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SCIENTIFIC SURVEY OF PORTO RICO AND THE VIRGIN ISLANDS

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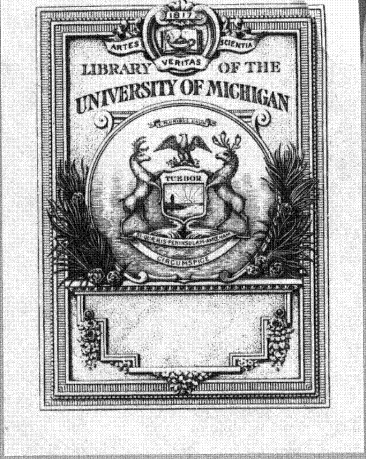
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SCIENTIFIC SURVEY

OF

Porto Rico and the Virgin Islands

VOLUME I—Part 4

The Physiography of Porto Rico—*A. K. Lobeck*

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THE PHYSIOGRAPHY OF PORTO RICO

By Armin K. Lobeck

CONTENTS

INTRODUCTION

Porto Rico, the easternmost of the larger Antilles, is a rugged mountain mass trending east and west for a distance of over one hundred miles, flanked by uplifted limestone plateaus on its north and south sides. It lies well within the tropics, in the latitude of 18 degrees north, and is subject to the influence of the steady northeast trades. The persistence and regularity of the trade winds can not fail to excite the notice of the northerner who is accustomed to more variable conditions. Their effect upon the island is pronounced and shows itself in the marked contrast in precipitation between the north and south sides. An elevation of about 2000 feet prevails throughout much of Porto Rico, so that the trades are forced to rise and precipitate their moisture over the northern two-thirds of the island (Fig. 1). Out of the brilliant sky dense cloud masses form with great rapidity over the uplands and several downpours may be expected during the day throughout most of the year. But when the winds reach the lower lands of the southern coast they have not only lost a large part of their moisture, but in their downward journey they have been transformed into drying winds, with the result that this whole coastal area is almost barren and parts of it experience months, or even years, without rainfall. Irrigation is there essential for the cultivation of large

crops, and in the southwestern corner of the island, where there occur the longest periods of drought, considerable areas are densely covered with cactus. Over the rainy windward portion of Porto Rico streams are numerous and always flowing. In the dry leeward portion, river courses are intermittent and coalescing alluvial fans fringe the shallow coast for many miles. The trade winds are also responsible for the strong waves of the north coast, which have thrown up beaches and bars and have developed a magnificent stretch of cliffs. This is in marked contrast with the southern coast, where there is almost no disturbance to the water and mangrove swamps abound.

The shape of Porto Rico in general is that of a rectangle, with a long east-and-west dimension of 110 miles and a north-south width of 35 miles, giving the island an area three-fourths that of the state of Connecticut.

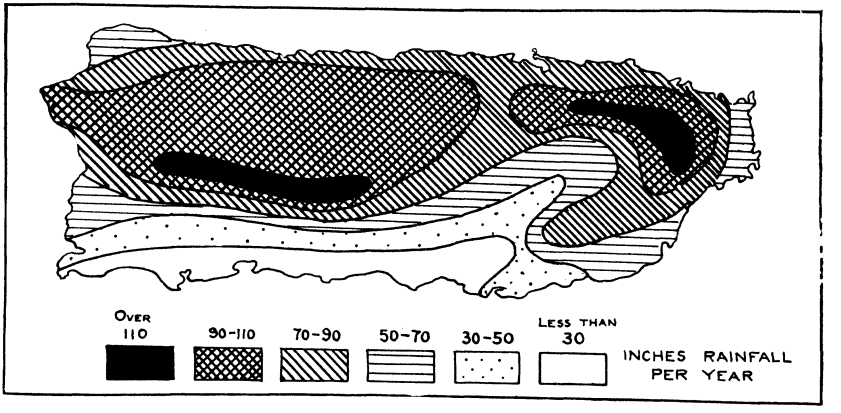

FIG. 1.—*Map showing the average annual rainfall in Porto Rico*

The population of Porto Rico is approximately half that of Manhattan Island, roughly between 1,200,000 and 1,250,000 people. It is, in fact, one of the most densely inhabited regions of the globe. Although there are some 65 to 70 villages on Porto Rico, the people are predominately rural and are scattered quite uniformly over the entire island, even throughout its most rugged portions. The largest three cities—San Juan, Ponce, and Mayaguez—have populations from 35,000 to 50,000. Many of the smaller villages contain less than 1000 people, but most of them average between 1000 and 2000. The towns are invariably built compactly around the public square or plaza which the cathedral fronts on the east. The only extensive part of the island not settled is the area comprised in the Luquillo National Forest, which covers the higher portions of the Luquillo Mountains.

Coffee, tobacco, sugar, and citrus fruits make up almost the entire agricultural output of Porto Rico. Coffee-raising is confined to the upland areas, tobacco is the important product of the Caguas and Cayey valleys in the east, sugar is the great crop on the extensive flood plains and coastal regions, and the raising of grape-fruit and oranges has been developed in the hills along the north coast west of San Juan. In spite of its splendid possibilities the island is far from being self-sustaining in the matter of food, and the great mass of the natives depends almost entirely upon the rice, beans and salt fish shipped from the states.

Compared with the conditions of living within the continental United States, even in the smaller and more remote towns, life in Porto Rico must seem at first to a visitor from the north very difficult, but to be fair one must take into account the vicissitudes through which the country has passed and realize what splendid headway is now being made in the direction of culture. On the other hand, no visitor, even while adjusting himself to the mode of life in Porto Rico, can fail to be charmed by the idyllic beauty of her scenery and the splendor of her setting under the tropic skies.

PHYSIOGRAPHIC HISTORY

The physiographic history of Porto Rico takes us back to an oldland composed of a complex mass of igneous rocks (Fig. 4). The rock types involve sedimentaries of volcanic origin and intrusive masses ranging in size from those showing only a few feet of outcrop to the largest one covering almost one-eighth of the island. Under the influence of subaërial erosion, this oldland was reduced to a rather perfect peneplane except for two well-defined monadnock groups. The smaller of these groups now comprises the Luquillo Mountains at the eastern end of the island. The larger one is known as the Cordillera Central and forms the main crest of the mountainous area of Porto Rico. It is probable that Porto Rico is essentially a block or horst bounded by faults, and it is likely that several of the larger elements comprising the oldland mass are due to faulting which antedated the first peneplanation. No direct evidence on this point is available.

Uplift of this the first peneplane stimulated a new cycle of erosion. Over most of the island only a mature stage of dissection was reached in this new cycle, but along the north coast an east-west belt about ten miles wide was reduced to base-level, which for convenience may be known as the second or lower peneplane. A corresponding belt on the south side of the island was also worn down far less effectively, probably be-

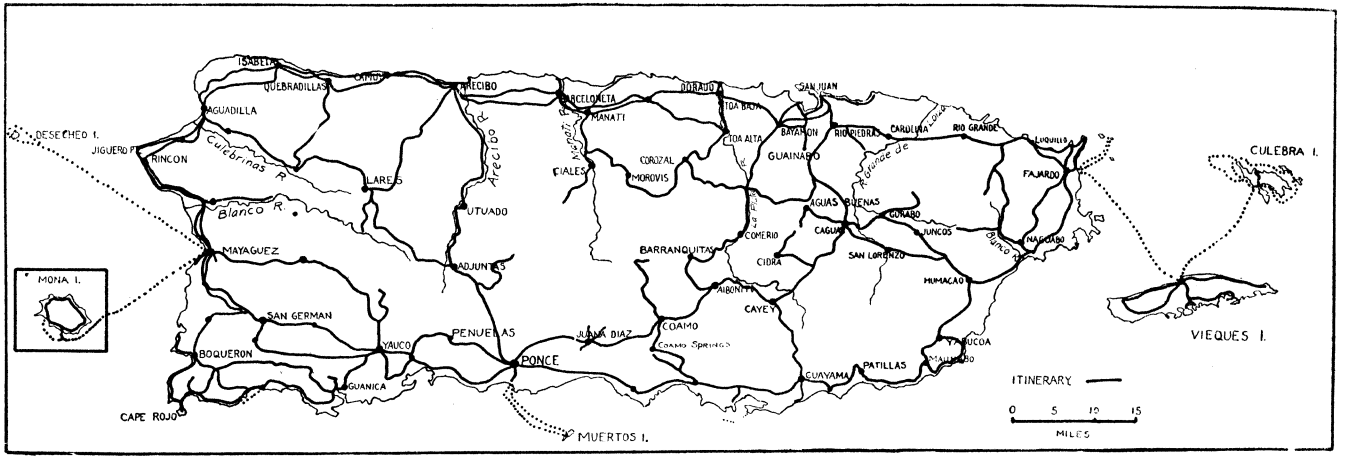

FIG. 2.—*Sketch map of Porto Rico showing regions visited*

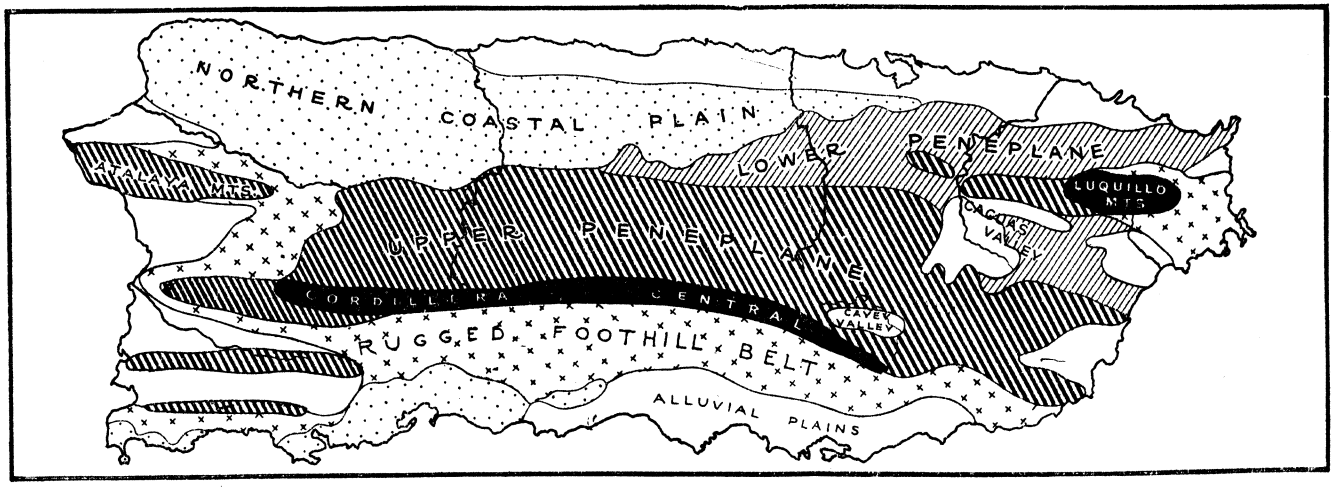

FIG. 3.—*Map of Porto Rico showing the chief physiographic regions*

cause of inadequate rainfall. Submergence of much of the oldland mass then permitted the deposition of a coastal plain upon both the

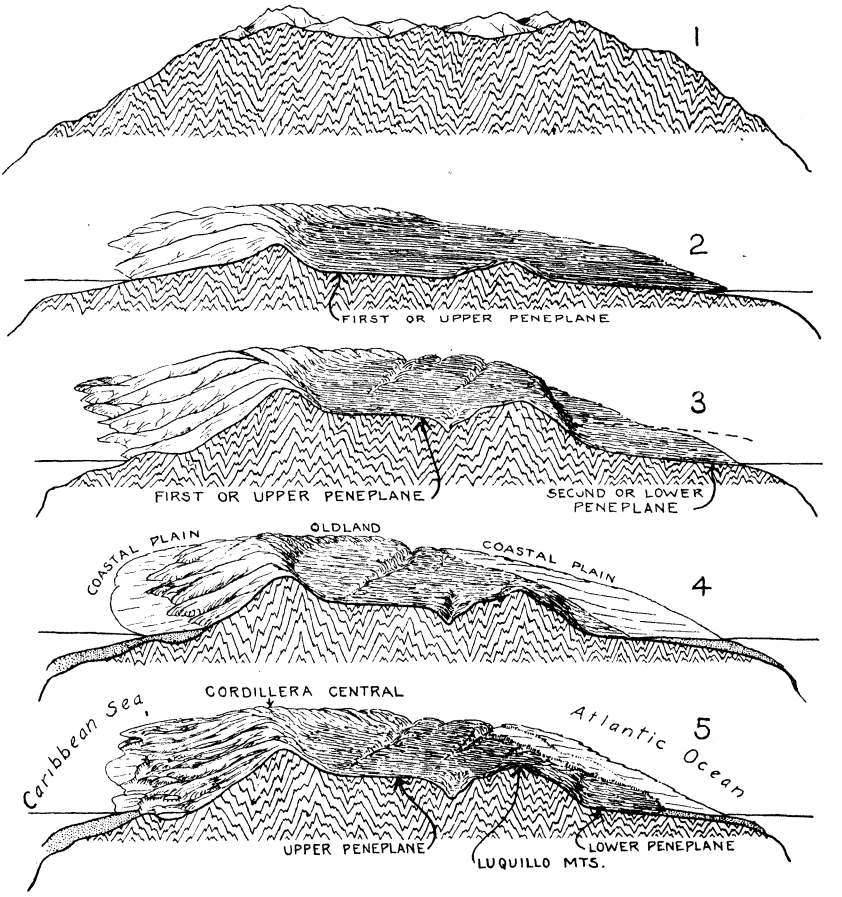

FIG. 4.—*The main stages in the physiographic development of Porto Rico*

1. The initial complex mountain mass of Porto Rico.
2. After the first peneplanation. Showing the monadnock group forming the Luquillo Mountains and the cordillera Central.
3. The peneplane has been uplifted and dissected and a second lower peneplane has been formed along the north side of the island.
4. The whole island has been lowered, its northern and southern flanks have been covered with coastal-plain deposits, and the mass as a whole has again been raised.
5. Dissection of the coastal plain has taken place. Distinct cuestas appear on both the north and south sides of the island.

north and south sides of Porto Rico. That on the north side covered most of the lower peneplane at the east end of the island and

in the western part even extended so far inland as to rest upon the first or higher peneplane; that on the south side was deposited upon a very irregular oldland surface. Dissection of both the coastal plains was then initiated by uplift. The coastal plain on the north side acquired a well defined belted character, exhibiting two pronounced cuestas, each surmounted by the so-called haystack hills of the limestone country. These parallel east-west belts of hills alternate with other belts of lower country, which on account of the sharpness of dissection have a plateau-like aspect. The inner cuesta of the north coastal plain in places fronts a broad inner lowland from which the basal deposits of the coastal plain have been removed. The outer or northern cuesta usually looks down upon one of the plateau-like belts just mentioned. On the south side of Porto Rico a distinct cuesta was developed, but occasionally it is obscured by the irregular topography of the oldland upon which it rests.

After the dissection of the coastal plains the entire coast suffered a slight submergence, the result possibly of the melting of the continental ice sheets at the end of glacial time. The recent changes which have taken place since this submergence involve the deposition of alluvium along stream courses and its dissection to form terraces, the building of extensive alluvial fans on the south coast, the silting up of bays, and the work of the waves and wind, which has been most pronounced on the north side of the island. Finally there is some evidence of a slight emergence at a very recent date.

For ease of reference the physiographic history of Porto Rico may be divided into several events or stages which can be tabulated as follows:

1. The oldland, a complex mass of igneous rocks consisting of sedimentaries and intrusives subjected to subaërial erosion.
2. The first or higher peneplanation with monadnocks.
3. Uplift, mature dissection, and development of the second or lower peneplane on the north and south sides.
4. Partial submergence and deposition of coastal plains on the north and south coasts, to be known as the Tertiary coastal plains.
5. Uplift, dissection of coastal plains, and continued erosion of the oldland.
6. Slight drowning of entire coastline.
7. Recent changes involving:

   a. The deposition of alluvium in stream valleys, in drowned bays, and as alluvial fans on the south side of the island.
   b. Wave and wind work.
   c. Slight emergence.

The discussion of these stages will follow the order of succession of events as given above, and in pursuing it the reader will do well to make frequent reference to the accompanying large map.

THE OLDLAND

The rocks of the oldland comprise what has been termed the Older Series by Dr. Berkey. While over large areas the erosion of the oldland mass has not been appreciably affected by variations in the character or the structure of the rocks, there are districts where quite the reverse is true. A brief consideration of the rock types and the simpler deformations which have taken place in the older series will therefore be of distinct help in appreciating the present topography.

Volcanic Tuffs and Shales

As is to be expected in a region isolated from a continental mass, practically none of the formations have a clastic derivation. Volcanic tuffs represent the most abundant of the rock types and they are usually massive in habit and made up of andesitic fragments. This implies a practical absence of quartz, a condition which is true also of the shales. These two rock types, together with the igneous intrusives of the andesite-diorite family, make up the bulk of the older series, and as they grade into and are frequently indistinguishable from each other it is practicable to draw a few generalizations regarding the effect of erosion upon them.

Although it is usually true that weathering has gone to considerable depths, 20 to 30 feet being quite common, most streams are cutting into rocky beds. Berkey (1915, p. 34) has remarked upon the striking manner in which badly decayed outcrops resist destruction or removal by ordinary weathering and erosion agents. He mentions three factors to account for this stability of the soil mantle:

> One is the clinging character of some of the vegetation which tends to bind the soil together; another is the small range of temperature variation, which reduces disintegration or disruption tendencies to a minimum; and still another is the low content of inert or refractory materials, such as quartz, in the rocks whose destruction has furnished the soils; all of which factors favor the making of a specially tenacious soil.

It is probable that the last factor is by far the most important.

In general, the hillside slopes throughout the older series are very steep, 30 degrees being exceedingly common and 40 to 45 degrees not rare, but this does not hold true in the granite areas where rolling topography and

gentle slopes are the rule. In spite of the fact that the tenacious character of the soil, due to its high clay content, enables the vertical cuts of trails to stand for long periods and prevents the washing of steep hillsides, it is no uncommon thing to see slumping of the ground even on moderate slopes, and occasionally land slides of really great proportions. A large landslide may be seen a few miles north of Yauco on the trail to Maricao, where the mountain sides for the space of a thousand feet above the valley floor have given way.

Another factor which may be of significance in developing steep slopes and the characteristic *cuchillo* or knife-edge divides on the members of the older series is the torrential character of the rainfall. The average annual rainfall over the upland portion of Porto Rico is between 80 and 90 inches, or more than twice that for the vicinity of New York. But, unlike the precipitation of middle latitudes, where the duration is to be measured in hours, and even days, and the amount in hundredths or tenths of an inch, the average duration of a shower in Porto Rico is ten or twelve minutes, and there are numerous instances of successive showers which totaled 10 inches rainfall in twelve hours, while amounts of 4 to 5 inches in twenty-four hours are of frequent occurrence. A record of 23 inches for twenty-three hours, as an example of an extended period of heavy precipitation, and of 1 inch in nine minutes for a short period may suggest to the reader that important consequences must result from the accumulation and run-off of so great a volume of water in so brief a period of time. Those portions of Porto Rico which have only moderate rainfall, but apparently the same general rock make-up as that of the mountainous rainy district, exhibit much smoother and more rounded slopes.

Another phase of the situation, dependent upon the plasticity of the weathering product derived from the quartz-free volcanics, is the imperviousness of the soil mantle. This encourages a large and exceedingly rapid run-off, as may be appreciated from the fact that many streams immediately rise 15 to 20 feet after heavy showers. In one case the Plata River, twenty-five minutes after it began to rise, poured over the dam near Comerio in a sheet 15 feet or more in thickness throughout the entire 575 feet length of the dam, the flood continuing all day at 10 feet above the dam.

The impervious character of the soil causes not only a rapid run-off, but also an accumulation of water in all the little pockets and irregularities of the surface. In consequence the trails over the upland portion of the island, except during the comparatively dry months of January and February, are often veritable sloughs of red mud, which is both unctuous and tenacious and exasperatingly slippery.

GRANITE

Next in size to the areas of tuffs, shales, and associated igneous intrusives making up the bulk of the island are two or three areas underlain by large intrusions of granite. The largest of these covers most of the southeast corner of the island from Caguas to Yabucoa. In general, the granite is less resistant than the volcanic rocks and most of this region has been reduced to a more or less open lowland. At the north the limits of the lowland coincide rather closely with the extent of the granite, but the southern margin is less definite and much of the granite still retains the upland level. Throughout the granite area the hillsides are covered with large weathered blocks and boulders, and the soil is distinctly granular and resembles a fine gravel. There is a marked contrast between the cleaner condition of the native huts and the tidier way of living in this area, where the soil is porous, and the usual filthy condition which prevails over most of the island where mud is such an important factor.

A second granite mass, of unknown extent, is found in the region about Utuado, in the west central part of the island, but its effect upon the topography is not marked. The granite is massive and jointed, and in a minor way some control is exerted upon stream position. Even a master stream like the Arecibo River follows joint planes for short distances. Pot-holes, a feature observed practically nowhere else in Porto Rico, occur along this river, and their presence is ascribed to the substantial and massive character of the granite.

SERPENTINE

Besides the granite intrusions there are in the western part of the island one or two masses of serpentine of smaller areal extent. They resist erosion more readily than the adjacent rocks and appear as round, full-bodied forms topped by more or less level surfaces. They constitute the so-called *mesas* near Mayaguez and similar larger masses farther east. The weathering of the serpentine has produced a thick, red covering of limonitic soil and has given rise to the smooth-flowing outline of the crest of the mountains which is distinctly characteristic of the region north of San German, where the bulk of the range looks much like the back of a gigantic elephant.

LIMESTONE

The fourth group of rocks occurring in the older series exerts by far the most effective control over the erosional forms. These are the crystalline limestones. Almost invariably they stand up as distinct ridges,

despite their high solubility and the frequent caverns to which this character gives rise. The two most prominent of the limestone belts make up the chain of hills known as the *Cerros,* running from Cabo Rojo to Yauco, and a parallel chain to the south extending from Boqueron Bay to Guanica. The relation between these two belts is discussed below under "Structure." Another limestone ridge runs from Juana Diaz eastward to Salinas, the formation being known as the Coama tuff limestone. Other smaller belts occur in the interior, as, for instance, the Aguas Buenas limestone; but they are usually too insignificant in thickness materially to affect the topography, although their ragged white outcrops may be a conspicuous feature of the landscape.

STRUCTURE

The usual trend of the members of the older series is in a west to east or a northwest-southeast direction (Fig. 3). Over large areas it is next to impossible to determine the strike at all, owing to the massiveness of the formations and their decomposed condition; and even where the strike is to be recognized the yielding character of the rock, due to the advanced state of decay, makes it a negligible factor in controlling stream position.

South of San Juan a definite alignment of features in a northwest-southeast direction reflects a greater degree of structural control than is commonly the case in the volcanic members of the older series. There is a high, continuous ridge which persists from near La Muda southeastward to the gap cut by the Rio Grande; and running parallel to the ridge on its south side is a distinct subsequent lowland developed on weaker rock, not occupied throughout its length by any one stream. The road from San Juan to Caguas follows this narrow lowland for several miles east from La Muda. At the west end of the island the east-west trend of the Atalaya Range is in sympathy with the strike of the formations, as may readily be seen at many places on its southern flank.

In the region about Coamo Springs there is a well-defined parallelism in the series of ridges developed upon the Coamo limestone and its associated formations. This limestone, which has already been mentioned, strikes from the northwest to the southeast, has a pronounced dip to the southwest, and gives rise to the most marked feature in this stretch of the southern coast. The main ridge or hogback in its highest part, in the vicinity of Juana Diaz, has an elevation of almost a thousand feet higher than most of the hills of the coast region. Its uneven crest, interrupted by several deep water-gaps, descends more or less regularly until it pitches beneath the alluvial plains near Salinas, but large outliers are found along the continuation of its strike at Central Aguirre.

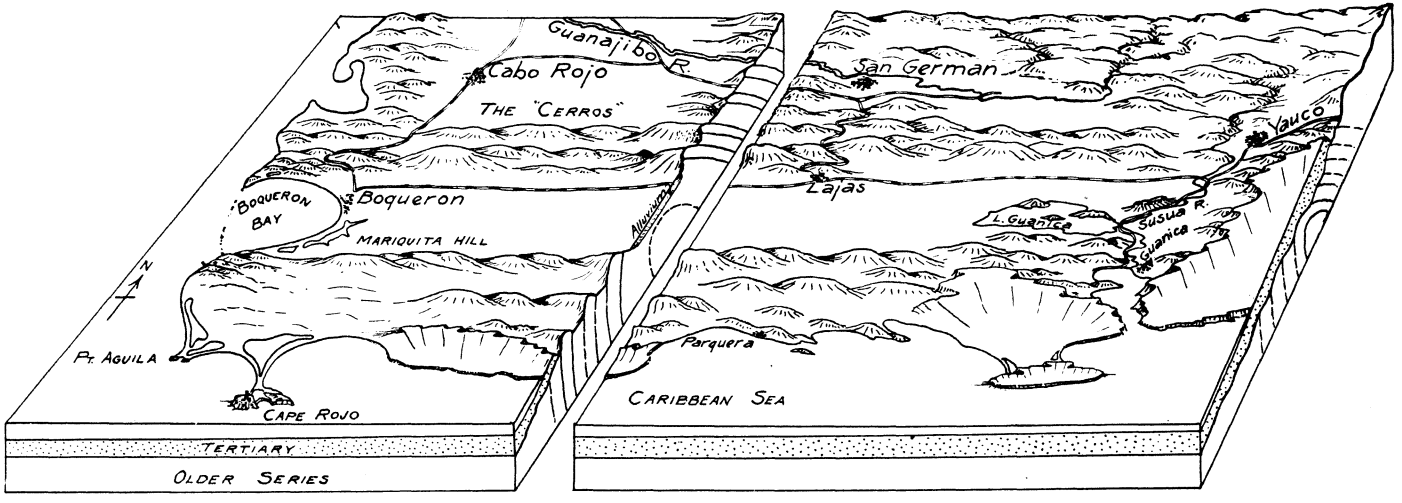

FIG. 5.—*Block diagram of the southwest corner of Porto Rico*

The structure of the older series is a huge anticline pitching west at Boqueron and east between Yauco and Guanica.

The southwestern corner of Porto Rico (Fig. 5) appears to be a huge anticline, pitching to the west below Boqueron Bay and to the east beneath the Tertiary series at Yauco. The north and south limbs of the anticline stand up as two parallel ranges separated by a broad valley developed on the axis of the anticline. The north limb of the anticline is known as the *Cerros* and is by no means a well-defined ridge. Rarely can the northward dip of the limestone and adjacent formations be noted. The topography developed upon the southern limb is expressed by a series of more

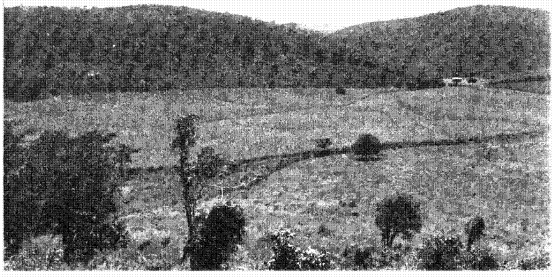

FIG. 6.—*Appalachian ridge structure in the oldland rocks between Boqueron and Parguera*

A subsequent valley, in the foreground, and a ridge transected by a water gap.

or less parallel and elongated hills which are thoroughly suggestive of Appalachian ridges on a reduced scale (Fig. 6). On the north side of Boqueron Bay, and in particular near Guaniquilla Point, the usual east-west strike of the formations swings around toward the south, and it is one of the resistant layers which forms the barrier across the mouth of the drowned anticlinal valley represented by Boqueron Bay.

THE FIRST OR HIGHER PENEPLANE

THE PENEPLANE

As one approaches San Juan by boat from the north the remarkably even skyline over the central part of the island presents striking testi-

mony of the first recorded period of base-leveling imposed upon the folded mass of the older series. If there were an earlier planation, all evidence of it was removed by the wide extent and perfection of the erosion which produced the peneplane represented by the present summit levels. The

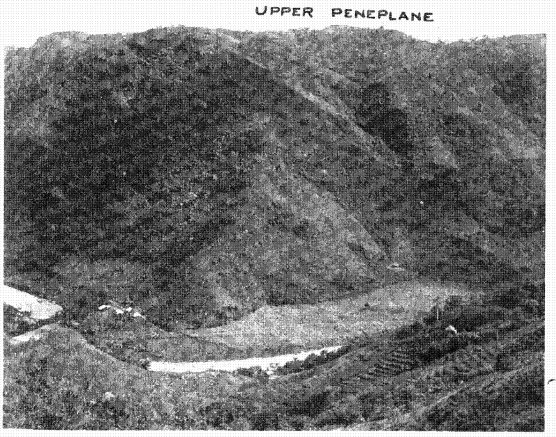

FIG. 7.—*Valley of the Manati River above Ciales*

A gorge in the oldland cut below the level of the upper peneplane.

notches of the Plata and Bayamon rivers are the only breaks in the otherwise continuous skyline and give the first intimation of the thorough dissection which has occurred. Deep gorges, bold canyons, in fact (Fig. 7), are the rule, and the ramifications of the headwaters in steep-sided valleys and ravines is unusually bewildering to one exploring the mountains on

foot. The peneplane was best developed, or at least its remnants have been best preserved, in the central part of the island. All the way from the Plata River region westward to Lares its fairly accordant skyline forms the controlling element in the topography. West of Lares the peneplane has been so extensively dissected that only isolated remnants and spurs are to be recognized, the Atalaya Range forming the largest unit; and east of Caguas the prevailing level of the country is so much below the upland surface that it must be considered as a lower base-level formed at the time of the second peneplane. The same is true of the region about Cayey (Lobeck, 1919, p. 535).

It is believed that the accordant level of the hill-tops on Vieques, having an elevation of about 600 feet, represents the upper peneplane, this assumption being based mainly on the fact that the Tertiary formations rest upon a lowland cut below that level. On Culebra there is no accordance of level, neither is the Tertiary represented to furnish a key to the situation, but because of similar orders of magnitude of the features to those of Vieques it is probably safe to assume that the tops of the hills roughly indicate the upper level (Fig. 40).

Monadnocks

The Luquillo Mountains

This range stands up as a prominent mass at the eastern end of Porto Rico. The upper peneplane flanks it only on its western side; above it the mountain summits rise over a thousand feet; elsewhere they drop in long radiating spurs to the coast or abruptly to the adjacent lowlands. Having an elevation of nearly 4000 feet, these mountains form one of the most imposing features of Porto Rico.

The best explanation for the position of this monadnock mass is the presence of more resistant rock types, though in the field the rocks here appear to suffer weathering as readily as those over most of the adjacent upland. A puzzling feature is the fact that all sorts of rocks are represented in the area, including tuffs, limestones, and even granite, which is so non-resistant in the tropics, on the southern flank of the range. The possibility that the mass represents an upwarped part of the upper peneplane can not readily be entertained because the peneplane remnants appear to fringe it so nicely on the west and to form a narrow shelf on the south, and because the peneplane can not be recognized elsewhere about its base. It is quite possible that a better knowledge of the rocks involved would show that the higher areas are actually made up of more resistant types.

The Luquillo Mountains, as a whole, are maturely and deeply dissected, and though at a distance they appear as a unit mass, a traverse of the range shows them to be made up of several culminating peaks separated by gorge-like valleys 1000 to 2000 feet deep. El Yunque, "the anvil," is the highest of the peaks and has an altitude of close to 4000 feet. Although the Luquillo Mountains are forested, rock ledges and bold and imposing cliffs are not uncommon. The Luquillo National Forest covers most of the range and is the only extensive part of Porto Rico still preserving the virgin timber. Contrary to a general conception, this original tropical forest is not an impassable jungle, but is pleasingly open and park-like. Tree ferns abound, and occasionally one meets with flowers of great brilliancy, but there is almost no animal life. Even birds are rare. The sound of running water is always to be heard, so frequent are the streams. The higher parts of the range are almost continually drenched in a heavy mist. Nowhere else in Porto Rico may one walk for hours without seeing one of the thatched huts of the natives or without meeting people at every step.

THE CORDILLERA CENTRAL

Practically all of the other residuals rising above the peneplane level are concentrated in a chain of peaks along its southern margin, known in the western part as the Cordillera Central and further to the east as the Sierra de Cayey. Many of these peaks, especially in the west, rise to the same or to an elevation even greater than those of the Luquillo Mountains. Viewed from the south, the whole range has the appearance of a ragged escarpment with long, irregular spurs trailing down between steep-walled and cirque-like valley heads. Just as the lower peneplane, to be described later, reached a far greater degree of perfection on the north coast than on the south, due presumably to the abundance of rain on the north side and its almost complete lack on the other, so it seems that the same cause may have been effective in the disposition of this chain of monadnocks along the southern edge of the higher peneplane. In the region south of Adjuntas a wide belt of country is involved in the Monadnock group, and here it is not always easy to say just what the elevation of the peneplane is; but further east the belt becomes narrower, and in the Sierra de Cayey only one or two masses rise above the well-marked peneplane level.

THE SECOND OR LOWER PENEPLANE

From San Juan on a clear day the sharp break between the higher and lower peneplanes twelve miles to the southwest is a sufficiently marked

feature to be easily noted. The escarpment was mentioned by Semmes in his report on the San Juan District. In the space of only a mile or two there is a descent of 1000 feet or more northward to the lower peneplane. Although Semmes briefly entertains the idea that there has been simply a warping of one peneplane, all the evidence, both here and elsewhere, points to the later development of a lower base-level. The strongest evidence is the fact that the lower level is to be recognized between the spurs coming down from the higher one, and that more or less extensive basins like the Caguas and the Cayey Valleys have been opened out upon softer rocks below the prevailing upland. A corresponding lower level on the southern side of the island has also been produced by erosion, but the stage of development is not so advanced as that which characterizes the lower peneplane on the north coast.

The escarpment, which virtually marks the northern limit of what is known as the mountainous part of Porto Rico, is not to be seen west of Ciales. The coastal plain in the western half of the island laps so far over the oldland as to bury completely the lower peneplane if it was developed there. Just south of Corozal the break between the two peneplanes is more marked and regular than anywhere else. Further to the east the spurs from the upland level become more and more confusing until directly south of San Juan, in the region around La Muda, it is quite impossible to distinguish with any degree of satisfaction between the elements of the landscape.

It is not possible to know just how far the Tertiary coastal plain formerly extended over the lower peneplane on the north coast, but it is quite probable that much of the area was covered and that the inner lowland now developed represents a stripped belt. Were it not for the irregular surface, both on the north and south sides of the island, upon which the Tertiary was laid down, it might be argued that wave planation was a factor in developing the lower peneplane. But the ruggedness of the buried surface, especially on the southern coast, favors the theory of subaërial erosion, although it is not unlikely that waves were effective during the transgression of the sea in which the coastal plain was deposited. Throughout the eastern half of the north coast region, from Morovis to the base of the Luquillo Mountains, the lower peneplane is a gently rolling surface with few interruptions rising above the general level. The streams are numerous, but the depth of dissection is rarely over 100 to 200 feet (Fig. 8).

On the south coast conditions are quite analogous to those on the north side of the island, but the reduction toward a lower level did not advance far enough to justify the term peneplane over any extended area. As

previously suggested, this condition is explained by the contrast in precipitation on the north and south coasts. On the north coast the stage of development reached was one of old age, since rejuvenated, whereas on the south side of the island the region in general may be described as still in maturity.

Although the general elevation of the region a few miles back from the south coast is much below that of the upland peneplane level, there is still very great relief, and the whole belt of country flanking the southern margin of the upland is characteristically rugged. The escarpment marking the break between the higher and lower levels on the south side of

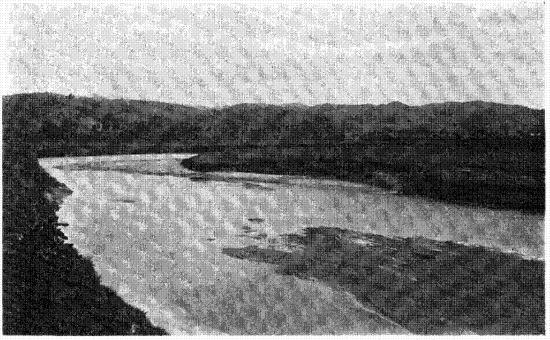

FIG. 8.—*The valley and flood plain of the Rio Grande de Loiza near Carolina*

The tops of the hills represent the surface of the lower peneplane below which the valley has been opened out.

Porto Rico is the most extensive physiographic feature on the island and at the same time the most imposing. It would be even more imposing if it were not that the spurs and foothill country cover such a wide belt and have such considerable elevations as partly to detract from the prominence of the main crest. In the eastern portion near Guayama the face of the escarpment is exceedingly irregular and is broken by great cirque-like valley heads, whose walls attain a steepness not exceeded elsewhere in Porto Rico. Slopes of 40 degrees are common, and even 50 degrees is frequently noted. In its western half the upland margin has a fairly definite east-west trend and the foothill country becomes narrower.

We may say, then, that it is this foothill country on the south side of Porto Rico which corresponds with the lower peneplane on the north side. On the north side rejuvenation is evidenced by the incision of the streams 200 feet or so below the peneplane level; on the south side the effect of the uplift is not so apparent, because the new cycle was introduced while the work of the earlier cycle was still in its youthful stage, and the result was a continuous down-cutting. Locally, however, there is some suggestion of the development of a lowland before the advent of the new cycle.

A study of a typical profile across the island and a comparison of the lower peneplane on the north and south coasts both above and below sea-level is helpful to an appreciation of its true character. Such a profile is shown in Fig. 9, which represents an approximately north-south section through San Juan. The essential features to be noted are:

a. The higher peneplane forming the great upland portion of Porto Rico, fringed along its southern margin by the chain of monadnocks known as the Cordillera Central.

b. The lower peneplane, well developed on the north side of the island, but represented on the south side by a belt of greater ruggedness.

c. The pronounced break or escarpment dropping down from the upper to the lower peneplane on both the north and south sides of Porto Rico.

d. The extension of the lower peneplane as a continental shelf beneath the Atlantic Ocean on the north side of the island and beneath the Caribbean Sea on the south side.

e. Remnants of the Tertiary coastal plain resting upon the lower peneplane of the north coast in the region of Bayamon. On the south coast alluvial deposits bury some of the irregularities of the lower peneplane. Further west along this same coast similar irregularities are buried under the cover of the Tertiary coastal plain.

The progress of erosion during the second cycle is attested not only by the denudation of the north and south coastal areas, but also by basins in the interior of the island, notably two in the eastern part. The larger of these, which for convenience may be known as the Caguas Valley, is drained in its western part by the headwaters of the Rio Grande and in the east by several small streams flowing in the opposite direction. Its reduction to a lower level seems to be due entirely to the weakness of the underlying granite rock. The high remnant of the upper peneplane which forms an imposing barrier on the north side of the entire Caguas lowland has been trenched by a narrow valley which serves as an outlet for the Rio Grande. The southern margin of the lowland is more difficult to define because in many places the higher peneplane is not so well preserved. In general, the smooth and gently rolling surface of the low-

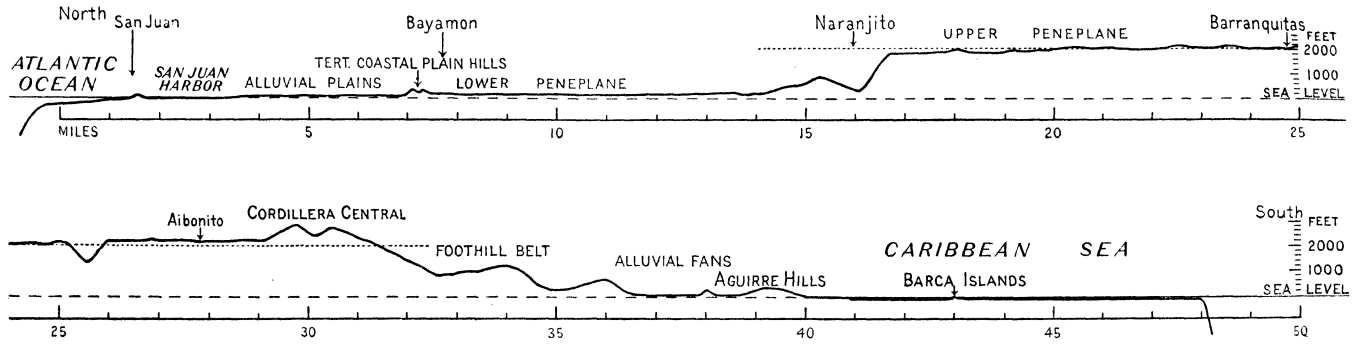

FIG. 9.—*North-south profile through Porto Rico*

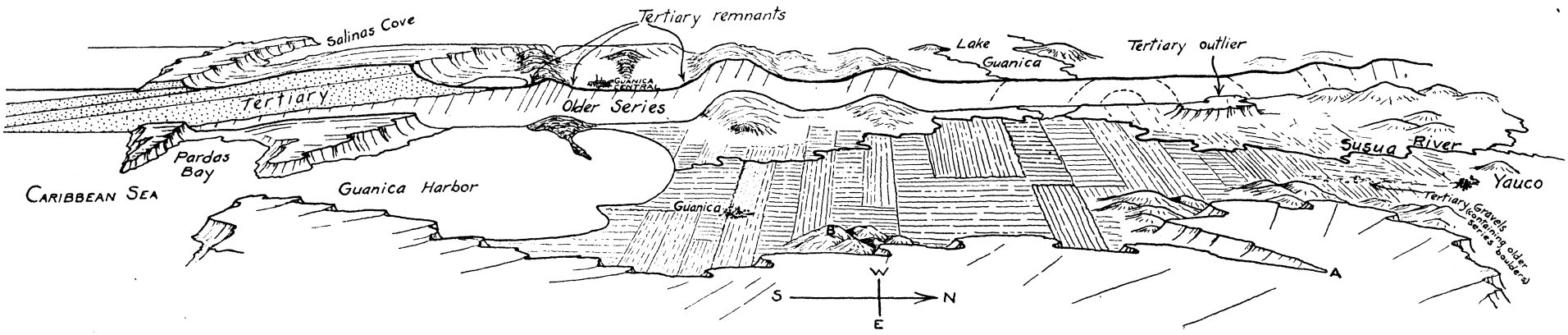

FIG. 10.—*Diagram of the Guanica district*

The essential feature to be noted is the relation of the Tertiary coastal plain to the oldland rocks and the fact that the oldland upon which the coastal plain was deposited was a very hilly region. Two coastal-plain cuestas are distinctly shown. The inner lowland has been drowned to form Guanica harbor and the ends of the outer lowland have likewise been submerged, forming Salinas Cove and Pardas Bay. Occasional remnants of the coastal plain are to be found in the oldland region, notably near Guanica Central and south of Yauco.

The point A on the diagram marks the position from which Fig. 11 was taken. The point B marks the position of the observer in Fig. 12.

land has strong resemblance to the lower peneplane of the north coast, but the abundance of weathered granite blocks which cover it give it quite a different aspect in detail. In the northwestern part of the Caguas lowland between Caguas and Gurabo the rolling country representing the lower base-level has been opened out by the Rio Grande and its tributaries, whose flood plains lie 200 to 300 feet below the surface of the lowland. Some hills of more than ordinary prominence have their bases buried in the alluvium. They trend in a general east-west direction in accordance with what seems to be the structure of the older rocks. The average elevation of the surface of the Caguas lowland is about 550 feet, which is over 1000 feet below the bordering upland. Whether the rather high and more or less open valley in which the town of Aguas Buenas stands is a correlative of this same lowland it is difficult to say, but it seems probable and indeed almost certain that all the basin-like depressions and occasional broad valleys, which break up the upland surface and which are quite common in the eastern half of Porto Rico, were formed during the same cycle of erosion marked by the development of the lower peneplane on the north coast. In the region around Cidra the high upland level has not been preserved, neither has a well-defined lower base-level been opened out, except possibly very locally.

The second depression, known as the Cayey Valley, is much smaller and stands at a far greater elevation than the Caguas lowland, but nowhere shows a well-defined lower peneplane. It is drained by the headwaters of the Plata River, which doubtless have discovered more yielding formations in this part of their course than a few miles downstream, where the valley is narrow and gorge-like.

Erosion at the western end of the island during and since the second period of base-leveling seems to have proceeded continuously. The result has been simply the mature dissection of the higher upland. The demarcation between the different cycles is not expressed by any well-marked lower peneplane such as has been described for the north coast. That some of the valleys are really the time equivalents of the lower peneplane is suggested by the fact that they are filled with deposits of the Tertiary coastal plain where it now laps over the spurs of the higher upland, thus showing that the valleys hold the same position relative to the upland as the more extensive lower peneplane does further to the east. In the case of such a stream as the Culebrinas River, it is not possible to demonstrate exactly how much of the valley was cut before the deposition of the Tertiary coastal plain or how much afterward, for the reason that it is difficult to determine just how much of it was filled with the Tertiary deposits. The river instead of being a subsequent stream developed at

the base of the Tertiary cuesta, as it appears to be, is in reality a stream which has resumed a former course as the limestone which buried its original valley was worn and dissolved away. Further mention of this will be made under the discussion of post-Tertiary erosion.

The distinction between the two periods of base-leveling can hardly be made in the southwest corner of the island, but it is highly probable that erosion during the second cycle opened out two broad valleys, that of the Guanajibo River and the Boqueron-Yauco anticlinal valley, almost to their present extent before the Tertiary period. A point in favor of this interpretation is the fact that the Tertiary in the Yauco-Guanica region filled the end of the broad Boqueron-Yauco anticlinal valley. One large hill of coastal plain deposits and many remnants in the form of basal gravels still remain.

On Vieques the work of erosion during the second period of base-leveling produced the lowland and the valleys on the east and south coasts, now partly covered with the Tertiary coastal plain deposits. On Culebra the development of the large valleys probably proceeded during this time. These valleys, like the ones on Vieques, have since been drowned. The largest, known as Great Harbor, was formerly a coaling station for the United States Navy.

In brief, the second period of base-leveling is represented on the north coast of Porto Rico, east of Morovis, by a well-developed peneplane. On the south side of the island the same time interval is represented in general by the development of a belt of rugged country; in the interior by the erosion of the Caguas and Cayey valleys; on the west end of the island by the mature dissection of the higher upland, and by two broad valleys in the southwest corner; on Vieques by the formation of broad valleys, since drowned, and of the lowland on the south coast; and on Culebra by the excavation of valleys, later drowned like those of Vieques.

DEPOSITION OF THE TERTIARY COASTAL PLAIN

The character of the oldland surface upon which the coastal plain was laid down and the nature of the material deposited strongly merit careful consideration if a clear explanation is to be had of the features later to result from the dissection of the coastal plain. It is especially important in this case because Berkey (1915) believes there is a fault between the Tertiary coastal plain and the oldland on the south coast, whereas the present writer has come to the conclusion that all the evidence cited in favor of a fault can better be accounted for on the basis of an alternative interpretation. Three essential facts may be presented in this con-

nection. First, the Tertiary coastal plain on both the north and south sides of Porto Rico as well as on Vieques was deposited in many places upon a diversified oldland surface, and this fact, it is believed, explains the apparent faulting in several localities. Second, the basal beds of the coastal plain, where deposited upon an irregular oldland, frequently contain many boulders and gravel beds of the older rocks. Recognition of the origin of these gravels makes possible a better understanding of the former extent of the coastal plain. Third, in a few localities where the Tertiary coastal plain rests upon a comparatively smooth oldland the

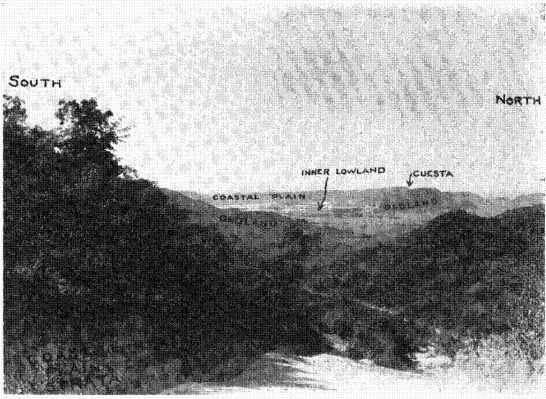

FIG. 11.—*The inner lowland at Guanica*

Showing the inface of the Tertiary coastal-plain cuesta where it is being stripped from the hills of the irregular oldland surface. See Fig. 10.

basal beds are represented by a red clay which appears to have been derived from the oldland. The significance of these facts may now be considered.

No part of Porto Rico shows more clearly the relation between the coastal plain and the oldland than the region about Guanica on the south coast. The general relation between the Tertiary and the older series in the Yauco-Guanica region may be understood by referring to a diagram (Fig. 10) and photographs (Figs. 11 and 12). Examination of this diagram will show that the Tertiary has been deposited upon a very hilly

oldland, representing the dissected eastward pitching end of the Boqueron-Yauco anticline. Immediately south of Yauco the hills are of crystalline limestone of the older series and these are overlapped on the southeast by the Tertiary cuesta. Although they are more or less interrupted by gaps, permitting direct access from the flood plain of the Susua River eastward to the Tertiary, these oldland hills can be traced in a swinging arc as far south as Guanica. Here, just east of the town, some bedded volcanics are associated with the limestone. They strike northeast-southwest or east-west and are presumably a continuation of the formations having an east-west trend at Guanica Central. The presence of a large hill of Tertiary as well as abundant occurrences of the basal gravels proves that this

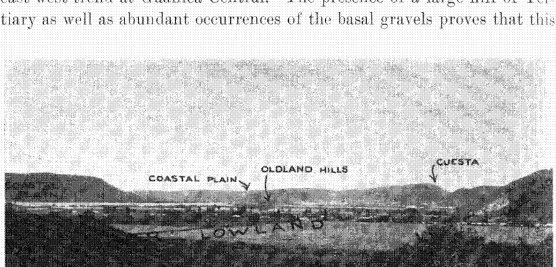

FIG. 12.—*The inner lowland at Guanica*

Showing the inface of the Tertiary coastal-plain cuesta where it is being stripped from the hills of the irregular oldland surface. See Fig. 10.

valley had reached approximately its present development before Tertiary time. This belief, that modern erosion changes are not to any considerable degree accountable for the present size and shape of the older series hills, but that they are simply being unburied of their Tertiary cover, is abundantly strengthened by a study of the district adjacent to Guanica Central. At Guanica Central the oldland hills can be seen actually emerging from beneath the coastal plain, and on their flanks there still remains a coating of chalk, attesting the recency of their unburial. This deposit may be seen at the base of the crystalline limestone hill near the stone-crushing plant of the Guanica mill. Nearer to the Guanica Central the coating left upon some of the dark older series volcanic rocks appears

like a sheet of plaster or whitewash only a fraction of an inch in thickness. There are numerous other localities where the irregular character of the oldland surface may be readily observed. For instance, just back of Ponce to the northwest there is a group of hills representing an isolated part of the Tertiary cuesta. It is separated from the oldland by a narrow inner lowland not more than half a mile or a mile wide. On the north side of the miniature inner lowland the irregular hills of the oldland are as high or even higher than the cuesta face. The beds of the Tertiary coastal plain are in no way disturbed along the cuesta front. They are primarily chalky in character, with few fossils, and belong to what Berkey has termed the "Ponce chalk beds." The flanks of the oldland hills facing the lowland are covered over with loose coral heads and soil, but on the summit the older series rocks are abundantly exposed. The inference drawn from these facts is that the Tertiary was laid down upon an irregular oldland surface and that the hills nearest the cuesta, having been most recently stripped of their Tertiary cover, represent approximately the oldland surface at the time of deposition. If this is true, there is good reason to expect to find in places an abrupt transition from the Tertiary beds to the older series, thus simulating in the field conditions which commonly accompany a fault. Not far from Ponce, on the road to Adjuntas (K 4.8), a natural section is provided by the Canas River, and there one may see a sudden passage from the horizontal chalky beds of the coastal plain at the south to the dark oldland rocks at the north. The actual contact is more or less confused, but on either side within short, horizontal distances the older and the younger series are well displayed and there is no disturbance in the bedding of the latter. This is one of the localities which Berkey cites as evidence for a fault, but the writer is convinced that the abrupt transition is due to the irregular character of the oldland surface. Mention may be made of still another place on the south coast. Along the road between Ponce and Peñuelas (K 10), just before it comes out on the face of the cuesta, conditions indicating a sudden change from the coastal plain to the oldland are repeated and additional facts of interest are observed. Berkey bases his reasons for placing a fault at this point upon the abrupt contact, the inclination of the Tertiary strata, and the drag of the beds. These latter features, the writer believes, have been brought about by the collapse of underground caverns and the development of sink-holes, which are of great abundance in this locality and are especially liable to form along the contact of the Tertiary and the older series. The character of the Tertiary here, limestone beds alternating with fine older series gravels, is in keeping with the belief that the Tertiary was laid down very close

to the older rocks and militates somewhat against the assumption that faulting of any considerable throw has occurred.

On the north side of Porto Rico the irregularity of the oldland surface is of two kinds. In the eastern part, where the coastal plain rests upon the well-developed lower peneplane, an occasional monadnock occurs. Against these monadnocks the coastal plain deposits now abut abruptly or have only recently been stripped away. Four miles southwest of Toa Alta (K 4, Toa Alta-Corozal road) the cuesta stands directly over a monadnock of the oldland, whose surface still preserves remnants of the Tertiary limestone isolated from the main mass. The second type of irregularity is that found further west, as in the Lares region, where the coastal plain extends so far inland as to bury completely the lower peneplane and to cover partly, or even entirely, the spurs coming down from the higher peneplane. Where the coastal plain reaches so far as to rest upon the surface of the higher peneplane the thickness of the deposits is slight. Where it fills the old valleys between the oldland spurs the thickness of the deposits is great. The present streams are apparently re-excavating the old valleys by a process of subterranean erosion beneath the limestone.

On the island of Vieques the coastal plain rests upon an oldland of decided relief. At the eastern end the Tertiary is represented as a low cuesta which, if continued westward across the small inner lowland, would abut abruptly against the older series hills, while on the south coast the remnants of the Tertiary now form islands in bays of the oldland, as is the case at Chiba Bay.

The fact that the basal Tertiary contains boulder and gravel beds of the oldland rocks is worthy of attention, because it is the basal remnants which frequently provide a clue to the former extent of the coastal plain, and unless their character is recognized they may be mistaken at first for more recent flood-plain gravels. Two miles south of Yauco, in the valley of the Rio Yauco (near the American Railroad bridge), the basal Tertiary is exposed along the carreterre. There is evidence that gravels of material from the oldland rocks are prominent as an element in what are undeniably basal beds of the Tertiary coastal plain. In the road cut are shown the long worm-tubes, so common in the Tertiary, on both the north and south sides of Porto Rico as well as on Vieques. These occur in position, are sometimes 18 to 20 inches in length, and always taper upward. The fact that they are vertical, in spite of the pronounced southward dip of the beds, argues that there was little or no tilting of the strata during uplift, and that the beds were deposited in an inclined position upon the sloping surface of the oldland. On many of the rolling

hillsides and in the road cuts around Yauco there are exposed very coarse gravels, which have a superficial aspect much like those of the present alluvial flood plains. These are unquestionably basal Tertiary, and suggest that the conditions on the south coast at and just before the beginning of Tertiary deposition were similar to those of the present. The best and most accessible occurrences are along the main road just east of Yauco and for several kilometers on the road to Guanica. The gravels in several places seem to fill pockets in the same manner as does the alluvium of the modern streams. The presence of the basal Tertiary throughout the valley of the Susua River (Fig. 17) indicates that the oldland hills south of Yauco were at one time completely buried by the coastal plain.

Just east of Juana Diaz the basal Tertiary contains beds of oldland conglomerates alternating with fossiliferous layers. This is a country locally of rolling hills of the older rocks, and while exact contacts were not observed one would infer, with considerable assurance, that the basal Tertiary occurs as patches upon and in the depressions of this older surface. On account of the obscure effects which these basal Tertiary deposits exert upon the topography, the observer is very liable to underestimate their extent, and in mapping the region is apt to consider most of it older series. For several miles along the road west of Juana Diaz the basal Tertiary gravels occur. Casual observation would place them with the coarse gravels of the present flood-plain deposits, though they are sufficiently different in character to be more or less readily distinguished. The beds in which they occur are usually white or gray chalk and the boulders themselves are much more weathered than those of the present streams. On the north side of the island, about a mile east of Moca, on the Lares road (K 7 to K 10), many exposures of a heavy conglomerate of the older rocks are to be seen. These are remnants of the basal Tertiary which filled valleys of the oldland. They are extremely well weathered and in places (as at K 12.1) have the appearance of a soil derived from the decay of the older rocks. Close inspection, however, reveals the fact that the apparent residual soil is in reality made up of bedded conglomerates, with boulders varying in size up to two or three inches in diameter. At the base of the Tertiary cliffs (Fig. 13), on the eastern end of Vieques, there is a thick bed of oldland conglomerate.

In all of the places which have just been described the Tertiary coastal plain rests upon an irregular oldland and its basal beds are made up of conglomerates derived from the older rocks. In contrast with this there are places where the coastal plain has been deposited upon a very smooth oldland surface, and in such places the basal beds are reddish clays with

no boulders. Topographically the effect in those places has been the development of more or less extensive flat areas where the more soluble overlying limestones have been removed. Such features are to be seen between Bayamon and Rio Piedras on the north coast. In no other part of Porto Rico has the Tertiary been deposited upon such an even surface. Most of the inner lowland is a stripped part of the lower peneplane; it has a distinct seaward slope and monadnocks upon it are rare. The basal clayey layers of the Tertiary coastal plain upon which the flat tracts are developed cover a part of the inner lowland adjacent to isolated remnants of the Tertiary cuesta.

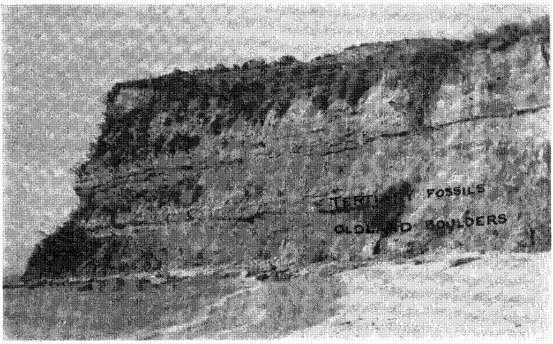

FIG. 13.—*Basal Tertiary south of Yauco, along the Guanica road*

The Tertiary here consists of older series gravels filling former stream channels. In one place the actual contact of these beds with the surface of the older rocks may be seen.

It is probable that the coastal plain deposits never arched entirely over the oldland. The occurrence of beds of small gravels, derived directly from the older series at intervals throughout the coastal plain deposits and the abundant clay content of the coastal plain limestones, makes it seem likely that a large area of the oldland remained continuously subject to erosion. The belief that the coastal plain did not reach over the whole island is also substantiated by the abrupt termination of the coastal plain deposits against the lower slopes of the upland mass, especially on the south side of the island.

UPLIFT AND DISSECTION OF THE TERTIARY COASTAL PLAIN

Character of the Uplift

The uplift of the oldland which brought the Tertiary coastal plain above sealevel appears to have been greatest in the western part of the island in the region approximately between Lares and Yauco. This is indicated by the fact that near these two places, on the north and south side of the island respectively, the north coastal plain and the south coastal plain attain their highest elevations and at the same time reach farthest inland. On the north coast stratigraphic studies by Hubbard, as well as those by Semmes, show that the lowest coastal plain beds in the Lares district (the Lares limestone, lower Oligocene) stand at an elevation several hundred feet higher than the lowest beds further east in the vicinity of Corozal, although the latter are of a higher geological horizon (upper Oligocene). This indicates not only a greater uplift of the island in the Lares region than further east, but also suggests that the Lares area stood at a lower elevation at the beginning of Tertiary deposition. In other words, it appears that the Lares region was uplifted some 500 feet or so higher than the region around Corozal, some 35 miles eastward. A warping of this amount would give to originally level strata a slope of much less than a degree. The warping of the coastal plain, then, while having hardly any effect upon the attitude of the coastal plain beds, has lifted above sealevel a much greater extent of the coastal plain in the western part of the island and a progressively smaller area toward the east. The dip of the coastal plain beds is one or two degrees toward the north away from the oldland on the north side of the island. An inclination of this amount may readily have been the original inclination of the beds at the time of deposition. In fact, on the south side of the island beds having a dip of five to ten degrees apparently preserve their original angle, for they are traversed diagonally by worm-tubes, still standing in the vertical position of growth. Therefore it is unsafe to cite this northward dip as due to the greater elevation of the oldland. It would appear more reasonable to say that the oldland and the coastal plain portions of the island were uplifted uniformly above the sea, but that the western part of the island suffered a greater elevation than the eastern.

While a differential uplift appears to offer the best explanation, it nevertheless may well be argued that the coastal plain was not warped during uplift but that its various dips are the initial dips of deposition due to the fact that the plane upon which it was laid down was not a

land of the north coast. It is true that on the south side of the island the cuesta is not so continuous a feature, but by no means is it entirely lacking, and if it appears vague in places this is always due to the irregular oldland upon which it rests. Finally, Berkey notes the existence of "crush zones, slight folding and drag" in the strata of the coastal plain deposits near Peñuelas (K 10) on the Ponce-Peñuelas road, and the pronounced tilting of the coastal plain beds a mile southwest of Juana Diaz. All of these disturbances are extremely local and, in the writer's opinion, are due unquestionably to the collapse of the beds about sink-holes. These are very common features and exert a marked effect upon the topography in both localities cited. A more thorough discussion of this point is taken up in a subsequent part of this report.

Dissection of the Coastal Plains

The dissection of the coastal plains has resulted in a main cuesta and a series of more or less distinct secondary cuestas, with other features of a belted coastal plain, on both the north and south coasts; but the drainage development departs from the normal owing to the overwhelming preponderance of limestone in the coastal deposits. An essential point to be kept in mind is the irregularity of the oldland surface upon which the limestone was laid down. This affects not only the relative height of the cuesta in different places along its front, but it also exerts a control upon the position of underground river systems. By the collapse of overlying beds the subterranean channels eventually form the main drainage lines of the district. As the north and south coastal plains are isolated units, it is believed that a clearer presentation of the main features can be made by treating each separately.

The Northern Coastal Plain

Normally a coastal plain when first uplifted above the sea is drained by consequent streams of two types—initial and extended. Since it is thought, for several reasons, that the coastal plain never spread much further upon the oldland than it does now near Lares, it is believed that the several master streams crossing to the coast originated as extended consequents. The streams that may be so designated are the Arecibo, the Manati, the Plata, the Bayamon, and the Rio Grande. All of these have their sources far back in the mountains, and those in the western part, where the coastal plain is highest, have cut deep, vertical-walled trenches beneath its surface (Fig. 14). But it is only an assumption to assert that these trench-like valleys were formed in the ordinary way by direct

down-cutting. What seems more probable is that, though at the time of their origin these streams flowed upon the surface, an underground system was soon developed along the buried valleys of the oldland. The ultimate collapse of the beds above the underground drainage lines resulted in the well-formed valleys now trenching the coastal plain.

The Tanama River, a tributary to the Arecibo, still preserves a subterranean middle course and appears to follow a channel the complete collapse of whose roof has not yet been effected. The main evidence in favor of this history of stream development is the fact that the old pre-Tertiary valleys of some streams, as, for instance, the Camuy River valley east of Lares, which were buried by the Tertiary deposits, appear to have been

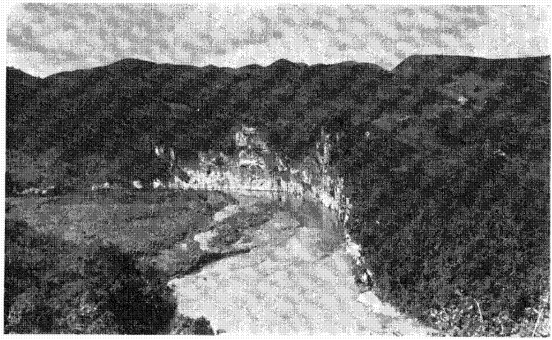

FIG. 14.—*The gorge of the Manati, incised below the surface of the coastal plain*

reoccupied by the present streams. This is to be noted where the streams enter the cuesta face and pass from the stripped upper portion of the valley into that part still filled with limestone. It is inferred that the underground portions of such streams as the Tanama and the Camuy rivers are following the old buried valleys. These streams are similar in origin to the "resurrected" streams of the southern states described by McGee (1891). In the cases cited by McGee, however, the old valleys were covered over by only a shallow deposit and the streams upon the retreat of the ocean had no difficulty in finding their earlier channels. In the Porto Rico case the valleys were completely filled, and it was only the inability of the filling material to withstand solution by water seeping

along the buried channels which resulted in the resurrection of the original valleys. The Culebrinas River is another example of a resurrected stream. Its course appears to follow an old drainage line and cuts diagonally across the coastal plain formations, thus truncating several cuestas. Its tributaries have stripped away all of the Tertiary on the southern side of its valley except the few isolated remnants in the Aguada region. Part of its broad valley, therefore, functions as an inner lowland, but the stream itself can not be classed as a subsequent stream, at least in reference to the coastal plain. It was indeed originally subsequent if it is presumed that its course was determined by less resistant members of the oldland rocks.

Whether there are any streams to be definitely classed as initial consequents upon the coastal plain it is difficult to say, but presumably the Cedros as well as the shorter streams along the coast are examples. As for large, well-defined examples of typical subsequent streams developed on the coastal plain, one must doubt if there are any. Two tributaries of the Arecibo, the Caguanitas and the Limon rivers, might appear to hold such a position, for they flow at the base of a cuesta. But their gorges are cut so deeply into the older rocks as to make it unlikely that all this cutting took place in post-Tertiary time, especially since the limestone cuesta has retreated hardly any from their valley sides. It is more probable that these are also resurrected streams which have succeeded in regaining their old courses by the removal of the limestone which buried them. The best and about the only examples of subsequent streams developed upon the north coastal plain are the Guatemala and other minor tributaries to the Culebrinas between San Sebastian and Moca. These have been developed upon the Cibao limestone between the two cuestas, and have succeeded in opening out a large subsequent lowland, larger than any other lowland developed within the limits of the coastal plain. It is also believed that short east-west trending sections of the Guajataca River are subsequent in origin.

THE BELTED CHARACTER OF THE COASTAL PLAIN

The coastal plain on the north side of Porto Rico may be concisely described as a belted coastal plain gradually increasing in width from the east, where it occurs only in patches, to its broad western end. Let us amplify this picture by a description of each of the successive belts.

The inner lowland.—Normally the innermost belt of a coastal plain is its inner lowland. On the north side of Porto Rico an inner lowland extends eastward from Morovis. East of San Juan remnants of the coastal

plain are almost entirely lacking, but the rolling coastal country all the way to Rio Grande and Luquillo is simply a continuation of the inner lowland further west. In reality this inner lowland is the stripped surface of the lower peneplane, which has already been described. It is therefore rather a part of the oldland than of the coastal plain. In places, however, it apparently still preserves remnants of the lowest coastal plain deposits. This is the case between Bayamon and Rio Piedras. Here the usual rolling surface of the inner lowland gives way to rather flat expanses of country. When these distinctly flat areas are dissected by streams, as, for instance, in the case of the Bayamon River, and further east as well, they have the aspect of alluvial terraces. The best preserved portions of these basal beds appear to be those areas closest to the remnants of the cuesta. Between Ciales and Lares no inner lowland appears and the inner cuesta rests upon the spurs of the rugged oldland. West of Lares the open lowland drained by the Culebrinas River system functions as an inner lowland. The Culebrinas River flows toward the northwest and truncates the east-west cuestas and belts of the coastal plain. Therefore its valley is not a true inner lowland. Rather, as previously stated, the river appears to have resumed its course on the oldland, which was buried by the coastal plain—that is to say, it is resurrecting its buried channel. The fact that its course follows the general strike of the older rocks and that it has no relation whatever to the weaker beds of the coastal plain bears out this interpretation.

The Lares limestone cuesta.—The southernmost or inner cuesta is developed upon the Lares limestone, a massive formation which gives rise to exceedingly rugged, hilly topography. The hills are close-set, 100 to 200 feet high, and dominate the cuesta from Lares to the region about Morovis, east of which point the main cuesta is somewhat less pronounced and more discontinuous. Where this belt exhibits its maximum width, in the Lares region, it is only about two miles wide and is the narrowest of the chief belts of the coastal plain. At Lares the cuesta face is a striking topographic feature, having in places an absolute elevation of about 1800 feet above sealevel. It stands 500 to 600 feet or more above the floors of the valleys at Lares, but where the cuesta rests upon the spurs of the oldland it has a face measuring only 100 to 200 feet in height. Throughout its extent the cuesta face cuts through the conical hills which happen to stand at its edge, and the resulting cliffs, exposing a cross-section of the almost horizontal white limestone, are perfectly vertical and usually bare of vegetation. From Lares to Ciales the cuesta has the same general aspect. Its crest-line is irregular and the white cliffs marking its front are conspicuous at long distances. Conical or irregular hill-

typify this belt. They appear to be the remnants of a continuous surface left after the collapse of underground cavities, brought about by the ready solubility of the massive limestone. The hills are always small in areal extent. The depressions between them are usually without drainage outlets. Toward the north the hills of this belt become lower and gradually disappear where the Cibao limestone, which is soft and shaly, overlaps them; but the tendency to form conical and irregular hills can actually be seen in the sides of valleys cut below the rolling country of the Cibao limestone into the underlying Lares formation.

The Cibao limestone lowland.—The next belt to the north is technically a lowland. Actually it has the aspect of a rolling plateau. This lowland belt is three to four miles wide and may be traced from between San Sebastian and Moca eastward to Morovis. In its eastern portion it appears to develop a series of minor cuestas, as may be seen in valley sides of the Manati River and along the Morovis road. The general aspect of this lowland belt, however, is that of a plain, sometimes deeply incised by streams, but almost always devoid of the numerous haystack hills which characterize the belts to the north and to the south. The limestone (Cibao limestone) making up this belt has a tendency to develop flat benches or terraces along the walls of streams which have cut below the surface of the plain. Benches of this kind are due to differential erosion upon the members of this formation and are distinct features in the walls of the valley of the Manati River. Two of these, an upper and a lower bench, the one standing a hundred feet or so above the other, are especially striking. They slope perceptibly toward the north, where they dip below the next higher hill-forming beds. The western end of this lowland belt between San Sebastian and Moca has been reduced by the Guatemala and other minor tributaries of the Culebrinas to a decidedly lower level.

The Los Puertos limestone cuesta.—The fourth belt consists of rugged and bold hills, limited on the south by a distinct cuesta face which looks down upon the lowland just described. It may be traced all the way from Moca to the Arecibo River. Further to the east the cuesta face becomes less defined, but the belt of hills persists. The formation responsible for this belt is the massive Los Puertos limestone. Its pure character has encouraged the development of caves and sink-holes. The depressions are much larger than those in the Lares belt and, as Hubbard has pointed out, frequently occur in a series trending toward the ocean, as if induced by well-formed underground drainage lines. The hills are high and rugged and angular in outline. Their aspect is often that of the *mesas* and buttes of the southwestern United States, especially where they are

a little set apart from their neighbors. In the midst of the hills the broad, flat-floored depressions, sometimes several acres in extent, grass-covered, and walled in by high and ragged limestone cliffs, rich in the luxuriance of tropical vegetation, are picturesque in the extreme.

The Quebradillas limestone lowland.—Next to the north and extending to the coast is a broad lowland or plain, in large part undissected. Like the other lowland to the south, this one also has the aspect of a plateau because of the canyon-like nature of the stream courses which occasionally break its surface. It forms a belt five miles in width in the western part, becoming somewhat narrower and more diversified toward the east until the Arecibo River is reached. East of this point the uninterrupted plain-like character entirely disappears and the region is made up of haystack hills and intervening flat expanses. Hubbard has assigned the term Quebradillas limestone to the strata responsible for this topographic belt. At the western end of the island this rolling belt extends along the coast from Aguadilla around to Camuy in a fine stretch of wave-cut cliffs approximating 200 feet in elevation. Throughout most of their extent, however, the cliffs are at the present time protected against wave attack by narrow beaches. Between Hatillo and Arecibo the hilly back country slopes gradually seaward and the wave-cut cliff is usually not present. In the western part of this lowland belt, as in the region between Aguadilla and Isabella, shallow depressions or sinks, frequently holding small ponds, abound. Even when no water is visible, the fact that these depressions serve to collect water is attested by the presence of large trees growing in them. Elsewhere the landscape is open and presents the aspect of a rolling plain.

SPECIAL FEATURES OF THE NORTH COASTAL PLAIN

To divide the eastern portion of the north coastal plain, in general that part east of the Manati River, into belts such as have just been described is not expedient because the haystack hills become such prominent features throughout, whereas in the western part of the coastal plain the haystack hills were most numerous on the cuesta-forming belts and were infrequent on the intervening lowlands. In the eastern part of the coastal plain the entire country is characterized by the presence of the haystack or *pepino* hills.

There are two elements in the landscape (Fig. 15), the hills and the flats. Locally the proportionate area involving each form varies from 100 per cent hills to 100 per cent flats. Practically all the features of the limestone district owe their presence and form either directly or indi-

rectly to the prevailing tendency toward underground drainage. Caverns and sink-holes form everywhere. At first the depressions are small in area, with rough, irregular bottoms and no outlets; but as further collapse of their walls takes place, and as the roofs of adjoining caverns give way, separate sinks become connected and the floors widen out and become flat. It may happen that the floors of adjacent depressions are not at the same level because the underground solution is controlled by more or less unevenly distributed shaly beds in the limestone. Berkey thus explains the discrepancy in level between adjacent depressions as well as the terraces which prevail where more extensive flat areas have been opened out between the hills. As the sinks widen, the angular-shaped hills remaining isolated upon the flat plains have a close resemblance in form to the *mesas* and buttes of the western United States. But when they are further re-

FIG. 15.—*Open haystack belt between Barceloneta and Arecibo*

duced in size a softer outline is assumed and then they become typical haystacks, occasionally quite conical in form.

One of the extreme stages, that in which the flat areas so predominate that the hills are only rare and therefore conspicuous features on a more or less level plain, is represented in the region around Bayamon. Between this point and Rio Piedras there are stretches of country exceedingly flat, at least in profile view, but they have suffered moderate dissection and often have the aspect of a terrace above the observer. Traced to the south, these flat expanses imperceptibly become more and more irregular and the rocks of the older series begin to outcrop. In fact, these flats merge with the rolling topography of the lower peneplane. Throughout this region and on the road to Guaynabo the flat tracts above the streams are planted in orchards of oranges and grape-fruit, and occa-

sionally cultivated for pineapples. The description of the haystack hills and the accompanying flats just given for the eastern part of the coastal plain applies equally to those belts in the western part where the haystacks prevail. An unusual feature and one of more than ordinary interest results where the waves of the Atlantic have pushed back the high cliffs near Quebradillas to such a point as to bring the coast next to one of the open flats. A marine-cut terrace is thereby simulated (Fig. 16). The slope of the terrace surface is toward the north and conforms with the slight dip of the Tertiary beds. An observer noting this feature for

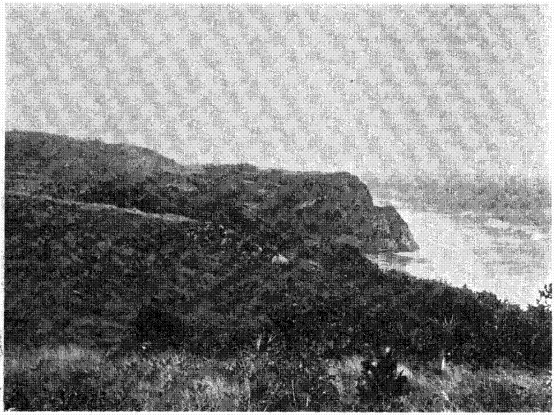

FIG. 16.—*Apparent wave-cut bench at Quebradillas*

It is due to differential erosion upon the almost horizontal beds of tertiary limestone. A very slight seaward dip is to be noted, conforming with the dip of the bedding.

the first time will immediately assume that it is due to wave planation, when the land stood at a lower level. But after having become familiar with the flat stretches described above, and having noted their characteristic development throughout much of the area immediately to the south of Quebradillas, he has no difficulty in assigning to the apparent wave bench a similar origin. If differential erosion has been the factor in forming this terrace, similar terraces would be expected along the sides of valleys cut in the Tertiary coastal plain. Such are to be seen in their best development along the Manati River, and have already been described.

ISOLATED REMNANTS OF THE TERTIARY

East of San Juan the remnants of the coastal plain are small and infrequent. There is a group of hills just east of the highway between San Juan and Rio Piedras, and an east-west trending row of hills northeast of Carolina, entirely surrounded with alluvial deposits. These are conspicuous features in an otherwise monotonous landscape, and their altitude, although inconsiderable, suggests that the coastal plain formerly extended much further south over the flat rolling country between Carolina and Rio Grande. Whether a greater amount of material has been stripped from the oldland in this eastern end of the coastal plain than in the western part it is impossible to ascertain; but it does not seem unlikely, inasmuch as there is a greater precipitation in the east.

THE SOUTHERN COASTAL PLAIN

Eastern portion, Juana Diaz to Yauco.—Even more than on the north side of the island, the coastal plain on the south has been cut into blocks by transecting streams. In the eastern part between Ponce and Juana Diaz the valleys of the streams crossing to the south are wider than the remnants of the coastal plain remaining between them. The coastal plain remnants stand up as isolated masses of hills, more or less flat-topped when seen from a distance, and with a gentle southerly slope. Their bases appear to be buried in the alluvium of the river flood plains. At close range the contrast between the steep cuesta front and the gentle back-slope is not evident, but from a commanding viewpoint the landscape resolves itself into the customary orderly elements of a maturely dissected coastal plain. There is good reason to believe that the Tertiary in the region between Ponce and Juana Diaz was laid down in a former bay in the oldland. The deposits filling the head of the bay have since been stripped away and their place partly taken with alluvium. The resulting flat-floored inner lowland looks like an estuary extending back into the foothills of the oldland (Fig. 17). The character of the deposits, which as noted by Berkey are more shaly in this region, is in accord with the assumption that the Tertiary beds were laid down in an estuary in the Juana Diaz region, an estuary which received the waters of the Jacaguas River. The streams coming down from the oldland have swift and turbulent courses, with frequent falls and rapids over rock ledges, until they emerge from their comparatively narrow valleys and flow out upon the flood plains of the open valleys in the coastal plain province.

Part of the city of Ponce is built on the southern slope of a block of Tertiary hills lying between the Portugues and Canas rivers. On its

north side this block displays a well-defined cuesta face overlooking the inner lowland, which has here narrowed to a valley not more than a mile wide. At one point a distinct notch interrupts the face of the cuesta. Communicating with this notch on the back slope of the cuesta is a winding valley, now unoccupied by any stream. This valley was apparently formed by one of the extended consequent streams crossing the coastal plain. That it was occupied by a stream coming down from the oldland is attested by the fact that in its bed well-rounded boulders of the older rocks occur. This would suggest that the diversion of consequent streams has been effected by the subsequent drainage occupying the inner lowland.

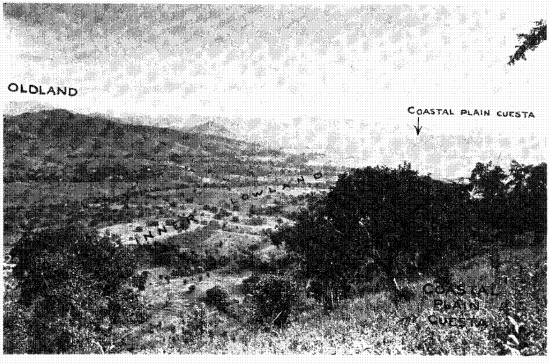

FIG. 17.—*The inner lowland of the south coast, looking eastward from cuesta face back of Ponce*

At the present time the floor of the inner lowland has been cut down 100 feet below the floor of the abandoned valley crossing the cuesta. Just west of Ponce the Tertiary remnants become much larger. The surface of the blocks, while having a general southward slope, is exceedingly irregular. The cuesta between Ponce and Peñuelas is usually very well defined, but, as previously demonstrated, the irregularity of the oldland surface upon which the Tertiary was laid down is occasionally accountable for a failure of the customary features.

The road from Ponce to Peñuelas runs for a considerable distance on the face of the well-defined cuesta, continuing thence along the inner lowland to Yauco. The cuesta is interrupted between Ponce and Yauco by

the gorges of several extended consequent rivers coming from the oldland. At Yauco it loses its sharp character because erosion exposes the irregular oldland hills upon which it rests, though its face can be seen all the way to Guanica, where it becomes steep and imposing again.

Western portion, Guanica to Cape Rojo.—The topography in the region about Guanica has been previously discussed. It is interesting to add that in a minor way the coastal plain remnant southwest of Guanica displays a belted character. Two cuestas occur. The two ends of the small subsequent lowland intervening between the outer and inner cuesta are now drowned to form Pardas Bay on the east and Salinas Cove on the west (Fig. 10).

An idea of the fragmentary extent of the coastal plain in the southwest corner of Porto Rico may be gained from the map. All but the

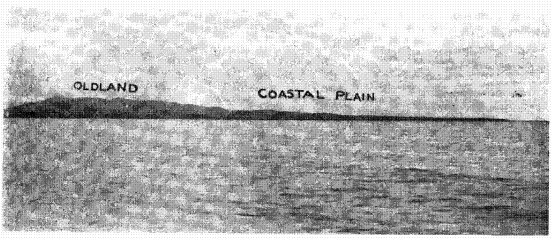

FIG. 18.—*The Tertiary coastal plain lapping upon southern flank of Mariquita Hill*
View eastward across Sucia Bay near Cape Rojo.

westernmost remnants show a distinct cuesta (Fig. 18). The Morillos de Cabo Rojo and the islands forming Point Aguila are low remnants of the coastal plain formerly cut off from the mainland as a result of drowning, but now attached to it by a beautiful series of connecting beaches.

Sink-holes and the question of assumed faulting.—The question of underground drainage and the sagging and collapse of cavern roofs acquires undue physiographic importance because the resulting deformations of strata have been ascribed by Berkey to major faulting. Several lines of evidence have been cited by Berkey as seeming to favor faulting between the Tertiary and older series on the south coast. They have been briefly presented and discussed. It is the intention at this point, however, to dwell more thoroughly upon the matter of "crush zones, slight folding and drag," noted by Berkey in the strata of the coastal plain near

Peñuelas, and the pronounced tilting of the beds a mile southwest of Juana Diaz. The desire here is to show that these deformations are all local in character and are due to the sagging and bending of strata during the formation of sink-holes.

Sink-holes are of common occurrence on the south coastal plain. The cuesta face between Peñuelas and Ponce and much of its back slope is surmounted by hummocky and conical hills, suggesting in some degree the hills on the cuesta front at Lares. Depressions without outlets are common. There are also many large depressions which serve as continuous drainage lines for insequent as well as for consequent streams, and appear to have been originally subterranean channels. Abundant

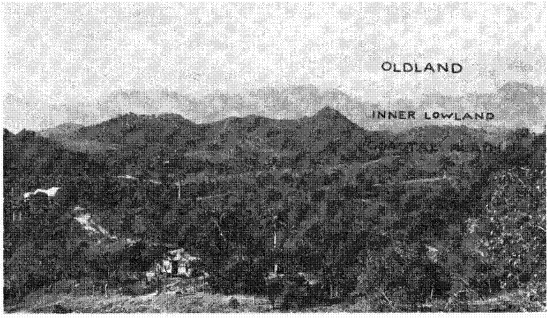

FIG. 19.—*The surface of the coastal plain between Ponce and Peñuelas*

Showing the haystacks and sink holes which characterize it. View looking north toward the mountainous oldland.

sink-holes and haystack hills are characteristic of the region between Ponce and Peñuelas (Fig. 19).

Careful observation of the dips of the limestone along the road between Ponce and Peñuelas lead to the following generalizations, which appear to be well founded:

1. The dips have no uniformity in direction and are constant only for very short distances, although the general dip of the formations is to the south.

2. The local dips are invariably toward a depression.

3. The dips along the cuesta front are just as variable as elsewhere and for the same reason.

4. The angle of dip is rarely over 10 or 15 degrees. Where the sink-holes are large the dips are gentle, but the tilt of the beds may be very marked where the depression is only a few yards across.

The usual appearance of the gentle dips is shown in Fig. 20, a view near the cuesta front at K 9.5-6 on the Ponce-Peñuelas road, looking northward toward the oldland. The dip here is 9 to 10 degrees toward the north, a direction not compatible with the idea that the older series had been faulted up. The dip in this case is toward the center of a large depression. In the field its relation to the depression is readily noted.

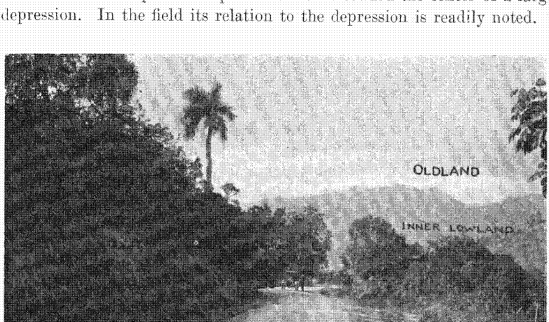

FIG. 20.—*Beds of the coastal plain dipping slightly toward the oldland*

Near cuesta face (K 9.5) on the Ponce-Peñuelas road, looking toward the oldland. The dip of the strata is due to a sink-hole depression.

Let us now turn to several localities which deserve closer attention. The first of these is near K 10 on the Ponce-Peñuelas road. Here the Tertiary beds lie in a highly tilted position upon the older series, as if they had been dragged into that shape by an upheaval of the older rocks. Perhaps the best way to acquaint the reader with the situation and at the same time present the writer's interpretation of the facts is to refer to the accompanying diagram, which is drawn from sketches made in the field (Fig. 21). The interpretation is comparatively simple. The collapse of a cavern has taken place just at the point where the Tertiary rests upon one of the hills of the older series. This is to be expected

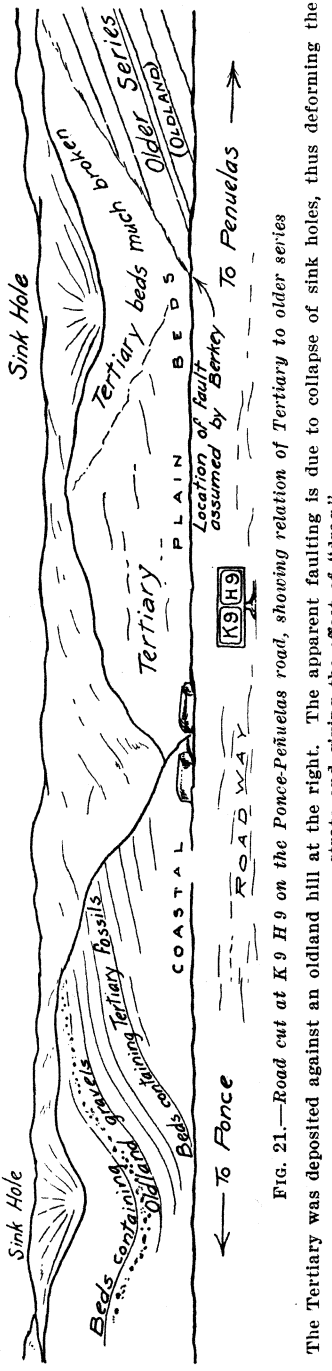

FIG. 21.—*Road cut at K 9 H 9 on the Ponce-Peñuelas road, showing relation of Tertiary to older series*

The Tertiary was deposited against an oldland hill at the right. The apparent faulting is due to collapse of sink holes, thus deforming the strata and giving the effect of "drag."

along the contact because here underground drainage is likely to be concentrated. As collapse took place the Tertiary beds were dragged down, simulating in every way true faulting. The extent of the slipping at this particular point is extremely local, not more than a few feet. The whole phenomenon, without the presence of the oldland hill, is duplicated a few feet to the south, as shown in the diagram. Throughout this section, as elsewhere, layers of older series gravels alternate with the fossiliferous beds of the Tertiary limestone. This suggests that during the deposition of the Tertiary the erosion surfaces of the oldland were in close proximity, such as would be the case if the Tertiary were laid down upon an irregular topography. The abrupt transition, therefore, from the Tertiary to the oldland is rather to be expected.

A second locality deserving particular attention is along the Jacaguas River, just a mile southwest of Juana Diaz. An almost vertical cliff has been cut by the river in a high hill of Tertiary beds. Some of the beds are highly tilted, showing dips of 30 to 35 degrees. Because this occurrence is not far from the line of the assumed fault, Berkey is inclined to believe that the apparent uptilting of the Tertiary strata is due to the disturbance of faulting. A careful study of this locality, however, leads me to ascribe the pronounced local dip of the beds to the collapse of cavities. This resulted in the formation of sinkholes on the surface of the ground. In this locality a cross-section of one of

the sink-holes is provided, and it is to be noted that the beds dip toward the center of the depression (Fig. 22). The variation in dip from place to place along the section, sometimes toward the north and sometimes toward the south, would seem to suggest that the dip is due to local causes. Since it is evident that variations in dip, at least occasionally, may be brought about by the bending of strata beneath a sink-hole, it would appear unsafe to use the occasional southward dip as evidence of a major fault. Moreover, north of the section cited—that is, between it

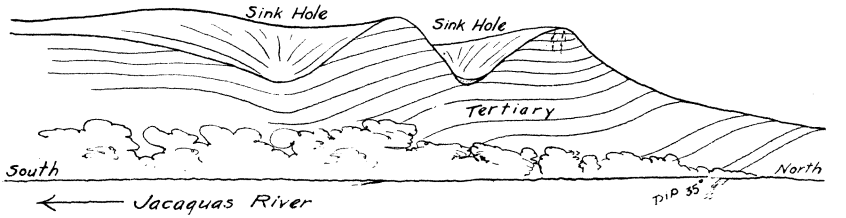

FIG. 22.—*Section of hill along Jacaguas River one mile southwest of Juana Diaz*
The variations in dip are due to collapse of sink holes.

and the position of the assumed fault—the beds flatten out and become horizontal. In addition it is worth while to note that Berkey estimated a great thickness for the Tertiary at this point. He states that "for considerable distances an average dip of 30 to 36 degrees was estimated and the total thickness represented, based upon the width of the belt, must be at least 3000 feet." With this estimate I am unable to agree, and am therefore inclined to reduce the figure to approximately 500 feet, or 600 feet at most.

VIEQUES

The dissection of the coastal plain on Vieques has resulted in a well-defined though small cuesta at its eastern end and on the south coast. Parts of the inner lowland have since suffered drowning.

RECENT SLIGHT SUBMERGENCE

GENERAL

Most of the coast line of Porto Rico shows evidence of recent submergence. However, many of the bays which resulted from the drowning of stream valleys have since been filled with alluvium. Indeed, the great alluvial plains bordering the lower courses of the rivers constitute not only one of the most striking and characteristic features of Porto Rico, but also one of the island's most valuable assets; for it is upon these ex-

tensive level tracts that the majority of the sugar-cane is grown. The term playa as used in Porto Rico refers to these plains. In general, the activities of each plain center in an important village built upon it, as, for instance, Fajardo, Naguabo, Humacao, and Yabucoa. The seaports for these villages are, respectively, Fajardo Playa, Naguabo Playa, Humacao Playa, and Yabucoa Playa, and in these cases the term playa is used in its true etymological meaning, referring to the shore. Bays not yet filled with alluvium are the exception and are to be found only in those situations where there are no large rivers to bring down material to the sea. This is especially true on local extremities, as in the northeast part of the island on San Juan Point. It is usual, however, to find such bays cut off from the ocean by a bay-mouth bar.

That the drowning occurred since the dissection of the Tertiary is evidenced by the drowned inner lowland and the drowned subsequent valleys eroded in the Tertiary coastal plain, as in the Guanica region and on Vieques. The effect of drowning is to be noted at the east and west ends of Porto Rico much more than on the north and south coasts. There are a number of reasons for this. First, the old subsequent valleys developed along the general east-west strike of the older series rocks are much wider and are opened out much farther inland than those formed by the north-flowing or south-flowing streams. Examples of such valleys are those of the Fajardo, Rio Blanco, Humacao, and Yabucoa at the east end of the island and the Culebrinas, Añasco, and Guanajibo at the west end. In the second place, the large alluvial deposits of the north and south coasts have buried many irregularities and have pushed the shoreline so far seaward as to disguise the effects of drowning. Third, the dissection of the Tertiary coastal plain on the north side resulted mainly in narrow valleys or left much of it intact so that slight submergence did not appreciably alter its outline.

East Coast

San Juan Point is the most northeastern promontory of the island. It is really a complex tombolo. Owing to the scarcity and small size of the streams, the bays which have been cut off from the ocean by long sand beaches have not been entirely filled with alluvium and the drowned aspect of the coast is thus somewhat preserved. The entire east coast of Porto Rico, from San Juan Point to Yabucoa, presents the usual features indicative of drowning, an irregular shoreline, characterized by promontories and islands. The general appearance of this part of the coast may be gained by noting Fig. 23. Along the stretch of coast in the southeast corner of Porto Rico between Yabucoa and Maunabo the valleys which

suffered drowning were very small and have since become clogged with alluvium. The headlands, and the alluvium deposits as well, are being cut back by the waves.

South Coast

The south coast from Patillas to Ponce is made up of low alluvial flats or else the edges of alluvial fans trimmed by the waves, so that what earlier evidence there may have been of drowning is now lost. There are occasional hills, as, for example, at Central Aguirre, now entirely surrounded by alluvial deposits. These doubtless were islands immediately

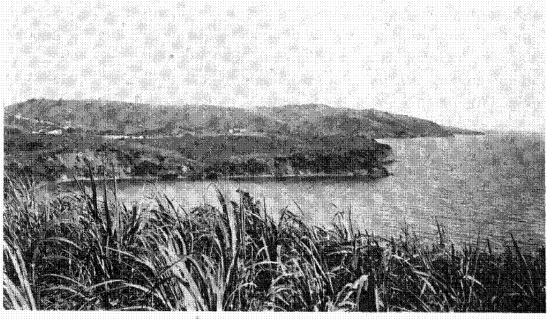

Fig. 23.—*The drowned coast of eastern Porto Rico*

View north of Fajardo, looking toward San Juan Point. Most of the headlands have been cliffed by the waves.

after submergence. West of Ponce the submergence affected not only some of the subsequent valleys between the cuestas of the coastal plain, but also parts of the inner lowland. Guanica Lake is apparently a drowned portion of a broad valley or lowland in the oldland itself. It has since been cut off from direct communication with the sea by the deposits of the Susua River. Guanica Harbor is a part of the drowned inner lowland (Fig. 10) and Pardas Bay, as well as Salinas Cove, near Guanica, are parts of a drowned subsequent valley. Guayanilla Harbor apparently has a similar origin. The region about Parguera on the southwest coast exhibits further evidence of drowning in the peninsulas and islands of the oldland. The Morillos de Cabo Rojo represent parts

of the coastal plain detached as a result of submergence, but now connected with the mainland to form a complex tombolo of rare beauty.

West Coast

The west coast of Porto Rico is in many respects similar to the east. The three largest rivers—the Guanajibo, Blanco, and Culebrinas—emerge from the hills upon extensive flood plains, which are apparently alluvium-filled estuaries. Boqueron Bay still displays rather distinctly its drowned character. Whether the drowning affected the entire valley from Boqueron to Guanica it is impossible to assert definitely, but it seems very likely that this was the case. Though most of the valley floor is now spread over with alluvium, it is very low and swampy, and the wells put down through the alluvium yield water of a distinctly saline character. The divide between Guanica Lake and the marshes draining westward to Boqueron Bay is low and in times of heavy rains covered with water, so that even now a very slight rise of sealevel would effect a junction between Guanica and Boqueron bays (Fig. 5). North of Boqueron Bay the west coast is only moderately irregular, but this is because the bays have to so large an extent been filled with alluvial deposits.

North Coast

Along the north coast of Porto Rico evidences of embayment are not striking.

Theoretical Considerations

Amount and cause of submergence; glacial control

Vaughan (1916) has made a study of the Virgin and Leeward Islands and St. Thomas, to the east of Porto Rico, as well as of other West Indian islands, and concludes from an investigation of hydrographic charts that the recent submergence in this whole region has been approximately 20 fathoms. He notes also that "there is in the Virgin Islands and in Cuba clear evidence of a lowering of sealevel by about 20 fathoms, perhaps more, previous to resubmergence." He states in addition that in other places, as, for instance, off the north side of St. Thomas, the west side of Anguilla, the southeast coast of Antigua, and Mosquito Bank off Nicaragua, the similarity of submarine profiles suggests that a lowering of sealevel preceded resubmergence. What caused this lowering and subsequent rise of sealevel? To cite Vaughan again: "As it affects a large area, it appears too widespread to be explained by local crustal movements. The changes in position of strand line here noted are more rea-

sonably explained by a lowering of sealevel due to the withdrawal of water in the Pleistocene ice epochs to form the great Continental glaciers and the raising of sealevel after each epoch through the melting of glaciers." The amount of drowning, 20 fathoms, proposed by Vaughan, agrees closely with Daly's estimates (1915) of the rise of sealevel due to ice melting.

SUBMARINE PROFILES EAST OF PORTO RICO; ORIGIN OF CORDILLERAS REEFS

A submarine profile just east of Porto Rico reveals a sea floor under Vieques Sound standing at a depth of 8 to 16 fathoms. Much of it is flat, but it appears to be made up of different levels or terraces. To the north of the Cordilleras Reefs and Culebra Island there is a second flat area or bench 5 to 10 miles in breadth. This stands approximately 30 fathoms below sealevel and is separated from the higher level to the south. just described, by a distinct break or submarine escarpment. Upon this escarpment stands the east-west trending chain of islands known as the Cordilleras Reefs. Vaughan has expressed the opinion that the outer bench represents a surface reduced by marine planation during the last period of maximum glaciation when the sealevel was lowered some 20 fathoms and then submerged. The escarpment he considers a wave-cut cliff marking the southern edge of this bench. As for the apparent terraces on the shallower flats to the south, Vaughan suggests that they may have been formed as a result of oscillations in water level during the different glacial epochs, or in places they may represent submarine terraces being formed at the present time. The depth of the outer platform, as before stated, is approximately 30 fathoms. This depth below sealevel Daly (1915, p. 182) estimates as the present position of platforms cut and built by the waves during maximum glaciation. The essential line of reasoning as to how this present depth was brought about is as follows: It is assumed that in weak materials open-ocean waves can quickly form a bench about 10 meters below low-water level, but that abrasion in greater depths is infinitely slower; that in the course of 50,000 years the depth of the bench surface would probably not be increased to more than 20 meters or roughly 10 fathoms. It is also assumed, after careful estimates, that the maximum lowering of level in the tropical ocean during the Pleistocene was 30 fathoms below present sealevel. This amount added to the 10 fathoms cut by the waves would leave the bench surfaces now 40 fathoms below sealevel as a maximum. Variation in the strength of the wave attack in different localities and in the character of the material eroded, as well as in other factors, would account for the slight

variation in the present depth of the benches. As a rule, a depth of 30 fathoms would be the average.

No other theory has been proposed which so well accounts for the approximate accordance in level of submarine benches at a depth of 30 fathoms the world over. And there is apparently no other way to explain the escarpment marking the inner margin of the platform than to assume that it is the wave-cut cliff cut during the time the platform was being beveled. From the crest of this escarpment rise the Cordilleras Reefs. This line of reefs may be explained as a range of dunes capping the escarpment and formed of the material cut from the platform during its erosion in Pleistocene time. The summit of the ridge in its highest points rises some 50 to 60 feet above the escarpment on which it stands. The bed rock making up this platform is apparently Tertiary limestone, although no limestone outcrops on the immediate mainland. There is a marked cross-bedded structure of the limestone material composing the islands, and in general aspect they suggest dune formation. If the glacial-control theory is accepted, then it must be assumed that the top of the escarpment stood slightly above sealevel during the Pleistocene. Dune formation was therefore possible. In the western part of Porto Rico dunes of similar height are now forming. The Cordilleras Reefs appear to be the eastern expression of the San Juan formation occurring on the mainland.

RECENT CHANGES

The changes which have been effected in Porto Rico since the period of drowning, though all going on simultaneously, can be most clearly treated as separate topics. They involve the following events or processes:

The deposition of alluvium in stream valleys, in drowned bays, and as alluvial fans on the south side of the island.

Wave and wind work.

A probable slight emergence.

Alluvial Deposits

Extensive alluvial deposits form broad plains known as playas along the lower courses of most of the rivers of Porto Rico. These deposits, especially those on the east and west ends of the island, apparently fill estuaries caused by drowning. In the case of the Fajardo, Naguabo, Blanco, Yabucoa, and Maunabo rivers on the east coast and the Guanajibo, Mayaguez, Blanco, and Culebrinas on the west coast, this relationship is distinct. Undoubtedly portions of these plains are flood plains

developed by the widening out of the lower courses of the rivers. The surface of the alluvial plains along the lower river courses grades into the surface of the terraces which occur further upstream. During excessive rains the rivers overflow much of the playa areas. There, old courses, meanders, and other usual features of flood plains are to be observed. In occasional instances the rivers bring down sufficient sediment to extend the flood plain forward into the sea as a delta. But this occurs only in protected places where the waves and currents along shore are weak. The Fajardo River entering Vieques Sound appears to be a case in point.

Along the north and along the south coast the alluvial plains extend as a broad strip parallel with the coast rather than as estuarine fillings. However, there is a distinct contrast in the aspect of the alluvial deposits of these two coasts. The north coastal stretches are low and swampy. The plains on the south side stand considerably above sealevel. Along the north coast the deposits are often typical flood plains with almost horizontal surfaces. The deposits on the south coast are more truly alluvial fans with a pronounced seaward slope. Practically all of the low north coast is fringed with barrier reefs. The waves of the south coast, however, have thrown up no such reefs; there the alluvial plains pass imperceptibly into the mangrove swamps along the shore, which shallows out for long distances, and only in one or two places, as, for instance, south of Guayama, have the quiet waters of the Caribbean cut away the non-resisting alluvium to form low cliffs.

Occasional observers have suggested that the low plains bordering the coast of Porto Rico, as also on other West Indies islands, represent a sea floor recently uplifted. It is true that in isolated places there is evidence of recent uplift in Porto Rico to an extent of 20 or 30 feet. On the other hand, it is rather certain that these coastal deposits are not of marine origin. Old stream channels filled with gravel, combined with angularity of the boulders, lack of assortment, and poor bedding, indicate that they are alluvial fans deposited by streams.

Most of the streams flowing across the alluvial plains of the south coast usually carry very small volumes of water. "Owing to the infrequency and small amount of the precipitation and the relatively porous character of the soil reducing the percentage of run-off, as well as the smallness of their catchment basins, they discharge minimum volumes of but 50 to 100 second-feet" (Wilson, 1899). In time of flood, however, they attain maximum discharges of nearly 10,000 to 20,000 second-feet, almost equal to that of the maximum of the larger northward-flowing streams. In the drier season of the year, during the months of January and February, even the larger streams of the southern coast do not flow through on the

surface. Their boulder-strewn channels are marked here and there by pools of water, and it is a common thing to find that during these periods the extemporized trails and roads of the natives follow the stream beds, which occasionally lie as much as 20 to 30 feet below the general surface of the plains. In their lower courses the rivers are not confined by such high banks and nearest to the coast they flow on the surface of the flood plains (Fig. 24).

None of the deposits along the coast west of Ponce can be classed with the alluvial fans just described. They are typically flood plains filling broad valleys and terminating apparently in delta deposits.

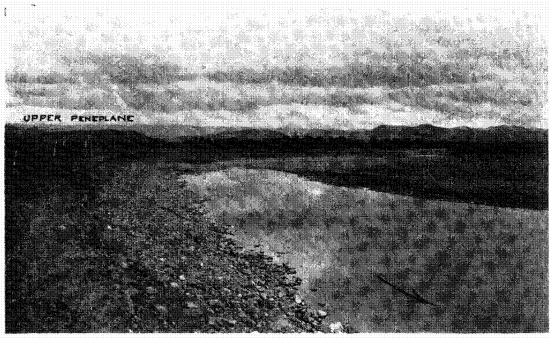

FIG. 24.—*Lower course of the Descalabrado River during the dry season*

This is one of the southward-flowing streams east of Ponce, all of which are subject to great variation in volume. In the distance appears the even skyline of the Porto Rico upland.

Perhaps brief mention should be made of the coarse wash from the hillsides in the southeast and southwest corners of the island. This constitutes very local features, although similar deposits were observed along the northern margin of the Boqueron-Yauco Valley. Deposits of this type occupy a position intermediate between talus accumulations and true alluvial fans.

Terraces are almost universal features along the Porto Rico rivers. Even well upstream, sometimes actually in the headwater portions, alluvial deposits occur. Except on the broad plains near their mouths the streams are now cutting well below the original surface of the alluvium.

The resulting terraces are occasionally 100 feet or so above the stream. The terraces of the Plata River may be cited as a striking example (Fig. 25). Just at the mouth of the gorge (near K 13 on the Comerio road), where the river emerges from its course through the upland, they may be easily visited. Their elevation above sealevel is about 290 feet, some 100 feet above the surface of the river. Their surface apparently slopes downstream and becomes continuous with that of the alluvial deposits of the north coast. In the alluvial-covered Caguas lowland terraces are common features. Perhaps the finest are those along the Gurabo River.

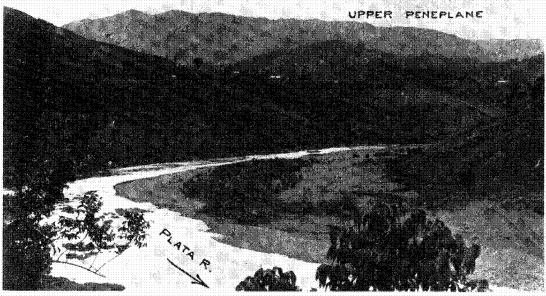

FIG. 25.—*The high terrace of the Plata River at K 13 on the Comerio road.* This terrace is over 100 feet high and dies out upstream, where the valley becomes narrow and gorge-like.

Most of the flood-plain surface of this lowland is out of reach of any present-day floods and seems to record an earlier period of more active deposition.

All the streams entering the east coast have broad flood plains which grade upstream into high alluvial terraces. This is true of the Fajardo, the Rio Blanco, and the Humacao. Some of the best-formed terraces on the island were seen along Peña Pobre Creek, a tributary to the Rio Blanco above its main flood plain (Fig. 26).

The terraces of the Coamo River and its branches, on the south side of

the island, are more readily observed than those of most of the other streams in Porto Rico. East of Coamo the military road follows the Cuyon River, a valley deeply filled with alluvium, into which the stream is now incising itself. The town of Coamo stands upon a distinct terrace and the road from Coamo to Coamo Springs runs on the top of a terrace. At Coamo Springs Hotel several terraces may be seen. The lowest one, upon which the hotel is built, stands 100 feet or so above the river. The main valley of the Coamo River above the town of Coamo is heavily filled with alluvium. In cutting into this material the stream has in several places superposed itself upon hard rock ledges and this has resulted in pronounced waterfalls.

The steep gradient attained by the alluvial deposits on the south side of Porto Rico may be appreciated by the fact that in the upper valley of the Jueyes River, less than three miles back from the coast, the surface of the alluvium which fills the subsequent valley behind the Coamo limestone

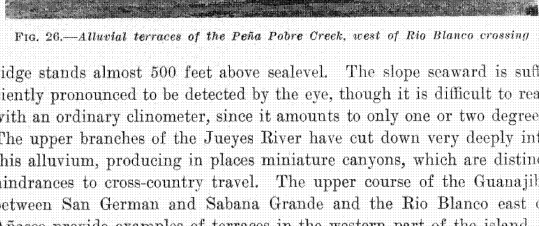

FIG. 26.—*Alluvial terraces of the Peña Pobre Creek, west of Rio Blanco crossing*

ridge stands almost 500 feet above sealevel. The slope seaward is sufficiently pronounced to be detected by the eye, though it is difficult to read with an ordinary clinometer, since it amounts to only one or two degrees. The upper branches of the Jueyes River have cut down very deeply into this alluvium, producing in places miniature canyons, which are distinct hindrances to cross-country travel. The upper course of the Guanajibo between San German and Sabana Grande and the Rio Blanco east of Añasco provide examples of terraces in the western part of the island.

The smallest, but in some ways the most striking, of the alluvial deposits of Porto Rico are those clogging the short, open valleys in the southeast corner of the island between Maunabo and Yabucoa. These valleys head back only a mile, or even less, from the coast and are separated by headlands subject to wave attack. The surface of the alluvium is exceedingly steep and is now only in the initial stage of dissection. Along the shore these deposits are terminated by low cliffs 20 feet or so

in height, which are usually fringed with a narrow beach. The alluvium is entirely the result of wash from the granite hills, whose slopes are covered with a very deep residual soil, granular in texture, but so firmly held together by its lime content as to be extremely brittle and ringing like cast iron under the hammer. The walls of the streams in the alluvium, like the sides of the gullies in the granitic soil, maintain an almost vertical attitude.

Two explanations may be offered for the development of terraces in Porto Rico, which, however, are not incompatible with each other. The first one suggests that the recent slight uplift of the island rejuvenated the streams and caused them to incise themselves below the flood deposits formerly laid down. The evidence of uplift, to be presented later, hardly justifies assumption of an uplift greater than 20 to 30 feet, and this is insufficient to account for the high terraces everywhere observed. According to the second explanation, the streams of Porto Rico have changed in general from aggrading streams to degrading streams, without necessarily any change in the relative position of land and sea. In the streams of New England such a condition is recognized. During the end of glacial time the rivers were heavily charged with debris and accordingly filled their channels with alluvium. But when the ice-sheets ceased to provide material for the streams to carry, their preglacial vigor was regained and terraces were formed as they cut down into the alluvium. We do not know just what causes may have contributed to the earlier overloading of the Porto Rico rivers. It is not unreasonable to think, however, that during glacial time climatic conditions in Porto Rico were different from those of the present. Not that any glaciers existed there, for there is no evidence of this, but it is conceivable that a heavier rainfall prevailed. Such a climatic condition is thought to have accounted for the ancient Lake Bonneville in Utah. In Porto Rico a prolonged period of heavy rains, though adding to the actual volume, would at the same time overload the streams with sediment. The rapid run-off makes almost every drop of rain that falls an active erosional agent, and because the effectiveness of the erosion is not in direct proportion to the run-off, but increases at a much greater rate, the tendency is therefore toward an overloaded condition of the streams below the steeper headwater portions. Increase of rainfall at the end of the glacial period would therefore add greatly to the load of the streams and cause aggrading of their courses where the slopes were modest. With the dying-out of these conditions degrading would again come into play until the stream profile prior to glacial times was restored. Terraces thus formed would grade into the present flood plains of the lower river courses.

Wave and Wind Work

CAPE SAN JUAN REGION

Wave attack on Porto Rico has been much more effective on the north than on the south coast. In brief, it may be said that wave action has resulted in the development of marine cliffs throughout much of the northern coastal plain region, bay bars and cliffed headlands in the drowned oldland portion of the east and west coasts, barrier beaches and the consolidation of sand dunes to form the so-called San Juan formation on the north coast. It is believed that the subject can be best presented by means of a regional description.

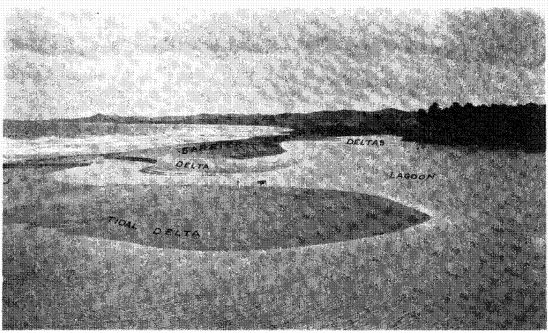

FIG. 28.—*Tidal deltas at Luquillo*

Formed behind a bar which has been built across the mouth of several confluent streams.

COAST OF THE CAPE SAN JUAN REGION

The coast of Porto Rico between Luquillo and Cape San Juan may be described as a shoreline of submergence in the submature stage of development. The headlands have been cut back, bars have been built across the bays, and the contour of the coast line is becoming approximately straight. Many of the bays have been entirely filled with alluvium; others remain as open lagoons. A sketch map of the region (Fig. 27), based on a rough field sketch, is serviceable in indicating the salient features. The successive building of bars nearer the mouths of the bays so as to form a succession of lagoons is well shown in Yegua Cove. Already

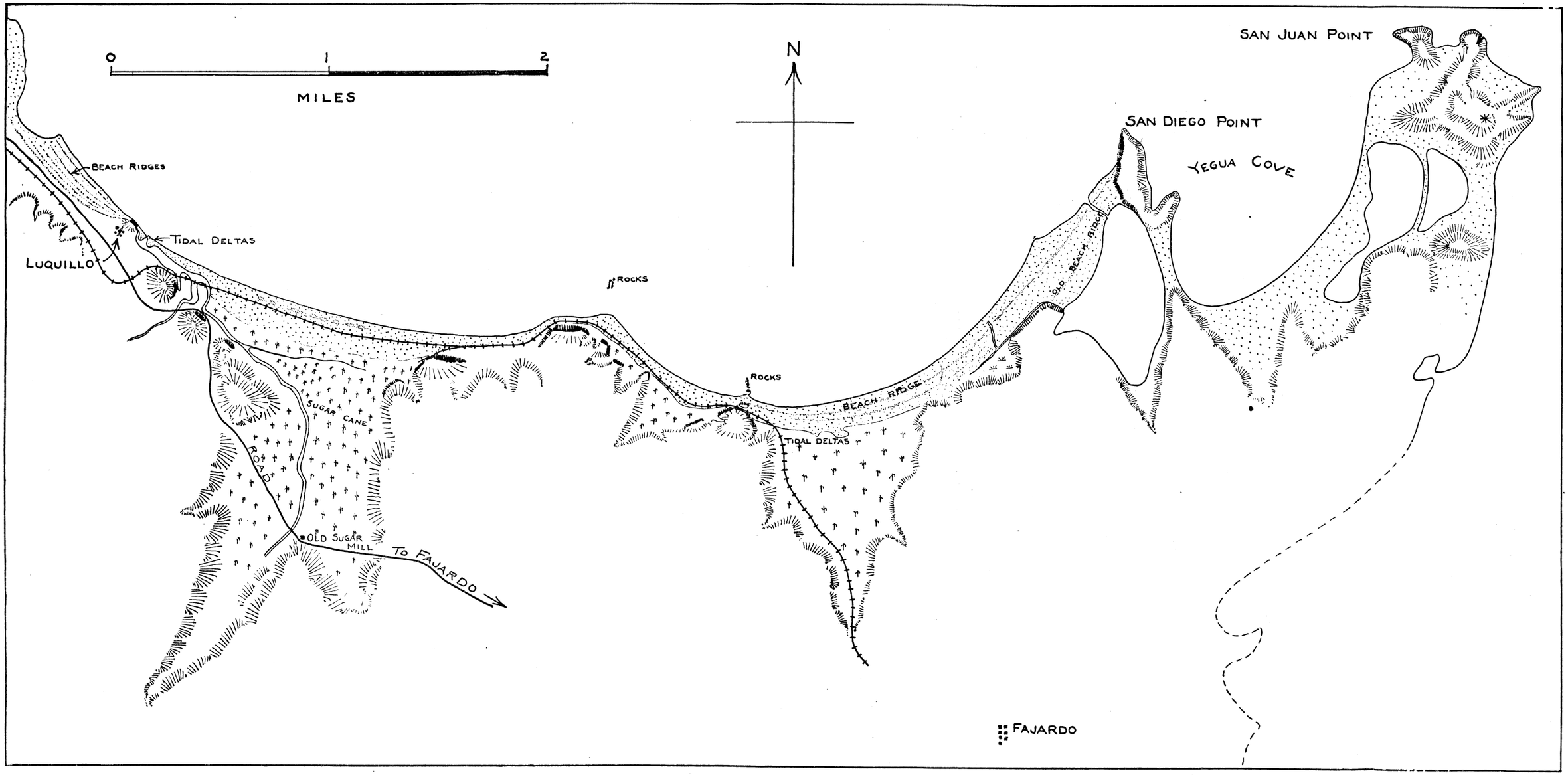

FIG. 27.—*Sketch map of the coast east of Luquillo*
Showing bars built across the mouths of drowned valleys.

two bars have been built near its head, thus forming two lagoons, and at the present time a third bar is forming across its mouth. The cliffing of the headlands, in sympathy with the successive bars which are strung across between them, is a feature frequently observed, and is especially notable at Point San Diego. Attention has already been called to the fact that the bays receiving the larger streams have been completely filled with alluvium, whereas on Cape San Juan peninsula, where the streams are small, open lagoons still remain. Most of the beaches show interesting minor features in the form of tidal deltas either built out into the lagoon, as at Luquillo (Fig. 28), or almost buried under the later deposits of alluvium.

FIG. 29.—*Tidal flats just east of Point Embacaderos*

In the pools, corallines and branching forms of Porites grow. Occasionally large masses are torn up by the waves.

Beach ridges are common in this region. Just west of Luquillo at least ten parallel ridges were counted, each having a height of about five feet above the intervening swales. These ridges are extremely difficult subjects to bring out clearly in a photograph. The succession of parallel ridges shows that the coast line has advanced seaward. Just offshore the water is extremely shallow. At low tide, although the range in water level does not amount to more than one or two feet, considerable areas of tidal flats are exposed, such as may be seen just east of Point Embarcaderos (Fig. 29).

Wave action upon the headlands serves to emphasize the system of joints which are so well developed in the oldland rocks, especially in this

northeastern corner of Porto Rico. Here, as on Culebra and its near-by islands, the cliffs are featured by sharp clefts along the prominent joints which in general trend in a northeast direction (Fig. 30).

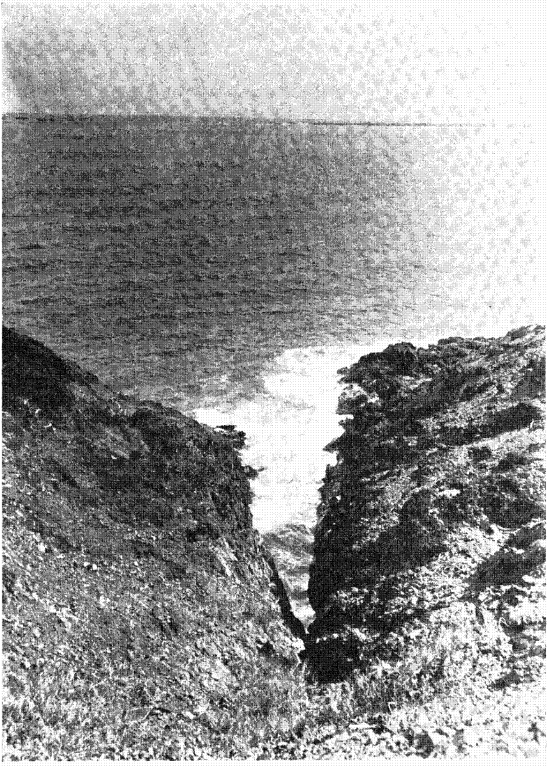

FIG. 30.—*Wave action along joint plane, San Juan Point*
In the distance part of Cordilleras Reefs.

EAST COAST

The long, palm-fringed beaches strung between the headlands of the east coast constitute one of the most picturesque features of this part of the island. The former bay or lagoon cut off from the sea by the beaches has in most cases become filled with alluvium, and the extensive flat tracts or playas which result have already been described. They constitute the great and fertile sugar lands of the island. In general, the beaches are made up of a succession of obscure ridges and are covered with groves of cocoanut trees, which in a distant view contrast strikingly with the cane lands behind them. The promontories are always undergoing wave attack. Occasionally older cliffs may be seen, now protected by a tract of sandy beach.

FIG. 31.—*The Caribes Islands*

An offshore bar cutting off Jobos harbor from the Caribbean.

The smaller streams flowing upon the playas, especially during low stages, find their outlets to the sea blocked by the bars just described, but the larger streams are able to maintain an opening through them. All of the water-courses bring down much fine material which, if it is carried out in front of the bar, serves as a supply for the storm waves when they come to throw up another beach. Occasionally, when the supply of alluvium is excessive, or the waves and currents are not sufficiently vigorous to dispose of the material carried through the bar, it is dropped to form a delta. This is the case at the mouth of the Fajardo River, as is readily

appreciated by an observer on one of the hills overlooking Fajardo Harbor. Abandoned marine cliffs stand back from the shore in line with the original bar. The finest of the east coast beaches are those built across the valleys of the Blanco, Humacao, and Yabucoa rivers.

SOUTH COAST

Along the south coast the waves beat with far less vigor than they do on the north or east coasts, where they are impelled by the steady and powerful northeast trade winds. East of Guayama the headlands are still

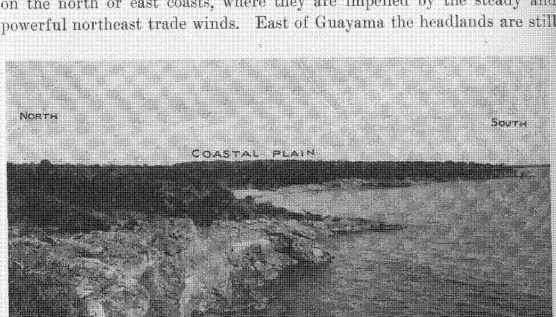

FIG. 32.—*The low southward sloping coastal plain east of Cape Rojo*
The cutting back by the waves has been very slight.

being attacked, and the small alluvial fillings already described are being cut away; but between Guayama and Ponce the transition from land to sea floor is a most gradual one and only rarely, as south of Guayama, are the modern waves cliffing the stream-laid gravels of the extensive flood plains. West of Guayama practically no cliffing occurs, but there are occasional places where insignificant shore bars have been thrown up. The mangrove-covered flats, known as the Caribes Islands (Fig. 31), appear to have such an origin, and the lagoon lying back of them, known as Jobos Harbor, is exceedingly shallow. It is similar in origin to the Laguna de Las Mareas. Most of the coast, however, exhibits no features which can be ascribed to wave action. The alluvium brought down by

the streams seems to be pushing the shore line seaward against the ineffectual attack of the weak waves.

West of Ponce fewer large streams enter the sea; none at all in the southwest portion of the coast beyond Guanica. The low remnants of the Tertiary coastal plain are cliffed seaward (Fig. 32). The bench offshore is exceedingly shallow for several miles and the waves which reach the land are consequently very weak. Coral colonies apparently isolated provide material which has been thrown up to form low reefs, barely coming to the water's surface.

FIG. 33.—*The marine cliff forming the edge of the Tertiary coastal plain on the north coast west of Isabela*

Now protected by a beach one-fourth of a mile in width, which bears along its seaward margin a high ridge of wind-blown sand.

In the vicinity of Cape Rojo the work of the modern waves may be seen in the delicate tracery of beaches connecting two groups of islands with each other and with the mainland. The lagoons thus cut off can best be described as shallow salt flats and are usually known as salinas. These natural evaporating basins have been somewhat improved by artificial methods, and represent one of the three important sources of crude salt now shipped from the tropics. The block diagram of the region (Fig. 5) presents the aspect of the two complex tombolos.

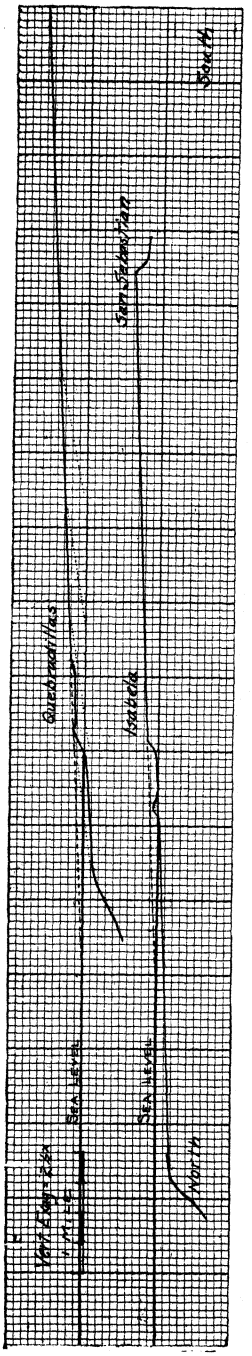

FIG. 34.—*North-south profiles through the margin of the coastal plain at Quebradillas and Isabela*

WEST COAST

The irregularity consequent upon the drowning of the west coast of Porto Rico has been destroyed by the development of beaches and the filling of the bays. Occasional lagoons still remain, as at Lake Joyuda. The beaches customarily reveal their stages of development by parallel ridges, a feature well marked between Point Guanajibo and Mayaguez. As a whole, the work of the waves along the west coast has produced effects similar to those along the east coast, but cliffing of headlands has been much less pronounced.

NORTH COAST

The north coast from Aguadilla to Camuy is characterized by marine cliffs, averaging over 200 feet in height, cut in the limestone coastal plain. Considerable stretches of these cliffs, however, notably to the west of Isabela, are no longer subject to wave attack, owing to the protecting beaches built in front of them, in places to a width of one-quarter to one-third of a mile (Fig. 33). A protecting beach in front of a marine cliff is a normal feature in the process of wave erosion along a steep coast. It represents a temporary reversal of conditions from those favoring cutting to those favoring deposition and is quite analogous to similar alternations in the life of a stream.

The extent to which the sea has cut back into the Tertiary coastal plain may be estimated by carrying the slope of the plain surface seaward until it meets sealevel. With a slope of 1½ degrees, the distance is approximately two miles. It must be remembered that the outer thin edge of the wedge was easily removed, and it may also be as-

sumed that cutting has been long active and was going on before the period of submergence. Fig. 34 provides two profiles from this part of the coast. The one through Isabela does not need any especial explanation beyond what has just been said. The other profile, through Quebradillas, seems to be anomalous, in that the continuation of the slope of the coastal plain surface meets the sea even beyond the edge of the narrow continental shelf. Two interpretations are possible: first, the dip of the strata is steeper than the slope of the plain surface. If the normal dip of the beds instead of the slope of the plain surface be continued seaward from the cliff, assuming that this is approximately the top of the series, sealevel is reached less than a mile from shore and within the limits of the continental shelf; second, faulting may have taken place at the edge of the continental shelf, so that the Tertiary coastal plain was broken off during uplift. The apparent marine bench, shown in the profile near Quebradillas, standing at an elevation of 150 to 200 feet, has already been explained as being due to differential erosion along bedding planes.

East of Camuy most of the north coast is low and bordered with alluvial deposits. Fringing the shore is a chain of sand dunes exhibiting all stages of consolidation and dissection and in part constituting the San Juan formation about to be described. These sand deposits frequently hold the position of barrier beaches, in which case they have behind them marshy lagoons or open bodies of water. This is the explanation of Lake Tortuguero near Manati, San Juan Harbor, and the smaller lakes of San José, Cangrejos, and Piñones to the east.

The prevailing drift of the water along the north coast is toward the west, as a result of the strong trade winds from the northeast. In the coves between the minor promontories formed by remnants of the San Juan formation secondary eddy currents are developed. These affect the bars at the mouths of streams and serve to deflect the stream outlets toward the east. In Fig. 35 several sketch maps illustrate this tendency in the case of the Bayamon and Cocal rivers and San Fernando Creek near San Juan, and of the Arecibo, Manati, and Cibuco rivers further west. In each instance the mouth of the stream is diverted eastward.

THE SAN JUAN FORMATION

This interesting formation occurs only along the north coast of Porto Rico, and is described by Berkey as a series of solidified or fossil sand dunes dating from the Pleistocene. At San Juan city, which is built upon the formation, its elevation is 100 feet above sealevel. Nowhere else does it rise to quite this height. Almost everywhere associated with

the solidified dunes are other dunes of loose sand now forming. Even these unquestionably very recent dunes show tendency toward solidification. Therefore, it is difficult to draw a sharp line between the two types of dunes and, in the opinion of the present writer, there has been an uninterrupted process of dune formation. In a bold way the San Juan formation may be pictured as occupying the position of a broken barrier reef

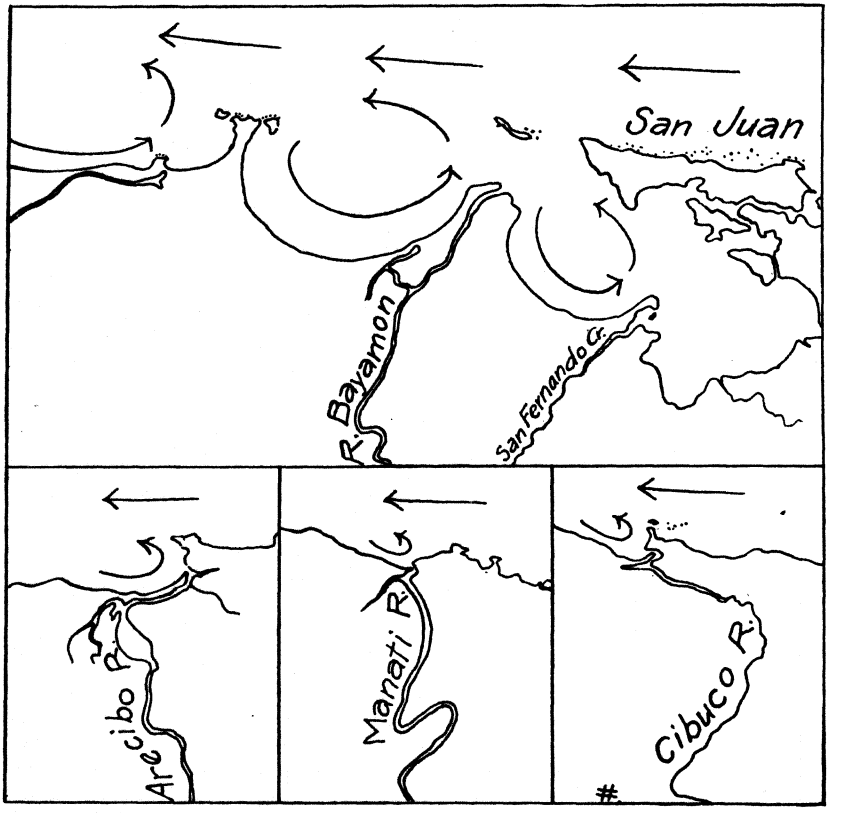

FIG. 35.—*River mouths of the north coast*

Showing the effect of secondary eddy currents in diverting the rivers toward the east.

along the north coast, continuing eastward in the Cordilleras Reefs, and finding its easternmost expression in a small mass just off the northwest corner of Culebra Island. Behind the barrier there is usually a marshy lagoon or open body of water, but occasionally the dunes rest directly upon the mainland. The cross-bedded structure is almost everywhere a pronounced feature. In addition there are two or three other features of unique character which apparently demand special explanation.

The first of these exceptional features is to be noted in the cliff of the San Juan formation immediately east of Arecibo. This cliff faces toward the south and overlooks the broad flood plain of the Arecibo River. The cliff face shows the strikingly cross-bedded structure with steep dips characteristic of the San Juan formation; but it shows also a series of horizontal lines crossing the structure, but in no way interfering with it. This unique feature Berkey has suggested was induced by the gradual submergence of the sand dune after formation. He therefore associates it with the oscillation of the coast line believed to have occurred recently in the island's history. The cross-bedding is therefore to be considered the primary structure of the dunes and the horizontal lines a secondary matter. In addition to these horizontal consolidation lines, as they might be termed, there occurs a prominent horizontal layer of sand near the base of the cliff. This layer is unconsolidated and of course interrupts the cross-bedded structure which occurs above and below it. Inasmuch as neither of these two features—that is, neither the horizontal consolidation lines nor the interrupting horizontal layer of sand—is a feature to be noted elsewhere in the San Juan formation, it seems reasonable to believe that a local cause might furnish the necessary explanation. The Arecibo River, which flows not far from the base of the cliff, is a powerful stream and is subject to extreme oscillations of level. It is therefore suggested that the horizontal unconsolidated layer near the base of the exposed part of the formation represents a deposit of alluvium left by the stream upon a part of the sand dune which it had truncated in its endeavor to break through to the coast during heavy floods. The upper cross-bedded part of the formation represents the dune material built upon the alluvium when the river had subsided or altered its course to a different channel. The alluvial layer may therefore be considered a part of the river's flood plain upon which later dune-building has taken place.

The secondary structure or horizontal consolidation lines occurring above this sandy layer may have been induced by subsequent rises in the level of the river so as partly to submerge the more recently built dunes. This is a very probable event, for it is on record that the Arecibo River in heavy floods deeply submerges its flood plain. Such an event is aided by the very narrow outlet to the sea which the river now has between the continuous dune formation on either side. During the heavy floods of 1896 much of the town of Arecibo was submerged, indicating a rise of 20 to 30 feet at that time. A rise of 30 or 40 feet would account for practically all the phenomena now observed. It is to be noted, too, that the secondary horizontal structure is to be observed only on the landward side of the dune in rather close proximity to the river and adjacent to its

flood plain. The conclusion, then, regarding the secondary horizontal structure is that it does not necessarily indicate a rise of sealevel. As an alternative explanation the rise of the river level in floods is offered, and it is shown that such an event is a probable occurrence.

Another unique feature of the San Juan formation, and one which the writer has not seen described elsewhere, is the series of small terraces occurring near sealevel and having characteristics which may be briefly summarized as follows:

1. The terraces always occur within the range of present wave action.
2. In appearance the terraces resemble those of the well-known Mammoth Hot Springs in Yellowstone Park.
3. There is no order whatever in the arrangement or size of the terraces.
4. The terraces have not been *cut* by the waves; they have been formed by the precipitation of material around the rims of shallow basins as the water overflowed. This material usually has a pinkish hue and may be easily distinguished from the granular sandstone of the formation.
5. The terraces are practically horizontal.
6. The cross-bedding of the sandstone cuts across the terraces at all angles.
7. Where irregular masses or blocks have fallen into the water, they first assume a very jagged character, but as loose material is filled in and cemented into the crevices, and as the water pouring in and out precipitates lime around the edges, gradually the sharp, angular forms give way to a terraced aspect and the original disordered make-up becomes obscure.
8. Terraces of this type are developed not only in the San Juan formation, but also at the base of the Tertiary limestone cliffs near the west end of the north coast (Fig. 36).

The conclusion from these observations is that consolidation is now rapidly going on in the zone of water action. Other observations along the coast bear out this statement. For instance, it is to be noted that the modern beaches are occasionally firmly cemented like a pavement.

The stone reefs of Brazil described by Branner (1904) is a well-known example of a modern beach now consolidated. Branner suggests that local lithification may be brought about in the following ways:

1. By carbonated rain water dissolving out the lime carbonate in the upper portions of calcareous sands and depositing it in the lower portions.
2. By the escape of carbon dioxide from the sea water when the surf breaks upon the beaches.
3. By the escape of carbon dioxide from sea water where it is warmed by the tropical sun.
4. By the submarine escape of carbon dioxide about volcanic vents.

The first three of these explanations would undoubtedly apply to the consolidation of the sand dunes along the north coast and to the development of the terraces described. In addition to these explanations, it may be noted that spray from the waves is continually being blown inshore for hundreds of feet along the north coast of Porto Rico, so that the seaward side of the dunes is kept moist. The constant evaporation of this sea water and the liberation of carbon dioxide would encourage lithification, especially on the surface of the dunes. Invariably it is that portion of the dunes exposed to the ocean which is most thoroughly lithified. All degrees of lithification are to be noted, from that of a mere crust on the

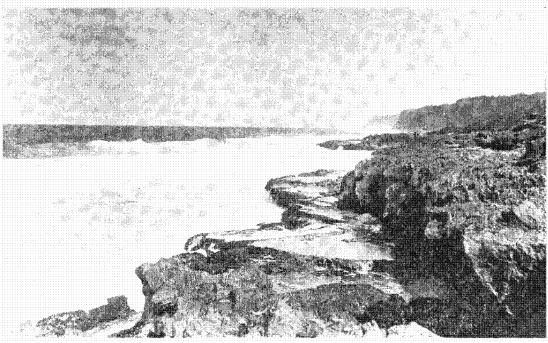

FIG. 36.—*The coast east of Quebradillas*

Showing terraces in the Tertiary coastal plain which resemble in all respects those formed in the San Juan formation. The mode of origin in each case is similar to that of the terraces of the Mammoth Hot Springs.

outside of a sand dune, kept moist by the spray from the waves, to that of a hard rock mass so firmly cemented and thoroughly infiltrated as apparently to have lost its original cross-bedded aspect. For this reason there appears to be no satisfactory means of distinguishing the earlier from the more recently formed dunes.

The original definition of the San Juan formation as proposed by Berkey was meant to apply only to those consolidated dunes along the north coast. Since then, however, other observers have extended the use of this term more or less subconsciously to cover all deposits of a consolidated character or recent age. For instance, the thick coating of

consolidated beach material consisting of coral heads, boulders, gravel and shells covering the uplifted wave-cut platform of Desecheo Island is conveniently spoken of as the San Juan formation. Likewise the bench of coarse consolidated material fringing the south side of Mona Island, and the slightly uplifted consolidated beach on Muertos Island, call to mind the San Juan formation. The present writer is in favor of applying this term to all these occurrences. It is apparently impossible to divide sharply the very recent ones from the older ones or the non-consolidated occurrences from those completely lithified. Nor does it seem expedient to separate those occurrences which are strictly of dune origin from those which constitute beaches, so intimately are they associated with each other.

SUMMARY

The San Juan formation may then be described as the beach material and its associated dunes, consolidated or unconsolidated, now uplifted or submerged, which was formed around the coast of Porto Rico in recent geological time. The chain of islands forming the Cordilleras Reefs running eastward from Porto Rico toward Culebra may be considered as a series of dunes capping a wave-cut escarpment. They were formed probably during the Pleistocene and partly submerged at the end of the glacial period. These dunes would be the earliest representatives of the San Juan formation. Along the north coast of Porto Rico the bordering reefs with their dunes are essentially barrier beaches. Locally they are being vigorously cut away by the waves, and in other places a tendency toward beach widening seems to prevail. Where the beaches and dunes are undergoing wave erosion they commonly are strongly consolidated. This is the case in the central and eastern part of the north coast. Where the beaches are being widened by the addition of material seaward, the growth of new dunes prevails and these in general are not so strongly consolidated. This is the case in the western extremity of the island, north of Isabela, where protecting beaches have been built along the coast at the base of the earlier formed wave-cut cliffs. Finally, included in the San Juan formation, are the deposits of more or less consolidated beach material capping the uplifted beaches along the shores of Desecheo, Mona, and Muertos islands and at occasional points on the mainland, as, for instance, on Rincon Point.

Probable Very Recent Slight Emergence

Several kinds of evidence have been noted by different observers favoring a recent emergence of Porto Rico and the smaller islands near by. A

study of the region as well as a careful evaluation of the evidence collected by others lead to the conclusion that there has been a recent emergence of not more than 40 feet. Most of the evidence lies in the western half of the region and there is practically no evidence in the eastern part. Some of the evidence presented, indicating an uplift greater than that just mentioned, I believe to be invalid. In the following pages all of the lines of evidence are discussed. They may be essentially grouped as up-

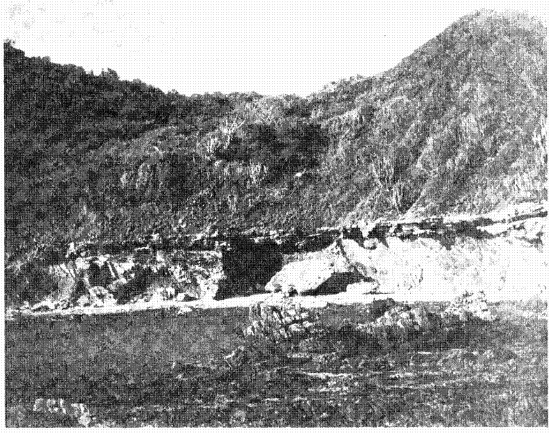

FIG. 37.—*The uplifted beach on the south side of Desecheo Island*

In the foreground may be seen part of the wave-cut platform truncating the older series rocks.

lifted beach deposits and terraces or benches. The beach deposits occur on Desecheo, Mona, and Muertos islands, and near Point Jiguero and other isolated localities on the mainland. The terraces or benches occur on Desecheo Island and near Quebradillas, Guayama, Point Jiguero, and Mayaguez on the mainland.

Desecheo Island lies some twelve miles to the west of Point Jiguero and is formed entirely of older series rocks which have been truncated by a wave-cut platform now uplifted to a height of 20 feet above sealevel (Fig. 37). The term "uplift" is used because the common evidence in

all the West Indies favors a movement of the land rather than one of the sea. Marine benches and terraces lack a uniformity of elevation in the various islands. The bench on Desecheo intermittently rims the whole island, but is preserved to a greater width and in much better perfection on the south coast. There it may be as much as 100 yards wide, cutting sharply across the upturned edges of the volcanic sediments and ending abruptly on its landward side against the steep hill slopes which are presumably wave-cut cliffs. The platform dips seaward in all directions from the island and thus passes down gradually into the water. The surface of the platform is heavily coated with a thick deposit of consolidated beach material consisting of coral heads, boulders, gravel, and shells. The coral heads appear occasionally to be in position, as though still attached to the places where they grew. The evidence which this island presents surpasses that noted elsewhere and would indicate a minimum uplift of 20 feet.

Mona Island is fifty miles to the southwest of Porto Rico. On its southern side is a platform several hundred yards wide in places. Its surface stands 10 feet or so above sealevel. The platform is composed almost entirely of consolidated beach material consisting of coral heads and modern shells. Its inner margin is made up largely of talus from the limestone cliffs, all thoroughly cemented. The platform is everywhere made up of this heterogeneous material. Nowhere is it a rock platform. Its outer margin, in the zone of water action, shows terraces like those described for the San Juan formation. These terraces are not due to wave cutting, but to the deposition of material around the edges of shallow depressions. Along the southeast coast of Mona Island, a mile or two south of the lighthouse, remnants of the former beach may be seen adhering to the lower portion of large talus blocks standing in the water at the foot of the cliffs. The blocks are as large as a two-story or three-story building. The presence of beach material at their base indicates the extreme recency of uplift. The evidence on Mona Island favors a minimum uplift of five to ten feet. It is certain that the uplift here was less than that on Desecheo.

Fringing the north side of Muertos Island, near Ponce, is a little ledge of fragmental beach material consisting of shells, coral heads, and limestone fragments firmly cemented together (Fig. 38). It is only a few yards wide and stands now some five or six feet above sealevel. The evidence here would suggest an uplift approximating that on Mona Island, but very much less than that on Desecheo.

Near Point Jiguero, Hubbard reports finding consolidated sands and gravels with modern corals and gastropods resting upon the Tertiary at

an elevation of 40 to 45 feet above sealevel. A mile south of this point Hubbard reports similar gravels at 35 feet above sealevel. Near the lighthouse the same investigator found sand and gravels with modern shells resting on truncated rocks of the older series at an elevation of six to ten feet. This evidence would appear to favor an uplift in this locality of approximately 40 feet.

At other isolated localities uplifted beach material favors an uplift of 12 to 15 feet. On Point Aguila, forming the southwest corner of Porto Rico, a more or less consolidated layer of shells and beach material rests upon the Tertiary at 10 to 15 feet above sealevel. Near Quebradillas, at

FIG. 38.—*The uplifted beach on Muertos Island*

the mouth of a small canyon, a bench 15 feet above sealevel and about 50 feet in width is developed upon the Tertiary limestone and is covered with consolidated gravels and coral heads apparently in place. The mere presence of the bench alone is not good evidence of uplift. Differential erosion commonly results in the development of benches in the almost horizontal Tertiary rocks. Near Barceloneta modern shells and large coral heads occur in consolidated gravels at 12 feet above sealevel.

In the search for uplifted beach material on Porto Rico the investigator must guard against mistaking the numerous occurrences of Indian shell heaps for natural deposits. Usually in these cases fragments of

pottery and other criteria, such as black soil, indicative of former camp sites, will reveal the true origin. Such shell heaps were noted near Rincon, Coamo Springs, and on Vieques.

The splendid example on Desecheo Island of a marine bench uplifted 20 feet above sealevel has already been described. Near Quebradillas there is a pronounced terrace (Fig. 16) along the coast, having an elevation of 180 feet above sealevel and a width of one-quarter to one-third of a mile. This terrace is developed upon the almost horizontal Tertiary limestone and it is strongly suggestive of wave planation. The question of its origin, however, has been discussed, and it was pointed out that the terrace is due to the differential erosion of the limestone along the bedding planes. In this region the surface of the coastal plain consists of groups of haystack hills separated by intervening flat areas. It happens that at just this point the present waves have cut back to one of the "flats," and thus an uplifted marine-cut terrace is simulated.

Part of the town of Guayama is built upon rock terraces, which apparently stand slightly above the alluvium deposits of the playas or flood plains. Berkey (1915, p. 48) has interpreted these as due to marine cutting. A careful study of this locality, however, leads the present writer to the conclusion that their flat surfaces have been produced by the planing action of the stream which deposited the alluvium, in this instance the Guamani River. The reasons for this belief may be briefly summed up as follows:

1. The rock terraces lie in the mouth of the valley of the Guamani River and may be traced upstream between the valley walls.

2. The surface of the terraces stands approximately at the same elevation (180 feet) as the surface of the highest part of the alluvial plains and the slope of the two is practically identical. Much of the alluvial plain has been recently cut away by the river. Those regions consisting of hard rock stand up now as terraces.

3. Parts of the terraces are covered with angular gravel exactly like the material composing the alluvial fans.

4. There is no cliffing of the mountain spurs back of the terraces.

5. Flat rock surfaces of similar character are to be observed elsewhere, as along the lower course of the Jueyes River, so intimately related with the alluvial deposits as to leave no doubt that they were formed at the same time the alluvium was laid down.

6. The rocks of the older series are so much decayed that in numerous places throughout Porto Rico they are being beveled across by the streams on their present flood plains.

7. Similar truncating and planation of strata by streams at the point

where they emerge from a mountainous area is to be noted in other parts of the world. For instance, near Cody, Wyoming, where the Shoshone River emerges from its canyon, there is a splendid terrace whose surface bevels across dipping strata. In this case no agent other than the river could have been operative. Similar conditions are to be noted in the Ortiz Mountains of New Mexico. The conclusion regarding the Guayama rock terraces is that they are river-cut and do not represent an uplifted marine bench.

A small terrace occurs at Point Jiguero, its inner margin standing some 80 feet above sealevel. Because it holds a position near the mouth of a stream, somewhat similar to those at Guayama, it may have been formed in a similar way. Moreover, it is developed upon almost horizontal beds of Tertiary limestone, and the strong tendency toward the development of flat areas by differential erosion would somewhat favor such an explanation. Its position along the coast gives it the aspect of a marine-cut bench, but consideration of other factors just mentioned favors considering it as due to stream origin.

Near the Reform School, just south of Mayaguez, a narrow bench, standing 12 to 15 feet above sealevel, can apparently be ascribed to no origin other than that of wave planation. It truncates the older formations, but a search did not reveal the presence of beach material.

Most of the evidence cited would indicate an uplift less than 20 feet. Apparently the greatest uplift indicated is at Point Jiguero, where Hubbard finds beach material as high as 35 to 40 feet above sealevel. The easternmost piece of evidence noted was on Muertos Island, 50 miles to the east of Point Jiguero, where the uplift was considerably under 10 feet. The eastern end of Porto Rico and the islands to the east nowhere revealed any indication of recent change of sealevel. The westernmost evidence was on Mona Island, some 50 miles west of Point Jiguero, where a modest uplift of 10 feet or so was indicated. Nowhere are there displayed series of terraces similar to the splendid examples featuring the coast of Cuba.

BRIEF NOTES ON ADJACENT ISLANDS

Desecheo

This small island, lying 12 miles to the west of Porto Rico, is almost circular in shape and has a diameter of about one mile. It is made up entirely of older series rocks, striking almost east-west, but crossed by joint systems which in general run transverse to the structure. The little harbor providing a refuge on the south coast appears to be developed

along such a joint plane, to which is due also the valley in the hills above. Around the base of the island is an uplifted wave-cut platform and beach, having its inner margin 20 feet above sealevel. This has been described in the preceding pages and is illustrated in Fig. 37, which also shows a part of the small harbor and the valley above.

No flowing streams are to be found on the island. The extremely dry conditions favor an extensive growth of cactus, although a forest of medium-sized trees covers many of the slopes. A brief but interesting

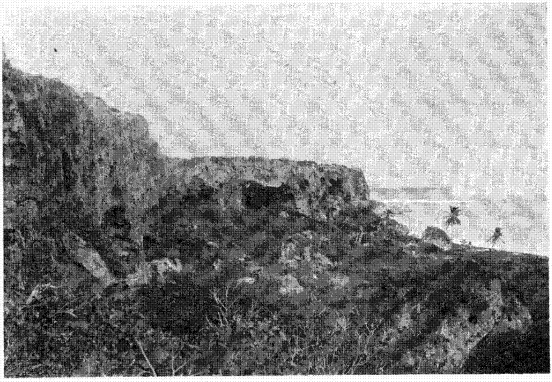

FIG. 39.—*East coast of Mona Island*

Showing its plateau character and some of the caves which honeycomb it.

account of the vegetation of the island has been given by Dr. N. L. Britton (1914).

MONA

Mona Island, 50 miles to the southwest, is not within sight of Porto Rico except from the higher summits, and it then appears as a low haze on the horizon. This island, as well as its little neighbor, Monita Island, is a remnant of the Tertiary, having an almost horizontal surface, which ends abruptly on all sides in cliffs 150 to 200 feet above the sea. Though, in general, circular in shape, its outline is angular, a feature due to the jointing which divides the limestone into large blocks. The entire island is literally honeycombed with caves (Fig. 39). These are developed in

one of the more soluble limestone layers outcropping about 75 feet above the sea and form one of the important sources of guano in the Porto Rico district. Along the southwest coast there appears good evidence of recent uplift in the narrow platform at the base of the cliffs. It stands 10 feet or so above sealevel, has a width of several hundred yards, and consists of consolidated beach material containing coral heads and modern shells. The inner margin of the platform is made up of talus from the limestone cliffs, thoroughly cemented. The outer margin, in the zone of wave activity, shows terraces at the water level like those described for the San Juan formation. Along the southeast coast, a mile or two south of the lighthouse, remnants of the former beach still appear adhering to the base of large talus blocks standing in the water at the foot of the cliffs.

There is practically no soil on the island, and passage over the top of the plateau is arduous in the extreme on account of the sharp and jagged surface of the limestone and the abundant growth of cactus. The only water is that from the rain which accumulates in the slight irregularities on the surface of the rock. Over this forbidding country there roam small herds of wild goats, cattle, and pigs which have escaped from domestication and have taken on characteristics in keeping with the harsh conditions of life to which they are now subjected. For instance, the pigs have apparently reverted to a type of boar. Prominent tusks, two or three inches long, were noted on one which had been captured. The animal is so vicious that the natives always carry their long, sharp machetes for self-protection. Besides the lighthouse, a small temporary camp is located on the island for the workmen who are employed in removing the guano from the caves. These people supply themselves with fresh meat by hunting, a wild goat or two being the usual result of their efforts.

Vieques

The narrow channel between Vieques and the eastern coast of Porto Rico is nowhere more than 60 feet in depth and in general is a great deal less. This island, like Culebra, was presumably separated from the mainland as a result of submergence. It is low-lying and is made up mainly of the oldland rocks. These are flanked on the east end and south side by remnants of the Tertiary coastal plain. A well-formed cuesta has been developed, and the subsequent drowning of the island has permitted the sea to enter the inner lowland at several places along the south coast. Some facts regarding the Tertiary coastal plain have already been given. The accompanying diagram (Fig. 40) is a sketch drawn looking south from near Culebra Island and conveys a fair idea of the general aspect of

FIG. 40.—*Sketch of Culebra and Vieques Island*
Vieques from the north, Culebra from the south.

Vieques. Among the minor features of interest are the alluvial deposits clogging the valleys on both the north and south sides, resembling those near Yeguas Point on the southeast corner of Porto Rico. At Playa Grande a graceful and picturesque beach has been thrown across one of the drowned bays which has not yet been filled with alluvium. The low headlands throughout the coast are being cliffed by the waves.

In general the island is dry, as evidenced by the common occurrence of cactus, although it is not at all barren. The raising of cattle is the most important industry in the hilly parts, but the broad inner lowland on the south side, as well as extensive tracts on the north, are devoted to the production of sugar-cane.

CULEBRA

Culebra and its numerous adjacent cays is represented wholly by the oldland rocks, which are moderately folded, although no prevailing trend in the structure was noted. The salient features of the topography are controlled by erosion along strong joint systems, the major one running in a northwest-southeast direction and a minor one almost transverse thereto. Great Harbor and Flamingo Bay are valleys developed along the line of the major system and later drowned. This island exhibits the customary features due to drowning. Deep bays indent its coast and numerous islets lie offshore. The head of Flamingo Bay has been cut off from the sea by a beautiful beach, and owing to the small size and intermittent character of the contributary streams the lagoon is but slowly being filled with alluvium.

There is now only a small settlement on this island, which was formerly an important coaling station for the United States Navy. Dairying and the raising of cattle appear to be the only industries. No sugar-cane is grown here.

MUERTOS

The Caha de Muertos (Fig. 41), or the "box for the dead," is a coffin-shaped remnant of the Tertiary coastal plain lying offshore from Ponce. An islet at its west end is made up of steeply tilted rocks of the older series,

sharply planed across by a platform over which at one time the Tertiary beds undoubtedly extended. Along the south shore of the larger island the older rocks outcrop. Presumably the island consists of a base of old-land rocks capped by a layer of the coastal plain limestone 100 to 200 feet thick. Apparently the presence of the more resistant old rocks at

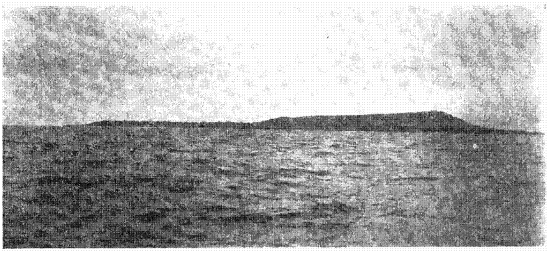

FIG. 41.—*Muertos Island from the north*

the base has prevented the destruction of the island by the waves. The north shore is fringed with what appears to be an uplifted beach of consolidated limestone fragments, shells, and coral heads, now standing five to six feet above sealevel (Fig. 38).

ACKNOWLEDGMENTS

The field-work on this problem occupied a period of five months, from September 1, 1916, to February 1, 1917, and constitutes one of the special studies of Porto Rico carried on by the New York Academy of Sciences. To Dr. C. P. Berkey I am personally grateful for the kindly aid and faith which he showed in the undertaking. The other members of the Department of Geology of Columbia University have taken abundant interest in the problem, and I use this opportunity to express my high regard for all of their suggestions. I am especially appreciative of the encouragement and inspiration rendered by Dr. Douglas W. Johnson and for his untiring and critical advice.

The officials of the Porto Rican Government have been most courteous in helping to overcome some of the difficulties in the field, and I desire to acknowledge the aid afforded by Governor Yaeger in the matter of transportation and of Colonel Shanton, Chief of the Insular Police, in presenting me with testimonials to his various officers.

Finally, I am more than pleased to include the name of Mr. Fernando Oliver, of Añasco, whose perseverance and pluck during three months of arduous work in the capacity of interpreter and assistant are deserving of mention.

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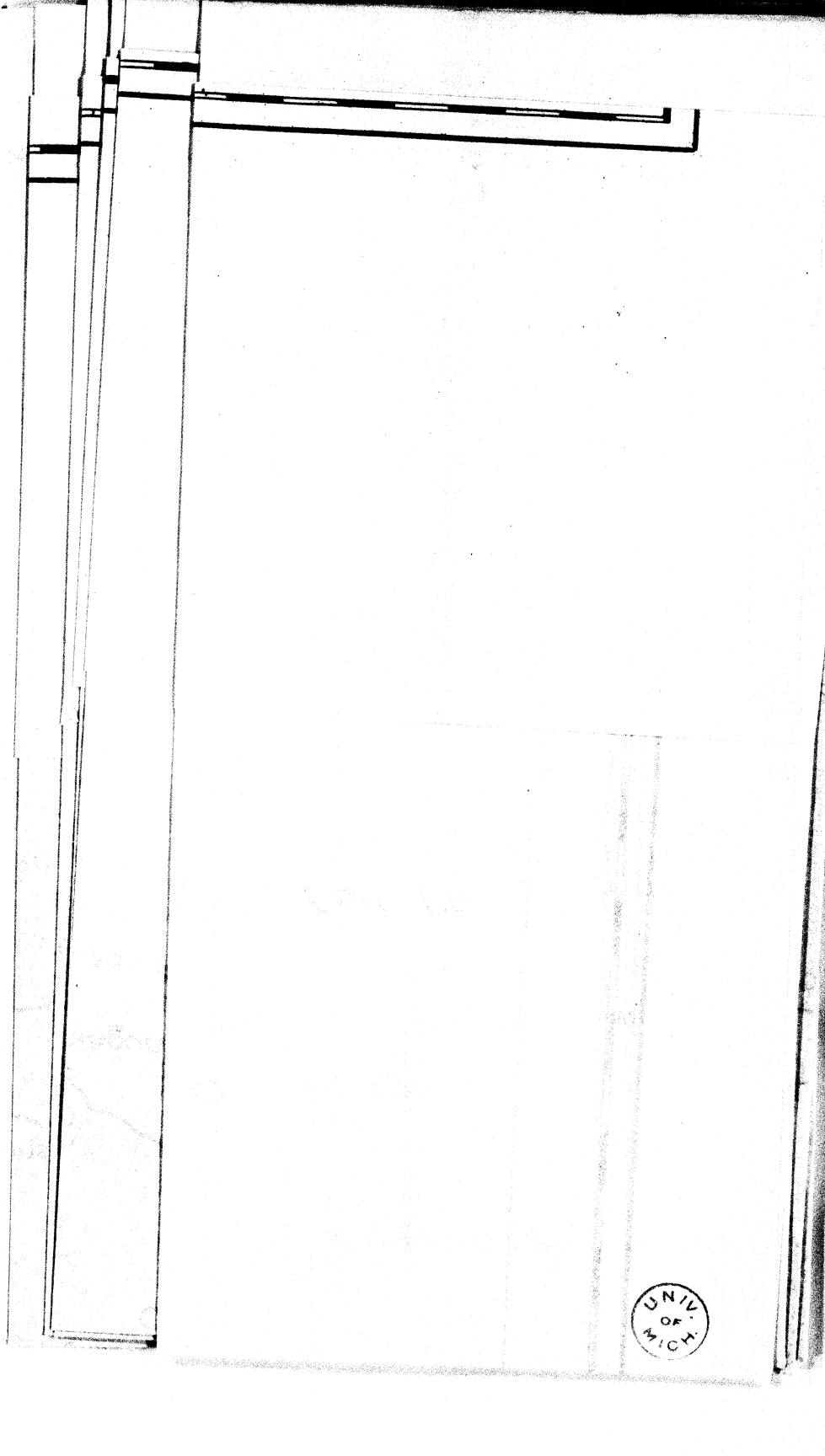

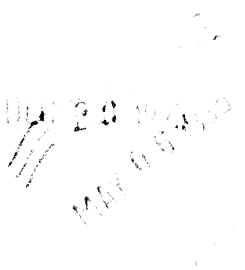

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SCIENTIFIC SURVEY OF PORTO RICO AND THE VIRGIN ISLANDS

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