be dug out by hand labor whenever it builds up to the threatening height. In essence, therefore, the river maintains the nonprotected position of its mouth only by the intervention of man. Without this it would establish a protected mouth at the side of Punta Vacía Talega to the west. That it had not done so at the time of the first colonization of Puerto Rico in the early 16th century suggests that the intervention by man in the maintenance of its outlet may date from early Indian times. In this regard it is interesting to note that another aspect of the Río Grande de Loíza may be the result of the engineering activity of the Indians. The river has a remarkably straight course for the last 3 miles—very unlike the meandering paths followed by all the other rivers of the north coast as they cross the marshy coastal plain. Moreover, abandoned channels (fig. 51) show that today's straight course did not always exist. Is it possible, then, that the almost unnatural straightness of the river is the result of channel straightening and outlet maintenance by the aboriginal population? The question rightfully belongs to archeology. As yet no data have been unearthed to support such a hypothesis (Rouse, 1952a). Much remains, however, to be learned of Puerto Rican prehistory.

RÍO DE LA PLATA

The Río de la Plata enjoys the double security of two protected mouths. The mouth of the principal river channel is in the shelter of Punta Boca Juana, north of the town of Dorado. This is at the western edge of a broad alluvial tract over which the river flows in its lowest course. Branching off to the east from the main channel of the river and about 1½ miles south of the mouth is a narrow overflow channel, the Río Cocal, which has an outlet 4 miles to the east (fig. 47). The mouth of the Río Cocal empties at a small point of sandy reef limestone, Punta Corozo, through a narrow passageway eroded in the limestone.

RÍO GRANDE DE ARECIBO

This large river, like the Río de la Plata, has two outlets, although unlike the latter river only the auxiliary outlet is protected. The major trunk of the river lets out at the east edge of the town of Arecibo where it cuts through a broad sandy beach. During most of the year, however, this outlet is closed by a bar of beach sand. A perennial outlet is maintained by means of a right-bank lateral channel that connects with the main trunk just in back of the mouth and that empties into the ocean at the side of the rocky hill about a mile to the east. The reason the main stem of the river has not yet migrated to the protected mouth is probably that the flood discharges of this river are generally great enough to wash out the bar at the mouth. In recent years this process has been helped by man and at the present time an elaborate tidal gate has been placed across its mouth.

BEACH-FACETED PEBBLES

The faceting of pebbles can be achieved just as effectively by the abrasion of beach sand, as it shifts back and forth with the swashing of the surf, as by wind abrasion, glacial scour, or any other natural grinding process. This should be given recognition in considering the environmental significance of faceted pebbles in the geologic section.

Good examples of beach-faceted pebbles (fig. 48) were found on the beach just west of the mouth of the Río Grande de Manatí. They probably occur elsewhere, where the essential conditions are met (Frankel, 1955, describes them from South Africa). The faceted pebbles are from conglomeratic beachrock. The process apparently depends on (a) the pebble being held firmly in the beachrock, and (b) the loose sand that veneers the beachrock, and that is rolled back and forth with the swash of each wave, being composed mainly of hard siliceous minerals rather than the softer carbonates. The abrasive action of the shifting sand grinds the surface of the beachrock. Later destruction of the beachrock by solution releases the faceted pebbles; in the locality just mentioned they are found lying loose about the beach.

FIGURE 48.—Beach-faceted pebbles from beach west of mouth of Rio Manati. Upper and lower left pebbles were still partly embedded in beachrock pavement.

Distinguishing between beach-faceted pebbles and ventifacts in older sedimentary sections should not be difficult. The difference in sedimentary environment should provide a clue, the former type occurring in littoral marine sediments and the latter in deposits with continental characteristics. The surface of the facets should also provide a useful criterion. Ventifacts not uncommonly exhibit a minor pitting and fluting of the facet due in part to the delicate etching out of minor differences in hardness. The grinding of beach sand on the other hand is a much more massive and uniform process. Facets are worn smooth; there is no minor pitting or fluting that would reflect a one-way movement of the abrasive. The sand shifts back and forth and the result is an abrasive action similar to that imparted by a grinding lap after a specimen has been shifted about on the surface of the wheel.

QUATERNARY SHORELINE CHANGES

The following notes attempt to reconstruct several of the coastal changes of Puerto Rico during the last hundred thousand years and establish the stratigraphy of some of the Quaternary coastal deposits. Most emphasis is given to the north coast and the varied sequence of rocks that are found there—which in the past have been lumped under the term "San Juan formation." While the full significance of these rocks await the clarification that will come only with detailed study, the following remarks will sketch in the general framework of the geology and suggest the position of the deposits in the Pleistocene sequence.

AGE OF PRESENT SEA LEVEL

The term "present sea level" as used here is the present mean sea level plus or minus about two feet. Criteria that are discussed below for recognizing mean sea level, such as beach ridges, beachrock pavements, sea-level nips, and tidal terraces, allow a margin of error that in the writer's opinion is about two feet in either direction. The margin of error is due to uncertainty as to the maximum altitude range of several of the physiographic features and the lack of precise measurement of the features themselves and of the factors controlling their position. Thus, the writer feels fairly certain that the upper level of a sea-level nip lies at an altitude that is close to what he judges to be mean high wave crest, but it is highly doubtful if he could determine this level with a precision greater than about two feet. Fortunately, the small tidal range of the Puerto Rican coast has resulted in intertidal markers of exceptional usefulness for the purposes of this study.

Dealing in terms of "present sea level" implies a certain stability of that level. To some readers this may appear an unjustified assumption, inasmuch as evidence gathered in other places has suggested to other workers that the relative position of sea and land has been continually changing during Recent time. For example, H. L. Movius, Jr., (1953) shows a series of curves of relative sea levels in northeast Ireland, in which the last 4,000 years have been characterized by continual change; Umbgrove (1950, fig. 32) has come to a like conclusion concerning sea levels in Holland; and several comprehensive tide-gage studies, such as those of Gutenberg (1941) and Marmer (1949), indicate a decided shifting of sea level within the past 100 years. In Puerto Rico, on the other hand, there is apparently convincing evidence of stability—within the range indicated—of the present sea level for a considerable period of time. Hence to the writer it seems as justifiable to refer to the present sea level as a stillstand as to refer thus to any of the past sea levels that have left their mark in well-formed marine benches or beach deposits—recognizing always the possibility of continual fluctuations within the described limits. The writer suggests that the eustatic fluctuations recorded by tide gages represent fluctuations within the range of present sea levels as defined above.

ADVANCING SHORELINES AS GAGE

Three coastal areas of Puerto Rico possess a broad development of old beach ridges that give strong evidence of a long history of shore advance and permit a rough estimate to be made of the length of time entailed by this advance. These are: the Ensenada de Boca Vieja, just west of San Juan (fig. 49); the coastal

Figure 49.—Ensenada de Boca Vieja. From Bayamón topographic sheet.

Base from U.S. Geological Survey topographic map, Bayamón quadrangle area about the mouth of the Río Grande de Loíza, extending east to Punta Miquillo (fig. 51); and a short stretch of coast southeast of Ponce at Punta Cabullón (fig. 52). The deltaic nature of these coasts has already been mentioned. In the first two of these areas there is a belt of younger ridges that rise to, or close to, the height of those marking the present shores. But behind this belt is a swampy tract and a belt of ridges that are 6 to 10 feet lower. It seems reasonable to conclude that the outer belts of higher beach ridges were fashioned by the sea at present level, whereas the older ones possibly date from times when sea levels were not more than 2 fathoms (12 feet) lower than at present. In the Punta Cabullón area the altitude of all the beach ridges is the same as the altitude as those that are forming today. There is no evidence that any of these older beach ridges were formed during periods of higher sea level.

The length of time it has taken for a shore to advance from the oldest beach ridge to its present position is estimated by extrapolation based on the amount of beach advance that has taken place in a marked time interval. This can be done where a "historic" site falls within the belt of fossil beaches or where records, or old maps, allow some estimate to be made of shore advance within a given time interval. Thus, for an early colonial town site or an archaeologic site whose approximate dates are known, it is assumed that the site, when established, was on the shore. Because this may not actually have been so, we determined in this manner a maximum rate of beach advance which, when divided into the total width of higher beach ridges, yields a minimum figure in years for the duration of present sea level. This minimum figure is supplemented in two places by measurement of beach advance over a 15-year period made on photographs from the 1936 and 1951 aerial surveys.

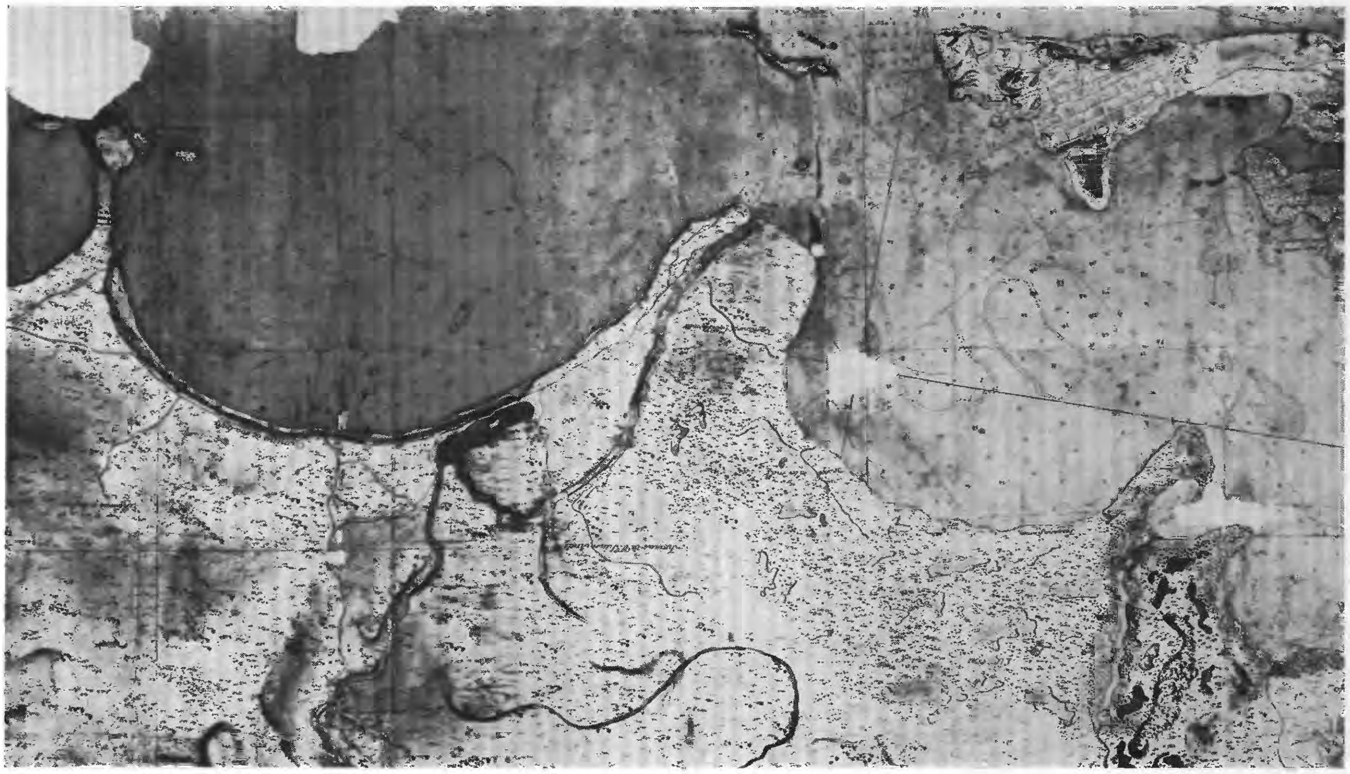
Obviously, such a semiquantitative method contains a full quota of assumptions that may stretch its numerical validity fairly thin. Fortunately, most sources of error tend to minimize the computed age of the beach-ridge festoons; and, for its geologic interest, a minimum age is more important than a maximum age. Among the sources of error are: (a) A variable rate of shore advance, including the possibility that intervals of retreat have alternated with intervals of advance. Alternate shore advance and retreat are probably impossible to detect or evalute. Similarly, variations in the rate of advance cannot be detected. Considering, however, the probable constancy of pertinent geologic factors, such as the amount of sand brought down by the rivers and the chances of sand being lost from the area by longshore drift at different stages in the building out of the shoreline, the rate of advance may be fairly constant for a given shore. (b) The uncertainty whether the older beach ridges in the Loíza Aldea area (fig. 51) are very low because they were formed when the sea level was one or more fathoms lower than at present, or whether they are low because of erosion. Because these questions cannot be resolved, only those beach ridges whose topographic expression is visible on the ground and which have approximately the same altitude as present ridges are utilized in the measurement—which, again, tends to minimize the computed age.

ENSENADA DE BOCA VIEJA

At the midpoint of the bay (fig. 49) a belt of beach ridges extends back for about 4,100 feet from the present shore. These ridges are clearly discernible on air photographs but do not find sharp expression on the topographic map.

The only basis for judging the advance of this shore is by the use of old maps. Inaccuracies of cartography in the 18th-century maps allow, however, only a general impression to be gained. Two of the better maps of that century are shown in figure 50. The oldest of the two, by Francisco Fernández Valdélomar (1747), seems superior to that of Thomas O'Daly (1776) in the delineation of the Río Bayamón. By comparing these maps with recent topographic maps of the U. S. Geological Survey (fig. 49) it will be seen, using the course of the Río Bayamón (particularly its secondary outlet) and a road that skirts the river on the west as a guide, that there has been little change in the shoreline during nearly 200 years. From an examination of abandoned courses of the river that are evident in places on the aerial photographs, it seems very possible that the shore has advanced only about 200 feet since the survey for O'Daly's map was made in 1776. Fernández Valdélomar's map substantiates the impression of only slight shore advance. There was no advance of the shore between 1936 and 1951; in fact, there was an appreciable retreat (probably as a result of sand-digging by man). A well-defined beachrock pavement, which marked the shore prior to the massive removal of loose sand from behind it by shovel and truck, may have marked a relatively stable shoreline here.

If the shoreline advanced 200 feet in 160 years (1776 to 1936), we can compute, by simple ratio, about 3,300 years for the accretion of 4,100 feet of shoreline at Ensenada de Boca Vieja under a relatively stable sea level. The degree of uncertainty of the figure can be gaged from the data. In the writer's opinion, 200 feet of beach accretion since 1776 is very possibly too large, which would suggest an even greater age for the present sea level.



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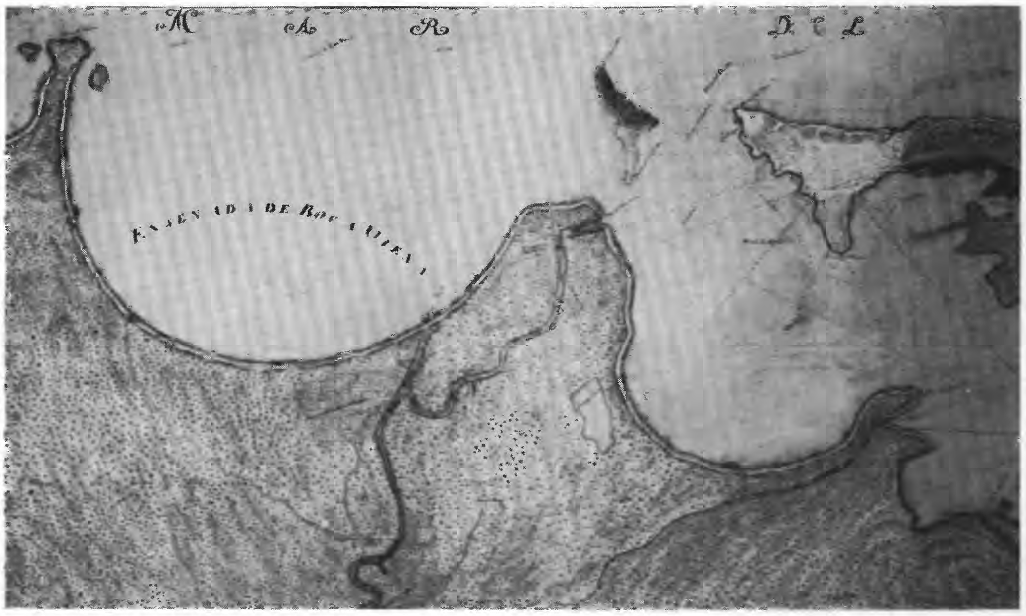


B

FIGURE 50.—Eighteenth-century maps of the Ensenada de Boca Vieja, by (*A*) Thomas O'Daly, 1776; and (*B*) Francisco Fernández Valdélomar, 1747. Both maps reproduced by courtesy of the U. S. National Park Service, San Juan, P. R.

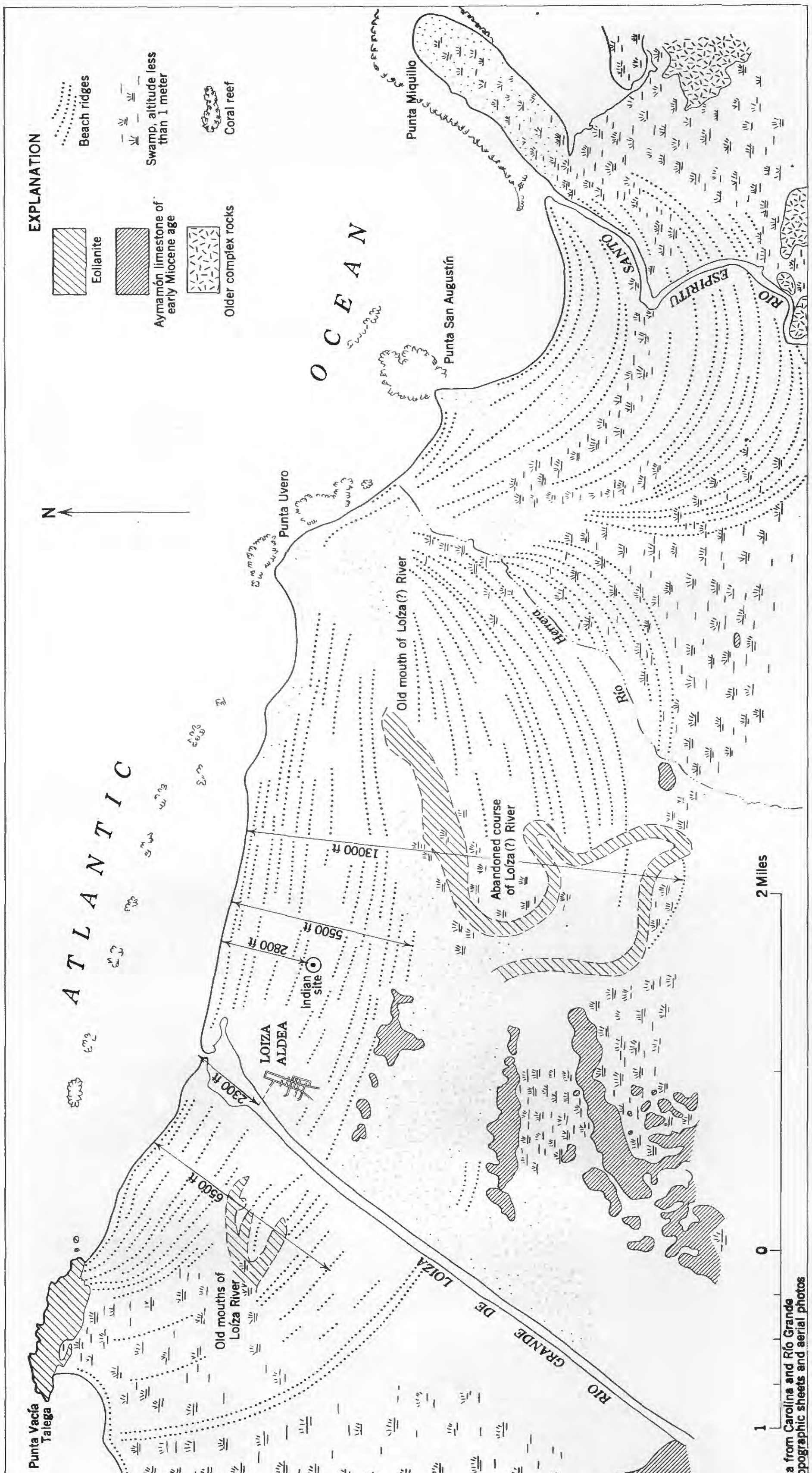


FIGURE 51.—Coastal geology, Punta Vacía Talega to Punta Miquillo.

PUNTA VACÍA TALEGA TO PUNTA MIQUILLO

The coastal area both east and west of the Río Grande de Loíza has the deepest and most extensive series of fossil beach ridges and relict shorelines on Puerto Rico (fig. 51). These can best be appreciated on aerial photographs where it can be seen that they extend from Punta Miquillo on the east to beyond Punta Vacía Talega on the west. The band of fossil beaches form three interconnected lunate festoons, the western one of which was apparently anchored on one side by the formerly more extensive eolianite ridge of Punta Vacía Talega and on the other by lower Miocene limestone knobs that are situated just southeast of the town of Loíza Aldea. The middle festoon was anchored by the latter knobs on one side, and on the other possibly by a reef that is now on the landward side of Punta Uvero. The easternmost festoon was controlled on the west by the reef of Punta Miquillo, which in turn probably rests on a knob of lower Miocene limestone.

The topographic expression of these fossil beaches varies from well-defined sandy beach ridges, attaining altitudes of 12 feet at a few places close to shore, to very low swales in the interior at altitudes of 3 feet or less. The latter ridges, or traces of ridges, are barely perceptible on the ground, though they show up well from the air. It is possible that they were formed at a sea level that was 1 to 2 fathoms (6–12 ft.) lower than the present datum. In fact, a slow shift from lower to present sea level is possibly recorded by the transition from the featureless marsh on the south to beach ridges of increasing prominence and altitude on the north.

There are two "historic" markers falling within the festoon of beach ridges. One is the town of Loíza Aldea, which dates from the early 16th century (probably the first quarter of the century), and the other is an archaeologic site located less than a mile east of the town of Loíza Aldea (211,840 m, 66,330 m), which was described orally to the writer by Professor Ricardo E. Alegría, University of Puerto Rico. The archaeologic site belongs to the preceramic culture of Puerto Rico, which Rouse (1952b) places between 849 A. D. and 929 A. D. (Rouse's Period I) although Alegría (oral communication) is inclined to make it somewhat older.

The Indian site provides a better gage than the town site of Loíza Aldea for determining the age of the shoreline deposits, because it is more constricted in area and, although not much farther inland from the present shore, is at least 600 years older. The Indian site is about 2,800 feet from the 1940 shoreline (the date of the survey of the Río Grande topographic quadrangle, on which these measurements are made) and the belt of better preserved beach ridges is approximately 5,500 feet wide at this meridian (fig. 51). Multiplying 1,050 (age in years of the Indian site, dated 890 A. D. according to the best estimate) by the ratio 5,500:2,800, we derive a figure of 2,060 as the minimum number of years it took to build out 5,500 feet of shoreline.

Estimates based on location and age of the town site of Loíza Aldea provide a figure that is much smaller but is considered less reliable, because the chance that the original town site was immediately adjacent to the water's edge is unlikely, whereas the Indians are known to have favored this type of location for their villages. In addition, precise location of the site of the original settlement of Loíza Aldea is not known, and today the town measures at least 1,400 feet from north to south. The oldest landmark is the church, which, according to Alegría (oral communication), probably dates from the 17th century. Nevertheless, using this partly ruined church as a measuring point (it is approximately 2,300 feet from the shore) we derive a figure of 1,100 as the minimum number of years since the oldest beach ridge (enclosed by a 2-meter contour line) was formed. This beach ridge is about 6,500 feet from the 1940 shore and is on the left bank of the Río Grande de Loíza.

Measurement of the amount of beach advance that is recorded by the aerial surveys of 1936–1937 and 1951 provides yet another method of deriving a rough estimate of the age of present sea level. According to computation based on the average of photogrammetric measurements made at several positions along the beach, the shore built out approximately 50 feet in 14 years, or 3.57 feet a year. Dividing this amount of annual advance into the total width of the belts of beach ridges (obtained in the computation of the town and the archaeologic sites) yields 1,825 and 1,540, respectively, for the age in years of the oldest shoreline.

The total width of the beach ridge festoon, if measured on the aerial photographs to include those old shorelines with very indecisive topographic form, is about 13,000 feet. Assuming that the total 13,000-foot width of the belt of fossil shorelines have accumulated at the above rates, we derive 3,640 (using 3.57 feet a year) and 4,875 (using the Indian town site as a measuring rod) as the age in years of the oldest shoreline that is still visible. This possibly dates the onset of a sea level 1 to 3 fathoms lower than at present.

SOUTH COAST, PUNTA CABULLÓN

On the south coast, about 2 miles southeast of the city of Ponce, a short stretch of coast east of Punta Cabullón is undergoing the most rapid advance of any present Puerto Rican shore (fig. 52). A series of well-

FIGURE 52.—Prograded coast near Punta Cabullón, east of Ponce. Note that the present shore is discordant to the simple arcuate form of the older shores. The factor that apparently controls the present configuration is the presence of two small reefs offshore, around which waves are both diffracted and refracted.

marked beach ridges in a lunate pattern extend inland about 6,400 feet from the shore. Beach ridges on this coast are particularly low; and on the topographic map of the area (Playa de Ponce quadrangle) none of them, including modern beach ridges, attain an altitude of 2 meters. As measured on the 1936 and 1951 aerial photographs the shore advanced 75 feet (an average of measurements at four different shore positions), or 5 feet a year, in the 15-year period, 1936–1951. Dividing 6,400 by 5 gives 1,280 for the advance in years of the shoreline recorded here.

The average of the six figures, whose derivations have just been described and which are shown in table 4 (excluding the two higher figures for the maximum width of beach ridges), is 1,850. This is construed as a minimum age, and therefore one is probably justified in rounding it off to 2,000. This, it will be noted, is very close to the figure derived by using the preceramic Indian site as a measuring rod—which, in the writer's opinion, is the method with the strongest quantitative base. The two higher figures for the maximum width of the beach ridge festoon suggest that in the interval roughly between 2,000 and 4,000 years ago, sea level was one to two fathoms lower than today. The transition between this level and the present level may, however, have been gradual.

TABLE 4.—*Age of the present sea level as computed from advancing shorelines*

Coastal area	Measuring "gage"	Calculated age of oldest shoreline definitely associated with present sea level (see text) (years)
1. Ensenada de Boca Vieja (Bayamón quadrangle).	18th-Century maps	3,300
2. Punta Vacía Talega to Punta Miquillo (Carolina and Río Grande quadrangles).	Old church, town of Loíza Aldea	1,100+
Do	Preceramic Indian site	2,060+
Do	Beach advance, 1937–1951 (aerial photos)	[1] 1,825 [2] 1,540
3. Punta Cabullón	Beach advance 1936–1951 (aerial photos).	1,280
Punta Vacía Talega to Punta Miquillo.	Preceramic Indian site	[3] 4,875
Do	Beach advance, 1937–1951 (aerial photos).	[3] 3,640

[1] For 6,500 feet of shore advance.
[2] For 5,500 feet of shore advance.
[3] For 13,000 feet of maximum width of old shorelines. This may include a lower sea level.

RECEDING SHORELINES AS GAGE

The stability of present sea level as indicated by prograding shorelines is further substantiated, though only qualitatively, by other lines of evidence. For example, there are several places in the vicinity of San Juan that show the effects of considerable shore erosion at present sea level. One of the most striking examples is the abandoned beachrock pavement off the Boca de Cangrejos (fig. 53). This well-preserved pavement curves one-fourth of a mile out to sea from the low eolianite ridge at Punta Cangrejos and at low tide resembles a low stone jetty. Because of its position within the present intertidal zone it is clear that it outlines a beach formed at present sea level and indicates

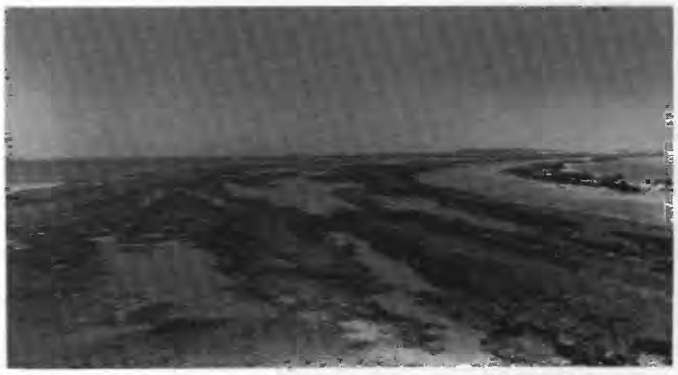


FIGURE 53.—Abandoned beachrock pavement, Boca de Cangrejos, east of San Juan. The land behind this former shore once occupied the area to the left.

FIGURE 54.—Superimposed beachrock pavements, north shore of San Juan. Old maps indicate that the older shore existed in the latter part of the eighteenth century.

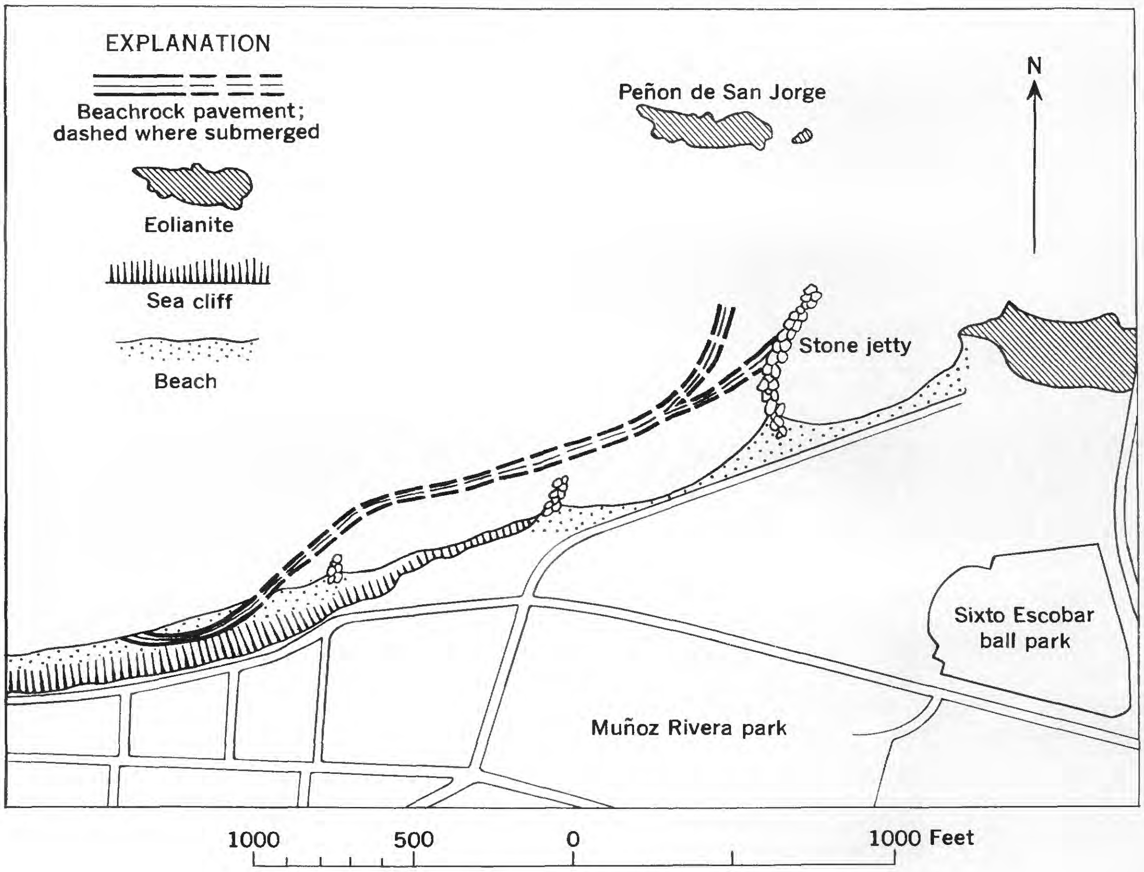


FIGURE 55.—Map showing relict beachrock pavement, San Juan.

a profound change in shore outline with the removal of at least 1,200 feet of shore. Late 18th century maps do not record a shore resembling that outlined by the abandoned pavement. It seems certain therefore that the pavement is relict of a beach that is older than the late 18th century, though by how much one cannot say.

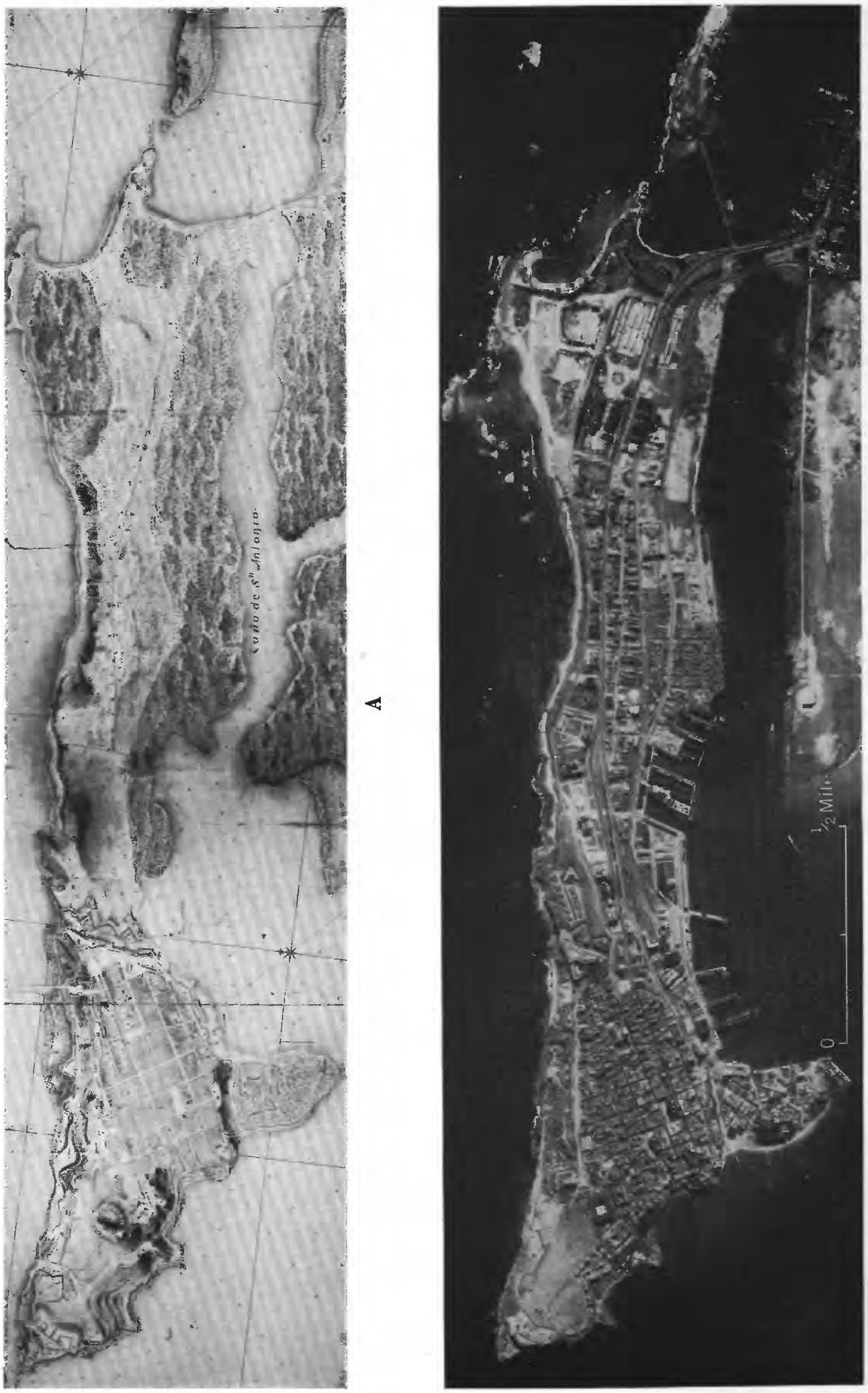
A less striking example of relict shore outlined by beachrock is on the north shore of San Juan. At the foot of the cliff west of Parque de Muñoz Rivera (188, 100 m, 70,300 m) there are two superimposed beachrock pavements (figs. 54 and 55), both of which presumably were formed at the present sea level, although the more recent of the two of necessity overlies the older and therefore rises several feet higher. The older pavement is broadly cuspate; the younger pavement is straight and conforms to the present straight shore. Traced along its strike, the arcuate pavement does not maintain its horizontality but dips beneath sea level as it trends out to sea. On a calm day it can be traced along the shallow bottom to the east for almost one-fourth of a mile.[4] Thomas O'Daly's excellent 1771 map of San Juan, which is worth comparing with a modern areal photograph (fig. 56), seems to show at least the western part of this former shore. That part of the relict shoreline that curves to the north and is shown by the northern prong of the submerged pavement off Parque de Muñoz Rivera, however, predates O'Daly's map.

It is evident that considerable shore erosion has taken place in the relatively straight stretch of coast between Punta Salinas and Punta Boca Juana (fig. 47). This is indicated by traces of the former meandering course of the Río Cocal—in the form of oxbow sloughs—that now lie just back of the beach, behind the foredune. Because the old river course is incised in alluvium and swamp deposits that grade to present sea level, it seems most probable that the river channel was also graded to present sea level. Part of Thomas O'Daly's 1776 map (fig. 50A), shows the eastern end of this stretch of straight coast. By comparing this map with a modern one (fig. 47), it can be seen that at least that part of the shore had already receded to approximately its present position in O'Daly's time.

SEA-LEVEL NIPS

Sea-level nips provide very incisive evidence of sea-level stability, particularly the deep, low nips that

[4] The explanation for the phenomena of a beachrock pavement draped on an undulating surface has been discussed earlier (p. 48). Mainly it results from a gradual undermining of the uncemented sand foundation of the pavement in a relatively sheltered setting. The pavement is thereby eased down vertically without an appreciable lateral shift.



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B

FIGURE 56.—Maps of San Juan—eighteenth century and photomosaic. (*A*) Map by Thomas O'Daly, 1771. Courtesy of the National Park Service, U. S. Department of the Interior, San Juan, P. R. (*B*) Aerial mosaic, 1935.

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FIGURE 57.—Large eolianite blocks allegedly placed by Spanish engineers in 1797 to help close mouth of Laguna del Condado to invading English.

occur in protected shores. The rate of nip solution in eolianite is known from one locality, El Boquerón (fig. 57), and although it is questionable whether these data can be applied rigidly to other nips, it is worth considering here as a very general measuring rod with which to gage the age of some of the deeper nips in eolianite. As described earlier (p. 93), the nip (fig. 58) about the base of one of the boulders is presumably the work of 155 years of sea-level solution. This nip is from 10 inches to 4 inches deep. Nips 12 or more feet deep are not unusual in eolianite on the north coast of Puerto Rico. If we use 10 inches per 155 years as a representative rate of nip formation, a 12-foot nip would represent the work of 2,200 years; and if we use 4 inches, we derive 5,400 years. However, the factors involved in the rates of nip incision are not fully known; because of the probability of considerable variation in rate, these two figures should be construed only as showing the possible length of time involved in the formation of some of the deeper nips and, in consequence, the possible duration of the present sea level.

FIGURE 58.—Sea-level nip on lagoonal side of one of the eolianite blocks of figure 57.

TIDAL TERRACES

Tidal terraces provide yet another sea-level marker. They have an average level at, or slightly above, mean high tide; some are 2 to 3 feet above high tide. No attempt will be made to estimate the length of time required for the formation of these tidal terraces except to say that the width of some suggests that they are not of recent origin, and an estimate of several thousand years for their development, in the writer's judgment, would seem appropriate.

HISTORICAL MONUMENTS

The curious old maritime gate to San Juan was constructed in 1641. (See Puerto Rico Reconstruction Authority, 1940.) This structure, still standing and very well preserved, includes a small wharf at the foot of the city wall on the bay side which connects with the gate by a short ramp. The entire construction is of rubble and brick. The present sea level seems appropriately located with respect to the level of the wharf and the general engineering and constructional features of the structure. Thus, below present high-level we find rubble but above, brick construction. An old box sewer built of bricks emerges just above high tide at the foot of the wall on the east side. Large blocks of eolianite at the foot of the Casa Blanca wall,[5] immediately to the west, are deeply nipped at present intertidal levels, so that the upper surface of the nips is only a few inches above high tide. At this locality, where manmade and naturemade sea-level markers are juxtaposed, a picture of sea-level stability in recent centuries is again conveyed.

CRUSTAL STABILITY

The data just described indicate that there has been negligible crustal movement of the coastal areas of Puerto Rico in the last few thousand years—that is, unless one wants to postulate a very improbable synchronization, in time, rate, and direction, of eustatic and crustal displacement. Moreover, the occurrence of marine terraces and marine deposits, which will be described below, at altitudes that accord closely with those from coastal areas in many other parts of the world offers fairly strong evidence that vertical crustal movement has been slight since sometime in the late Pleistocene. The marked crustal instability of Puerto Rico that has been mentioned by Zapp, Bergquist, and Thomas (1948); Meyerhoff (1927, 1933); Lobeck

[5] Casa Blanca was constructed in 1523.

(1922); and Hubbard (1923)—among others—as having occurred in the Quaternary, should therefore probably be restricted to early and perhaps middle Pleistocene time.

There are, however, no unequivocal examples of high marine terraces on the Puerto Rican mainland that might possibly reflect large epeirogenic movements in the Quaternary (this may not be true for Isla Mona; see chap. C). The writer agrees with Lobeck (1922) that the high coastal terraces in limestone of early Miocene age in the vicinity of Quebradillas are probably expressions of the stratification of this rock and its manner of wasting. The marked variations in altitude of each of these terraces casts doubt on the wave-cut origin postulated by Hubbard (1923) and Zapp, Bergquist, and Thomas (1948).

STRATIGRAPHY OF THE CEMENTED DUNE COMPLEX OF THE NORTH COAST

The form and distribution of the cemented dune complex of the Puerto Rican north coast have been described earlier (p. 79, fig. 27). It will be recalled that these low hills form (a) offshore rocks and islets, (b) rocky dune-shaped headlands, and (c) somewhat higher and broader soil-covered hills, either on the coast (fig. 59) or not far back of the coast. Close study of these hills reveals a complex stratigraphy reflecting not only a sequence of eolian accumulation but also marine deposition. This stratigraphy is thought to be tied to Pleistocene sea-level changes. In general, both the sequence of material and the geologic setting are quite similar to those described by Sayles (1931) for Bermuda.

Gleason and Cook (1927, p. 53) suggested that these low hills could be separated into outer (or younger) and inner (or older) fossil dunes (fig. 27). This interpretation is essentially correct except that the older cemented dunes are generally compounded of eolian and marine beds, and some of them include relatively young as well as older eolian deposits. In addition, Miocene rocks crop out in the lower slopes of many of the older cemented dunes, so that, strictly speaking, the word "dune" is somewhat misapplied for these hills. It will be retained in this report for the sake of consistency, though the reader will understand that some hills are only partly eolian in origin. The occurrence of lower Miocene deposits in the bases of the older cemented dunes indicates that these dunes are supported on pedestals of Miocene rock. Prior to Pleistocene deposition these pedestals must have been east-west ridges and alined haystack hills, just like the hills of middle Tertiary rock of the north coast today. In Pleistocene time these hills provided the foundation, first for marine deposition that took place with a gradually rising sea level, and then, with a decline in sea level, for successive cappings of dune sand which drifted onto the hills from successively lower shorelines.

MIOCENE BASEMENT

For a distance of about three miles west of the edge of the town of Arecibo there are numerous exposures of Pleistocene eolianite resting directly on Miocene deposits (pl. 11 *A*). The lower Miocene here is predominantly uncemented sand and is less indurated than the overlying crossbedded eolianite. A late early or early middle Miocene age for these sandy beds is indicated by the following fauna collected by the writer at two localities.

FIGURE 59.—Castillo del Morro, San Juan, guarding the entrance to the harbor. San Juan is built on a Pleistocene ridge made up of marine and eolianite deposits.

Lists of fossils from sandy beds of early or middle Miocene age, vicinity of Arecibo

	USGS locality	
	17952	17953
Protozoa (identified by W. Storrs Cole):		
Foraminifera:		
Archaias sp	-------	×
Operculinoides tamanensis Vaughan and Cole	-------	×
Echinoderma (identified by C. Wythe Cooke):		
Clypeaster? sp	-------	×
Schizaster loveni Cotteau	-------	×
Bryozoa (identified by R. S. Bassler):		
Holoporella orbifera Canu and Bassler	-------	×
Cupuladria canariensis Busk	-------	×
Mollusca (identified by W. P. Woodring):		
Gastropoda:		
Livonia? sp	-------	×
Natica (*Naticarius*) aff. *canrena* (Linné)	-------	×
Stigmaulax aff. *sulcata* (Born)	-------	×
Orthaulax? sp	×	-------
Ficus sp	-------	×
Siliquaria sp	-------	×
Rhinoclavis cf. *plebeium* (Sowerby)	-------	×
Cypraea aff. *spurca* Linné	×	×
Trivia cf. *pediculus* (Linné)	×	-------
Persicula cf. *venezuelana* (Hodson)	×	-------
Mitra (*Cancilla*) cf. *henekeni* Sowerby	-------	×
Oliva sp	×	×
Olivella cf. *muticoides* (Gabb)	×	-------
Conus sp. 1	-------	×
Conus sp. 2	×	×
Conus cf. *longitudinalis* Pilsbry and Johnson	×	-------
Knefastia? cf. *jaquensis* (Sowerby)	-------	×
Glyphostoma sp	×	-------
Bulla cf. *sarahberlineri* (Maury)	-------	×
Pelecypoda:		
Glycymeris cf. *pennacea* (Gmelin)	-------	×
Anomia? sp	×	×
Spondylus sp	×	×
Pecten (*Pecten*) aff. *ventonensis* Cooke (and aff. *P. barretti* Woodring)	×	×
Chlamys sp	-------	×
Aequipecten sp. [Hubbard's *Pecten* (*Plagioctenium*) *cercadica* Maury]	×	×
Lyropecten (*Nodipecten*) *nodosus* (Linné)?	×	×
Ostrea (*Dendostrea*) aff. *frons* Linné	-------	×
"*Pycnodonte*" *haitensis* Sowerby?	-------	×
Mercenaria (*Ventricola*) sp	-------	×
Macrocallista maculata (Linné)?	×	-------
Periglypta sp	-------	×
Lirophora aff. *paphia* (Linné) [and aff. *L. hendersonii* (Dall)]	-------	×
Americardia aff. *media* (Linné)	-------	×
Trigoniocardia cf. *haitensis* (Sowerby)	-------	×
Laevicardium serratum (Linné)?	-------	×
Corbula (*Varicorbula*) aff. *prenuncia* Spieker	×	-------

Locality 17952: Arecibo quadrangle; small rocky point 1 mile east of Arecibo lighthouse. Meter-grid coordinate: 126,050 m, 72,025 m.
Locality 17953: Arecibo quadrangle; large borrow pit south side of Highway 2 and a few hundred yards west of Ron Rico distillery. Meter-grid coordinate: 119,850 m, 70,950 m.

The Miocene sand beneath the eolianite is weathered a deep red to a depth of over 4 feet where it is exposed in the road cut facing the Ron Rico distillery just west of Arecibo. The eolianite covers a much dissected surface, and in the road cut in front of the distillery it completely fills a steep V-shaped gully in the Miocene sands.

The small hill that flanks the protected mouth of the Río Grande de Arecibo at El Vigía, about a mile east of Arecibo, received some attention from Berkey (1915, p. 142–147) and Meyerhoff (1933, p. 114) because of the interesting sequence of Pleistocene sediments exposed in the road cut. The Pleistocene deposits in this exposure (pl. 11 *B*, fig. 60) rest on Miocene pink calcareous sandstone, which is the cemented equivalent of the lower or middle Miocene sands west of Arecibo. The planed surface of the Miocene pedestal is about

FIGURE 60.—Pleistocene section at El Vigía, east of Arecibo. Thin paleosol horizon, halfway up face, separates eolianites. At eye level is marine boulder bed resting on estuarine sediments.

11 feet above sea level on the north side of the hill and slopes slightly to the south.

About a mile east of El Vigía, in a small rocky point on the shore, the same pink calcareous sandstone crops out beneath a thin cover of marine and eolian Pleistocene. At this place the surface of the lower or middle Miocene is about eight feet above mean tide and very much pitted. It is veneered with a red paleosol.

The Miocene basement of the cemented dunes that flank the mouth of Río Grande de Manatí (pl. 11 *C*) crops out in the right bank of the river, just south of the narrow protected river mouth. The Miocene here is a dense cream-colored limestone that is typical of most of the Aymamón limestone.

Farther east, in the sides of a ditch that provides the outlet for the Laguna Tortuguero, the base of the exposed section (pl. 11 *E*) is a nodular coralliferous limestone that is probably lower Miocene. It is capped by a red paleosol, 2–5 feet thick.

Miocene dense yellow limestone crops out at several places in the eolianite ridge (pl. 11 *F*) just west of the mouth of the Río de la Plata, north of Dorado. It occurs at about the high-tide level at the western end of the ridge at Punta Fraile where point and beach meet, and it also underlies a much eroded beachrock pavement near the eastern end of the point (fig. 22). In a small cove near the western end of the ridge, a deep red clayey paleosol crops out at beach level, overlain by marine Pleistocene. The clay contains fragments of dense limestone similar to the lower Miocene rock, black iron oxide nodules, and mottlings of light-colored clay which are typical of older soils on the north coastal plain (see "Older Alluvium" in chap. A; also

Roberts and others, 1942). Here it probably is a residual soil developed on the Miocene pedestal.

Although no Miocene was recognized at the base of the cemented dune that forms the island of San Juan, low knobs of the Aymamón limestone flank the adjoining Santurce hill on the east (chap. A, pl. 2). Water wells drilled in this hill at 192,800 m, 67,410 m and at 191,070 m, 67,700 m hit dense limestone at approximately 36 feet below sea level in the former well and residual soil overlying dense limestone at approximately sea level in the latter. Other water wells flanking the Santurce hill also encounter the shallow pedestal of Miocene rocks. (See McGuinness, 1946.)

PLEISTOCENE MARINE DEPOSITS

Pleistocene marine sediments of a wide variety of textural types are found in the lower part of the older cemented dunes. These deposits generally crop out only on the south slope. They are covered by eolianite on the north slope, but where a ridge is much dissected they may crop out on the north flank as well. They also crop out intermittently in the low sandy beaches as low rocky pavements which are very commonly surmounted by beachrock.

At El Vigía a thin section of marine sediments occurs between the Miocene pedestal and the overlying eolianite (pl. 11 *B*). At the south side of the hill crossbedded sand containing clay lumps grades upward into a buff compact silty clay containing carbonized plant remains. These are probably estuarine deposits. The clay is overlain by a 2- to 6-foot bed of rounded cobbles and boulders up to 3 feet in their longest dimension, many of which are encrusted with coral identified by Dr. John W. Wells as *Siderastrea radians* (Pallas). The boulders consist mostly of pink lower or middle Miocene calcareous sandstone—the same rock that crops out at the base of the section—and sparse cobbles of older complex rocks. The proximity of the Río Grande de Arecibo at the time these coarse deposits were formed is indicated, and the picture that is conveyed is of a gradually rising sea that transgressed onto alluvial or estuarine deposits. The Miocene boulders indicate wave erosion, either of an adjacent knob of calcareous sandstone or of a thick residual soil developed on calcareous sandstone and containing "undigested" pieces of the underlying rock. The top of the thin boulder bed lies at an altitude of about 14 feet, and the bed is overlain by eolianite.

The outcrop of Miocene calcareous sandstone located about a mile to the east is also overlain by 2 to 3 feet of coarse gravel consisting of the same type of cobbles. Corals are more abundant here, however, and Dr. Wells recognized *Acropora palmata* (Lamarck), *Dichocoenia stokesi* Milne Edwards and Haime, *Diploria strigosa* (Dana), and *Monastrea cavernosa* (Linné). These are all wave-resistant Pleistocene and Recent surface-reef species. In this locality the top of the boulder-coral bed lies from 10 to 11 feet above mean tide, and the bed is capped by several feet of eolianite.

Exposed in a small quarry (139,900 m, 72,110 m) at the foot of the 41-meter hill, just west of the mouth of the Río Grande de Manatí, is white to yellow friable calcareous sandstone and nodular limestone, rich in coral heads and broken coral fragments of Pleistocene age. Dr. Wells identified the following surface-reef assemblage: *Diploria clivosa* (Ellis and Solander), *Diploria strigosa* (Dana), *Siderastrea siderea* (Ellis and Solander), and *Solenastrea bouroni* (Milne Edwards and Haime). An echinoid, *Clypeaster* sp., probably *C. rosaceus* (Linné), was identified by Mr. C. Wythe Cooke. The upper surface of this reef deposit is deeply pitted and covered with a residual paleosol, which in turn is overlain by eolianite.

Immediately east of the mouth of the Río Grande de Manatí, a thick section of Pleistocene marine deposits is exposed on the south slopes of the older cemented dune (pl. 11 *C*). Overlying the lower Miocene limestone is a conglomerate consisting predominantly of rounded to subrounded pebbles of older complex rock up to 6 inches in diameter. The bedding dips about 10° north and probably represents a deltaic accumulation at the mouth of the Manatí river. This conglomerate rises to an altitude of about 45 feet, and raises the provoking question of what has happened to the floodplain alluvium that certainly must have filled the broad coastal lowland and river valley to the south to at least this altitude at the time the gravel was deposited. The only likely explanation for the absence of these deposits is that they were stripped away during subsequent low sea levels. Perhaps some of the older alluvium (chap. A) includes remnants of this once extensive high-level fill. Overlying the conglomerate is a reef deposit similar to that west of the river. Corals collected from here were identified by Dr. Wells as: *Monastrea annularis* (Ellis and Solander), *Acropora palmata* (Lamarck), and *Diploria strigosa* (Dana). These deposits may be as much as 50 feet thick and where mapped attain a maximum altitude of about 120 feet (36½ m), which is the highest occurrence noted by the writer of Pleistocene marine deposits on the north coast.

North of the Laguna Tortuguero, several miles to the east of the Manatí area, the marine Pleistocene takes on a different aspect. There it is represented by a broad development of dense limestone (pl. 11 *E*) that is unique among Pleistocene rocks on the Puerto Rican mainland, although it is duplicated by the Lirio limestone of Isla Mona (chap. C, of this report). The section that overlies the paleosol (which had developed on lower Miocene rock, as seen in the drainage canal) consists of the following units in ascending order. (a) A thin-bedded sandstone dipping at a low angle seaward and having a cobble layer at the base. This is probably a littoral sand and may be the equivalent of the conglomerate in the Arecibo area. (b) Very porous, though tough, coarse-sandy reef rock made up principally of broken fragments of calcareous algae, small mollusks and some corals, of which *Orbicella cavernosa* is most prominent. This reef rock is much iron stained and pitted where it crops out along the shore, east of the canal. A collection of small mollusks from this deposit were examined by Mr. W. P. Woodring, who identified the following shallow-water assemblage: *Fissurella* cf. *nodosa* (Born), *Nerita* cf. *tessellata* Gmelin, *Hipponix* cf. *antiquatus* (Linné), *Cypraea* cf. *spurca* Linné, and *Columbella mercatoria* Linné. Although only 20 feet of this sandy reef deposit is exposed above sea level in the sea cliff south of Punta Chivato, a water well several hundred yards southeast of Punta Chivato penetrated 50 feet of this rock without reaching the base of the deposit (McGuinness, 1946, well Vb 80). (c) Overlying the reef rock are about 30 feet of thick-bedded, dense, very fine grained limestone, prevailingly white in color but with some pink and yellow mottlings. This limestone resembles some of the lower Miocene limestones, particularly the Lares limestone (Zapp and others, 1948), but its Pleistocene age is demonstrated by its stratigraphic relation with the underlying reef rock. Fossils are rare in the dense limestone and none were collected. This limestone apparently underlies the broad terrace at Punta Chivato.

Marine deposits probably of Pleistocene age crop out along the southern slopes of the low coastal hill at Punta Cerro Gordo and are well exposed in the small quarry at the west end of the ridge, at the edge of the village. The quarry section is as follows:

Reference No.	*Description*	*Approximate thickness (feet)*
6	Eolianite; friable calcareous sand	
5	Eolianite; crossbedded calcareous sand	10
4	Paleosol, brown sandy loam	1
3	Marl, nodular, rich in *Porites* (like No. 1)	3
2	Sandstone, white, thin-bedded, friable; abundant Foraminifera	6
1	Marl, nodular, rich in *Porites;* very friable, showing some surface hardening. Consists of fragments of *Porites* sp. (very much recrystallized), algal nodules, small shells and fine lime sand, and silt. Color, white to light yellow. Probably a lagoonal deposit. Upper part of bed exposed	7½

Foraminifera from the *Porites* marl (No. 1) were examined by Mrs. Esther R. Applin who listed: *Amphistegina lessonii* d'Orbigny, *Amphistegina floridana* Cushman and Ponton, *Archaias* sp., *Elphidium* cf. *macellum* (Fichtel and Moll), calcite molds of *Rotalia* cf. *tholus* Galloway and Heminway, and molds of *Quinqueloculina* cf. *seminulum* (Linné).

Mr. Woodring identified the following mollusks from the same bed: *Neritina* (*Vitta*) cf. *virginea* (Linné), *Cerithium* sp., *Metulella* (*Thiarinella*) sp., *Olivella* sp., *Bulla* sp., and *Andara* (*Cunearca*) sp.

Dr. Wells named the following corals: *Eusmilia fastigiata* (Pallas), *Montastrea annularis* (Ellis and Solander) and *Porites* sp.

The corals, particularly *Eusmilia fastigiata* (Pallas), indicate a Pleistocene age, although Mrs. Applin thought the Foraminifera had a Miocene aspect. Unfortunately the mollusks are not diagnostic. Lithologically this marl resembles other *Porites* marls of the north coast and particularly the marl at the west end of Punta Fraile, several miles to the east.

Reef deposits crop out widely on the Punta Fraile ridge, but the best exposed section is at the west end, overlying the pitted surface of lower Miocene limestone which rises to about high-tide level here.

Pleistocene section at west end of Punta Fraile

6. Eolianite; nonfossiliferous thin-bedded sandstone.
5. Marl, yellowish, nodular, sandy, horizontally bedded; contains coral and coralline algal fragments and some thin friable sandstone with *Strombus gigas.*
4. Sandstone and conglomerate, calcareous, horizontally bedded; many coral heads, some 12 feet across.
3. Marl, white, containing *Porites;* consists of a dense concentration of recrystallized fragments of *Porites* sp. embedded in a white silty marl, and a few coral heads.
2. Sand, quartz, light-gray, clayey, 2-foot bed; sand very angular and poorly sorted; no fossils.
1. Buff clay (paleosol?).

Corals from the above section were identified by Dr. Wells as *Acropora palmata* (Lamarck), *Dichocoenia stokesi* Milne Edwards and Haime, *Diploria strigosa* (Dana) and *Montastrea cavernosa* (Linné), which are all Pleistocene to Recent species.

On the other hand, Mrs. Applin thought the Foraminifera from the white *Porites* marl had a Miocene aspect. The fauna was meager and poorly preserved and included calcite molds of *Quinqueloculina* sp., *Q.* cf. *Q. philippi* Reuss, *Triloculina* sp., *Pyrgo* sp., as well as better preserved *Spiroloculina* cf. *S. antillarum* d'Orbigny, *Nonion* cf. *N. grateloupi* (d'Orbigny), *Reussella* cf. *R. glabrata* (Cushman), *Valvulammina cornucopia* Galloway and Heminway.

Ostracodes in the white *Porites* marl, according to Mr. I. G. Sohn, who studied them, are not diagnostic as to age, though a species close to *Loxoconcha antillea* Van den Bold of the Miocene of Cuba was noted. The fauna reported is: *Loxoconcha* sp. aff. *L. antillea* Van den Bold, *Trachylebris* (?) spp. indet., gen. indet.

There is therefore some uncertainty as to the age of the *Porites* marl. If it is Miocene it is unlike any deposit of this age known to the writer from the broad outcrop of these rocks on the north coast.

Marine deposits similar to those described crop out on the south side of Punta Salinas. At San Juan yellow marly beds and reef rock can be found above high-tide levels in the bluff on the bay side of the El Morro military reservation and below the Casa Blanca. Reef rock and littoral sandstone also crop out at a few places near the base of the cliff on the north side of San Juan, east of the San Cristóbal fortress (pl. 11 *G*).

Marine Pleistocene deposits were not seen in Punta Maldonado or Punta Vacía Talega, although they may occur beneath the eolianite.

Reef rock, identical in appearance to those just described from the cemented dunes, crops out at intertidal levels on beaches along much of the north coast. There is a possibility that these deposits are of a more recent origin than the reef rock in the cemented dunes and date from the relatively recent five-foot sea-level stand. Further work is needed to clarify the position of the low-altitude reef rock.

EOLIANITE

Overlying the marine deposits are cemented dune sands (eolianite). These are predominantly thin bedded sandstone of uniform grain, in places showing pronounced crossbedding and, except for occasional shells of land snails, unfossiliferous. It is not everywhere a simple matter to differentiate sandstone of a littoral marine origin from eolianite, and the two can readily be confused in the absence of diagnostic features. Criteria used by the writer to recognize marine sandstone from eolianite in the field are (a) the presence of pebbles or cobbles, (b) corals and large marine shells that could not be transported by terrestrial hermit crabs, or (c) thin sandstone that is interbedded with obviously marine deposits. On the older cemented dunes that are underlain by marine sediments, the eolianite is generally thickest on the north or ocean side. The younger dune ridges (fig. 27), however, seem to consist entirely of eolianite.

The eolianite was deposited in several discrete time intervals, separated by periods of soil formation. This is clearly shown by (a) paleosols within the eolianite section, (b) differences in the degree of cementation (though this is not always apparent), and (c) the different spatial relations of the eolianite bodies. Thus, the oldest eolianite occurs only in the older hills on the south, which have cores of marine Pleistocene upon a Miocene foundation. The line, or lines, of dunes to the north mark the positions of successively younger dunes. However, wind-blown sands must have continued to carry up onto the older dunes to the south throughout the periods of dune construction, for eolianite of several generations can generally be found on the older and higher hills, whereas the younger eolianite ridges on the north may contain sand of only the most recent generation.

From the stratigraphic standpoint, therefore, the best place to study the sequence of Pleistocene deposits is in the older dunes, for it is in these places that the superposition of eolianites separated by paleosols provides a clear picture of the total sequence. Four separate bodies of eolianite (here designated eolianites E_1 to E_4 can be recognized in the cemented dune on which the old city of San Juan is built (pl. 11 *G*). This is the maximum number of intervals of sand accumulation recorded in any single locality, and other older dunes on the north coast show for the most part only three eolianites.

It is generally difficult to distinguish the age of an eolianite if its occurs alone, for hand specimens of the four eolianites resemble one another. In places, however, the older two or three eolianites (E_1–E_3 in pl. 11) are much better cemented than the youngest (E_4), whereas on surface exposures the youngest (E_4) can generally be recognized from the three older eolianites by a lack of soil or signs of iron oxidation. The older eolianites, if not actually covered by a red residual soil, are nearly everywhere marked by some trace of a former soil cover, such as iron staining or thin pockets of cemented red soil. Moreover, very commonly joints and solution pits show a thin lining of secondary $CaCO_3$ (caliche).

PALEOSOL

The significance of "paleosol" as a term has been discussed elsewhere (Kaye, 1951). Essentially these are either old soils that have developed over a very long period of time, or soils that were formed under different pedologic or geologic conditions from those of today. What this means in time terms is obviously not fixed, and undoubtedly cutoff dates separating soils from paleosols differ from area to area, depending on the geological setting. In the context of the north-coast eolianite, the term "paleosols" implies soils formed prior to the deposition of E_4.

Paleosols of Puerto Rico are of two main types: soils of accumulation and residual soils. Both types of soil were also noticed in Bermuda by Sayles (1931), who described their significance. The soil of accumulation is generally a relatively thin stratum, resting on the underlying eolianite with a clean, sharp contact. The surface of the underlying eolianite is unpitted. The soil is generally gray to brown and zonation is generally not well developed. According to Sayles, this is not a residual soil formed by the decomposition of the underlying rock but is a sedimentary accumulation, probably wind blown. The residual soil, on the other hand, generally rests on a pitted surface and is well zoned and predominantly red.

Paleosols may be found interbedded between eolianites, or they may crop out on the surface. In some places along the shore the soil has been recemented and appears as red indurated zones in the eolianite. Paleosols, particularly the residual variety, vary in thickness and to a certain extent in the development of their soil profiles. The thickest exposed paleosol is in the stretch of cliff on the north side of San Juan, east of the Medical School, where about 40 feet crops out above the beach. In texture the paleosols are all generally sandy and reflect the composition of the parent rock.

SECTIONS OF EOLIANITE

EL VIGÍA AND PUNTA MORRILLOS

The section of eolianite at El Vigía and Punta Morrillos (pl. 11*B*), about 1 mile east of Arecibo, may include E_1 to E_4. There is some uncertainty whether the sandstones in the El Vigía hill that underlie the prominent paleosol are eolianites or consolidated littoral marine deposits. There are two sandstones, one filling a shallow channel eroded in the underlying Pleistocene marine deposits and the other overlying it. The former is a very well cemented crossbedded rock; the latter is friable, dips gently to the northeast, and has very minor crossbedding. The brown sandy loam paleosol that is so conspicuous in the road cut (fig. 60; see also Meyerhoff, 1933, fig. 23), is from 8 to 12 inches thick and is a paleosol of accumulation. Overlying it is a crossbedded, friable eolianite that has two structural peculiarities whose significance is not known, one of which Berkey (1915, fig. 15) noted but which the writer could not detect. Berkey observed a double bedding, or pseudobedding, where conspicuous horizontal partings resembling bedding cut across the steeply dipping crossbedding. A structural peculiarity that is still visible around the edge of the hill is the sudden reversal of dip from south to north and a narrow intervening zone of brecciated eolianite that marks the break. Perhaps it is a coincidence, but beneath the brecciated transition zone the paleosol nearly pinches out. The structural significance of this relation is tantalizingly elusive. Eolianite E_3? is covered in places by a residual paleosol, which is about 5 feet thick on the north slope of the hill and has the following profile:

Soil horizon	*Description*	*Thickness (inches)*
A	Sand, loamy, gray	12
B_1	Loam, sandy, red, stiff	24
B_2	Loam, sandy; mottled red and yellow	24

A few hundred yards to the north of the El Vigía hill is Punta Morrillos, a typical E_4 dune.

RIO GRANDE DE MANATÍ

A good section is exposed in a small quarry at the foot of the 41-meter hill that lies just west of the mouth of the Río Grande de Manatí (Barceloneta quadrangle). Above the eroded surface of the marine Pleistocene, as exposed in the lower part of the quarry, are 6 to 8 feet of white, much crossbedded eolianite (E_1 or E_2). The surface of the eolianite is deeply pitted and is overlain by a conspicuous paleosol. The soil has a gray-brown loamy sand A horizon and a fox-red, clayey sand B horizon. Overlying the paleosol is a well-cemented eolianite (E_2 or E_3).

PUNTA TORTUGUERO AND LOS MOLINOS

Four bodies of eolianite are exposed (pl. 11 *D*) in the Punta Tortuguero-Los Molinos section located north of Manatí and just east of El Alto (pl. 1). The older dune rises to an altitude of about 188 feet here. Its north face is a nearly vertical cliff, which is about 100 feet high in places and may be a former sea cliff (fig. 61). The dune is separated from the long E_4 dune on the north by a sandy plain, or valley, about 10 feet above sea level (fig. 18). In the cliff of the older hill, a thick section of unfossiliferous well-cemented sandstone is exposed that is divided by a distinct thin paleosol in the upper part (fig. 61). The lower sandstone is well cemented and shows only local crossbedding. The base of the dune is indented by shallow caves containing some dripstone. The paleosol is a soil of accumulation from 2 to 3 feet thick. It is overlain by light-colored highly calcareous eolianite E_2 which is separated from E_3, on the crest of the hill, by another paleosol of accumulation. This soil averages 24 inches in thickness and consists of a reddish-brown loamy sand where it is exposed in a road cut near the top of the hill. In the same cut the overlying E_3 is a white to light-yellow friable crossbedded eolianite.

SAN JUAN

Probably the most complete section of eolianite is at San Juan, in the vicinity of San Cristóbal fortress, the Capitol, and the Medical School (pl. 11 *G*). The oldest eolianite crops out as a low narrow reef only a few feet above high tide, at the foot of the cliff in front of the Capitol. This "reef" seems to be the crest of an old

FIGURE 61.—Old sea cliffs in Pleistocene deposits, Punta Tortuguero, north of Manatí. A conspicuous paleosol within the eolianites can be seen near the top of the cliff. The lower part of the cliff is broken by shallow sea(?) caves.

dune ridge. It passes under the nearly vertical E_2 cliff that bounds San Cristóbal on the east and is separated from it by a thin red paleosol. The upper surface of E_2 is much pitted and is overlain by a thick residual paleosol. The old soil is exposed in front of the Capitol and to the east, where the following profile is easily recognizable.

Profile of E_2 *paleosol in front of Medical School*

Soil horizon	Description	Thickness (inches)
A_1	Sand, loamy, gray; consists predominantly of well-sorted quartz; where undisturbed stands in vertical face.	10–27
A_2	Essentially the same, but more compact and lighter in color.	12–20
B_1	Sand, loamy, dark reddish brown, with slight mottling; compact and slightly cohesive; includes pea-sized black iron-cemented nodules.	0–18
B_2	Loam, sandy, tough and rubbery; mottled and streaked brick red, orange, and yellow. (In front of Medical School this horizon is at least 20 feet thick and occurs at beach level.)	0–240

The paleosol in the cliff face east of the Capitol is the thickest that has been noted in the eolianite sequence. From its relation with the E_2 eolianite in the cliff in front of the Capitol it seems to be an accumulation on the south or lee side of the E_2 dune. Some slope wash may therefore have added to its thickness.

At the east edge of San Cristóbal, the very thick E_2 paleosol is overlain by a thin eolianite (E_3), which in turn is overlain by a red paleosol. Farther east, in front of the medical school, this E_3 paleosol rests directly on the E_2 paleosol and the intervening eolianite is missing. The E_3 paleosol is zoned in much the same manner as the underlying soil but is very much thinner.

Profile of E_3 *paleosol in front of Medical School*

Soil horizon	Description	Thickness (inches)
A_1	Sand, loamy, gray	8
A_2	Same, but more compact, less friable	24
B	Sand, loamy, dark brick-red, slightly mottled; compact and slightly plastic. This rests on the horizontal surface of the A_1 horizon of the E_2 paleosol at an altitude of 25 feet.	30

On the top of the hill on which San Cristóbal is built, a fourth eolianite (E_4) occurs. This probably dates from the construction of the partly submerged dune ridge that lies about 380 yards offshore here and whose presence is marked by a string of small rocks.

PUNTA VACÍA TALEGA

Three superimposed eolianites crop out on the cemented dune called Punta Vacía Talega (pl. 11). Because the youngest eolianite is covered in places by a well developed soil it is assumed that E_4 is missing and that the eolianites represent E_1 through E_3. The E_3 paleosol is seen at the western end of the ridge where it dips below sea level. The E_2 paleosol is exposed along the ocean front in the central section of the ridge where it is nearly horizontal, lying at an average elevation of 16 feet above sea level. Both the E_1 and E_2 paleosols are red, well cemented, and relatively thin (possibly from having been partly washed away before cementation). In places the E_2 paleosol is rich in the shells of the large land snail *Pleurodonte* (*Caracolus*) *marginella* (Gmelin), which is common in Puerto Rico at the present time. The E_3 paleosol shows the following profile where it is well preserved in a small meadow on the north side, close to the west end of the ridge.

Profile of E_3 *paleosol, Punta Vacía Talega*

Soil horizon	*Description*	*Thickness (inches)*
A_1	Sand, loamy, dark reddish gray	2–7
A_2	Sand, friable, loamy, light red	5–7
B_1	Loam, plastic, tough, cohesive, dark Indian red; black iron oxide stains in vertical joints.	12–18
B_2	Loam, sandy, deep red (overlying pitted eolianite).	30

LA CORDILLERA

The chain of small islands and rocks off the northeast tip of Puerto Rico, La Cordillera, consists entirely of oolitic eolianite. On Cayo Icacos (Icacos Cay), the largest of the islands, four lines of cemented dunes are indicated, all alined west-northwest. The islets and rocks of this "reef" probably represent, for the most part, the emerged tops of these dunes. Neither paleosols nor clear-cut examples of superimposed eolianites were seen by the writer during his brief visit to Cayo Icacos, although the topographic form of the chain of hills seems clearly to reflect three and possibly four cycles of dune formation.

GEOLOGIC INTERPRETATION OF THE EOLIANITE

The formation of foredunes and of sand drift well in back of the beach has already been mentioned in connection with the origin of eolianite (p. 79). Because all four generations of eolianite can be seen extending below sea level at one or more places, it is evident that they were deposited when the sea level was lower than at present. The connection between dune building and lower sea levels has been explained by Sayles (1931) for the Bermuda eolianite. The same reasoning can also apply to Puerto Rico. The essential factor is that a lowering of sea level exposes to the atmosphere broad sand-covered banks and offshore slopes. Rising sea levels, on the other hand, create no new conditions that are conducive to the wind transportation of sand. One can imagine, for example, the probable consequences of a rise in sea level along the north shore of Puerto Rico today. Broad bays would form in back of the cemented dunes that would themselves be transformed to barrier islands, ever narrowing as seas level rose. There would be little sand for the wind to transport on the narrow barrier islands, and such sand as there was would probably drift over the island to fall into the bay behind.

Negative shifts of sea level would therefore tend to be responsible for the building of high foredunes and extensive sand drifts, whereas with positive shifts there might be little or no eolian construction. It seems likely that the greatest dune building followed the most rapid and profound negative shift (assuming that the climatic factor, particularly windiness, was relatively constant throughout the Pleistocene). With lines of dunes to mark former shores, we can expect that the more profound negative sea levels may have left dunes that are now deeply submerged and thus are unaccounted for in this catalogue of periods of dune construction. Perhaps, therefore, the eolianite and eolianite ridges we see today are those connected with only the relatively "shallow" Pleistocene sea levels.

The last change in sea level seems to have been positive and consisted of a rise from the base of the E_4 dune—that is, from a depth of approximately 5 fathoms (30 feet). That the last sea-level shift was not negative is deduced from the fact that the surfaces of the E_4 dunes show no evidence of higher sea levels in the form of sea-level nips or tidal terraces. As described earlier (p. 89), eolianite shores are almost everywhere characterized by these features today. A higher sea level, therefore, would certainly have left a scar on the sides of the E_4 dune. The unlikelihood that higher nips and terraces have been effaced by subsequent surface wastage of the eolianite are indicated by a consideration of the profile of the typical E_4 ridge (fig. 62). As already noted (p. 80), the original dune form of these ridges is still preserved, broken only by the nip and (or) tidal terrace of present sea level; the profiles of the dune surface above and below sea level (exposed in very low tides) seem to form a continuous curve (fig. 36). If, on the other hand, we suppose that higher nips and terraces did exist but have been effaced by weathering of the dune surface, we might expect a definite discordance between the dune profile above and below present sea level (fig. 62). Because such a discordance in profile is generally lacking, it seems reasonable to conclude that nips and tidal terraces of a higher sea level never incised the surface of the E_4 ridge and that in consequence the last eustatic shift was that which raised the sea level from the base of these dunes to its present position. This suggests

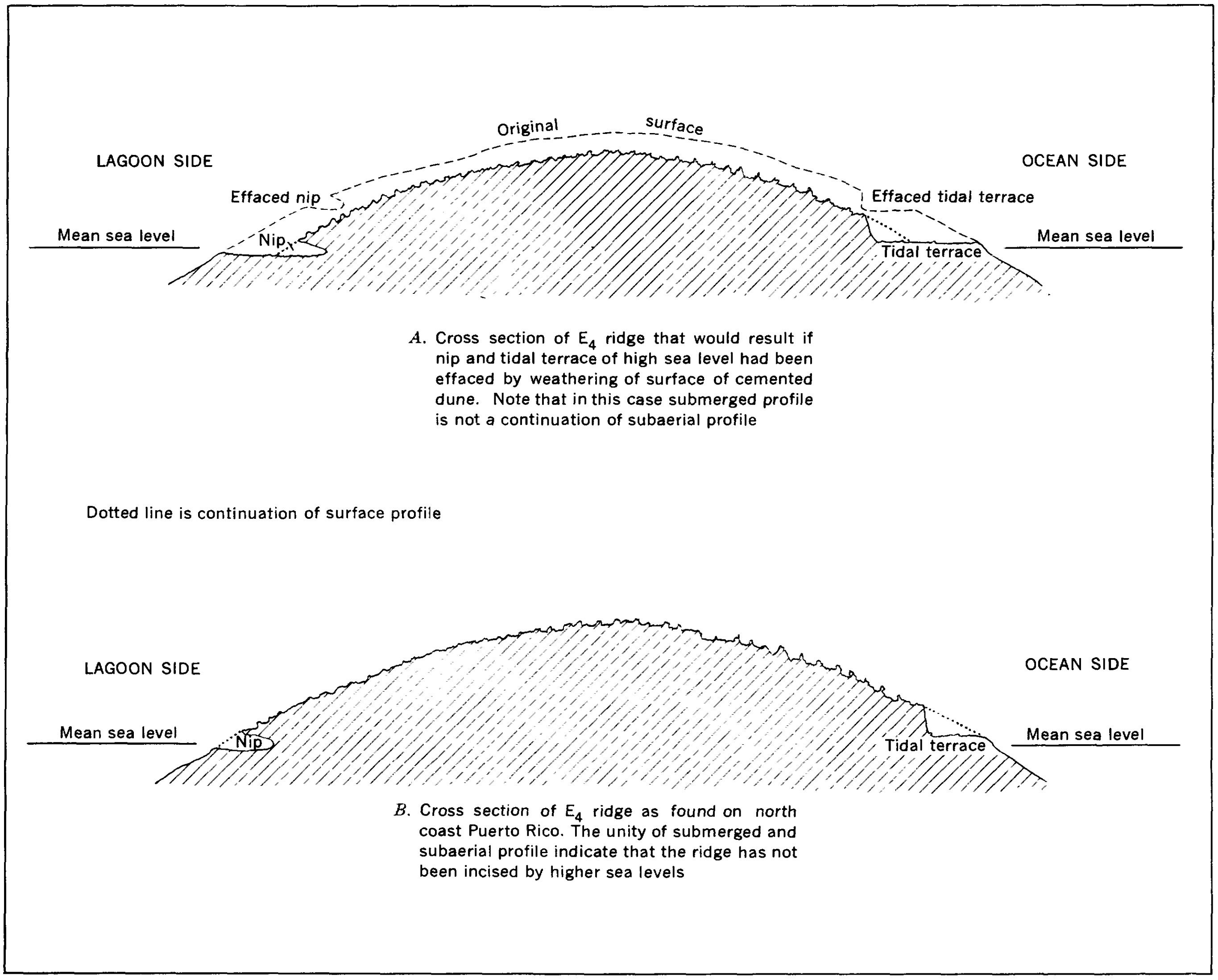

FIGURE 62.—Profile of an E_4 dune, evidence that the 5-fathom sea level is more recent than the 5-foot sea level.

that E_4 is late Wisconsin (Mankato?) or early post-Wisconsin in age.

The ages of eolianites E_1, E_2, and E_3 are much more difficult to determine, and no fossils permitting an age differentiation were found.[6] Sayles (1931) attempted to estimate the lengths of time involved in the formation of the several Bermudian paleosols of the residual variety. He assumed a constant rate of eolianite solution (the eolianites of Bermuda are very pure carbonate rocks) and thereby computed the length of time it took to dissolve the thickness of rock necessary to produce the required thickness of insoluble residue. Because all the Bermuda eolianites are oolites of a very high purity having very small variation in insoluble content, this method probably has a certain validity. Unfortunately a comparable approach to an age determination of the Puerto Rican paleosols can not be used because the carbonate content of the eolianite varies immensely. In a similar manner the modern beach sands of the north coast vary within a mile grading from sands having over 90 percent insoluble to sands having only 10 percent insoluble (for example, immediately east and west of Punta Vacía Talega). The variations in insoluble content of the Puerto Rico eolianites, both vertically and horizontally in a given dune, does not permit an average insoluble composition to be determined without very extensive sampling and analysis. At this stage of our knowledge, there-

[6] Land snail shells from the E_4 ridge at Punta Tortuguero (fig. 29) were identified by Drs. H. A. Rehder and R. T. Abbot of the U. S. National Museum as: *Alcadia striata* (Lamarck), *Farcimen croceum* Gmelin *Drymaeus elongatus* (Roeding), and *Pleurodonte* (*Caracolus*) *marginella* (Gmelin). All of these species are common in Puerto Rico at the present time. Except for the E_2 paleosol at Punta Vacía Talega already mentioned, this is the only locality that yielded well-preserved shells.

fore, the thickness of paleosols in Puerto Rico are an uncertain guide as to age.

The ages of paleosols have been gaged in the western and central parts of the United States by their degree of pedologic maturity—that is, the state of soil profile development (Thorp, 1949); but here, again, the method seems to offer only little help in Puerto Rico. Soil profiles developed on the three older paleosols are as strongly marked as those formed on pre-Pleistocene rocks of the north coast (Roberts and others, 1942), which presumably date from the early Pleistocene or earlier. Lacking, as we do, a geologic basis for dating our soils within the Pleistocene, the full age significance of the E_1 to E_3 profiles escapes us, except, perhaps, to note that the barely preceptible profile development of the sand on the higher E_4 dunes indicates that E_3 is considerably older. For this reason mainly it is suggested that E_1 to E_3 are early Wisconsin and older in age.

The climatic significance of the paleosols is somewhat obscure. Sayles (1931) postulated that the Bermuda paleosols formed under different climatic conditions from those that prevailed during dune construction. Thus he suggested a cool dry climate for the dunes and a warm moist subtropical climate for the soils. It is not evident that the same conclusions can be drawn for Puerto Rican paleosols. Indeed, all that can be safely inferred from them is that they represent a lengthy period of little to no accumulation and that they were formed above the sea level of the time.

Since all of the paleosols occur at and apparently extend below the present sea level, it would appear that their formation did not coincide entirely with sea levels higher than the present. This raises the possibility that both dune accumulation and subsequent soil formation may have occurred during a single stand of the sea level. Such a change in eolian activity could possibly have come about in several ways: (a) Spreading vegetation eventually may have anchored the sand and reduced blowing; (b) the building-out, or prograding, of the shore may have caused areas of sand deposition to move away, farther to the north; or (c) a climatic change may have occurred, particularly a reduction in wind velocities.

The separation of soil formation and dune cementation into separate intervals is also not necessarily indicated. It is very possible that sand cementation took place at depth even as soil was developing at the surface. A well-known example of this, though admittedly not necessarily a parallel to the processes we are here concerned with, is the formation of the lime-enriched zone in the course of soil development in semiarid climates.

OTHER QUATERNARY COASTAL DEPOSITS

The lighthouse at Punta Higuero, at the westernmost tip of Puerto Rico, stands on a small terrace whose upper surface is approximately 40 feet above sea level. The terrace is underlain by thinbedded, friable, coarse-grained sandstone and fine conglomerate. The bedding is horizontal. The writer found no fossils in this deposit. The fine conglomerate lies unconformably on the truncated edges of dipping beds of older complex shale and sandstone. The unconformity is a slightly sloping wave-cut surface at an altitude that ranges from about 6 to 12 feet along the shore beneath the lighthouse. Although the conglomerate yielded no fossils, it is quite likely that this is a Quaternary marine deposit (not eolian, as claimed by Hubbard, 1923, p. 98).

About 4 miles south of Mayagüez, a chain of low hills, underlain for the most part by serpentine, are veneered with very fine quartz sands and yellow silty clays. The deposit is poorly exposed but auger holes along the crest of the ridge have in places penetrated 5 feet of sand and clay above the serpentine. The sand and clay is covered by a well-developed soil. No fossils have been found. This deposit is puzzling. It has none of the aspects of a marine origin, and its position makes it difficult to explain as of alluvial origin. The manner in which it mantles the rolling topography suggests that it may be eolian. Similar uniform fine-grained quartz sands occur on the surface in the western end of the Valle de Lajas, about Las Arenas, and on the flats north of Cabo Rojo, at the southwest corner of Puerto Rico. Although these deposits lack dune form they may also be eolian in origin.

At Punta Águila, northwest of Cabo Rojo, both Mitchell (1922) and Lobeck (1922) noted a consolidated layer of shells and beach sand resting on lower Miocene limestone at an elevation of 10 to 15 feet above sea level. Michell also called attention to what he thought was eolianite overlying lower Miocene limestone at the Cabo Rojo lighthouse, although to the writer this deposit seems conformable with nodular marly limestone both above and below it, and the entire sequence appears to be part of the lower Miocene.

Elevated Quaternary marine deposits occur on some of the islands off the coast of Puerto Rico. On Isla Desecheo, in the Mona Passage east of Punta Higuero, is a well-formed wave-cut terrace that stands 20 feet above sea level (Lobeck, 1922, p. 367–368). This terrace truncates steeply dipping older complex rocks, and it is veneered with several feet of coralliferous beach deposits.

Isla Mona, farther to the southwest, is capped by a dense white limestone, the Lirio limestone, presumably of Pleistocene age (chapter C, this report). Lithologically it resembles the limestone at Tortuguero. It rises to a maximum elevation of about 260 feet. Elevated reef rock and littoral sands that flank the south shore of Isla Mona show a sea level about 12 to 15 feet higher than at present.

Much of Isla Caja de Muertos, off the south coast of Puerto Rico, is rimmed by an elevated reef platform ranging from 12 to 15 feet in altitude. This level is common elsewhere in the Caribbean for elevated reefs. An emerged reef platform on the Cayman Islands in the western Caribbean is 12–15 feet above sea level (Matley, 1926). A similar reef platform at this level also forms Anegada Island, British Virgin Islands, in its entirety (Earle, 1924). Daly (1934, p. 157–161) has listed other elevated strands at this level from both the Atlantic and the Pacific.

ELEVATED WAVE-CUT TERRACES

Mitchell (1922), Hubbard (1923), and Zapp, Bergquist, and Thomas (1948) considered a series of rather locally developed terraces in the middle Tertiary limestones of both the north and south coasts as wavecut in origin. These terraces occur in the vicinity of Guánica, on the south coast, and Quebradillas, on the north. The marked variation in altitude of these terraces makes it difficult, however, to ascribe them to wave erosion. The present writer is inclined to agree with Lobeck (1922) that they probably formed in a nonmarine environment and are controlled by the stratification of the rock.

A 40- to 50-foot terrace, probably of marine origin, occurs west of the lighthouse on Isla Caja de Muertos. The Punta Tuna lighthouse, at the southeast corner of Puerto Rico, near Maunabo, is built on a small and apparently wave-cut terrace about 50 feet in altitude.

Fringing much of Isla Desecheo is a very well formed terrace cut in steeply dipping older complex rocks at an altitude of 20 feet (Lobeck, 1922). The writer has seen this closely from the air but did not land on this island.

The wave-cut(?) cliff north of Manatí, near Punta Tortuguero (pl. 11*D* fig. 61) contains several shallow caves whose sills lie at an altitude of about 20 feet. The floors of many caverns on Isla Mona, which seem to lie at an altitude of about 25–30 feet, may represent a former water table that was fixed by a sea level at about this altitude.

At the south end of Punta Chivato, north of Tortuguero, a narrow 20-foot terrace is eroded in the dense Pleistocene limestone (pl. 11), and at the south edge of the point a terrace ranging from 12 to 15 feet in altitude at the inner edge is eroded in coarse-grained sandy reef rock that is Pleistocene in age.

The possibly most widespread marine terrace is 4–6 feet in altitude. It is particularly prominent on the east coast where it is cut in older complex rocks, and it is also found cut in the older eolianite (E_1–E_3) and in Pleistocene marine deposits of the north coast. It has been described by Hubbard (1923) from Isla Desecheo.

TABLE 5.—*Quaternary data probably reflecting positive eustatic sea levels.*

Reference No.	Location	Altitude (feet)	Remarks
1	Isla Desecheo	5	Lower wave-cut terrace, bevels older complex rocks.
2	East coast of Puerto Rico, many places north and south of Playa de Naguabo.	5	Wave-cut bench in older complex rocks.
3	Small rocky shore two miles east of Arecibo.	4–6	Narrow erosional terrace in lower Miocene calcareous sandstone.
4	Near outlet ditch of Laguna Tortuguero.	4–6	Pitted surface of reef rock along beach.
5	Punta Fraile, north of Dorado.	4–5	Narrow pitted terraces in E_3.
6	San Juan, in front of Capitol, below east wall of San Cristóbal.	6	Narrow pitted terrace in E_2.
7	Vicinity of Punta las Tunas, east of Arecibo.	6½	Conspicuous berm in eolianite just in back of beach.
8	Small valley west of Punta Tortuguero at foot of cliff, north of Manatí.	6±	
9	West of Punta Caracoles, east of Arecibo.	10–12	Level plain behind beach underlain by reef rock.
10	Punta Higüero, west coast	6–12	Sloping wave cut bench eroded on dipping older complex rocks.
11	Isla Mona	[1] 12–15	Reef-rock terrace on south coast of island.
12	Isla Caja de Muertos	[1] 12–15	Sloping terrace of Quaternary littoral sandstone containing cora heads.
13	El Vigía and one mile to east, east of Arecibo.	12–14	Top of boulder bed marking top of marine Pleistocene.
14	Port of Quebradillas, near Quebradillas.	12–15	Terrace underlain by reef rock (Hubbard, 1922, p. 97, 100, 104).
15	E. of mouth of Río Guajataca.	15–20	Elevated sea-level nip(?) in lower Miocene limestone suggests a 15-foot sea level.
16	Punta Águila	10–15	Elevated littoral deposit (Lobeck, 1922, p. 369).
17	Reform School, South of Mayagüez.	12–15	Narrow wave-cut terrace cut in older complex.
18	Punta Chivato, North of Laguna Portuguero.	[1] 12–15	Sloping terrace cut in Pleistocene marine coarse sandstone with corals.
19	Isla Desecheo	20	Wave-cut terrace beveling older complex rocks.
20	Isla Mona	[2] 25	Sill of many cave mouths on south coast.
21	Punta Tortuguero, North of Manatí.	20–25	Sill of sea(?) cave in old sea cliff; in E_1.
22	Punta Chivato	48–50	Top of coastal terrace underlain by dense Pleistocene limestone.
23	Punta Higüero	40–50	Undulating terrace underlain by Pleistocene marine sandstone and conglomerate.
24	Punta Tuna Light South of Puerto Maunabo.	[2] 50	Wave-cut bench in older complex rocks.
25	Isla Caja de Muertos	50	Well-formed terrace in Miocene limestone west of lighthouse.
26	Punta Manatí	[2] 120	Altitude of the highest exposure of Pleistocene marine deposit on the north coast.

[1] Measurement at inner edge.
[2] Approximate measurement.

NEGATIVE SEA LEVELS

Several lower sea levels have probably left their mark on the bottom topography offshore from the Puerto Rican coast. Data that are described below suggest the existence of sea levels approximately 2, 5, 10, 22, and 50 fathoms lower than the present. Of these levels, only the first three seem reasonably demonstrable immediately adjacent to Puerto Rico, whereas evidence for the last two is best developed in the bank surrounding Isla Mona.

The recognition on nautical charts of the topographic forms created by lower sea levels is at best an uncertain art. (See A. A. Miller, 1939; Hoffmeister and Wentworth, 1940; Zeuner, 1950b, 1952). For one thing, well-defined submarine levels may be the result of sedimentary aggradation rather than wave cutting. Likewise, steep submarine scarps, if they can be identified by means of the scattered soundings of a nautical chart, might represent something other than drowned sea cliffs of a lower sea level. Uncertainty also arises from the fact that, even assuming a number of such features are relicts of lower sea levels, it is not known with certainty whether the sea level accorded with the toe of the scarp (for example sea cliffs of Isla Mona, which are apparently actively receding, plunge well below sea level; see chap. C of this report). Neither can one be certain just how far above a wave-eroded platform the responsible sea level was. The depth of wave erosion for a given sea level will vary with the wave height and the nature of bottom sediment or rocks. Vaughan (1916) thought that wave abrasion extended to a depth of 10 fathoms (60 feet) in soft sediment. More recently Dietz and Menard (1951) have produced evidence to show that 5 fathoms is the probable maximum depth of wave abrasion. In any case, most submarine terraces formed by former sea levels lie below that level by at least a fathom and probably more commonly by several fathoms.

A moment's consideration of the variable incisiveness with which the present sea level has impressed its mark on coastlines will show that wave-cut platforms and sea cliffs that are graded to present sea level—that is, intertidal levels, either high, low, or mean—are relatively uncommon. A drowning of the present shores of the world would leave only scant and widely spaced evidence of the present sea level for the future submarine geologist to detect. The same poor development of sea-level markers probably characterized some of the low sea levels of the Pleistocene. In addition one must consider the probability that even such markers as may have been left have been partly obliterated with the passing of time, by either submarine erosion or by burial beneath later sediment or reef growth.

Without the benefit of fathograms from a continuously recording fathometer, the geologist is handicapped and must grope among the soundings of the nautical charts for a picture of the bottom. Because of the relatively wide spacing of the soundings, the fine and often essential detail, particularly of low but significant scarps, is lost. If the density of soundings is relatively uniform, one possible way of recovering this and correcting the picture is by a statistical survey of the soundings over a broad area. In this manner persistent scarps will show up as frequency minima and flats as frequency maxima. An attempt was made to locate low scarps in this manner by tabulating all the soundings on two extensive Puerto Rican banks on two charts (U. S. Coast and Geodetic Survey Charts 901, 904). Figure 63 shows the tabulated soundings of both charts as histograms and as cumulative curves. The latter curve is particularly graphic by simulating the resultant bottom profile. On Chart 904 ("Virgin Passage and Vieques Sound), where there are few soundings deeper than 30 fathoms on the shelf off the eastern Puerto Rican shore, a scarp at 10 fathoms and a terrace level at 28 fathoms are strongly indicated by the data. The broad bank off the southwest corner of Puerto Rico (Chart 901) again shows a 10-fathom scarp. The latter bank lies mostly at about 14 fathoms and drops off abruptly to deep water. A terrace at 7 fathoms is also evident on both charts.

The results of the statistical analysis are confirmed by a close study of the charts. Low scarps at 10 fathoms are apparent at many places, as are broad flats at 7 fathoms. Much of the banks off the southwest end eastern end of Puerto Rico have an average depth of 7 fathoms (pl. 10) and the 10-fathom scarp is strongly indicated off the south and northeast coasts of Vieques, as well as at other places east of Puerto Rico. The shelf about Isla Mona seems to be particularly well terraced and levels at 2, 7, 16, and 22 fathoms are indicated by soundings (fig. 63). The 2-fathom level is found closely associated with surface reefs in many places about the Puerto Rican coast.

The toes of scarps probably provide a more reliable sea-level marker than do terraces, for most of the terraces probably fall below the responsible sea level by at least a fathom. Thus the 5½- to 9-fathom level may well have been cut by a sea level at 5 fathoms. A sea level at this depth is suggested by various data: (a) Low scarps and slope breaks at this depth are indicated at several places, and seem to be particularly well developed about a fourth of a mile north of San Juan. (b) The submerged foredune is perhaps one of the best markers of former shorelines. Type E_4 cemented dunes rise from bottoms that for the most part seem to be between 2 and 4½ fathoms in depth. Because the base of a foredune is of necessity higher than intertidal levels, the sea level to which the E_4 dunes can be referred is estimated to have been 5 fathoms.

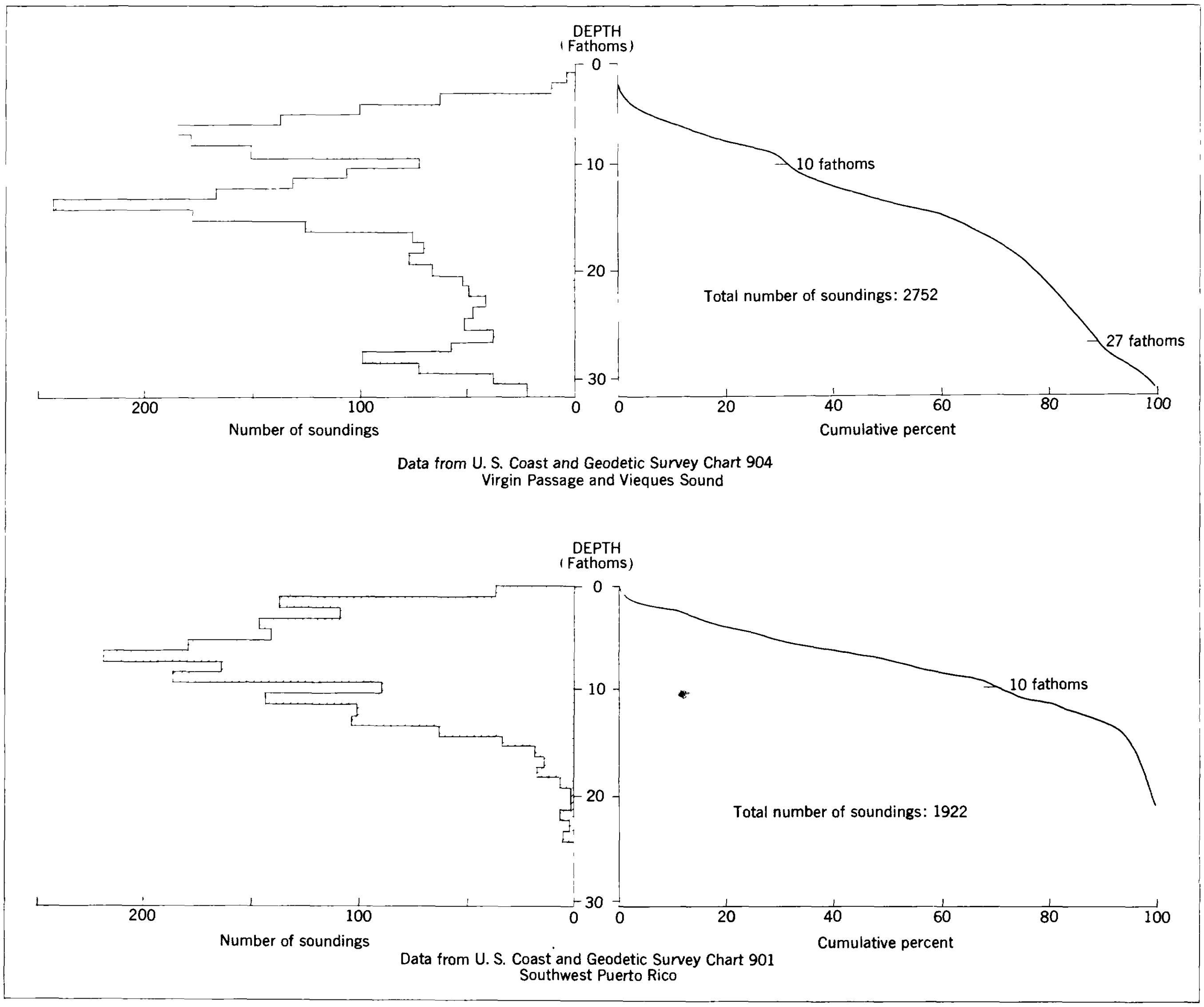

FIGURE 63.—Frequency of soundings of two Puerto Rican banks; from nautical charts.

Submarine terraces ranging from 11 to 17 fathoms may possibly have been formed by the 10-fathom sea level, and levels between 22 fathoms and 28 fathoms may have formed at a sea level that is tentatively picked at 22 fathoms. The 22-fathom level is prominent along the east coast of Isla Mona, and it has been cited by Jordan (1952), who charted it on fathograms, as being important off the west coast of Florida.

According to soundings on published charts, the well-known 50-fathom break in slope (this figure varies by five or more fathoms in either direction, depending on locality) at the edge of the shelf, which is usually attributed to the maximum negative sea-level stand of the Pleistocene (see Dietz and Menard, 1951), occurs only sporadically off Puerto Rico although it is well developed off Isla Mona.

CHRONOLOGY

The fossil corals in the marine deposits that crop out on the south side of the older cemented dunes indicate a Quaternary age for the entire marine-eolian sequence overlying the Miocene foundation. No fossils have been found that make possible a narrower age assignment than this for any of the deposits. Fitting the Puerto Rican sequence into the Pleistocene glacial section therefore involves, first, correlating the inferred sea levels with those in other parts of the world in order to insure that they are eustatic and not due to local tectonic movements, and then arranging them "logically," according to the premise of glacial control.

The duration of the present sea-level stand has already been discussed, and the probability is that it lasted between 2,000 and 3,000 years. The Puerto

Rican data also suggest that about 4,000 years ago the sea may have been 1 or 2 fathoms lower than at present. The next earliest sea level indicated is the 5-fathom stand at the time of cementation of the E_4 eolianite. The dates of this sea level are somewhat more problematical, but perhaps the Boylston Street fish weir, at Boston, provides us with a clue. This Indian structure has been dated by the radiocarbon method (Arnold and Libby, 1951, p. 113) as older than 3,851 (±390) years and younger less than 5,717 (±550) years. According to Johnson and others (1942) the position of the weir at the present time indicates a relative rise of sea level as great as 29 feet (5 fathoms). From this data, therefore, the transition from the 5-fathom sea level to a 2-fathom sea level is tentatively placed between 4,000 and 6,000 years ago. The onset of the 5-fathom sea level may have been post-Mankato, but there is little data with which to estimate its duration. All that can be said is that it lasted long enough to pile up large dunes and to allow these dunes to become sufficiently indurated so that they were not washed away during the subsequent rise of sea level. It will be recalled that foredunes associated with the present sea level generally show only incipient cementation and in places none at all (p. 82). It seems reasonable, therefore, to conclude that the 5-fathom sea level lasted at least as long as the present sea level, which would mean that it was established between 6,000 and 8,000 years ago, at the latest, and probably earlier.

If this interpretation is correct, there were no sea levels higher than the present in post-Mankato time—a conclusion that is given support by recent work on the Texas coast (Shepard, 1956), by Nilsson's (1948) study of the Northwest German Flatlands, and by Cooke's (1952, p. 43) interpretation of the Atlantic Coastal Plain terraces. This conclusion does not accord, however, with that of many geologists who have worked in the Pacific and even some who have worked in the Atlantic basin and who tend to assign a post-Mankato age to the 5- to 6-feet sea level (see Cloud, 1954; Fairbridge, 1950; Kuenen, 1950; MacNeil, 1950; and Parker, and others, 1955). Some workers (Cloud, 1954; MacNeil, 1950; and Parker, and others, 1955), have correlated this higher sea level with the time of the postglacial climatic amelioration ("Climatic Optimum"), which according to Flint and Deevey (1951) is tentatively fixed by radiocarbon dating at 3,000 to 6,000 years ago. It should be said, however, that the absence of high sea levels during the climatic optimum—as indicated by the Puerto Rican data—is not necessarily in disagreement with the theory of glacial control. It is quite possible, for example, that the climatic amelioration was slight or negligible in the polar regions (which at the present time contain 99 percent of the glacial ice of the world; see Flint, 1947), or that the climatic amelioration did not affect all places at the same time and therefore did not act as a worldwide glacial depressant. Confirming the latter possibility is the growth of glaciers from 3,000 to 5,000 years ago in Alaska (the Tustumena glaciation; see Rubin and Suess, 1956, radiocarbon sample W–299). In any case, the Puerto Rican data strongly suggest that the 5-foot sea level is Pleistocene rather than Recent. The disagreement between this conclusion and that of most workers in the vast Pacific area is, however, disquieting and points to the need for a concerted study of recent eustatic sea level changes.

Deeper negative sea levels.—Drilling along the central Texas coast has indicated that about 9,500 years ago sea level was at about −85 feet (Shepard, 1956). It very probably was lower during the maximum of Mankato substage of glaciation, about a thousand years earlier. Moreover, even lower sea levels probably characterized glacial maxima of the Cary and Tazewell substages. Unfortunately, not knowing what these sea levels were, there is scant basis for correlating any of the deeper submarine terraces and scarps with the glacial section. Isla Mona may, however, provide a clue as to the relative ages of the −132-foot (22-fathom) and −300-foot (50-fathom) levels, for the former is apparently much better developed than the latter, which is, as far as the sparse soundings tell us, not so much a level as a break in slope. If these levels are due to lower sea levels, then it seems likely that the more shallow level is the more recent. It was possibly during one of these lower sea levels that the E_3 dunes were formed. From the degree of development of the E_3 paleosol the eolianite dates from at least the early Wisconsin and may correlate with the Tazewell substage.

5-foot sea level.—This is thought to be older than the 5-fathom stand for reasons explained above. It presumably is interglacial or interstadial, and may have occurred during one of the interstadials of Wisconsin time or, following Cooke (1952), during the latter part of Sangamon time.

12- to 15-foot sea level.—The relative recency of this level is clear whenever it is found. But again, as with the 5-foot stand, what this means in terms of years is difficult to judge and many writers following Daly (1933) have placed it in postglacial time. It, like the 5-foot sea level, more probably dates from either a Wisconsin interstadial time (between Tazewell and Cary? substages) or, again following Cooke (1952), from Sangamon time.

25-foot sea level (7.6 meters).—This sea level apparently correlates with 25-foot sea levels on the Atlantic coastal plain, reported by Cooke (1945) as the Pamlico terrace and by others as the Suffolk scarp (Flint, 1947, p. 438–440). Cooke (1952) places the Pamlico terrace in the first part of the third interglacial stage [Sangamon]. Flint (1947) and Zeuner (1950) also assign a Sangamon age to this sea level (in the European section it is the Late Monastirian level, 7.5 m.). Recently McBurney and Hey (1955, p. 65) concurred on this date for terraces on the Libyan coast. It also seems reasonable on the basis of the Puerto Rican data.

50-foot sea level.—This level correlates with Cooke's Talbot terrace (42 feet), which he puts in the latter part of the second interglacial epoch (Yarmouth). On the other hand Zeuner (1950) lists the Main Monastirian terraces of Europe (18 m.) as early Sangamon in age. The European terraces are dated, according to that author, by extensive deposits of Paleolithic artifacts.

Eolianites (E_1–E_2)—Both of these may date from the low sea levels of the third glacial age (Illinoian). They probably do not date back to Kansan time. This conclusion follows if the assumption (see below) that the marine deposits underlying them are Yarmouth in age is correct.

120-foot sea level.—The highest altitude at which marine Pleistocene deposits of the north coast were found is about 120 feet. This is in the hill just east of the mouth of the Río Grande de Manatí. It is possibly the equivalent of either the Okefenokee terrace (145 feet) or the Wicomico terrace (100 feet) of Cooke (1952) and the Tyrrhenian sea levels of Europe which Zeuner (1950, fig. 47) places at 105 feet (32 m). Both authors place these terraces in the Yarmouth (second interglacial). As far as the Puerto Rican data is concerned, there is no argument with this conclusion.

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