NEW YORK ACADEMY OF SCIENCES

SCIENTIFIC SURVEY

OF

Porto Rico and the Virgin Islands

VOLUME II—Part 1

The Geology of the Lares District, Porto Rico—*Bela Hubbard*

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THE GEOLOGY OF THE LARES DISTRICT, PORTO RICO

By Bela Hubbard

CONTENTS

INTRODUCTION

Nature and Purpose of the Work

The present paper gives the results of a survey of the geology of the Lares District, Porto Rico, made during the summer of 1916 under the auspices of the New York Academy of Sciences and the Insular Government of Porto Rico. It is one of a series of reports, each covering the geology of a portion of the island.[1] The Lares District comprises the northwest corner of Porto Rico and Desecheo Island, a total area of about 500 square miles. The survey of this district involved the study of the rock formations, mineral resources and the making of a geologic map. As the field work was done in three months time, methods of the reconnaissance type had to be used. Before entering the field, a base map (3 inches = 1 mile) was prepared from available sources and this was divided into quadrangles of 5 x 2 miles. The field work consisted chiefly in running traverses across the general strike of the rock formations. All traverses were made by pacing or by the time elapse method. Elevations were obtained by aneroid. In recording the data, two methods were used:

1. Cavalry Sketching Case. The blue print quadrangles of the base map were used on the sketching case. Contours were sketched in for a distance of one-half mile or more on either side of the line of traverse.

2. Note Book Traverse, using Brunton compass and protractor. This method was found best for the more detailed work in limited areas, and during rainy weather. Photographs were used repeatedly as a means of gathering data for the topographic map. In portions of the area not covered by photographs or traverse, the topographic features shown on the map have been generalized.

The first two months of the field work were spent among the Tertiary rocks of the district, while the final month was spent in the area of Cretaceous rocks. Subdivision and correlation of the Tertiary formations was the most important problem to be worked out, and hence required the expenditure of more time than a well balanced survey would ordinarily warrant. A large number of fossils were collected in the Tertiary area, which have been described in Volume III, Part 2, of these reports.

ACKNOWLEDGMENTS

Acknowledgment is made particularly to Dr. C. P. Berkey for assistance and advice in almost every phase of the work. Dr. A. W. Grabau, Dr. D. W. Johnson and other members of the Columbia University Geology Department have given valued suggestions and aid. In the field work, every courtesy and assistance was given by the government officials at San Juan, and acknowledgment is made especially to Colonel George R. Shanton, Chief of Insular Police, Major Basil H. Dutcher, U. S. A., and Judge Bonner, Auditor. In Mayaguez, Mr. D. W. May, Director of the Agricultural Experiment Station, took very great interest in the work

[1] For an account of the plans and progress of the geological survey of Porto Rico, see Scientific Survey of Porto Rico and the Virgin Islands, New York Academy of Sciences, vol. I, part 1, pp. 1-10, 24-29, 1919.

and assisted in every way. Señor Narciso Rabell, of San Sebastian, a student of the geology of the island, aided in collecting many of the fossils, in giving valuable information, and in showing a lively interest in the progress of the work. The aid of the Insular Police in every town in the Lares District was a big factor in carrying on the survey. Residents of the district not only displayed the warmest hospitality, but showed a keen and intelligent interest in the purposes and results of the field work.

Previous Work

The list of articles dealing with Porto Rico is given in the Bibliography. Prior to 1916, little geological work of a detailed nature had been done in northwestern Porto Rico. R. T. Hill made a reconnaissance in 1898, and published several articles. He visited the Lares District, and made observations along the Lares Road, where he collected many fossil corals, later described by T. W. Vaughan. In 1914, in the course of their reconnaissance of the island, C. P. Berkey and C. R. Fenner covered the main routes of travel in the district, and noted many of the geologic features characteristic of this part of the island. During the same year, certain fossil localities in the district were visited by C. A. Reeds, where a large amount of material was collected. In 1915, E. T. Hodge made a brief reconnaissance of certain localities in the southern half of the district, to investigate the reported presence of oil shales.

GENERAL DESCRIPTION

The Antilles

Porto Rico, forming the easternmost member of the Greater Antilles, is an almost completely submerged complex mountain chain having a maximum elevation of about 28,000 feet above the adjacent lowlands or submarine valleys of the Atlantic and Caribbean. This mountain chain is more or less continuous in an east-west direction, its highest portions forming the islands of Cuba, Haiti-Santo Domingo, Jamaica, and others. Lateral branches of this chain form the Lesser Antilles and minor groups of islands.[2] The rocks of this Antillean chain are chiefly of Mesozoic age, and comprise volcanic flows, intrusives, and sediments of marine and continental origin. These rocks, as a whole, show evidence of having been formed during a more or less continuous period of volcanic activity, which reached a climax in extensive orogenic movements at the close of

[2] An excellent illustration of the sub-sea relief of the Antillean region is given in Bull. 103, U. S. Nat. Mus., Plate 73, 1919.

Mesozoic time. With the Tertiary, began a differential submergence, not affecting some portions of the region until Oligocene time, and resulting in a deposition of reef and shell limestones. Subsequent uplift in Miocene time, has exposed the fringing beds of Tertiary limestones on nearly all the islands of the Antillean group. Finally, there have been minor crustal movements and fluctuations of sea level during the Pleistocene Epoch. The crustal movements have continued to the present.

Porto Rico

As a result of the major geologic events just outlined, modified by minor events peculiar to the vicinity of Porto Rico, the following are the chief geologic and physiographic elements or units found on the island:

1. Complex mountainous oldland area, which makes up the core of the island. The rocks so far as known are all of Cretaceous age and comprise intrusives, flows, tuffs, ash, shales and other sedimentary rocks. The igneous rocks are predominantly andesitic, though other types occur. The structure is highly complex, marked by many thrust faults and overturned, folds. The predominant strike of the structure is northwest-southeast, as it is in most places throughout the older rocks of the Antilles. This oldland area is characterized by its mountainous aspect, steep soil-covered slopes, with marked absence of cliffs or other exposures of unweathered rock. The present cycle of erosion has reached maturity. The existence of at least two previous cycles of erosion has been shown by Lobeck (1922).

2. Elevated Coastal Plain. Marked by nearly horizontal deposits of reef and shell limestones of Oligocene age, deposited along the north and south coasts of the island (see Berkey, 1915). These limestones with basal shale members rest unconformably upon the Upper Cretaceous rocks, the time interval covering the Eocene period and the early Oligocene. The total vertical uplift reached a maximum of 1500 feet. The uplift on the north coast was differential, accompanied by gentle warping. On the south coast it was accompanied by local faulting and considerable tilting of the beds to seaward. Thus the north coast beds dip at angles averaging less than 5° in a seaward direction, while the average for the south coast is considerably greater.

Erosion of the present cycle (post-Oligocene) has affected these Tertiary limestones, chiefly by surface and subterranean solution, and has stripped the oldland area of a portion of its Tertiary covering.

3. Pleistocene to Recent Coastal Deposits. These include alluvial plains or playas at mouths of the large streams, elevated beach gravels,

and indurated dune sands. They represent the effects of Pleistocene variations of sea level, accompanied and followed by local crustal movements, which, over most of the island, have resulted in a series of uplifts totalling at least 200 feet.

The Lares District

This district contains a portion of almost every major geologic and physiographic unit to be found on the island. The Older Series, or Upper Cretaceous rocks, occupy the mountainous area south of the Lares Road. In this area there are remnants of the earliest post-Cretaceous or late Cretaceous peneplane, the first erosion cycle. Evidence of the second cycle, however, is not found within the district. The entire area north of the Lares highway is occupied by the overlapping, relatively undisturbed limestones, marls and shales of the Younger Series or Oligocene, resting upon an irregular surface carved in the highly disturbed Cretaceous rocks, and dipping gently seaward. This is the most complete development of these rocks to be found on the island. Post-Oligocene uplift has raised these massive reef limestones to a present maximum elevation of 1300 feet. Solution with extensive development of underground drainage has produced in this limestone belt a peculiar type of Karst topography with its *pepino* hills. The Pleistocene and more recent uplifts are well shown along the extensive coastline of the district. They are marked by marine terraces and elevated fossil beaches. The typical playas are developed at the mouths of the largest streams, particularly on the west coast.

THE CRETACEOUS FORMATIONS

As a whole, the rocks are more nearly similar to those of the Ponce District to the south than to the rocks elsewhere on the island. When compared with eastern Porto Rico, the most striking feature in the Lares District is the predominance of shales and volcanic clastics, with an absence of intrusives of the large batholithic type. The strike of the beds is northwest-southeast, as is the case throughout the rest of the island. In the Lares District, the average strike is north 50° west, although there are variations from this over considerable areas. The prevailing dip is to the southwest, and the northernmost beds are therefore the oldest, except locally in cases of repetition by folds and faults. In the eastern portion of the area, volcanic tuffs predominate, while in the western half, shales predominate. Of igneous rocks, none of the deep seated, batholithic types occur, although some coarse diorite was found in stream gravels near Añasco. The prevailing igneous rock in the district is andesite porphyry, occurring as sills, laccoliths, and irregular intrusive bodies.

Petrography

IGNEOUS ROCKS

The igneous rocks are characterized by a small petrographic range. Andesite porphyry makes up about nine-tenths of all the igneous material in the district. The textural range is from felsites to porphyries. Glasses are rare or not easily recognizable because of the devitrification and weathering. The following types have been determined, and their distribution shown on the geologic map:

TABLE 1

Name of Rock	Usual Occurrence
Quartz diorite porphyry..............	Irregular intrusives.
Andesite	Surface flows, usually amygdaloidal.
Andesite porphyry	Surface flows, sills, dikes, and laccolithic or elongate intrusive bodies.
Augite andesite	Surface flows, amygdaloidal.
Augite andesite porphyry............	Surface flows, sills, dikes, and irregular intrusive bodies grading into Gabbro porphyry.
Gabbro porphyry	Irregular intrusives, grading into Augite andesite porphyry.
Serpentine	Dikes and irregular intrusives of small size.

Quartz Diorite Porphyry. The only locality in which this rock is found is in the Rio Blanco valley south of Lares. It occurs as a boss of considerable size, and is associated with one of the most conspicuous centers of former volcanic activity in the district. The rock is comparatively resistant to erosion, and forms the prominent peak of Mt. Torrecillo (Fig. 1).

The principal minerals are plagioclase (andesine-oligoclase, andesine, labradorite), hornblende, and quartz. These minerals form the phenocrysts, many of them large and in some cases occupying much more space than the groundmass. The plagioclase occurs abundantly as microlites in the felsitic groundmass. The quartz crystals are not idiomorphic, but occur as sub-round grains, in some cases quite conspicuous in hand specimens. The accessory minerals are magnetite, apatite, rutile, and probably some orthoclase. The apatite crystals occur characteristically in the feldspar grains, and the rutile is confined to the quartz. Quartz is only

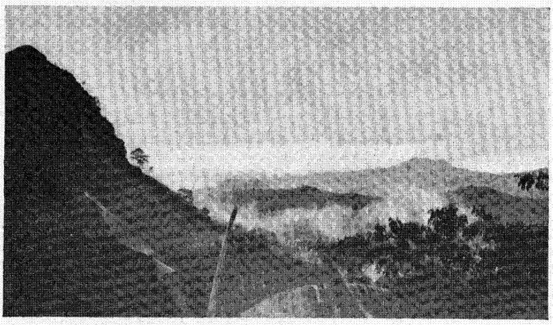

FIG. 1.—*View looking south from near K. 47, Lares-Rio Blanco Road*

Elevation, 1,500 feet. Mt. Torrecillo on the left, Cordillera Central of the Ponce District in the background, with low-hanging clouds marking the valley of the Rio Blanco in the middle ground.

an accessory constituent in some portions of the rock. The chief alterations are, hornblende to chlorite and serpentine; plagioclase to kaolin, saussurite, and carbonate; and magnetite to limonite.

The rock grades into andesite porphyry, and locally has a high content of tuffaceous material, and resembles a true tuff. Portions which are exceedingly high in tuffaceous material are generally highly kaolinized. One of the pockets of white kaolin is shown in figure 2.

The typical phases of the rock are readily recognized in the field by the freshness, resistance to erosion, light gray color mottled with black hornblende phenocrysts, and the conspicuous grains of quartz. It is quite different in general appearance from the monotonous andesite porphyries found throughout the district.

Andesite. Andesites of the type found in the Ponce District are rather rare. They occur in limited areas along the Rio Blanco east of Añasco. The most typical occurrence is on the north side of the Rio Blanco valley, one mile east of the terminus of the sugar railroad. This rock is locally amygdaloidal, and undoubtedly a surface flow. It is one of the few large exposures of andesite in the Lares District which is not porphyritic. In thin section, it shows micro-diabasic structure, produced by microlites or minute lath-like crystals of plagioclase (apparently oligoclase), with an interstitial groundmass of ferromagnesian mineral, probably entirely

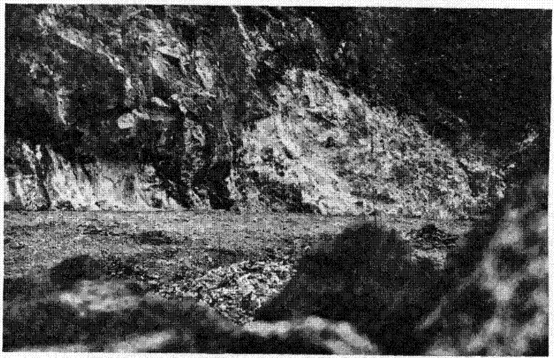

FIG. 2.—*K. 47.2, Lares-Rio Blanco Road at Mt. Torrecillo*

View looking across the road, showing pocket of white kaolin in quartz diorite porphyry.

hornblende, though some of this may be secondary from augite. The rock has undergone considerable alteration from weathering.

Andesite Porphyry. This is by far the most abundant type of igneous rock found in the district. Its chief occurrences as intrusive bodies are shown on the geologic map. It occurs as surface flows at other points, notably south of Aguada, and at K. 10.7 on the Mayaguez-Las Marias Road. Its extrusive origin in these instances is shown by the abundance of amygdaloidal cavities. In a few localities typical palisade structure is developed, as, for example, on the Rio Blanco, 1½ miles east of the end of the Lares-Rio Blanco Road (Fig. 3). Dikes of andesite porphyry intruded in massive tuffs are found at various points along the Rio

Blanco sugar railway, east of Añasco. This rock also occurs as sills in the tuffs and ash beds, but many of these are small and not shown on the geologic map.

Plagioclase is always the chief mineral and most persistent phenocryst-forming constituent. Of the plagioclases, andesine and andesine-oligo-

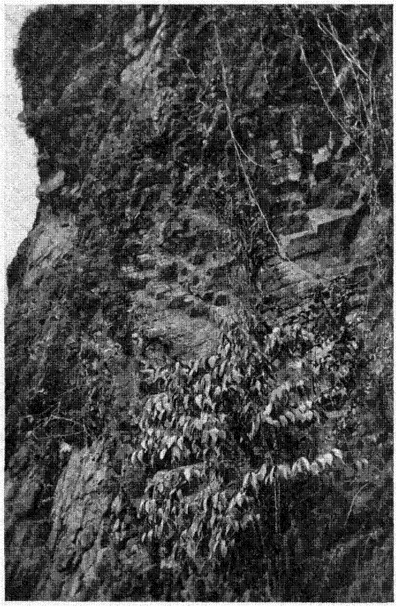

FIG. 3.—*Palisade structure in andesite porphyry*

Rio Blanco one and a half miles upstream (east) from the end of the Lares-Rio Blanco Road.

clase are by far the most common. In many cases, labradorite is present as a principal mineral with the andesine. Oligoclase rarely occurs as a principal mineral. Hornblende is the ever present ferromagnesian constituent. Where it is not abundant, the rock is pink or light gray in color due to the preponderance of feldspars, but where the ferromagnesian element is present in abundance, as is more commonly the case, the rock is gray or dark gray if labradorite is present. The accessory minerals are augite, magnetite, apatite, pyrite, and rarely ilmenite, albite, and quartz. The common alterations are, hornblende to chlorite, serpentine, epidote, limonite, calcite, and quartz; plagioclase to calcite, kaolin, quartz and saussurite.

The plagioclases occur also as microlites in the groundmass, and exhibit a marked parallelism in their arrangement as a result of flowage of the magma during crystallization. Fractured or fragmental phenocrysts are very common, also indicating flowage. Strain effects can in many cases be observed in the phenocrysts, as might be expected. The zonal effects of the plagioclase phenocrysts is one of the most typical features of nearly all of the andesite porphyries. These zones of growth are of variable composition, as shown by their slightly different extinction angles and differential alteration. In some crystals the interior is completely altered, while the border is fresh. In other cases the alteration has affected alternate zones, so that the concentric structure is visible in hand specimens of the rock. The abundance of carbonate as an alteration product of the plagioclases is illustrated by the fact that many of the weathered andesites effervesce with acid.

From a study of slides of the andesite porphyries certain associations of minerals are evident. Either andesine or andesine-oligoclase is always present as a principal mineral, and in some cases both varieties occur. With these either oligoclase or labradorite may be present, but oligoclase apparently does not occur with the labradorite. Where augite is present as an accessory mineral, labradorite usually occurs as a principal mineral. Ilmenite is associated with magnetite but does not occur unless magnetite is present. It is not nearly as common in the andesites of the Lares District as in similar rocks of the Ponce District.

Quartz and calcite are frequently found filling joints and small cracks. In a few localities pyrite and chalcopyrite occur in the quartz veins. The best example of this is found on the Rio Blanco near Alto Sano. The quartz veins occur in andesite porphyry dikes cutting massive tuffs. With the chalcopyrite are minor quantities of bornite. The veins are nowhere more than 3 inches thick, and most of them much less. In the amygdaloidal andesite porphyry in the area south of Aguada, and on the Rio Blanco sugar railroad, 3 miles east of Añasco, introduced matter is found in the form of amygdules, partially or wholly filling the cavities. The amygdules are chiefly of amorphous silica and zeolites. In the locality south of Aguada, massive veins of banded agate with core of crystalline quartz, occur abundantly, cutting the andesite porphyry, and apparently associated with nearby intrusive bodies of serpentine. The amygdaloidal cavities are elongate parallel with the flowage alignment of the plagioclase phenocrysts, and are lined with banded agate or other amorphous silica, the interior being filled with crystalline quartz. Where they are only partially filled, the quartz pyramids form small geodes, with incrustations of prehnite and other zeolites.

More or less tuffaceous material is present in practically all the andesite porphyries. In thin sections, this included matter is seen to consist mainly of broken crystals of feldspar, hornblende, and other minerals. It is often difficult to determine whether these are merely phenocrysts broken up by flowage during crystallization, or whether they are tuffaceous materials of extraneous derivation. Not infrequently fragments of devitrified glass, or lithlic fragments of more than one crystal are encountered, and these indicate the true nature of the broken crystals associated with them. In some cases the rock is so crowded with fragmental materials that it is impossible to tell whether it is of igneous or of clastic origin. In examining thin sections, one may be considerably surprised to find fragmental foraminiferal shells in what otherwise appears to be a typical andesite porphyry. The difficulty is increased by the fact that many of the tuffaceous crystalline fragments, especially the plagioclase, are so regular in form that they are not distinguishable from phenocrysts. It may truthfully be said that there are all gradations between a tuffaceous andesite and an andesite tuff.

Augite Andesite. The only known occurrence of this rock is in the southern half of the area of lava flows shown on the geologic map south of Aguada. It is a dark massive amygdaloidal to vesicular lava, in some places very ropy and scoriaceous. The amygdaloidal cavities have no regularity of occurrence which might indicate successive flows. In some places, the cavities are filled with amorphous silica, zeolites, and native copper with associated copper minerals. Elsewhere the amygdaloidal cavities are empty, and the rock is light in weight due to its extreme porosity. In some exposures it resembles a coarse pumice. The mineralized areas are associated with points and small fault crush zones. The latter are filled with calcite, stilbite, native copper, malachite, and other minerals associated with the copper. This mineralization fills both the crush zones and adjacent cavities in the rock. This locality is described more fully in the chapter on mineral resources.

In thin section, this lava shows a dark ferromagnesian groundmass with fine lathes or microlites of plagioclase (chiefly andesine) exhibiting perfect flow structure. Occasional small grains of ferromagnesian mineral show the presence of augite, but whether hornblende is present also was not determined.

Augite Andesite Porphyry. Next to andesite porphyry, this is the most abundant type of igneous rock in the Lares District. Like the former, it occurs characteristically as elongate intrusive bodies, apparently sills or laccoliths. It is also associated with the larger and more massive bodies of gabbro porphyry, of which it seems to form lateral offshoots. Examples of this relationship are found on the Mayaguez-Las Marias Road between K. 8 and K. 9, and south of the Lares Road near K. 37. In some other localities it is associated with, and seems to grade into andesite porphyry, as in the Rio Blanco valley south of Lares, and in the same valley farther west, near east terminus of the sugar railroad from Añasco.

This rock is distinguished in the field from andesite porphyry by its darker gray to greenish color, the latter being due to alteration of augite. The large phenocrysts of augite are another distinctive characteristic. There are all gradations between augite andesite porphyry and gabbro porphyries, depending merely upon the relative prominence of phenocrysts and groundmass. Both varieties of rock may frequently be found in the same outcrop. The principal minerals are augite, andesine-oligoclase, labradorite, andesine, and oligoclase. It is seldom that more than two of these are found occurring together as principal minerals. The commonest association is labradorite with andesine. The usual accessory minerals are magnetite, hornblende, one or more of the above named plagioclase varieties, apatite, and pyrite. Hornblende is present as a principal constituent in a few of the specimens. Occasionally what appears to be primary quartz is found in small quantity. The common alterations are, augite to chlorite, uralite, serpentine, and carbonate; plagioclases to saussurite, carbonate, kaolin and quartz; magnetite to limonite. Of introduced material, calcite occurs in minor quantities in some specimens.

Texturally, the rock is a typical augite porphyry, with the plagioclase phenocrysts generally smaller than the augite, though considerable of the latter is disseminated as small grains in the groundmass. The plagioclases are characterized by strain effects, zonal growth, and usually by parallel arrangement due to flowage. They are in many instances fractured, with the cracks filled by groundmass. A poikilitic habit is occasionally seen, with inclusions of ferromagnesian minerals in the plagioclase phenocrysts.

The outcrops of this rock are, as a rule, fairly fresh, but thin sections show considerable alterations. Secondary carbonate is often so abundant that the rock will effervesce with acid. This is especially true where there is a considerable quantity of included tuffaceous material.

Gabbro Porphyry. This rock is found on the Mayaguez-Las Marias Road between K. 8 and K. 9, and south of the Lares Road near K. 37. As previously noted, it is associated with the less porphyritic augite andesite porphyry. It forms rather large intrusive bodies which should be classed as bosses or volcanic necks. They do not exhibit the elongate form characterizing the andesite porphyries. In the case of the occurrence on the Mayaguez-Las Marias Road, the intrusive relationship to the adjacent shale beds is evident.

Mineralogically, the rock is about the same as the augite andesite porphyry, the chief difference being in texture. The commonest principal minerals are augite, andesine, and labradorite. As accessories, magnetite is present in every specimen, with usually some hornblende, apatite, and andesine-oligoclase. The characteristic alteration products, as in the augite andesite porphyries, are chlorite, secondary hornblende, serpentine, epidote, kaolin, carbonate, saussurite, quartz, and limonite. Strain effects, and evidences of fracturing and flowage during crystallization are characteristic. Likewise, the usual zone effects are seen in the plagioclases, with apparently the more acid variations making up the outer zones of the crystals. The groundmass is characteristically dark, due to the predominance of ferromagnesian constituents, and is usually marked by microlites and plagioclase. Quite often very little groundmass is present. In some specimens, the augite phenocrysts are very large, and the augite is greatly in excess over the feldspar. These phases are typical augite porphyrites, like those found near Maricao, in the Ponce District.

Serpentine. No outcrops of this rock were found in the Lares District, but its presence is shown by its surface weathering product, the typical red limonite soil with limonite concretions, like that covering the Mesa, southeast of Mayaguez. It is presumably derived from an olivine-bearing rock. The distribution of this material is shown on the geologic map in the volcanic area south of Aguada. It occurs in small irregular patches, lying wholly within the area of andesite lava flows. The serpentine probably occurs as dikes in the andesite. The limonite ore is similar in general character and origin to the Mayaguez ore, which has been described by Fettke (1918) and by Mitchell (1922) and shows that the Mayaguez serpentine body is undoubtedly intrusive into the adjacent shales, and hence represents one of the later phases of volcanic activity affecting Porto Rico. The Aguada serpentine is doubtless the contemporary of the Mayaguez intrusive.

SEDIMENTARY AND CLASTIC ROCKS

The sediments are almost entirely of clastic make-up, and derived in large part from volcanic sources. There is a total absence of sandstones and conglomerates, and very few of the fragments in the tuffs show even the slightest suggestion of roundness. Limestones are also lacking except in a few isolated instances of no importance, and even these contain minor quantities of tuffaceous material. The following types of clastic or sedimentary rock seem worthy of separate description:

TABLE 2

Name of Rock	Occurrence
Massive tuffs and agglomerate........	Chiefly in the eastern part of the district, and in the central zone called the Rio Blanco series.
Bedded tuffs	Interbedded with shales and ash.
Ash	Interbedded with shales and tuff, beds usually not as thick as the tuffs.
Ashy shale	Do.
Black shale	Southwestern portion of the district.
Lime shale	Wide spread, but characteristic of Pt. Jiguero region and the Atalaya Range north of Añasco.
Limestone	South of Las Marias and on Desecheo Island. As lenses of small extent in shale or tuff.
Chert	North of Mayaguez and on Desecheo Island, as lenses in shale.

Massive Tuffs and Agglomerate. These rocks are so deeply weathered that very little can be found out about their structure and composition.

In many places weathered exposures will show the lithic fragments apparently well preserved, but with the entire rock so badly decayed that it can be cut into slices with a knife as easily as clay. In the more

FIG. 4.—*Volcanic agglomerate, Rio Blanco near mouth of Rio Prieto*

The view shows two large slabs of lime shale imbedded in a matrix of finer pyroclastic material. This rock marks one of the centers of volcanic activity during late Cretaceous time.

massive exposures, not the slightest trace of bedding or assortment of fragments can be seen. In composition, they are for the most part made up of fragments of andesite porphyry. Kaolin and iron oxides are the chief weathering products. The more reddish areas of clay soil on the mountainous slopes in the southeastern portion of the Lares District are derived chiefly from these massive tuffs. The coarse agglomeratic phases are of more limited occurrence, usually being found close to the centers where volcanic activity was particularly strong. One of the best exposures of this type of rock is found in the Rio Blanco valley southwest of Lares, close to the mouth of the Rio Prieto. Large slabs of lime shale are found imbedded in a massive, compact agglomerate, made up largely of andesite fragments (Fig. 4). The lime shale occurs nearby in a relatively undisturbed condition, and alternates with thin layers of tuff.

FIG. 5.—*Volcanic agglomerate, with blocks of andesite porphyry*
South of K. 8, Lares Road.

Apparently the lime shale consolidated soon after deposition, leaving the interbedded tuff beds still unconsolidated, so that when the volcanic disruptive action took place, large slabs of the shale were thrown up and imbedded in the resulting agglomerate. The tuff layers, being unconsolidated, were completely broken up and distributed as groundmass in the agglomerate. This groundmass is composed of fragments of feldspar, quartz, calcite, magnetite, ferromagnesian minerals, pieces of andesite porphyry, and lime shale. Another type of agglomerate, in which the fragments are chiefly large blocks of andesite porphyry is well exposed south of K. 8, Lares Road (Fig. 5). This material lies immediately adjacent to a small boss or volcanic neck of augite andesite porphyry, and in turn is surrounded by thin beds of tuff and shale which have been differentially indurated and altered in proximity to the intrusive body and agglomerate (Fig. 6). A short distance from the area of volcanic activity, they are relatively undisturbed and are unaltered.

Bedded Tuffs. These are, for the most part, fine grained, and grade into typical ash beds. They occur characteristically interbedded with shales and ash, and are distributed throughout the district, though more abundant in the western part. While the coarseness of the material is

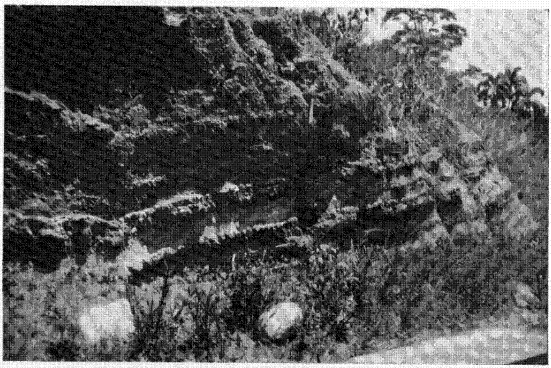

FIG. 6.—*Shales and thin-bedded tuff, showing alteration effects produced by a nearby intrusive body*

K. 8, Lares Road.

quite variable, even in short distances, few of the fragments are larger than one-half inch in diameter. They are composed of broken phenocrysts or crystalline particles derived from andesite porphyries, and hence contain the usual minerals, such as plagioclase, ferromagnesians, and magnetite. Where finely interbedded with shales, they contain a considerable percentage of calcite and quartz grains. Some of the quartz grains show slight traces of rounded edges, as though subjected to current action. Wherever the tuff is interbedded with black shale, the black shale forms a matrix for the angular grains of the tuff. Where interbedded with lime shale, they have a high content of calcite and fragments of the lime shale, and have many veins of calcite in localities of close folding or faulting. The bedded tuffs can usually be recognized in the field by their characteristic spheroidal weathering (Fig. 7) which distinguishes them from the occasional thin sills of andesite. This type of weathering is also to be found in the more massive tuffs (Fig. 8). It is sometimes difficult to distinguish such occurrences from conglomerate.

As has been pointed out by Berkey, Mitchell, and others, the tuffs are much more subject to surface weathering than igneous rocks of the same mineral composition. It is only where the tuff has been indurated, due

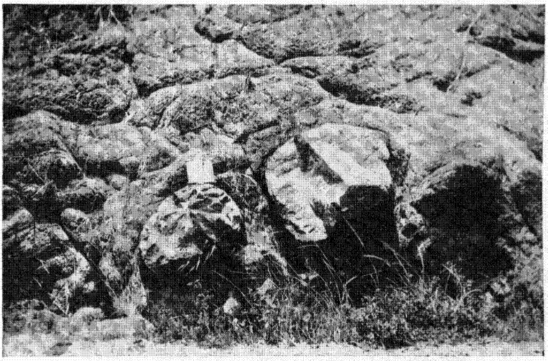

FIG. 7.—*Spheroidal weathering in bedded tuff*

Near K. 12, Aguada-Rincon Road.

to the action of a nearby intrusive body, that it is more resistant to erosion than the shale with which it is interbedded (Fig. 5). The tuff beds are characteristically thicker than the adjacent beds of shale. They range from 6 inches to several feet, and have no minor stratification, although some beds show a slight assortment of coarse and fine material.

Ash. Beds of ash occur with the shales and bedded tuffs. They resemble the shales, and where the outcrop is weathered the two are not distinguishable. Typical ash beds are not abundant. The most common occurrence is shale high in ashy material, and there are all gradations between a typical shale and a typical ash. Where the rock is exceedingly fine grained, it is sometimes impossible to determine the composition.

Any fine particles of volcanic glass which may have been present are usually not recognizable in thin sections, owing to devitrification and alteration. In some cases, minute rod-like particles are present, suggestive of fibrous glass or pele's hair, but these are invariably found badly altered by weathering. The ash beds grade, in texture, to fine grain tuffs which do not differ otherwise from typical ash. In thin sections, ash may usually be distinguished from shale by its lack of assortment of

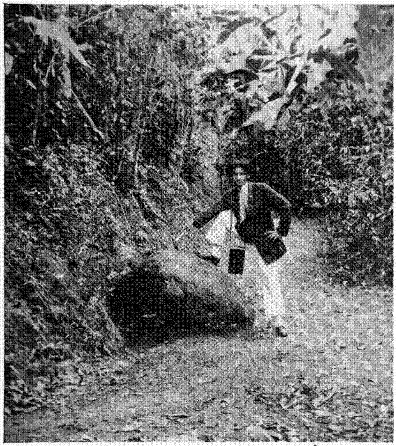

FIG. 8.—*Spheroidal weathering in massive tuff*
Exposure in ravine just west of the plaza at Lares.

particles and absence or scarcity of foraminiferal shells. In hand specimens it is usually distinguishable by its fracture. Berkey has pointed out the fact that the shales generally break with a blocky fracture, especially in the case of weathered black shale. The lime shales have a smooth, curved or almost conchoidal fracture. Typical ashes, however, have a rougher, more irregular fracture, due to the unevenness of the weathering which they have undergone. As a rule, the typical ashes are of slightly coarser texture than most of the shales, but this difference is not evident in hand specimens.

The ashes, and ashy beds in general, are divisible into two types,—calcareous and non-calcareous. The former are chiefly shales high in ash content, and carrying a few foraminiferal remains and grains of calcite. The calcite grains are in some cases slightly rounded and pitted as though by solution. The non-calcareous variety is made up chiefly of andesitic material, minute angular crystalline particles, and an indeterminate groundmass, containing possibly devitrified glass and altered crystalline fragments. They contain no foraminiferal shells and but very little calcite, except as introduced matter filling veins. Of the two types of ash, the calcareous is the more common in the southwestern part of the district, while in the northwest portion of the Cretaceous area, the non-calcareous variety predominates except in the area south of Moca.

Ashy Shales. Shales high in the ash content can usually be classified only by the use of thin sections. The depth to which they are weathered increases the difficulty. The weathered ashy shales are generally non-calcareous, and resemble the weathered black shale, but are higher in kaolinized material. They are typically reddish brown to gray in color, and at some places contain white patches or streaks of kaolin (Fig. 9).

Black Shales. These have been described by Berkey and Mitchell, and similar shales have been described by Semmes. Mitchell shows that the red, blocky shales exposed around Mayaguez are the weathering product of a black shale, found exposed as such, only in quarries or stream channels. Fresh exposures of this shale occur south and northeast of Consumo and at K. 3.7, Mayaguez-Consumo Road. There are all gradations between a pyritiferous black shale and a very dark lime shale. The black shale exposed near Consumo shows in thin sections, a dark opaque groundmass, apparently in part carbonaceous matter, in which are imbedded many foraminiferal shells, a few minute angular fragments of quartz and feldspar, and comparatively large well formed cubes of pyrite. The pyrite in crystallizing out has crowded the surrounding carbonaceous groundmass. Carbonaceous films, apparently small plant remains, are seen in some hand specimens of the rock. The only calcareous material visible in thin sections consists of foraminifera, but these are sufficient to cause the rock to effervesce with acid. A microscopic stratification or assortment is visible in thin sections, but is not evident in hand specimens.

A more calcareous phase of this shale occurs at K. 3.7, Mayaguez-Consumo Road. The rock in this locality is an alternation of thin bands of the dark foraminiferal shale with bands of fine grained andesitic tuff. The contact between the two is very sharp. In thin sections, the shale shows a dark carbonaceous groundmass with foraminiferal shells in abundance. The adjacent tuff layers are composed of angular fragments of andesite and fragmental crystals, all of which are imbedded in the same

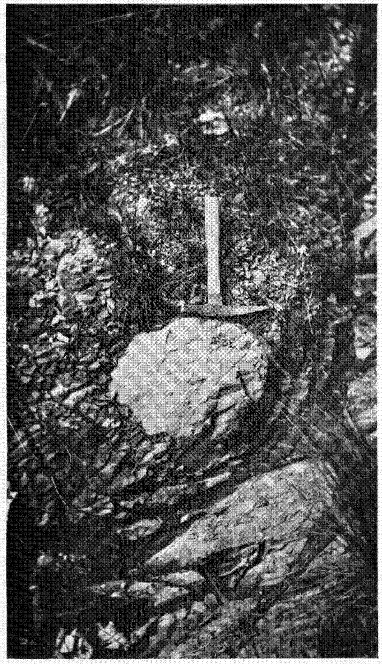

FIG. 9.—*Ashy shale showing kaolinized portions*
Rio Yauco Series, three miles east-northeast of Rincon.

dark groundmass which forms the bulk of the shale. Foraminiferal shells are found in the tuff layers with the carbonaceous matrix. In addition to foraminifera, the shale contains an abundance of radiolarian remains, marked by rounded bodies of amorphous or spherulitic silica. However, a few unaltered radiolarian shells occur.

Lime Shales. These are much commoner than the black shale. Typical exposures of lime shale are shown in figures 10 and 36. Many of the layers are highly calcareous, and have the character of a thin-bedded or banded, hard, compact limestone, dark bluish gray in color. Exposures of this type are to be seen in quarries along the automobile road crossing the Atalaya Range northwest of Añasco.

In thin section, this rock proves to be made up chiefly of calcite grains with a variable amount of volcanic matter, such as angular fragments of

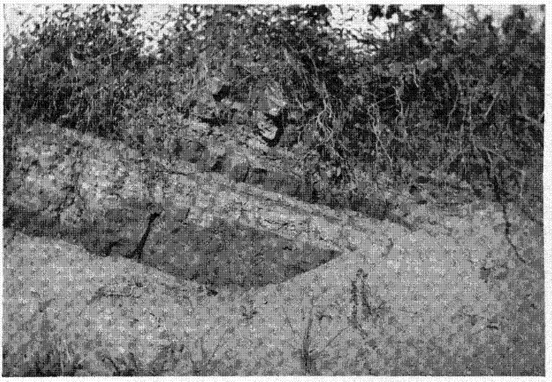

FIG. 10.—*Typical lime shales*

Rio Culebrinas Series, one and a quarter miles south of K. 5, Lares Road.

feldspar, hornblende, and magnetite. Considerable recrystallization of the calcite is evident, and this gives the rock its high density and compactness. Foraminiferal shells occur, often in considerable quantity, but in some specimens they are absent. Thus this rock differs from the pyritiferous black shale in that its calcareous content is not dependent upon the presence of foraminifera. The foraminiferal shells are all of microscopic size, and include indeterminate forms resembling *Globigerina* and *Rotalia.* In some cases their structure has been entirely destroyed by subsequent crystallization to aragonite. Some of the shells are fragmental, as though having been transported before deposition, but this feature is not common.

Owing to its high lime content, lime shale is more resistant to erosion and weathering than any other rock occurring abundantly in the Lares District. Along the Atalaya Range, north and northwest of Añasco, their influence upon the topography is rather marked. Other, less extensive, developments of the same type of shale occur on Desecheo Island, in the Rio Blanco valley near the mouth of the Rio Prieto, at certain points in the hills south of Moca, and along the automobile road northeast of Rincon.

Limestone. True limestone is almost unknown in the Cretaceous rocks of the Lares District, although one might class certain portions of the lime shale as a limestone.

A small but prominent inlier of limestone occurs southeast of the Mayaguez-Las Marias Road opposite K. 22. This rock is a hard, compact fine grained crystalline limestone, gray to pink in color, and white on weathered surfaces. The structure is massive, with no bedding visible in the outcrop. Bedding, however, may have been obscured, since the outcrop shows faulting and fracturing to an extreme degree, with numerous calcite veins. In thin section, the rock appears as a fairly pure limestone, made up almost entirely of recrystallized calcite grains with a very small admixture of tuffaceous material. It contains many foraminiferal shells (chiefly *Nummulites* and *Globigerina*) and fragments of *Radiolites.* Lithologically, the rock resembles the San German limestone of the Ponce District. A few thin beds of similar rock occur with the lime shales on Desecheo Island. These exhibit distinct stratification, and are banded by zones of tuffaceous material. The fossils are chiefly foraminiferal shells (*Globigerina* and others), in great abundance, and a few fragments of *Radiolites.*

Chert. Chert beds are of very local extent. They occur as lenses in the shales north of Mayaguez. Mitchell found an outcrop on the north side of Mayaguez Bay. Another exposure is to be seen just west of K. 2, Mayaguez-Añasco Road. Chert is also found in small quantity, interbedded with shales on Desecheo Island. In its field occurrence, this rock is conspicuous because of its relatively fresh, unweathered condition. The color varies from gray to pink, or reddish brown where stained by limonite. It is extremely hard throughout, but extensively fractured, and breaks into sharp, very irregular blocks, not having the conchoidal or curved fracture surfaces characteristic of most cherts. In thin section, under crossed nicols, it appears as a fine aggregate of amorphous silica, crowded with microspherulitic portions, which are very probably the remains of radiolarian shells. Tuffaceous material is present in very small amounts.

Stratigraphy

Owing to difficulties of field work and the limited time spent in the field, it is impossible to correlate rocks of similar lithologic habit occurring in various portions of the district. It is possible, however, to make larger subdivisions, each doubtless containing several formations. The geologic map shows two belts of shales, with a central belt of tuffs, intrusives, and extrusives. The northern or oldest belt of rocks comprises tuffs and intrusives in the southeast, which grade into shales to the northwest. This belt is called the Rio Culebrinas Series because of its development along the Rio Culebrinas valley. The central belt, predominantly tuffs and andesitic rocks, is called the Rio Blanco Series, from its exposure along the Rio Blanco. The Rio Yauco Series, in the southern portion of the district, is named from the Rio Yauco Shale, a term applied by Mitchell to the black shales which form a prominent part of this series between Mayaguez and Consumo. The relationship of these three series, as well as the complexity of the structure, is shown in the cross-sections (Plate I, Figs. 7-10). It should be noted that the boundaries of these subdivisions are marked more or less by gradational change from one prevailing type of rock to another, hence the boundary lines as drawn on the geologic map are somewhat arbitrary. On this map no attempt has been made to show all the occurrences of each type of rock. Thus where shale is the predominant rock, the entire area is mapped as shale, and only the larger tuff beds or intrusives are shown.

THE RIO CULEBRINAS SERIES

In the region south of Lares, this series is represented by a wide area of tuffs. Exposures of unweathered rock are so few that the true character of the underlying formation cannot be determined in most places. At least one small area of shale occurs east of Lares, and there are doubtless many others. Intrusive bodies of andesite porphyry, augite andesite porphyry, and gabbro porphyry are found, chiefly in the vicinity of Lares. To the northwest, the tuffs grade into shales. This transition is well shown by the alternation (interfingering) found in the section south of San Sebastian (Plate I, Fig. 7).

Still farther to the northwest, shale is the predominant material, but is interbedded throughout with ash and tuff. A small area of intrusive,

the prevailing dip is to the southwest. Most of the old volcanic vents are in this belt. Among these, the two most important ones occur south of Aguada and south of Lares in the Rio Blanco valley. The former is marked by the largest area of surface flows in the district, consisting of amygdaloidal rocks (andesite and augite andesite). It is in the augite andesite that native copper occurs. In this large area of surface flows are small intrusives of serpentine, marked on the surface by patches of iron ore like that occurring on the Mesa at Mayaguez. Another surface flow of augite andesite is found in the Rio Añasco valley about three miles east of Añasco. There is no native copper, however, in this rock.

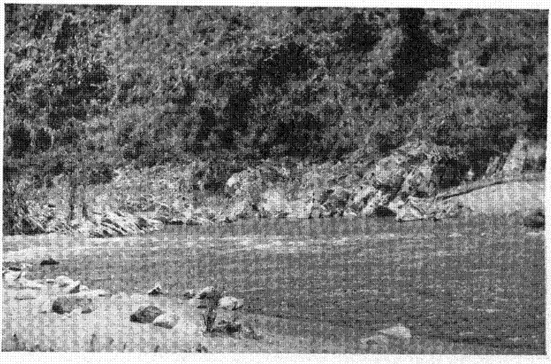

FIG. 12.—*Fault in Rio Blanco Series, Rio Blanco near mouth of Rio Prieto*

View looking south. The thin-bedded lime shales are seen on the left, dipping southwest. The massive thick-bedded tuffs are seen on the right, dipping steeply to the east. This discordance in dip and strike was found upon examination to be the result of a thrust fault of considerable magnitude.

The area south of Lares in the Rio Blanco valley is an old volcanic complex and probably represents the location of several former volcanoes. Only one area of undoubted surface flows is found in the Rio Blanco Series, but andesite porphyry showing columnar structure occurs along the river about 1½ miles east of the end of the Lares-Rio Blanco Road (see Fig. 3). The columns exhibit radial arrangement and probably mark an old volcanic throat. The size of the phenocrysts seems to show that this rock was not a surface flow. Northwest of this point is a rather large included area of shales, tuffs, and lime shales, lithologically similar to those of the Rio Yauco Series. This inlier of sediments has been badly faulted and cut up by the surrounding intrusives. In the Rio Blanco valley at the mouth of the Rio Prieto, the lime shales are faulted (Fig. 12) and broken up, forming in places a volcanic agglomerate of andesitic content, in which large slabs of the shale are imbedded (Fig. 4). The intrusion of quartz diorite porphyry, shown on the map in this volcanic area, is best exposed in a high peak known as Mt. Torrecillo (Fig. 1), located at K. 48-49 on the Lares-Rio Blanco Road.

The best exposures of the Rio Blanco Series are found along the sugar railroad east of Añasco in the Rio Blanco valley. Going upstream, one

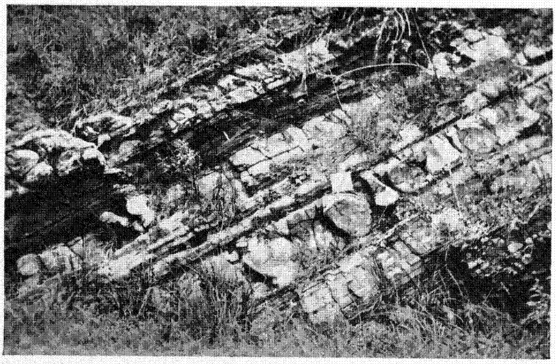

FIG. 13.—*Spheroidal weathering in fine-grained tuffs, alternating with shale* Rio Yauco Series. K. 12.2, Aguada-Rincon Road.

passes from the belt of Rio Yauco Series shales into a succession of tuffs, andesite flows and andesite porphyry intrusives, throughout which very little of the structure can be seen. Occasionally obscure bedding may be found in the tuffs, or the dip of a flow or sill of andesite may be distinguished. Here and there are small included patches of shale of very limited extent. The most curious and unexpected feature of the Rio Blanco Series is the presence of an isolated outcrop of limestone, rising from a monotonous area of deeply weathered rock, all apparently tuff. As shown on the map, this limestone lies 1½ miles southwest of Las Marias, and may be seen from a point near K. 22 on the Mayaguez-Las Marias Road. It is similar lithologically to the San German limestone of the Ponce District and contains *Radiolites* sp. and many foraminifera, including indeterminate species of *Globigerina, Nummulites* and an *Orbitoides* or similar form belonging to the *Orbitoides* group.

THE RIO YAUCO SERIES

This series, as previously noted, is predominantly an area of shales, often interbedded with ash and tuff, and with occasional andesitic flows and intrusives. Most of the shale is much less weathered than that of the Rio Culebrinas Series. This is due to the relative abundance of the hard gray-blue lime shales which are much more resistant to erosion and weathering than are the more ashy, easily kaolinized shales of the series to the north. It would seem that the Rio Yauco beds have undergone greater folding and faulting than the underlying rocks of the other two series, but this difference is probably only apparent, not real. The details of structure in the other two series are usually obscured by weathering.

The northern, or stratigraphically lowest, portion of the Rio Yauco belt contains much shale of the ashy type alternating with tuffs. Excellent exposures of these are found along the automobile road northeast of Rincon. A very characteristic feature of these beds is the spheroidal weathering of the tuffs (Figs. 7 and 13). Southeast from Rincon, and forming the range of hills known as Atalaya Peak, are developed the blue-gray, hard lime shales, often banded, and resembling the Peñuelas shale of the Ponce District. In the almost total absence of true limestone in the Lares District these lime shales are among the ridge-forming types of rocks to be found. Southeast from Añasco these lime shales grade into the pyritic black shale of the vicinity of Consumo, and its weathered product, the red kaolinized shales, are well exposed in the vicinity of Mayaguez.

Tuffs of the more massive type are more abundant southeast of Añasco Playa. An intrusive body of considerable size composed of gabbro porphyry, grading into augite andesite porphyry, is well exposed at various points from K. 8 to K. 10 on the Mayaguez-Las Marias Road. It is clearly intrusive into the shales. North of Mayaguez, near K. 2 (Mayaguez-Añasco Road), are several small areas of chert, occurring as lenses in the surrounding shale. They are apparently of radiolarian origin.

Desecheo Island, lying 15 miles west of Pt. Jiguero, contains more features of geologic interest than any area of equal size on the mainland. It is a continuation of the belt of lime shales of the Rio Yauco Series which form the back-bone of the Cordillera Central, known on the west coast of Porto Rico as Atalaya Peak. The arid climate of Desecheo has preserved the rocks in a relatively unweathered state, hence the structure can be well seen. The enormous amount of faulting and fracturing is well shown in figures 14 and 15. Among the special features should be mentioned the presence of chert beds like those north of Mayaguez, and of a few thin beds of limestone of the San German type, containing *Radiolites* and an abundance of foraminifera.

Structural Features

The strike of the beds is, as previously stated, northwest-southeast. On the map the lines designating shale have been drawn so as to indi-

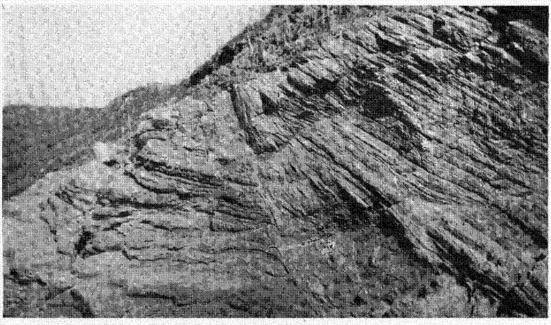

Fig. 14.—*Fault in Rio Yauco Series, northwest side of Desecheo Island*

cate the strike wherever known. The dip is to the southwest, at variable, but almost universally high angles. Variable or northeast dips denote folding or faulting, or both.

The characteristic structure of the series is shown in the four sections (Plate I, Figs. 7, 8, 9, 10). Figures 9 and 10 are generalized or ideal sections, and illustrate the difference between the east and the west parts of the Lares District. Figures 7 and 8 are based on traverses made across the series. Wherever the course of the traverse has deviated from the line of the section, the data has been projected on the section. The locations of the sections are not shown on the map, but may readily be seen from the designations of towns through which they pass.

Structurally, the rocks of the district are of two kinds,—massive and bedded. The massive rocks include the andesite intrusives, of laccolithic

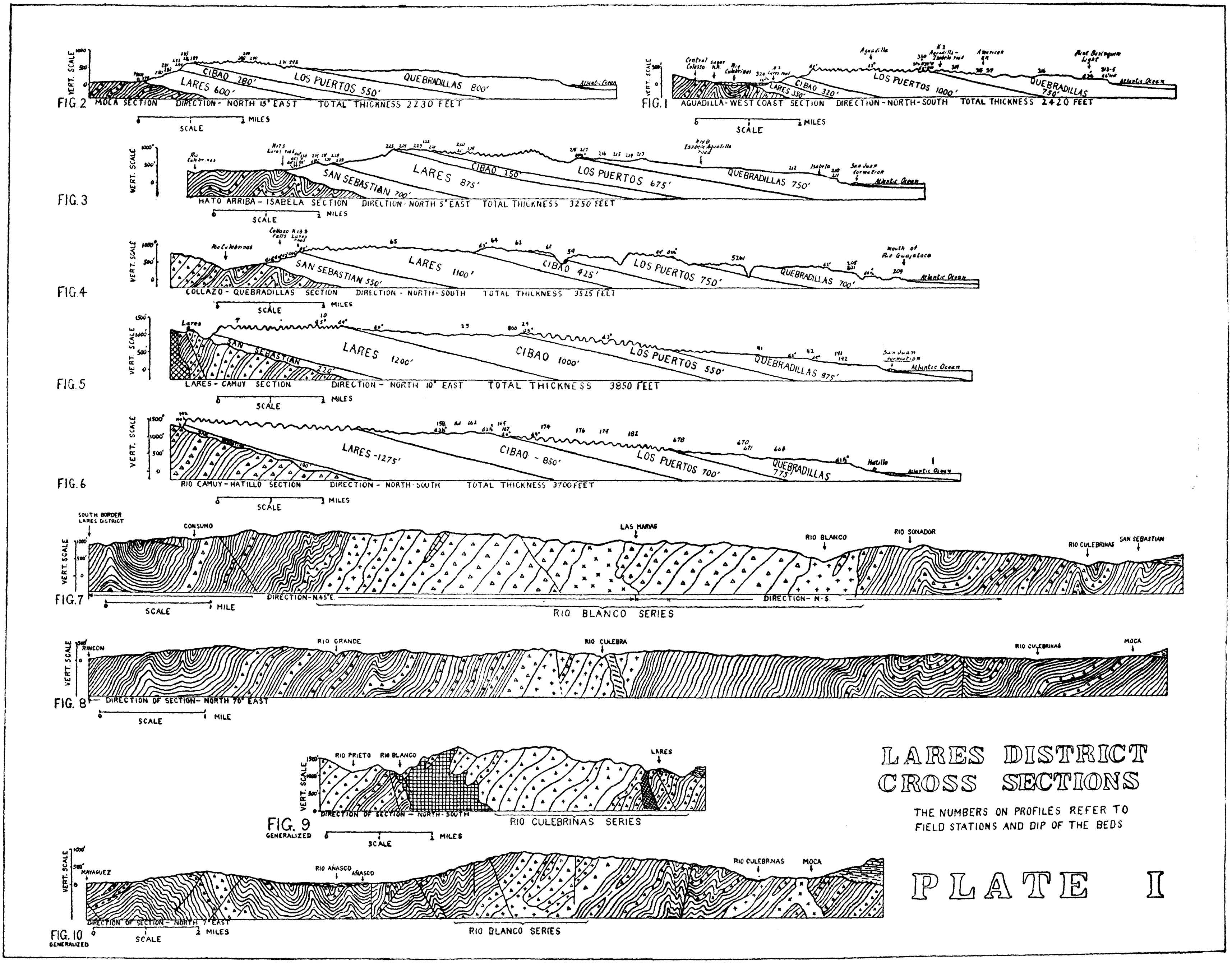
FIG. 2 MOCA SECTION DIRECTION - NORTH 15° EAST TOTAL THICKNESS 2230 FEET
LARES 600'
CIBAO 280'
LOS PUERTOS 550'
QUEBRADILLAS 800'
FIG. 1 AGUADILLA - WEST COAST SECTION DIRECTION - NORTH-SOUTH TOTAL THICKNESS 2420 FEET
LARES 350'
CIBAO 320'
LOS PUERTOS 1000'
QUEBRADILLAS 750'
FIG. 3 HATO ARRIBA - ISABELA SECTION DIRECTION - NORTH 5° EAST TOTAL THICKNESS 3250 FEET
SAN SEBASTIAN 700'
LARES 875'
CIBAO 250'
LOS PUERTOS 675'
QUEBRADILLAS 750'
FIG. 4 COLLAZO - QUEBRADILLAS SECTION DIRECTION - NORTH-SOUTH TOTAL THICKNESS 3525 FEET
SAN SEBASTIAN 550'
LARES 1100'
CIBAO 425'
LOS PUERTOS 750'
QUEBRADILLAS 700'
FIG. 5 LARES - CAMUY SECTION DIRECTION - NORTH 10° EAST TOTAL THICKNESS 3850 FEET
SAN SEBASTIAN 220'
LARES 1200'
CIBAO 1000'
LOS PUERTOS 550'
QUEBRADILLAS 875'
FIG. 6 RIO CAMUY - HATILLO SECTION DIRECTION - NORTH-SOUTH TOTAL THICKNESS 3700 FEET
LARES - 1275'
CIBAO - 850'
LOS PUERTOS 700'
QUEBRADILLAS 775'
FIG. 7 DIRECTION - N.45°E. DIRECTION - N.S.
SOUTH BORDER LARES DISTRICT
CONSUMO
LAS MARIAS
RIO BLANCO
RIO SONADOR
RIO CULEBRINAS
SAN SEBASTIAN
RIO BLANCO SERIES
FIG. 8 DIRECTION OF SECTION - NORTH 70° EAST
RINCON
RIO GRANDE
RIO CULEBRA
RIO CULEBRINAS
MOCA
FIG. 9 GENERALIZED DIRECTION OF SECTION - NORTH-SOUTH
RIO PRIETO
RIO BLANCO
LARES
RIO CULEBRINAS SERIES
FIG. 10 GENERALIZED DIRECTION OF SECTION - NORTH 7° EAST
MAYAGUEZ
RIO AÑASCO
AÑASCO
RIO CULEBRINAS
MOCA
RIO BLANCO SERIES
VERT. SCALE
SCALE
MILES
LARES DISTRICT CROSS SECTIONS
THE NUMBERS ON PROFILES REFER TO FIELD STATIONS AND DIP OF THE BEDS
PLATE I

or irregular form, some of the thicker surface flows, such as those south of Aguada, and the massive tuffs. The latter cover large areas, and are almost universally too deeply weathered to show their real structure. The few unweathered exposures show either very obscure bedding of massive proportions or else none whatever. The bedded rocks comprise chiefly the shales, with interbedded tuffs, the smaller andesite sills and flows. It is chiefly in these bedded rocks that the highly disturbed condition of the rocks can be seen.

Intrusives. These are characteristically of the laccolithic type, or occurring as sills in the bedded formations or massive tuffs. Their origin is indicated by their occurrence as elongate bodies following the general strike of the surrounding beds. Many of them may be surface flows, but their porphyritic habit is so nearly universal, and the phenocrysts of such considerable size that it seems safer to interpret them as intrusives. It is nearly everywhere impossible to solve this problem from the nature of the contact with adjacent sediments and volcanic clastics. The reasons for this are chiefly because of the deep surface weathering and absence of extensive exposures of fresh rock. Another factor is the similarity in mineral make-up of the igneous and clastic rocks, and the consequent absence of contact metamorphic effects. Some of the large and irregular igneous bodies, such as the gabbro porphyries, are obviously intrusive into the sediments. They cut across the beds and are not elongate parallel to the strike.

Folds. At various localities in the shale areas are zones of exceptionally strong folding and faulting, marked by crush zones and extreme variability of dips and strikes. Wherever the folds are exposed to view, they are seen to be overturned folds, usually pitching at considerably high angles. A typical example is shown in figure 11. These minor folds are superposed on major folds which form the largest and most continuous structural units of the shale areas. The best example is the *Añasco Synclinorium,* shown in the section on Plate I, figure 10. This great syncline in the Rio Yauco shales underlies the Añasco Playa. Its northeastern limb and a portion of its southwestern limb are exposed along the south side of Atalaya Range, northwest of Añasco. From Añasco Playa it extends southeast, across the Mayaguez-Consumo Road between K. 6 and K. 12. Other large synclines and anticlines occur northeast and southeast of Rincon. The axial planes of most of the minor folds dip with the adjacent and less disturbed beds, hence to the southwest. The pitch of the folds is to the northwest, though in some instances in the opposite direction.

In addition to this northwest-southeast system of major and minor folds, there is evidence of another, and probably later system, more of the nature of broad, extensive flexures, whose axes seem to extend in approximately a north-south direction, nearly normal to the strike. Evidence of this may be seen in the very gradual and progressive change of strike

FIG. 15.—*Fracturing with calcite veins, Rio Yauco Series shales, northwest side of Desecheo Island*

of the shales over certain areas of considerable size. This feature is shown on the map in numerous places, notably in the area of Rio Yauco shales lying south of Añasco and north of Mayaguez. The same movements which produced these north-south flexures probably were responsible, at least to some extent, for the plunging of the overturned anticlines and synclines above noted.

Faults. Both normal and thrust faults occur in great number. Usually, evidence of faulting is to be found only in the presence of crush zones. In such cases very little can be determined as to the nature or extent of the movement. They are probably for the most part thrust faults of considerable extent. Most of the normal faults seem to be of relatively slight movements, though very numerous, and in aggregate, doubtless represent displacement to be measured in thousands of feet. While the data are insufficient to make a positive statement, observations seem to show that the normal faults more commonly cut across the general strike of the formations, and hence are to be associated with the north-south flexures previously described. The thrust faults also cut across the strike of the beds, but on the average at lower angles, and

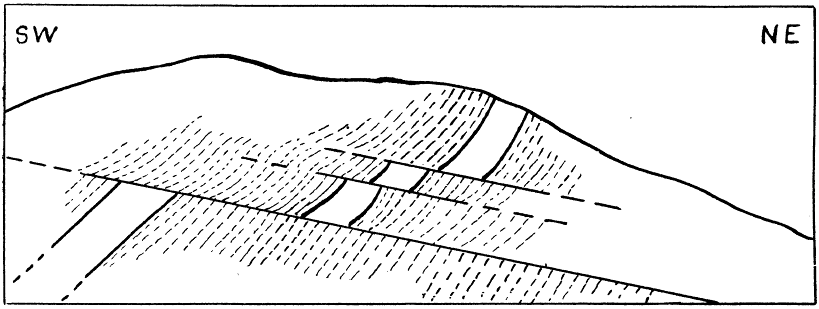

FIG. 16.—*Thrust fault in Rio Yauco shale*

K. 13.85, Mayaguez-Consumo Road. Strike of beds, N. 75° W., dip 45° S. W. Displacement, several feet.

hence are to be associated with the earlier, or mountain-building movements, which produced the intensive folding.

Except in the cases of minor faults, the amount of displacement could not be determined in any of the faults observed. Figure 12 shows a thrust fault which probably indicates a movement of some hundreds of feet. The view shows massive tuff beds almost normal to the adjacent shales, against which they have been faulted. No marked folding occurs in the vicinity, thus the discordance shown in the illustration could not have been brought about by any minor displacement. Thrust faults are well exposed on Desecheo Island, as shown in figure 14. The faults are accompanied by extensive fracturing, and the numerous joints thus produced have been filled with quartz or calcite. The extent to which the fracturing has gone is well shown in figure 15, illustrating an exposure on the northwest coast of Desecheo Island.

A minor thrust fault of special significance is exposed at K. 13.85 on the Mayaguez-Consumo Road. As shown in the illustration, figure 16, the fault plane dips at a very low angle and shows a displacement of only a few feet. It is located on the north limb of a large syncline, and is apparently a break thrust, produced during the folding. That it is not a normal fault is shown by the very slight dip of the plane. It, therefore, serves to emphasize the point previously made, that the thrust faulting was probably contemporaneous with the intensive northwest-southeast folding.

Thickness. The complexity of structure, absence of continuous outcrops, and limited time spent in the field make accurate determinations of thickness out of the question. In the section of Rio Culebrinas Series south of Moca the shales and tuffs measure over 3000 feet in thickness. This probably is near the maximum figure for this series. In the Rio Yauco Series, about 6000 feet of shales and tuffs are exposed along the Mayaguez-Las Marias Road from K. 13 to K. 19. A traverse across the series northeast from Rincon shows a total thickness of over 8000 feet. This measurement makes considerable allowance for duplication of strata by folding and faulting, and probably represents the maximum thickness of the entire Rio Yauco Series. The thickness of the Rio Blanco Series cannot be determined, owing to the massive character of the tuffs and the many intrusive bodies.

These estimates of thickness include the interbedded flows and intrusives, which, although individually small in the sections measured, doubtless make up a large portion of the total. The measurements take account of the larger folds and allow for many of the minor folds. The effect that faulting may have had in duplicating the succession of beds is, however, impossible to estimate, since the amount of movement along fault planes could in no case be determined. It should be pointed out that many faults, both thrust and normal, occur along the sections measured, and their effect has doubtless been to greatly increase the apparent thickness in each case. Nevertheless, it may be stated that the total thickness of clastic rocks exposed in the Cretaceous series of the Lares District is to be measured in thousands of feet. A conservative estimate for the entire group would be about 10,000 feet.

Age

The age of the Rio Yauco Series is Upper Cretaceous, as shown by the presence of *Radiolites,* and the same foraminifera characteristic of the Upper Certaceous beds in the Ponce District. The Rio Blanco Series is also probably Upper Cretaceous, though the presence in it of *Radiolites* is not as reliable evidence as in the case of the Rio Yauco Series, since the limestone which contains this fossil may be an in-faulted remnant from another series of rocks. The Rio Culebrinas Series is the oldest group in the Lares District, but there is no evidence to show that it is older than Upper Cretaceous in age. It has beds of lime shale which contain the same foraminifera as the Rio Yauco lime shales, but these minute organisms are hardly determinable specifically. There is no evidence of unconformity between or within the three series of the district. Mitchell has found the same to be probably true in the southward continuation of these beds in the Ponce District. There is no evidence of Eocene sediments in the Older Series of the Lares District, and likewise none in the Ponce District, as Mitchell has shown.

Correlation

The Rio Yauco Series is probably the equivalent of most of the shales in the Ponce District. Mitchell states that the Peñuelas shale is probably equivalent to the upper portion of the Rio Yauco shales. The lime shales of the Rio Yauco Series of the Lares District are lithologically similar to the Peñuelas shale, and may be equivalent. The presence of *Radiolites* cannot be used to correlate different members, since all the limestones as yet found in both the Ponce and Lares Districts carry this fossil, and have similar foraminifera. From stratigraphic and structural considerations, the following statements seem probable:

1. The Rio Yauco Series is equivalent to most of the sediments occurring in the Ponce District.
2. Other formations in the Ponce District of doubtful correlation will very likely prove to be younger than the Rio Yauco shales.
3. The Rio Culebrinas shales are older than anything in the Ponce District, but are probably not older than Upper Cretaceous in age.
4. The entire range of sediments from the lowest members of the Rio Culebrinas to the uppermost members of the Rio Yauco Series represent a continuous succession, unbroken by any unconformities or disconformities of appreciable magnitude.

Further correlation with areas of Porto Rico to the east is practically impossible at the present stage of investigation. The strike of the formations in the Coamo District, if projected, would seem to show that they pass northwestward across the northern half of the Lares District, covered by Tertiary formations. The presence of *Radiolites* in the Coamo tuff limestone is significant in showing that at least a portion of the formations exposed in the Coamo District are of Upper Cretaceous age.

Lithogenesis

The origin of the various types of igneous rocks has been pointed out in the discussion of the petrography of these rocks. The origin of the clastic rocks has likewise been referred to, but deserves further elaboration before attempting to outline the Cretaceous history of the district.

It has been noted that practically all of the clastic rocks contain material derived from volcanic sources. From the tuffs, which were entirely derived from such sources, to shales and limestone, which contain minor amounts of this material, the entire succession of beds show that they were deposited during an almost uninterrupted period of vulcanism. As Mitchell has pointed out, the massive tuffs, which show no bedding, were doubtless accumulated on land surfaces, while the shales and stratified tuffs and ashes were accumulated under water. The lime shales and black pyritic shales contain so many foraminifera that their marine origin seems highly probable. In the case of the limestones, interbedded with these shales, and carrying *Radiolites* and abundant foraminifera, their marine origin cannot be questioned. The alternation of massive unfossiliferous tuffs with shales and limestones containing marine organisms thus shows a frequent oscillation of level during deposition, in which arms of the sea frequently encroached on the land area. The sparsity of marine life, and the singularly small number of types making up the fauna, illustrate the very hazardous and unfavorable conditions for the development of living organisms. A glance at the geologic map will at once suggest, in view of the above interpretations, the significance of the predominance of massive tuffs in the eastern portion of the district. The land mass apparently lay to the east, and the invasions of the sea came from the west and southwest. The predominance of calcareous beds on Desecheo Island, and their relatively greater foraminiferal content, support this view. The greater abundance of limestone in the Ponce District to the south is also significant. The lens-like habit of the tuffs interbedded with the shales seems to indicate that rivers played an important part in the deposition of both the shales and bedded tuffs.

In regions subjected to periodic violent volcanic eruptions, we should expect the animal organisms inhabiting the adjacent sea to be killed off periodically in great numbers. Consequently, we should look for occasional strata crowded with fossil remains, with intervening beds containing exceedingly few fossils due to the rapid accumulation of clastic sediment and the scarcity of marine forms living under such continuously unfavorably conditions. This is precisely what is found in the sediments both in the Lares and Ponce Districts, as the following evidence shows:

1. The limestones of the San German type are in places crowded with the remains of *Radiolites.*

2. Certain beds of the lime shale show an abundance of foraminifera, while others show very few or none.

3. The black pyritic shale is indicative of the rapid accumulation of organic remains, chiefly foraminifera, and possibly plant matter.

4. The occasional chert beds seem to be derived from sudden and rapid accumulations of Radiolaria, and possibly other silicious organisms.

Foraminifera do not thrive in impure, sediment-laden waters. Their abundance in some of the layers of calcareous ash and lime shale containing ashy material, and the evenly banded character of these rocks, points to the following special conditions of deposition:

1. Quiet waters, free from strong currents, and presumably not very shallow.

2. Pure water, except during showers of volcanic ash, which resulted in a sudden pollution of the water, killing off of the foraminifera and other planktonic forms, and the rapid settling of both ash and shells on the quiet bottoms.

Geologic History

From the above data, including the descriptions of the various types of rock which occur in the Older Series, the conclusions regarding their age, and the interpretations of conditions under which they were formed, the following steps are given in the Cretaceous and early Tertiary history of the Lares District:

1. Pre-Cretaceous.—Unknown. The basement of the Upper Cretaceous volcanic flows and clastics has not been found in the Lares District, and probably will not be found.

2. Upper Cretaceous. Period of almost continuous volcanic eruptions of the explosive type, marked by the ejection of enormous quantities of lithic fragments and frequent showers of ash, resulting in the rapid accumulation of great thicknesses of clastic deposits. This action was accompanied throughout by lava flows of andesite and augite-andesite, and intrusives of the same material into the surrounding clastic rocks during their formation. There were frequent oscillations of level with invasions of arms of the sea covering portions of the western part of the district, and on one occasion, at least, extending as far east as Lares.

3. Late Upper Cretaceous. Final phases of vulcanism, marked by minor intrusions of magma of extreme composition, such as peridotite, now altered to serpentine. These final intrusives were accompanied by the beginnings of great orogenic movements.

4. Close of the Cretaceous. Orogenic movements, comprising extreme folding and thrust faulting, with the maximum forces applied in a northeast-southwest direction. This was probably the local phase of widespread crustal movements which outlined the present sub-sea mountain chain, the basement upon which the Antillean islands rest.

5. Close of the Cretaceous or Beginning of Eocene. Further crustal movements, involving north-south warping, normal faulting, and possibly accompanied by further uplift.

6. Eocene. Continuous erosion, and reduction to oldland surface of comparatively slight relief.

7. Early Oligocene. Renewed uplift, with dissection of the oldland surface to a region of considerable relief. Deposition of coarse gravels in valleys of torrential streams (seen southeast of Moca).

8. Middle Oligocene. The beginning of a partial submergence of the island with deposition of the San Sebastian shales in embayments along the north coast of that time. Further events are given in the discussion of the Tertiary and Pleistocene.

THE TERTIARY FORMATIONS

The most complete development of the Tertiary formations in Porto Rico is in the Lares District, and occupies the area between the Lares Road and the north coast. These formations are a structural unit (Berkey, 1915, p. 12), resting unconformably upon the highly disturbed Cretaceous rocks, and overlain unconformably by Pleistocene and Recent consolidated dune sands and beach gravels, limited to the coast line. The Tertiary beds are a series of limestones, in small part of coral origin, underlain nearly everywhere by basal shales, clays, marls, or conglomerates. The maximum thickness of the entire group is about 3800 feet, with the strata having an average dip of about 4° seaward. The range in age is from Middle Oligocene to Upper Oligocene.

Table 3 shows the subdivisions and names applied to the Tertiary formations of the north coast by previous writers and in the present paper. Hill's term Pepino Formation, although having priority over the term Arecibo of Berkey, will not be used in the present paper, because (*a*) the corals collected by Hill from his Pepino formation occur also in the

Table 3

SUBDIVISIONS OF THE TERTIARY OF THE NORTH COAST, PORTO RICO

R. T. Hill (1899 *c*, p. 15)	C. P. Berkey (1915, p. 17)	C. A. Reeds (1916, 1917)	D. R. Semmes (1916, p. 434)	B. Hubbard * (1917)	T. W. Vaughan (1919, p. 260)	C. J. Maury (1919, p. 214)	D. R. Semmes (1919, p. 55)	Subdivisions used in the Present Report †
	San Juan formation Pleistocene to Recent		San Juan limesand Recent	San Juan formation Pleistocene to Recent			San Juan consolidated dune sand Pleistocene	San Juan formation Pleistocene to Recent
	Unconformity			Unconformity			Unconformity	Disconformity
Pepino formation Miocene "At least 100 feet thick"	Arecibo formation Eocene? Oligocene Miocene? "At least 500-600 feet thick" — Quebradillas reef limestone	Arecibo formation Upper Eocene-Oligocene	Tertiary formations	Arecibo Group — Quebradillas limestone Upper Oligocene (Bowden)	"*Pepino* formation of Hill" Middle and upper Oligocene, possibly some Miocene"	Arecibo formation — Quebradillas limestone Lower Miocene (Bowden)	Arecibo formation Upper Oligocene (Bowden) "At least 500 feet thick in San Juan District"	Arecibo Group — Quebradillas limestone Upper Oligocene (Bowden) 700-875 feet
						?	?	
				Los Puertos limestone		Aguadilla limestone Upper Oligocene		Los Puertos limestone Upper Oligocene 550-1000 feet
				Cibao limestone Lower Oligocene		?		Cibao limestone Middle Oligocene 250-1000 feet
				Lares limestone Lower Oligocene		Lares limestone Upper Oligocene		Lares formation Middle Oligocene 350-1275 feet
Greensand marl Eocene or Oligocene	San Sebastian shale Probably Eocene	Collazo shale Upper Eocene		San Sebastian shale Lower Oligocene or Upper Eocene	?	Rio Collazo shales Middle Oligocene	San Sebastian shale Lower Oligocene	San Sebastian shale Middle Oligocene Max. 700 feet
Lignitic shale and clay Eocene								
	Unconformity			Unconformity			Unconformity	Unconformity
Cretaceous	Older Series Cretaceous		Older Series	Older Series			Older Series	Older Series Upper Cretaceous

* Proposed subdivisions, based on field work in 1916, and presented before the Geology Section, N. Y. Academy Sciences, in 1917.

† Same as were made by the writer in 1917. The ages assigned to the formations have been modified, as the result of a study of the fossils made during the summer of 1919.

Upper San Sebastian shale, and (*b*) *Pepino* refers to the lithologic and topographic character of the formation, and is therefore an undesirable term.

Stratigraphy

THE SAN SEBASTIAN SHALE

The existence of a basal shale was first pointed out by Hill (1899 *c*), who did not apply a formational name to it, but merely mentioned its position relative to the Pepino Formation. Berkey (1915) was the first to suggest a formational name (San Sebastian shale). Subsequently, Reeds gave the name Collazo shale, because of the excellent exposures and numerous fossils found at Callazo Falls, east of San Sebastian. Following Reeds, Miss Maury has used the name Rio Collazo Shales. In the present paper the name suggested by Berkey will be used, because (*a*) Berkey's name has priority, and (*b*) it is a more appropriate name than Collazo. A glance at the cross-section (Plate I) or columnar sections (Plate II) will show that the maximum development of this basal shale is near San Sebastian.

The columnar sections (Plate II) show the various types of material of which the formation is made. Although it is predominantly a shale, it consists in large part of dark bluish clay carrying seams of lignite with pyrite and marcasite, conglomerate and pebble beds (in most places unconsolidated), red calcareous sand or lime sand, green marl, and impure limestone. Many of the lignitic clays contain fossil leaves and fresh or brackish water molluscs. Sharks' teeth and vertebrate bones occur in many of the beds. The marls and red lime sands contain marine fossils, and as shown in the Collazo section (Plate II) alternate with the brackish or fresh water beds. The marls at the top of the formation carry an abundance of large coral heads. Limestone (argillaceous) is the only material in the San Sebastian formation which is firmly consolidated. In other strata, the lower the content of lime the less consolidated the material. Most of the "conglomerates," which predominate in the basal part of the formation, are merely loose gravels or pebble beds. Ground water has easy access in all strata except the dark blue clays, and it has leached out large quantities of calcium carbonate. Most of the fossil molluscs are found as molds with but small portions of the shell remaining.

As previously noted, the San Sebastian shale is thickest in the vicinity of San Sebastian. From this point it pinches out on the west and thins to 100 feet at the east end of the Lares District. Farther east, in the

Rio Arecibo canyon, it is absent (Berkey, 1915, p. 16). Thus, as compared with overlying formations, the San Sebastian is of local occurrence. That its relationship with the Cretaceous rocks is unconformable has been shown by Berkey, and is too evident to require further demonstration. The actual basal contact cannot be seen in any of the localities visited, but exposures close to the contact can be seen in several places, the most significant of which are in the immediate vicinity of Lares. From a survey of these exposures, the following features are to be noted:

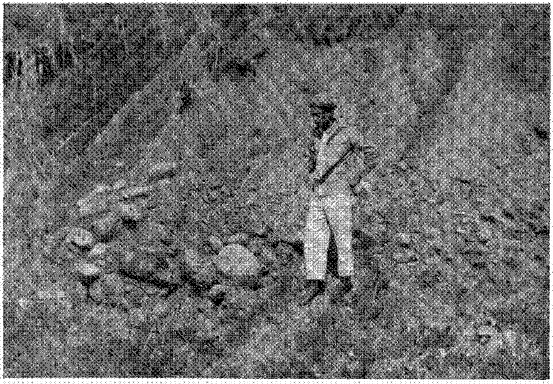

FIG. 17.—*Boulder clay and coarse gravel at base of the Tertiary*

K. 8.9, Lares Road, near Moca. This deposit lies unconformably on the Cretaceous rocks, which in this locality consist of shales, ash, and augite-andesite porphyry.

1. The surface upon which the San Sebastian shale was deposited was one of considerable relief (probably two or three hundred feet).

2. The San Sebastian rests not upon fresh, cleanly eroded Cretaceous rock, but upon badly decayed rock or residual soil. Portions of the basal San Sebastian at Lares are made up of reworked residual soil, differing in no respects from modern residual soil of the interior mountains, except that it contains, here and there, the molds of Tertiary fossils.

At K. 8.9, Lares Road, there is an interesting deposit of boulder clay and coarse gravel (Fig. 17) resembling glacial till in its general appearance. This material is unconsolidated, and composed of boulders of Cretaceous rocks imbedded in a kaolinized matrix. It contains absolutely no material which could have been derived from any of the Tertiary formations. To the northwest this deposit pinches out and is replaced by basal Tertiary pebble beds and shale (Lares formation) near Moca. These large boulders probably mark the channel of an Eocene early Oligocene river. Such coarse gravel would probably not be common in channels of old streams flowing on a peneplane. On the other hand, such deposits should be common in a region of considerable relief, such as is shown by the relationship of the basal Tertiary at Lares. At the top of the San Sebastian shale, the contact with the overlying Lares limestone is a gradational one. The change from marl to limestone by an alter-

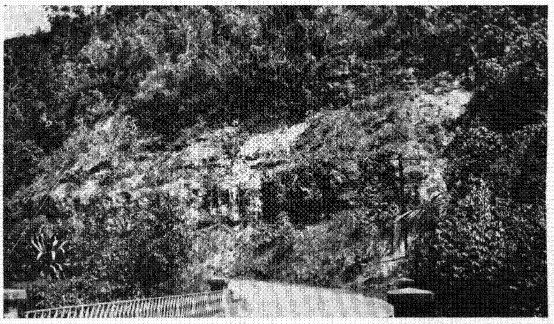

FIG. 18.—*Interfingering or alternation of limestone and marl, marking gradational contact of San Sebastian shale and Lares limestone*

Bridge at Collazo Falls, Lares Road. The more resistant beds of Lares limestone are seen just above the road and again near the top of the view.

nation (interfingering) of strata of the two types or rock is shown in figure 18.

From the sections (Plate II) it will be noted that pebble beds and lignitic clays predominate in the lower part of the San Sebastian shale. These individual beds, however, cannot be correlated in the different sections. In the section at Lares, the upper member is a red lime sand contaning *Pecten laresense*. This bed is traceable as far east as the Camuy River, but cannot be correlated with certainty with anything in sections to the west. The most continuous member in the formation is the zone of green marls with abundant corals, which forms the top of the San Sebastian formation at Collazo. This same zone, with the same corals, is found at the top of the San Sebastian in the Hato arriba section, west of San Sebastian. Some of the same corals occur in the basal portion of the Lares limestone in the cuesta just north of Lares, hence this portion of the Lares may possibly represent a limestone facies equivalent to the upper San Sebastian marl beds. In the Collazo section, immediately below this coral zone (zone C of Vaughan, 1919), is a zone of marl containing *Clementia dariena* and *Turritella tornata.* This zone likewise underlies the coral zone in the Hato arriba section, but the rock is much more calcareous than the same horizon at Collazo. To summarize, there are only three zones, of any considerable continuity in the San Sebastian shale:

1. Upper Zone (zone C of Vaughan). Marls with abundant corals, grading eastward into limestone and red fossiliferous lime sand.
2. The Middle Zone. Marls and other types of material marked by abundance of *Clementia dariena* and *Turritella tornata* var. *portoricoensis.*
3. Lower Zone. Predominantly lignitic clays and gravel beds, with some marine marl and limestone, the latter containing numerous tests of a small *Scutella* (like *S. mississippiensis*). The extremely local nature of most of the beds and fossil occurrences makes it inadvisable to attempt a finer subdivision of the formation.

THE LARES FORMATION

The term Lares Formation was first proposed by the writer (see Table 3) for the massive limestone overlying the San Sebastian shale, and most conspicuous north of the town of Lares, where it forms the cuesta and an extensive area of haystack or *pepino* hills. The distribution and boundaries of the formation were definitely shown in a paper presented before the New York Academy of Sciences in 1917. In a paper on the Porto Rican Tertiary, Dr. Maury (1919) uses the term Lares limestone for beds overlying the San Sebastian shale, but no distribution or stratigraphic limits are given. The chief horizon marker of the formation, according to Maury, is a large cerite shell (*Campanile* (*Portoricia*) *larica* Maury). This shell was not found by the writer in any of the numerous localities studied, but a very similar shell (*Cerithium* (*Campanile*) *collazum* Hubbard) was found in abundance in the San Sebastian shale, and sparingly in the lower part of the Lares formation. It should be stated in this connection that these shells are poorly preserved, and that the above two designations may represent the same species.

In the type locality, north of Lares, the Lares formation is a massive,

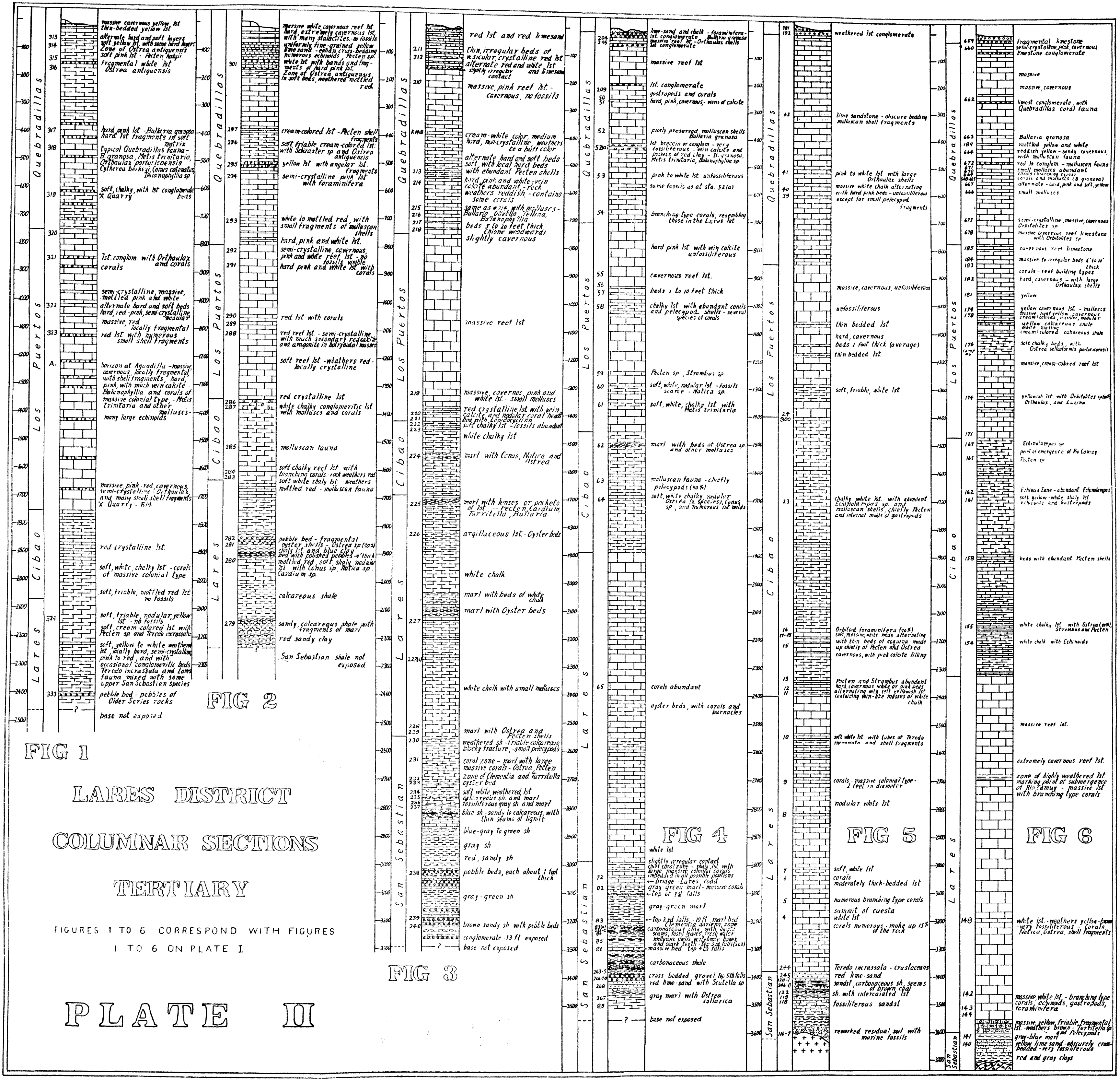
FIG 1
FIG 2
FIG 3
FIG 4
FIG 5
FIG 6
Quebradillas
Los Puertos
Cibao
Lares
San Sebastian
LARES DISTRICT
COLUMNAR SECTIONS
TERTIARY
FIGURES 1 TO 6 CORRESPOND WITH FIGURES 1 TO 6 ON PLATE I
PLATE II

cavernous, white limestone, with scattered portions of thin bedded, hard, or chalky limestone. As a whole, the Lares limestone is of shell and foraminiferal origin, although many massive, reef-like portions are made up in large part of corals. The coral limestone facies is so intimately mixed with the well bedded portions that it is not possible to estimate in what proportion the formation is of coral origin. However, the limestone should be classed as a reef formation. It shows the lateral gradation from stratified to massive structure, characteristic of reef formations in general. The massive portions are either largely of coral origin or else made up chiefly of foraminifera (*Lepidocyclina* and others) and microscopic shell fragments. In most localities, this massive rock is hard, compact, and partially crystalline, and extremely cavernous. The thin bedded portions are chiefly chalky and soft, or alternate hard and soft layers, many of which are yellowish from limonite stains. These strata are not true chalk, but finely ground limestone, practically a rock flour, derived probably from the adjacent reef structures. Most of the molluscan shells occur in these well stratified portions of the formation.

So far the description applies to the eastern part of the district. From the Rio Guajataca westward there is a change in facies. The white limestone, with its massive exposures and *pepino* hills, grades into a softer, more argillaceous limestone. The topographic expression of this difference in character of the rock is brought out in the geologic map. In the Hato arriba section, west of San Sebastian, the formation consists of alternating beds of white chalky limestone, argillaceous limestone, and marls with abundant oyster shells, (*O. virginica*). Still farther west, in the vicinity of Moca, the San Sebastian shale is missing, and the Lares formation is the basal member. It might easily be mistaken for the San Sebastian shale in this locality, because of its lithologic similarity, as shown in the columnar section (Plate II). The presence of typical Lares fossils, such as *Cardium cinderellæ alternatum* and *Pecten grabaui,* and the absence of nearly all of the most characteristic San Sebastian species, is sufficient evidence to show that these basal beds are equivalent to the Lares limestone of the eastern part of the district. South of Aguadilla, the formation is largely buried by the recent playa deposits of the Rio Culebrinas. However, the Lares formation occurs southwest of the Rio Culebrinas in a narrow coastal belt extending to Pt. Jiguero. Throughout this area the rock is a limestone, grading from soft white or yellowish chalky material to a hard, semi-crystalline limestone, predominantly white, but locally red in color. At the base of the formation, a small thickness of shale or gravel beds is present in most of the localities. At

Pt. Jiguero, however, the limestone apparently rests directly upon the upturned Cretaceous beds, though the actual contact is not exposed to view.

The contact with the San Sebastian shale has already been described as conformable. Similarly the contact with the overlying Cibao limestone is a conformable, somewhat gradational contact, though very definitely marked topographically. There is no evidence of a discordance of dip, of an erosion interval, or of a faunal hiatus between the Lares formation and Ciboa limestone. The same was shown to be true of the contact with the San Sebastian shale. The position of the Lares as basal formation in the west shows a progressive overlap during a gradual submergence of the oldland. No other interpretation of the above data is possible.

THE CIBAO LIMESTONE

This name is taken from the barrio of Cibao, north of Lares, where the formation is best developed. In the type locality (barrio of Cibao), the Cibao is essentially a soft, white, chalky limestone with an abundant but poorly preserved molluscan fauna. Interbedded with this white chalky limestone are:

1. Beds of marl with abundant oyster shells (*O. sellæformis portoricoensis*).
2. Beds of hard pink or white limestone with *Lepidocyclina* and *Orbitolites*.

The predominant softness of the material explains the rolling prairie lowland developed on this belt. The high content of argillaceous material in the rock is well shown by the extensive covering of red and black residual clay soils.

From its maximum thickness in the barrio of Cibao, the formation thins westward, and south of Aguadilla it is only 300 feet thick. The character of the rock is different in this locality, the white chalky facies containing a greater abundance of hard intercalated beds, many of which are red in color. No evidence was found of an unconformity, disconformity or faunal hiatus between the Cibao and the overlying formation. It is not possible to distinguish zones within the Cibao limestone which continue laterally throughout the formation. A white chalky zone, stratigraphically near the top, contains an abundance of an echinoid (*Echinolampus* resembling *E. aldrichi*). This echinoid zone can be traced from the Rio Camuy westward for at least six miles.

THE LOS PUERTOS LIMESTONE

The name is taken from the barrio of Los Puertos, north of Lares, where the formation is best exposed.

FIG. 19.—*Los Puertos limestone, massive reef type*

Exposed in vertical cliff, nearly 150 feet high, and in which there is very little bedding. Rio Camuy Canyon, five miles south of Hatillo.

The rock is predominantly a series of massive, reef-like beds, alternating with thin bedded chalky strata. It is a reef formation essentially like the Lares limestone, but with *pepino* hills developed on a greater scale with greater relief. Excellent exposures of this formation may be seen in the canyons of the Rio Camuy and Rio Guajataca (Fig. 19). The massive reef-like portions are hard, semi-crystalline, and very cavernous. The prevailing color is pink. Fossils are not well preserved and are chiefly small forms, including foraminifera (*Orbitolites* and *Lepidocyclina*). The thin bedded portions of the formation are soft chalky strata, alternating with harder strata. The soft layers are in many places stained with limonite, giving a varied coloring to the canyon walls. These thin strata are in some localities intercalated with other soft chalky beds containing angular fragments of hard reef-type limestone. The chalky beds are usually deeply weathered and contain very few fossils preserved well enough to recognize. Corals occur in the massive zones, but apparently for only a fraction of one percent of the entire formation. Foraminifera and molluscs are the chief contributors.

The Los Puertos limestone is entirely conformable with the overlying Quebradillas limestone, and shows no faunal hiatus. No zones, either fossil or lithologic, can be established in the Los Puertos limestone. Except for the variations above noted, the formation is lithologically a unit, just as it is a physiographic unit, with its distinctive belt of *pepino* hills. The columnar sections (Plate II) illustrate the differences found. In the west coast section, the formation contains a great deal of the hard, red, semi-crystalline limestone which is characteristic of portions of all the limestone formations of the Arecibo group in this part of the district. It will be noted (Plates I and II) that the Los Puertos limestone, while variable in thickness, does not thin to the west, as do the underlying formations.

THE QUEBRADILLAS LIMESTONE

As shown in Table 3, the name was first proposed by Berkey. It is named after the town of Quebradillas on the north coast, where the best exposures of the formation are to be found. The type fossil locality is near Quebradillas at the mouth of the Rio Quajataca (Fig. 20). This formation consists for the most part of a hard cavernous reef limestone, which has a flinty appearance. It is made up chiefly of minute shell fragments (molluscan and foraminiferal) and may be in part chemically deposted lime carbonate. A few corals occur, but these are not of the reef building type. In places, the formation is well bedded, with the hard flinty limestone alternating with soft white chalky limestone, or with layers of limestone breccia. Fossils occur in all of the beds, but are never found abundantly except in small areas or "pockets." These "pockets" are numerous, and do not all contain the same species. Some of them are extremely crowded with molluscan shells. Almost invariably the shell structures have been dissolved away, leaving only the external and internal molds. This characteristic, together with the general aspect of the rock, is so typical of the Quebradillas limestone that it affords a reliable means of recognizing the formation in the field. A typical exposure of the hard fossiliferous beds is shown in figure 20, which also illustrates the massive character. Other phases of the forma-

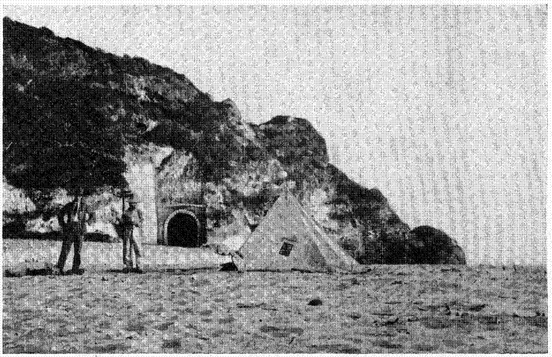

FIG. 20.—*Quebradillas limestone at the type fossil locality*

Showing sea cliffs and east entrance of American railroad tunnel. Mouth of the Rio Guajataca, west of Quebradillas.

tion of local extent occur at Isabela and on Pt. Borinquen. The sea cliffs at Isabela are made up in large part of a thin bedded red limestone, alternating with thin beds of indurated red lime sand, the entire exposure totalling 150 feet thick. The rock is largely fragmental in origin, relatively free from argillaceous matter, like all the rest of the formation, and almost unfossiliferous. On Pt. Borinquen, in the sea cliffs northeast of the lighthouse, is a 90-foot exposnre of a white to yellowish chalky limestone in which are interbedded vast numbers of large oyster shells (*O. antiguensis*), well shown in figure 21. This zone of *O. antiguensis* can be traced as far east as Isabela, and apparently occurs in the San Juan District.

The Quebradillas limestone is conformable upon the underlying Los Puertos limestone and the boundary between the two is somewhat arbitrary. The Quebradillas is much more uniform in thickness than the lower formations (see sections, Plates I and II). It is the most wide-

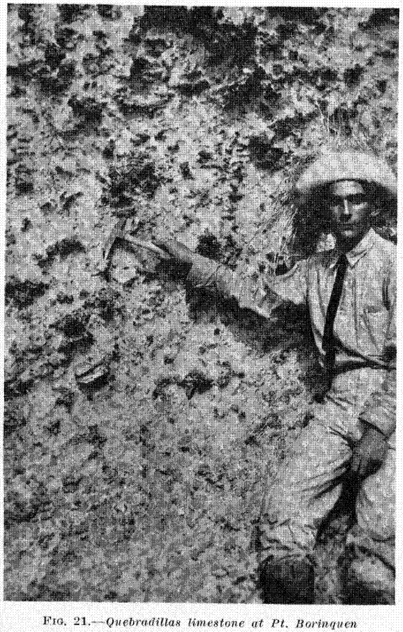

FIG. 21.—*Quebradillas limestone at Pt. Borinquen*

Showing shells of *Ostrea antiquensis* Brown imbedded in a soft, chalky limestone. The total thickness exposed is ninety feet, most of which is made up in large part of these giant oysters.

spread Tertiary formation in Porto Rico, and it marks the final deposition of a transgressing sea at the period of maximum submergence. The Quebradillas limestone rests upon Cretaceous rocks in the San Juan District and on Vieques Island and shows clear evidence of a progressive overlap.

Like the lower formations, the Quebradillas limestone is not readily divisible into zones or horizons, as an inspection of the columnar sections (Plate II) will show. Lithologically, there can be no subdivision. From a study of the distribution of the fossils, however, two zones of rather doubtful validity may be distinguished:

1. Upper Zone, including uppermost 200 to 300 feet, characterized by extremely abundant molluscan shells (Bowden fauna) and *O. antiguensis*.
2. Lower Zone, marked by relative scarcity of fossils and presence of *Orbitolites* mixed with Bowden fossils.

SUMMARY OF FORMATIONS

Table 4 (page 50) gives briefly the general make-up of the Tertiary of the Lares District, with a few of the important features by which the different formations are recognized.

STRUCTURE

It has already been pointed out that the Tertiary formations are a structural unit. There are no breaks anywhere in the series. Although there is no discordance of dip denoting an unconformity, it will be noticed from the dips recorded on the cross-sections (Plate I, Figs. 3-6) that those of the San Sebastian shale are somewhat erratic and in most cases at higher angles than those of the overlying formations. The sections further show that there is, on the whole, a gradual decrease in dip as one passes from the base to the top of the series. Thus, while the average dip of all formations is 4°, the San Sebastian averages over 6° and the Quebradillas between 2° and 3°. The erratic dips recorded in the San Sebastian shale are due in most cases to cross-bedding which cannot always be distinguished as such in the field. Frequently abnormal dips are noted in the limestone formations, but these were almost invariably found to be due to slumping resulting from underground solution. Such abnormal dips are in every case very local in extent. From the San Juan District west to Lares, the normal dip of the beds is to the north, but from Lares to the west coast it is to the northwest. The nearer the west coast the more westerly the direction of dip. The significance of this will be takn up later in discussing the Tertiary history.

Except for the gentle warping and local slumping above noted, no faults, folds or other structural features were observed anywhere in the Tertiary formations of the district. There are no dikes or other evidences of igneous action in any of the Tertiary rocks, hence all volcanic activity had died out before middle Oligocene time.

TABLE 4

TERTIARY FORMATIONS OF THE LARES DISTRICT

Group	Formations	Characteristic Index Fossils	Physiographic Expression	Lithologic Characteristics	Range in Thickness
Arecibo Group	Quebradillas limestone Upper Oligocene	*Metis trinitaria* *Orthaulax portoricoensis* *Ostrea antiguensis* *Bullaria granosa* *Chione woodwardi*	Plateau, broad valleys, low rolling hills, small *pepino* hills in isolated groups or in ridges.	Hard, pink, semi-crystalline, cavernous to soft, chalky limestones, low in argillaceous material. Fossils characteristically in isolated "pockets."	700 to 875 feet
Arecibo Group	Los Puertos limestone Upper Oligocene	Same as for Quebradillas limestone except *O. antiguensis*	Highest *pepino* hills in Porto Rico	Massive, hard, white or pink, semi-crystalline, very cavernous limestone; in many places thin-bedded, with alternate hard and soft layers. Fossils scarce.	550 to 1000 feet
Arecibo Group	Cibao limestone Middle Oligocene	*Echinolampas* sp. like *E. aldrichi*	Rolling prairie, moderate relief, low cuestas, sink holes, no *pepino* hills.	Soft, white or yellow, chalky, or argillaceous limestone. Fossils abundant but poorly preserved.	250 to 1000 feet
Arecibo Group	Lares formation Middle Oligocene	*Cardium cinderellæ alternatum* *Ostrea virginica*	*Pepino* hills in east, dissected cuesta in west.	Massive reef type limestone, locally thin-bedded and chalky. Limestone grades into shales, clays, and gravels in the west.	350 to 1275 feet
	San Sebastian shale Middle Oligocene	*Corbula collazica* *Ostrea collazica* *Cerithium (Campanile) collazum* *Clementia dariena*	Dissected cuesta	Green marl, lime sand (marine), fluviatile gravels, lignitic blue clays, shaly limestone, and carbonaceous shale.	100 to 700 feet

Age and Correlation

The various speculations and conclusions regarding the age of the north coast Tertiary formations has been shown in Table 3. The diversity of opinion is explained by the fact that not until the summer of 1919 has a detailed study of the fossils been made. A large collection of fossils made by Dr. C. A. Reeds in 1914 was described by Maury (1919), and her conclusions regarding the age of the formations are given in Table 3. During the survey of the Lares District in 1916, the writer made a very large collection of Tertiary fossils, all of which were recorded as accurately as possible as to locality and stratigraphic position. These fossils were studied during the summer of 1919, and the final conclusions regarding the age of the formations based on this study are shown in Table 3. It will be noted that the writer's conclusions agree with those of Dr. Maury with the exception of the Miocene or Oligocene age of the Quebradillas limestone. Dr. Semmes and the writer recognized in 1917 that the Quebradillas limestone is approximately equivalent in age to the Bowden marl of Jamaica. The remaining point at issue is whether the Bowden is Upper Oligocene or Lower Miocene. Evidence will be presented to show that it is Upper Oligocene.

About nine-tenths of all the fossils collected are molluscs.[3] Of these, 140 species or varieties have been described or recorded by the writer (Hubbard, 1921). A study of these fossils by horizons brings out some interesting results. In figure 22, the stratigraphic range of the fauna of each formation is shown graphically, the ordinate, or height of the curve at each formational horizon from left to right, denoting the total number of species of the fauna appearing in that horizon. Thus the curve of the Los Puertos fauna shows that a total of 17 species were recorded from the Los Puertos limestone. Of these, only 1 was present in the San Sebastian shale, and about 13 survived in the Upper Quebradillas limestone. These faunal curves illustrate the following facts:

1. All the faunas are transitional. There is no hiatus anywhere in the series. This corroborates the stratigraphic evidence.

2. The faunas of the San Sebastian shale, Lares formation, and Quebradillas limestone are somewhat distinctive. The faunas of the other two formations are mixed or transitional.

3. The San Sebastian fauna is almost wholly distinct from the Quebradillas fauna, and had almost died out in this region at the close of Middle Oligocene (Cibao) time.

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[3] Wherever the term "fauna" is used in the present paper it applies to the molluscan element, except where noted otherwise.

4. The Lares fauna contains three elements: (*a*) Species limited to the Lares formation, about 40 percent of the total. (*b*) Species left over from the San Sebastian. (*c*) A few species typical of the Quebradillas, marking the beginning of the invasion of the Bowden fauna.

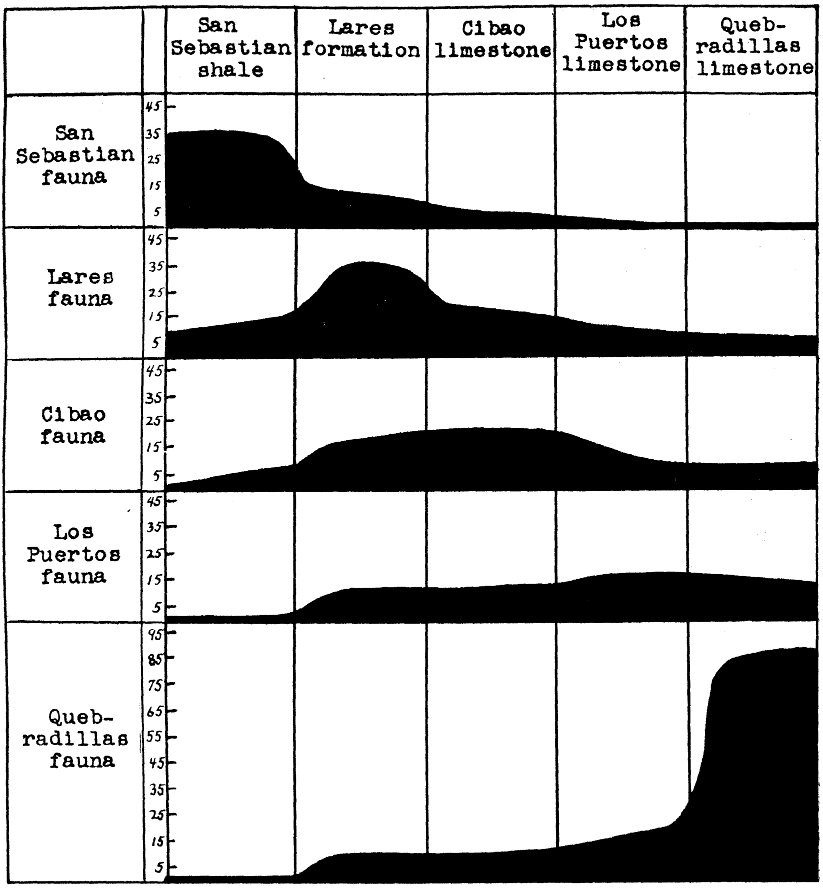

FIG. 22.—*Graphic representation of the range of the Tertiary faunas*

The figures at the left show the number of species.

5. The Cibao fauna has more in common with the Lares than with the Los Puertos, and hence the Cibao limestone should be grouped with the two lower formations in the Middle Oligocene.

6. The Los Puertos fauna is most like the Quebradillas fauna, and properly belongs in the Upper Oligocene. It marks a further increase of the invading Bowden species.

7. In general, the invasion of the region by new species was a more sudden process than the decline of the species already established. The only exception to this is the early appearance and gradual increase in number of a portion of the Bowden (or Quebradillas) fauna. The appearance of the bulk of the Bowden fauna, however, was relatively sudden. The term Bowden fauna, as used here, includes that characteristic group of molluscan types common to the Bowden marl of Jamaica and the Aphera-Sconsia formations of Santo Domingo.

8. It should be pointed out that a further collection and determination of species from these formations would undoubtedly alter the curves given above. Owing to the poor state of preservation of fossils in the Cibao and Los Puertos limestones, only a small percentage of their faunas could be determined and recorded. Further work in the Los Puertos limestone will probably increase the number of known Quebradillas (or Bowden) species in that formation, and show that the appearance of the Quebradillas fauna was not so sudden as the curve indicates.

9. The decline of the San Sebastian fauna was due to the change in bionomic conditions. Many of the San Sebastian species are brackish water forms, none of which survived the change to pure marine conditions, but some of which survived through Lares time. The latter are found chiefly in the western part of the district, where the Lares is to a large extent a brackish water or near shore deposit.

THE SAN SEBASTIAN FAUNA

The following is a list of the molluscs found in the San Sebastian shale and described by the writer (Hubbard, 1921). Those forms which do not occur above the San Sebastian shale are indicated by an asterisk:

* *Pecten* (*Pecten*) *laresense* n. sp.
* *Pecten* (*Chlamys*) *collazoensis* n. sp.
* *Pecten* (*Chlamys*) *portoricoensis* n. sp.
Pecten (*Chlamys*) *portoricoensis* var. *reticulatis*.
Pecten (*Chlamys*) *portoricoensis* var. *grandis*.
* *Pecten* (*Plagioctenium*) *rabelli* n. sp.
* *Amusium papyraceum* Gabb.
* *Amusium mauryi* n. sp.
* *Amusium* (*Propeamusium*) *hollicki* Maury.
Spondylus bostrychites Guppy.
Spondylus gumanomacon B. and P.
Ostrea collazica Maury.
* *Arca dariensis* B. and P.
* *Arca* sp. indet. (n. sp.).
Arca (*Scapharca*) *collazica* Maury.

* *Glycimeris collazoensis* n. sp.
* *Lucina collazoensis* n. sp.
* *Phacoides* (*Pseudomiltha*) *laresensis* n. sp.
* *Clementia dariena* Conrad.
Pitaria (*Hyphantosoma*) *carbasea* Guppy.
* *Solen* (*Plectosolen*) *collazoensis.*
Corbula collazica Maury.
Teredo incrassata Gabb.
Dentalium sp. indet.
* *Neritina* (*chipolana* var.?) *collazoensis* n. sp.
* *Crucibulum* (*Dispotaea*) *collazum* n. sp.
* *Natica* (*Ampulina?*) *collazoensis* n. sp.
* *Epitonium* (*Cirsotrema*) *collazoensis* n. sp.
Turritella tornata var. *portoricoensis* n. var.
* *Turritella planigyrata* Guppy.
* *Turritella mitchelli* n. sp.
* *Petaloconchus? collazoensis* n. sp.
Cerithium (*Campanile*) *collazum* n. sp.
* *Cypraea sancti-sebastiani* Maury.
* *Cassis* sp. indet.
* *Turbinella chipolana* var. *precursor* n. var.
Bullaria paupercula Sowerby

This list brings out the following important facts:

1. A large part of the fauna consists of new species or new varieties.

2. There are many brackish water and near shore forms. Among these are *Neritina, Ampulina, Cerithium* (*Campanile*) and a large number of pelecypods of fresh or brackish water type, most of which are specifically indeterminate and not listed above.

The San Sebastian fauna as a whole is unique among the Antillean Tertiary faunas so far described. It has, however, certain elements showing relationship with other faunas.

The fauna has a very strong resemblance to the Gatun (Upper Oligocene). In most cases, however, the species are similar, but not identical. It seems probable that a portion of the Gatun fauna was derived from the San Sebastian fauna. The following is a list of the San Sebastian species with their Gatun analogues:

San Sebastian.	Gatun.
1. *Glycimeris collazoensis* n. sp.	*Glycimesis gatunensis* Toula.
2. *Lucina collazoensis* n. sp.	*Lucina* sp., an undescribed shell in the Kemp collection, at Columbia University.
3. *Natica* (*Ampulina*) *collazoensis* n. sp.	*Natica* sp. indet. B. and P.
4. *Turritella planigyrata* Guppy.	*Turritella gatunensis* Conr.

5. *Turritella mitchelli* n. sp.	*Turritella altilira* Conr.
6. *Spondylus gumanomocon* B. and P.	*Spondylus scotti* B. and P.
7. *Amusium mauryi* n. sp.	*Amusium luna* B. and P.
8. *Arca dariensis* B. and P.	*Arca dariensis* B. and P.
9. *Clementia dariena* Conrad.	*Clementia dariena* Conr.

There are many forms showing a general Flint River aspect. Many of the indeterminate fossils found in the San Sebastian, and not listed or described in the present report, show that the fauna resembles the Flint River Oligocene fauna more closely than the species described would indicate. The two most notable Flint River types are:

San Sebastian.	Flint River, Ga.
1. *Turritella mitchelli* n. sp.	*Turitella halensis* Dall.
2. *Cerithium (Campanile) collazum* n. sp.	*Cerithium halensis* Dall.

There is a fairly large representation of Bowden and Aphera-Sconsia species, which migrated from Porto Rico before Bowden time, since they do not occur in the Quebradillas fauna. These are:

San Sebastian Shale.	Other Occurrences.
1. *Amusium papyraceum* Gabb.	St. Domingo, Bowden.
2. *Spondylus bostrychites* Guppy.	St. Domingo, Bowden, Tampa, Chipola, Anguilla.
3. *Spondylus gumanomocon* B. and P.	St. Domingo.
4. *Pitaria carbasea* Guppy.	St. Domingo, Bowden.
5. *Turritella tornata* var.	St. Domingo (type), Cumana.
6. *Turritella planigyrata* Guppy.	St. Domingo, Caroni Ser., Gatun.

Chipolan.

1. *Turbinella chipolana* var. *precursor* n. var.
2. *Neritina (Chipolana* var.?) *collazoensis* n. sp.

The variety of *T. chipolana* is more primitive than the Chipolan shell, and hence supports the evidence that the San Sebastian shale is older than the Chipola formation.

The Eocene aspect is only superficial, and there are actually few fossils closely related to American Eocene species. *Solen (Plectosolen) collazoensis* is strongly suggestive of Eocene species, such as *S. plagiaulax* Cossmann, *S. laversinensis* Lef. and Wat., and *S. obliquus* Sowerby, all from the Paris Basin. *Corbula collazica* Maury and *Ostrea collazica* Maury (especially the small variety with regular, divaricate ribs) might be considered to have an Eocene aspect. *Cerithium (Campanile) collazum* resembles some of the large Cerite shells from the Paris Basin Eocene, but is really much closer to the Flint River Oligocene forms, as previously pointed out.

The possible European connections of *Solen collazoensis* and *Cerithium collazum* have been referred to. One of the most interesting shells found in the San Sebastian shale is a *Cirsotrema,* described as *Epitonium* (*Cirsotrema*) *collazoensis* n. sp. Apparently, its nearest relatives are found in the Paris Basin. It is closest to *C. subspinosum* (Grat.) of the Aquitanian and *C. bourgeoisi* de Boury of the Helvetian. In Europe, the genus *Cirsotrema* ranges from the Eocene to the Pliocene, but those of the peculiar type represented by the above-named species are limited to the later Tertiary, and are particularly characteristic of the Aquitanian and Helvetian of the Paris Basin region.

In the discussion of the stratigraphy, it was noted that the San Sebastian shale is divisible into three zones:

1. Upper or Coral Zone (Zone C of Vaughan), 150′–200′.
2. Middle or *Clementia dariena* Zone, 50′.
3. Lower Zone, lignitic clays and gravels.

The corals are confined to the Upper Zone, and many of these same corals are found in the lower part of the Lares limestone. Vaughan (1919) lists the following species from the *Pepino* Formation, giving the other occurrences of each species:

1. *Astrocoenia portoricensis* Vaughan, Antigua, and Canal Zone.
2. *Orbicella costata* (Duncan), Antigua, Anguilla, Canal Zone.
3. *Antiguastrea cellulosa* (Duncan), Antigua, Florida, Georgia, etc.
4. *Meandra portoricensis* Vaughan.
5. *Leptoseris portoricensis* Vaughan.
6. *Pironastrea anguillensis* Vaughan, Anguilla.
7. *Siderastrea conferta* (Duncan), Antigua, Canal Zone, Anguilla.
8. *Cyathomorpha antiguensis* (Duncan), Antigua, Cuba, Mexico.
9. *Cyathomorpha tenuis* (Duncan), Antigua, Cuba.
10. *Diploastrea crassolamellata* (Duncan), Antigua, Cuba, Georgia.
11. *Astreopora portoricensis* Vaughan.
12. *Goniopora portoricensis* Vaughan, Antigua.

These corals are from the collections made by R. T. Hill, and a few collected by the writer. They are probably all from Zone C or Upper San Sebastian shale, with possibly a few from the basal Lares limestone. Vaughan points out that 8 of the 12 species occur in the Middle Oligocene of Antigua, and he concludes that this portion of the *Pepino* Formation is of Middle Oligocene age.

At Collazo, near the base of the San Sebastian shale, occurs a small echinoid *Scutella* resembling *S. mississippiensis* Twitchell of the Claiborne, but apparently a new species. While it resembles the Eocene species superficially, it also resembles some of the small *Scutellas* from the Pacific coast Miocene, and hence does not indicate an early Tertiary age for the basal portions of the San Sebastian shale.

The following foraminifera were found in the San Sebastian shale:

1. *Orbitolites* cf. *americana* Cushman, Zones 2 and 3.
2. *Polystomella* sp., Zone 3.
3. *Lepidocyclina* (Several species), Zones 2 and 3.

Of these, the first is by far the most abundant, and is found in all of the Tertiary formations of the Lares District. It is very similar in size and structure to *O. americana* Cushman, from the Culebra and Emperador formations of the Canal Zone. *Lepidocyclina* is also abundant. On the whole, these foraminifera indicate the Oligocene age of the San Sebastian shale, but they will require further study before anything more definite can be said.

Conclusion. The corals listed by Vaughan are undoubtedly conclusive evidence of the Antiguan, or Middle Oligocene age of the San Sebastian shale. The evidence of the other kinds of fossils is not so conclusive, but does not disagree with the evidence of the corals. The molluscan fauna, while somewhat mixed in its aspect, shows that the San Sebastian shale cannot be as old as Eocene. It is more nearly similar to the recognized Upper Oligocene than to the Lower Oligocene faunas.

THE LARES FAUNA

The following is a list of the molluscan fossils found in the Lares formation:[4]

Pecten (*Chlamys*) *portoricoensis* n. sp.
Pecten (*Chlamys*) *portoricoensis* var. *reticulatis*.
Pecten (*Chlamys*) *portoricoensis* var. *grandis*.
* *Pecten* (*Chlamys*) *grabaui* n. sp.
* *Pecten* (*Chlamys*) *grabaui* var. *aguadensis*.
Pecten (*Chlamys*) *grabaui* var. *hatoensis*.
Pecten (*Chlamys*) *grabaui* var. *guayabensis*.
* *Pecten* (*Aequipecten*) *lobecki* n. sp.
* *Pecten* (*Plagioctenium*) *cercadica* Maury.
Ostrea haitensis Sowerby.
Ostrea sellaeformis var. *portoricoensis* n. var.
Ostrea collazica Maury.
* *Ostrea virginica* Gmelin.
Ostrea cahobasensis var. *portoricana* n. var.

[4] Index of the Lares formation is indicated by an asterisk.

* *Lithophaga nigra* d'Orbigny.
Arca yaquensis? Maury.
Arca (Scapharca) collazica Maury.
* *Venericardia scabricostata?* Guppy.
. *Phacoides (Miltha) riocanensis* Maury.
Cardium (Laevicardium) cf. *serratum* Linné.
Cardium (Trachycardium) muricoides n. sp.
* *Cardium (Trachycardium) cinderellæ* var. *alternatum* n. var.
Pitaria (Hyphantosoma) carbasea Guppy.
Chione woodwardi Guppy.
Chione hendersoni Dall.
* *Semele* sp. indet.
Cyathodonta reedsi Maury.
Corbula collazica Maury.
Teredo incrassata Gabb.
Xenophora conchyliophora Born.
Turritella tornata var. *portoricoensis* n. var.
Cerithium (Campanile) collazum n. sp.
* *Xancus* n. sp.?
* *Mitra symmetrica* Gabb.
Bullaria granosa Sowerby.

In addition to these species, many indeterminate fossils, chiefly gastropods, were collected. Some of these are apparently limited to the Lares formation. The presence of some of the Antiguan corals in the basal Lares limestone indicated that the formation is Middle Oligocene in age. Other fossils indicating Oligocene age are:

1. *Agassizia* sp., a small species resembling *A. conradi* (Bouvé), Oligocene of Bainbridge, Georgia. It is apparently limited to the basal portion of the Lares limestone.

2. Orbitoid foraminifera, including *Orbitolites* cf. *americana* (Culebra and Emperador), and *Lepidocyclina* cf. *mantelli*, a large flat form. The same species occurs abundantly in the Juana Diaz shale and basal Ponce formation of the south coast of Porto Rico, and is listed by Mitchell (1922) as *Orbitoides mantelli*.

THE CIBAO FAUNA

The following list represents probably not more than a third of the molluscan species in this formation. Nearly all of the material is poorly preserved and largely indeterminate:

Pecten (Euvola) reliquus var. *portoricoensis* n. var.
Pecten (Chlamys) portoricoensis var. *grandis*.
Pecten (Chamys) grabaui var. *hatoensis*.
Pecten (Chlamys) grabaui var. *guayabensis*.
Spondylus bostrychites Guppy.

Spondylus gumanomocon Brown and Pilsbry.
Ostrea haitensis Sowerby.
Ostrea haitensis[5] var.?
Ostrea sellaeformis var. *portoricoensis* n. var.
Arca sp. Maury.
Cardium cf. *serratum* Linné.
Pitaria (*Hyphantosoma*) *Carbasea* Guppy.
Chione hendersoni Dall.
Teredo incrassata Gabb.
Hipponyx portoricoensis n. sp.

This list illustrates clearly the mixed or transitional character of the molluscan fauna. The only distinctive index fossil of the Cibao limestone is an echinoid, *Echinolampas* sp., which is very similar to *E. aldrichi* Twitchell of the Vicksburg Oligocene. This fossil is found in great abundance in the upper portion of the formation, and the zone in which it occurs can be traced from the Rio Camuy westward for a distance of 5 or 6 miles.

The basis for including the Cibao limestone in the Middle Oligocene has already been given in discussing the faunal curve (Fig. 22).

THE LOS PUERTOS FAUNA

A comparison of the following list of the Los Puertos fossils with the list of the Quebradillas species will show the close relationship of the two faunas:

Ostrea sellaeformis var. *portoricoensis* n. var.
Glycimeris portoricoensis n. sp.
Lucina cf. *chrysostoma* (Meuschen) Philippi.
Phacoides (*Miltha*) *riocanensis* Maury.
Cardium muricoides n. sp.
Chione woodwardi Guppy.
Chione hendersoni Dall.
Metis trinitaria Dall.
Teredo incrassata Gabb.
Xenophora conchyliophora Born.
Hipponyx portoricoensis n. sp.
Orthaulax portoricoensis n. sp.

The poor state of preservation, as previously noted, is the reason for the small number of species listed. Future work should increase the total of Bowden types in this formation, but the above list is sufficient to determine the age. *Orbitolites* cf. *americana* is the most abundant fossil throughout the formation and in the lower part of the Quebradillas limestone.

[5] Index of the Cibao limestone.

THE QUEBRADILLAS FAUNA

The following list includes all the species identified and described, but probably represents less than half of the entire molluscan fauna of this formation. Those forms which are an index of the Quebradillas limestone are designated by an asterisk:

* *Atrina rabelli* n. sp.
Pecten (Euvola) reliquus var. *portoricoensis* n. var.
* *Pecten (Nodipecten) nodosus* Linné.
* *Pecten (Chlamys) hodgii* n. sp.
* *Pecten (Plagioctenium?) borinquenense* n. sp.
* *Ostrea antiguensis* Brown.
* *Leda peltella* Dall.
Arca yaquensis Maury.
* *Arca (Scapharca)* cf. *donacia* Dall.
* *Barbatia reticulata* Gmelin.
* *Barbatia* cf. *bonaczyi* Gabb.
Glycimeris portoricoensis n. sp.
* *Chama involuta* Guppy.
* *Chama portoricana* n. sp.
Lucina cf. *chrysostoma* (Meusch.) Philippi.
Phacoides (Miltha) riocanensis Maury.
* *Phacoides (Miltha)* sp. indet.
* *Phacoides (Miltha)* sp. indet.
* *Phacoides (Lucinisca) calhounensis* Dall.
* *Divaricella prevaricata* Guppy.
* *Codakia magnoliana* var. *borinquenense* n. var.
Cardium cf. *serratum* Linné.
* *Cardium (Trigonocardia) sambaicum* var. *portoricoensis* n. var.
* *Cardium (Trigonocardia)* n. sp.? aff. *C. sambaicum* Maury.
* *Cardium (Trigonocardia) haitense* var. *cercadicum* Maury.
* *Cardium (Trigonocardia) haitense* var. *arecibocnse*, n. var.
* *Cytherea (Cytherea) berkeyi* n. sp.
Chione woodwardi Guppy.
* *Tellina strophoidea* n. sp.
* *Tellina portoricoensis* n. sp.
* *Tellina (Scissula) grabaui* n. sp.
* *Tellina* aff. T. *(Angulus) atossa* Dall.
Metis trinitaria Dall.
* *Psammosolen sancti-dominici* Maury.
Cyathodonta reedsi Maury.
Teredo incrassata Gabb.
* *Calliostoma portoricoensis* n. sp.
* *Turbo fettkii* n. sp.
* *Liotia (Arene) coronata* var. *portoricoenis* n. var.
Xenophora conchyliophora Born.
Hipponyx portoricoensis n. sp.

* * *Calyptraea* cf. *centralis* Conrad.
* * *Crucibulum auricula* var. *portoricoensis* n. var.
* * *Crucibulum auricula?* var.
* * *Natica canrena?* (Linné) Moerch.
* * *Turritella portoricoensis* n. sp.
* * *Turritella berkeyi* n. sp.
* * *Petaloconchus domingensis* Sowerby.
* * *Pyramidella portoricoensis* n. sp.
* * *Bittium* sp. indet.
* * *Cerithium portoricoensis* n. sp.
* * *Cerithium quebradillensis* n. sp.
* * *Modulus modulus* var. *basileus* Guppy.
* * *Strombus proximus?* Sowerby.
* * *Strombus bifrons?* Sowerby.
* * *Orthaulax gabbi?* Dall.
* *Orthaulax portoricoensis* n. sp.
* * *Cypraea spurcoides?* Gabb.
* * *Malea camura* Guppy.
* * *Strombina portoricana* n. sp.
* * *Phos costatus Gabb.*
* * *Phos elegans* var. *portoricoensis* n. var.
* * *Murex (Phyllonotus) cornurectus* Guppy.
* * *Alectrion gurabensis* var. *portoricoensis* n. var.
* * *Alectrion gurabensis* var. *varicum* n. var.
* * *Fusus henekeni* Sowerby.
* * *Turbinella chipolana* var. *arecibоense* n. var.
* * *Xancus validus* Sowerby.
* * *Mitra henekeni* Sowerby.
* * *Olivella muticoides* var. *portoricoensis* n. var.
* * *Olivella portoricoensis* n. sp.
* * *Cancellaria laevescens* Guppy.
* * *Turris albida* var. *haitensis* Sowerby.
* * *Turris albida* var. cf. *virgo* Lamarck.
* * *Drillia consors* var. *portoricoensis* n. var.
* * *Drillia grabaui* n. sp.
* * *Drillia portoricoensis* n. sp.
* * *Drillia semmesi* n. sp.
* * *Cythara* cf. *elongata* Gabb.
* * *Terebra quebradillensis* n. sp.
* * *Conus catenatus* Sowerby.
* * *Conus* cf. *marginatus* Sowerby.
* *Bullaria paupercula* Sowerby.
* * *Bullaria portoricoensis* n. sp.
* *Bullaria granosa* Sowerby.

The most striking feature of this list is the large representation of Bowden and Aphera-Sconsia species. The approximate age equivalence of the Quebradillas limestone with Bowden horizons in the West Indies is too evident to require further discussion.

TABLE 5—FAUNAL CORRELATION

EXPLANATION: A—Number of identical species in common. B—Number of similar species or varieties in common. * Data based on corals and foraminifera as well as molluscs. Elsewhere the data includes only molluscs.	SAN SEBASTIAN		LARES		CIBAO		LOS PUERTOS		QUEBRADILLAS	
	A	B	A	B	A	B	A	B	A	B
South Coast of Porto Rico: Ponce limestone*	3	1	4	1	4	1	4	1	16	5
South Coast of Porto Rico: Juana Diaz shale*	7	5	4	1	2	1	1	0	1	0
Caloosahatchie Pliocene	..	..	1	..	..	..	..	1	1	3
Jamaica (Bowden)	2	6	3	5	3	4	1	1	12	11
St. Domingo (Sconsia)	2	3	5	3	4	3	3	..	13	10
St. Domingo (Aphera)	3	5	8	7	2	2	4	2	20	17
St. Domingo (Samba Hills)	2	4	2	4	1	2	1	..	2	3
Total—Aphera, Sconsia, Bowden	..	..	..	..	..	..	..	..	27	28
Alum Bluff, Chipola, Oak Grove	..	7	2	3	2	5	..	..	3	15
Panama (Gatun)	2	8	..	3	..	3	..	2	2	14
Trinidad (Caroni)	1	..	..	1	..	..	1	..	4	2
Sombrero, W. I.	..	..	..	..	..	..	2	..	9	2

Duplin County, N. C. (Miocene)	..	..	..	1	..	1	..	1	..	3
Panama (pre-Gatun)	2	..	..	..	..	..	..	..	..	1
Tampa Silex	..	3	1	1	..	1	..	..	2	6
Haiti (Las Cahobas)	..	2	3	..	2	1	1	..	..	..
Georgia (Flint River)	..	2	1	1	1	..	..	..	1	1
Antigua (Antigua formation)	..	..	..	..	..	..	..	..	1	2
Vicksburg Oligocene	..	..	..	..	..	..	..	..	1	..
Claiborne Eocene	..	1	..	..	..	..	..	..	..	..
Europe (Acquitainian)	..	1	..	..	..	..	..	..	..	..
Europe (Eocene)	..	2	..	1	..	..	..	..	..	..
Miscl. Pleistocene, Recent	..	1	4	3	1	2	1	4	3	9
Antillian Region, Tertiary to Recent	6	20	13	16	5	7	6	5	29	47
New species not closely related to any known species in the Antillian Region	11		6		3		1		9	
Total number of species and varieties recorded	37		35		15		12		85	

Foraminifera are abundant and include *Orbitolites* cf. *americana* Cushman (lower Quebradillas) and *Polystomella?* sp. (upper Quebradillas). In the uppermost horizon and fragments of *Scutella* sp. and *Cidaris* sp. and a *Schizaster* resembling *S. scherzeri* Gabb, a species from the Sapote, Costa Rica and the Emperador limestone, Canal Zone. It also resembles *S. floridanus* Clark, of the Vicksburg Oligocene. Corals are not common in the Quebradillas, and none of the chief reef-building types occur. Semmes (1919) illustrates a Fungid coral, indeterminate, from the Quebradillas limestone of the San Juan District. This fossil occurs in the Lares District, but is not abundant. The commonest coral in the Quebradillas limestone (and equivalent horizons on the south coast and on Vieques Island) is a *Balanophyllia*. There seem to be two species (or varieties), each resembling species found in the Bowden or equivalent formations. Another abundant coral is a *Stylophora* like *S. affinis* Duncan.

SUMMARY OF THE FAUNAS

The molluscs, which make up about nine-tenths of the fauna, show that the uppermost Tertiary formation of the Lares District is of Bowden age. The basal member is shown by the corals, and less certainly by the molluscs, to be of Antiguan or Middle Oligocene age. There are only two distinct faunas, the San Sebastian-Lares and the Quebradillas. The others are mixtures of San Sebastian-Lares and Quebradillas (Bowden) types.

Table 5 (pages 62-63) is based upon the molluscan species above described[6] and shows the relative numerical distribution of the Lares District fossils in other localities and horizons of the West Indies and elsewhere. It shows the close relationship of the Quebradillas fauna with the Aphera-Sconsia faunas of Santo Domingo. Another feature brought out is the effect of geographical position upon the similarity of the faunas. Thus formations of the same age as the Quebradillas limestone, such as the Gatun formation and the Chipola-Oak Grove series, but situated at considerable distance from Porto Rico, have few identical species in common, but a considerable number of similar species or varieties.

CORRELATION WITH THE SOUTH COAST

The question of the correlation of the north and south coast Tertiary formations has been awaiting the collection and comparison of fossils.

[6] In the case of the two south coast formations (Juana Diaz and Ponce) the data include other types of fossils besides molluscs.

Berkey made no attempt at a correlation because the fossils then collected (1914) did not warrant it. Semmes (1919, p. 59) pointed out that the Ponce formation is "in part practically equivalent to the Arecibo formation of the northern coast," but he did not make any subdivisions of the south coast series. Maury (1919, p. 214), after a study of fossils collected by Reeds, made a correlation of the north and south coast Tertiary (Table 6). This correlation was advanced by Maury as a tentative one and is the first attempt of a detailed character. However, the evidence at hand seems to warrant certain departures from this correlation, as shown by the following considerations:

TABLE 6

	North Coast		South Coast
Middle Miocene	Subdivisions of the Arecibo formation.	?	
Lower Miocene		Quebradillas limestone with Bowden fauna and *Metis trinitaria.*	
Upper Oligocene		Aguadilla limestone with *Orthaulax aguadillensis.*	Ponce chalky beds with *Ostrea cahobasensis.*
		Lares limestone with *Campanile (Portoricia) larica.*	
Middle Oligocene	San Sebastian or Collazo shale	Rio Collazo shales with *Clementia rabelli.*	Guanica shaly limestone with *Ostrea antiguensis.*

1. Mitchell (1922) shows that the beds at Guanica are stratigraphically at or near the top of the Ponce formation. In speaking of the Ponce chalky beds, Berkey (1915, p. 14) says: "It is judged that the portion of the formation seen at Guanica is a still higher horizon, but the exact age values have not been worked out." From this, it seems evident that

the Guanica beds overlie the Ponce chalky beds, and are at the top of the column, not at the bottom as Maury stated.

2. The Guanica beds (together with the upper part of the Ponce beds to the east) carry a typical Quebradillas (Bowden) fauna, as will be shown later. *Ostrea antiguensis* which Maury lists from the Guanica beds is one of the best index fossils of the Quebradillas limestone.

Regarding the Juana Diaz, the basal shale member of the south coast group, Maury (1919, p. 215) says: "The Juana Diaz shales furnished very few molluscan shells. . . . The evidence at hand is too scanty for any definite stratigraphic conclusion regarding these beds." As shown by Table 5, and as will appear later, the Juana Diaz shale carries several of the best index fossils of the San Sebastian shale, among which *Clementia dariena* (= *C. rabelli* of Maury) is the most significant.

From a careful comparison of south coast fossils collected by Berkey, Lobeck, and Mitchell, with material from the Lares District, the correlation table (7) is proposed and is believed to be essentially correct. A more detailed comparison is impossible because the south coast series has not been definitely subdivided in the field.

TABLE 7

	NORTH COAST	SOUTH COAST
Pleistocene	San Juan formation	San Juan formation
	________Disconformity________	________Disconformity_______
Upper Oligocene	Quebradillas limestone	Guanica beds and Upper Ponce limestone.
	Los Puertos limestone	
		_______________?____________
Middle Oligocene	Cibao limestone	Lower Ponce limestone
	Lares formation	
		_______________?____________
	San Sebastian shale	Juana Diaz shale
	________Unconformity________	________Unconformity________
Upper Cretaceous	Older Series	Older Series

The essential points in the basis of correlation have been referred to, but the following lists of fossils from the south coast formations are offered as further evidence. The localities recorded are taken from notes by Berkey, Lobeck, and Mitchell:

FOSSILS FROM THE JUANA DIAZ SHALE

Name of Fossil	Localities	Remarks
Turitella halensis Dall	Juana Diaz, Yauco	Closely related to *T. collazoensis* of the San Sebastian shale.
Turitella halensis var. *alpha* Mitchell	Juana Diaz	
Scala? sp.	Juana Diaz	An internal mold. A similar or identical fossil occurs in the upper San Sebastian shale.
Pecten (Chlamys) portoricoensis n. sp.	Near Juana Diaz	Index of San Sebastian and Lares formations.
Clementia dariena Conrad (=*C. rabelli* Maury)	Juana Diaz	Index of San Sebastian shale.
Solen (Plectosolen collazoensis n. sp.	Juana Diaz, Yauco.	Index of San Sebastian shale.
Natica sp. indet.	Juana Diaz	Internal mold. Similar molds are found in the San Sebastian shale and range through the Cibao limestone.
Cypræa sancti-sebastiani Maury	Juana Diaz	Index of San Sebastian shale.
Pecten rabelli n. sp.	Juana Diaz, Yauco and K. 25, Ponce-Adjuntas road.	Index of San Sebastian shale.
Strombus sp. indet.	Yauco	Resembles some internal molds from the San Sebastian shale.
Venericardia cf. *scabricostata* Guppy	Juana Diaz, Yauco	Occurs in Lares formation.

FOSSILS FROM THE JUANA DIAZ SHALE—Continued

Name of Fossil	Localities	Remarks
Teredo incrassata Gabb.		Ranges throughout the series, north and south coasts and Vieques Island. Of no value as an index fossil.
Lepidocyclina? sp.	Juana Diaz, Yauco.	A large foraminifer, apparently the same as the one occurring abundantly in the Upper San Sebastian shale, Lares formation, and Cibao limestone.

FOSSILS OF THE PONCE LIMESTONE

Name of Fossil	Localities	Remarks
Orbilolites cf. *americana* Cushman	Ponce, Guanica	Quebradillas limestone.
Balanophyllia sp.	Widespread, along coast.	Extremely abundant in both the Quebradillas and the Upper Ponce limestones.
Stylophora sp. (like *S. affinis* Duncan)	Culebrinas Pt., and along coast.	Characteristic of Quebradillas and Upper Ponce limestones.
Strombus proximus Sowerby	Mona Island	Quebradillas limestone.
Bullaria cf. *paupercula* Sowerby	Mona Island	Quebradillas limestone.
Turritella cf. *gatunensis* Conrad	Mona Island	Apparently related to *T. portoricoensis* of the Quebradillas limestone.
Cardium cf. *muricoides* n. sp.	Near Guanica	Ranges from Lares formation to Los Puertos limestone.
Cardium cf. *lingualeonis* Guppy	Near Guanica	Bowden, Jamaica.

FOSSILS OF THE PONCE LIMESTONE—Continued

Name of Fossil	Localities	Remarks
Cardium haitense var. *cercadicum* Maury	Ponce	Quebradillas limestone.
Cardium haitense var. *areciboense* n. var.	Ponce, Culebrinas Pt.	Quebradillas limestone.
Corbula sp. indet.		A small species, not found in any of the north coast formations.
Chione woodwardi Guppy	Culebrinas Pt., Ponce, Guanica, Rio Yauco 2½ miles S. E. of Yauco.	Abundant in Quebradillas limestone.
Glycimeris cf. *portoricoensis* n. sp.	Guanica	May be the Quebradillas species.
Lucina cf. *chryostoma* (Meusch.) Phil.	Vieques Is., Culebrinas Pt., Ponce, N. W. of Ponce, near Guanica, K. 2.4, Ponce-Adjuntas road.	The most characteristic fossil of the Ponce formation. It occurs in the Quebradillas and Los Puertos limestones.
Phacoides (*Lucinisca*) *calhounensis* Dall	Near Ponce	Quebradillas limestone.
Cytherea (*Cytherea*) *berkeyi* n. sp.	Ponce, West of Ponce, N. E. of Ponce.	Quebradillas limestone.
Teredo incrassata Gabb.	Vieques, Ponce	Quebradillas limestone. No index value.
Ostrea antiguensis Brown	Guanica?	Quebradillas limestone. Reported by Maury from the Guanica shaly limestone.
Terebra cirrus Dall	Near Guanica	Found in the lower Alphera formation of Santo Domingo.
Terebra cf. *quebradillensis* n. sp.	Ponce	Resembles the Quebradillas species and may be the same.

FOSSILS OF THE PONCE LIMESTONE—Continued

Name of Fossil	Localities	Remarks
Arca (Scapharca) cf. *riocanensis* Maury	Ponce	Upper Aphera of Santo Domingo. Not found on the north coast of Porto Rico.
Bullaria granosa? Sowerby	Culebrinas Pt.	Quebradillas limestone.
Olivella muticoides var. *portoricoensis* n. var.	K. 75.2, Ponce-Peñuelas Road, Aguila Pt.	Quebradillas limestone.
Leda cf. *peltella* Dall	K. 75.2, Ponce-Peñuelas Road	Resembles this species, which is very typical of the Quebradillas limestone.
Metis trinitaria Dall	Culebrinas Pt.	Quebradillas limestone. Apparently rare on the south coast.
Ostrea cahobasensis var. *portoricana* n. var.	Guanica	
Boring Sponge?	Culebrinas Pt.	The casts of the burrows of some organism like *Chione*. These are so widespread and characteristic of the Quebradillas limestone that they may be considered as index of this horizon. Their burrows are chiefly in the large gastropod shells.

It is believed that the last list includes fossils from all horizons of the limestone overlying the Juana Diaz shale, and hence ranging from Lares to Quebradillas in age. It is inadvisable with the data at hand to attempt listing the fossils from the limestone as Upper or Lower Ponce. Nevertheless, it is evident that most of the more typical Quebradillas species occur near the coast and therefore in the upper part of the Ponce limestone.

COMPARISON WITH IMPORTANT ANTILLEAN LOCALITIES

Antigua. The Island of Antigua, in the Lesser Antilles, southeast of Porto Rico, is considered the type locality of the Middle Oligocene (Antiguan) of the Caribbean region. The island consists of an igneous basement upon which rests a series of tuffs with interbedded marine strata, and finally an uppermost limestone series known as the Antigua formation, and considered by Vaughan as the type section of the Middle Oligocene. The evidence given by Vaughan (1919, p. 259) is based upon the fossil corals which he finds chiefly in a 60-foot fossil reef at or near the base of the Antigua formation. The evidence of these corals shows that the Antigua formation is equivalent to the lower members of the Tertiary series in the Lares District of Porto Rico. On the basis of the corals, Vaughan puts the entire Antigua formation in the Middle Oligocene, and estimates its thickness at 350 feet. These conclusions apparently do not agree with evidence furnished by others who have studied the geology of this island. Of a list of 10 molluscan species from the Antigua formation, collected and described by Brown (1913, p. 598), 6 are identical with, and 3 are similar or related to species occurring in Antillean formations of Bowden age, while another species is characteristic of the Anguillan, or so called Upper Oligocene. The thickness of the Antigua formation is estimated by Spencer (1901) as "at least many hundred feet," and by Brown as "upwards of 1500 feet at least." It forms a belt about 5 miles in width, and Vaughan estimates the seaward dip to range from 10° to 15°. Taking the average at 10°, the thickness must be several times greater than Vaughan estimated, and hence more nearly comparable with the north coast series of Porto Rico. Consideration of the above conflicting evidence seems to show that more than one formation is represented in the Antiguan formation, and detailed stratigraphic work will have to be done before the Antigua formation can be regarded as the type section of the Middle Oligocene in the West Indies.

Santo Domingo. The highest Tertiary formations are the Aphera-Sconsia formations described by Maury (1917). These formations are approximately equivalent to the Bowden marl of Jamaica and to the Quebradillas limestone of Porto Rico. Correlation of the Orthaulax Zone of Santo Domingo and the pre-Quebradillas formations of Porto Rico cannot be made with certainty because no detailed stratigraphic work has been done in the older Santo Domingo formations.

Haiti. In Haiti, the Maissade beds (uppermost horizon) correspond with the Quebradillas limestone. The underlying formation (Las Cahobes) is probably equivalent to the San Sebastian shale, and overlying limestones below the Quebradillas, as indicated by its stratigraphic position. Among the fossils listed by Jones (1918, p. 738) from this formation are:

Turritella planigyrata Guppy.
Turritella tornata Guppy.
Venericardia scabricostata Guppy.

which in the Porto Rico section are limited to the San Sebastian and Lares formations.

Other localities. It is quite likely that future work will greatly increase the known number of localities in which the uppermost portion of the Tertiary is of Bowden age. The small key of Sombrero, 140 miles east of Porto Rico, is built up of a white limestone of Bowden (or Quebradillas) age. The following is a partial list of the fossils:[7]

Strombus proximus Sowerby.
Xenophora conchyliiphora Born.
Bullaria granosa Sowerby.
Tellina cf. *strophoidea* n. sp.
Cyathodonta cf. *reedsi* Maury.
Cardium haitense Sowerby.
Cardium cf. *sambaicum* Maury.
Chione woodwardi Guppy.

In addition to these, the casts of the Sponge (?) burrows, characteristic of the Quebradillas limestone, occur abundantly in the Sombrero limestone. The proximity of Sombrero to Anguilla, Vaughan's type locality of the Upper Oligocene, suggests the need of detailed stratigraphic work in this vicinity.

The conclusions regarding the correlation of the Porto Rican with some of the other Antillean localities is given in the accompanying table (8). This table is based on those by Vaughan (1919*a*, p. 595), Maury, and Jones, with minor changes. The chief departure from the authorities above named is the placing of the Bowden formation and its equivalents in the Upper Oligocene.

OLIGOCENE OR MIOCENE

The question of the Miocene or Oligocene age of the formations equivalent or approximately equivalent to the Bowden marl of Jamaica is one on which authorities do not agree. Within the last few years Vaughan, Maury and others have maintained that the age of these formations is

[7] Determinations by the writer from material in Paleontological Museum, Columbia University.

Table 8

PROPOSED CORRELATION OF ANTILLEAN TERTIARY FORMATIONS

Age	Porto Rico, North Coast	Porto Rico, South Coast	Santo Domingo	Haiti	Jamaica	Cuba	Panama	Sombrero	Anguilla	Antigua	Florida and Georgia	Maryland, Virginia, North Carolina, and South Carolina
Pliocene											Caloosahatchie marl	Waccamaw marl, etc.
Upper Miocene											Jacksonville formation	Duplin County marl, etc.
Lower Miocene											Shoal River marl	
Upper Oligocene	Quebradillas limestone 800 feet Los Puertos limestone 1000 feet	Ponce limestone 3000 to 4000 feet	Sconsia formation Aphera formation "Orthaulax inornatus zone"	Maissade beds 1000 feet Las Cahobes beds 6500 feet	Bowden marl	La Cruz marl Baracoa marl Miscellaneous limestones	Gatun formation Emperador limestone	Sombrero limestone ?	Anguilla limestone	Antigua formation (undivided) Thickness more than 1500 feet	Oak Grove Chipola	
Middle Oligocene	Cibao limestone 250-1000 feet Lares formation 350-1200 feet San Sebastian shale 700 feet	? Juana Diaz shale 3000 to 4000 feet	?	Thomonde beds 1500 feet	?	Guantanamo coral limestone	Culebra formation			Chief coral zone at base	Tampa Flint River	
Lower Oligocene				? Limestone series 8000 feet	Montpelier limestone	?	? Limestone ?			? Tuffs with marine beds ?	Vicksburg Group	
Upper Eocene				?	Cambridge formation Richmond formation	St. Bartholomew limestone	Tonosi ?			Seaforth limestone ? Igneous basement	Ocala limestone	

Lower Miocene. On the other hand, Dall and some other authorities still take the opposite view and place them in the Upper Oligocene. The writer believes that the position taken by Dall is correct. The evidence favoring the Miocene age of the Bowden is given by Vaughan and need not be reviewed here. The evidence favoring the Oligocene age may be summarized as follows:

1. The genus *Orthaulax* has until recently been considered an index of Oligocene age. It is now regarded by Cook and Vaughan as indicative of either Oligocene or Lower Miocene. This change in the status of *Orthaulax* is not due to any new discoveries of that genus in horizons higher than it has previously been known to occur, but is due to the placing of previously recognized Upper Oligocene formations in the Miocene nomenclature by Vaughan and others. The genus *Orthaulax* is one of the most abundant fossils in the Quebradillas limestone, as well as in the Los Puertos limestone. In the former horizon, there are at least two, and very likely as many as four species of *Orthaulax* present. According to Vaughan the Quebradillas limestone is Lower Miocene in age.[8]

If this view be accepted, then we must admit that the Lower Miocene fauna of Porto Rico is largely Oligocene in its general aspect. Thus one of the strongest arguments of the Miocene advocates is weakened, namely, that the Chipola fauna (and presumably its time equivalents) in its aspect "looks forward to the later Tertiary and Recent, rather than backward" (see Vaughan, 1919*a*, p. 573). It is true that *Orthaulax* has been noted as an exception to this statement, but every new discovery of abundant *Orthaulax* in strata of Bowden-Chipola age tends to increase the significance of this exception, and the Quebradillas fauna with its myriads of *Orthaulax* shells mixed with the host of Bowden-Aphera-Sconsia types furnishes one more difficulty in the way of any argument based upon the above quotation.

2. The presence of *Ostrea antiguensis* in great numbers at the top of the Quebradillas limestone. Maury regards this fossil as so excellent an index of the Oligocene that its presence in the Guanica shaly limestone is sufficient evidence for correlating this formation with the Antiguan.

3. The gradual appearance of some of the Quebradillas species, starting with the Lares formation (Antiguan).

4. The absence of any unconformity or marked faunal hiatus between the Quebradillas limestone and the lower limestones. The entire series is a structural unit.

5. Erosion interval and faunal break occurs in Porto Rico, as elsewhere, at the end of the Bowden time.

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[8] Personal communication.

6. Large representation in the San Sebastian shale of Gatun, Chipola, and Bowden types shows relationship with the Bowden horizon.

7. Two species in the San Sebastian shale (*Glycimeris collazoensis* and *Turbinella chipolana precursor*) apparently have closely related derivatives, showing slightly greater specialization in the Quebradillas limestone.

8. The marked difference of aspect between the San Sebastian and Quebradillas faunas is due chiefly to change in bionomic conditions. Thus the San Sebastian fauna, typically a lagoon or brackish water facies, was forced to migrate because of changing conditions. It reappeared in Bowden time in the Canal Zone (Gatun fauna), with considerable changes in species, but with the same general aspect it had in San Sebastian time. The San Sebastian and Gatun faunas have in common such characteristic species as *Clementia dariena* and *Arca dariensis.*

9. Inspection of the fossils listed from the Canal Zone shows that the Gatun formation has many species in common with the underlying limestones. Most of the change in faunal aspect may be explained by change of conditions of deposition. In Antigua, Bowden molluscan fossils are apparently so intimately mixed with Oligocene corals that no Upper Antiguan or Bowden horizon was differentiated there by Vaughan. In Florida, the Alum Bluff series is so closely associated with the underlying Tampa and Chattahoochee horizons that authorities are still not in agreement regarding the existence of a physical and faunal break, even after considerable stratigraphic work has been done. All are agreed, however, that there is a break at the top of the Alum Bluff group (= end of Bowden time).

10. In the San Sebastian shale is found species of *Cirsotrema* which is hardly distinguishable from certain species in the Helvetian (Miocene) of Europe. Species of *Campanile* and *Plectosolen* in the San Sebastan shale have allied forms in the European Eocene. Facts such as these suggest caution in attempting to decide the age of an American fauna by comparing it, in its general aspect, with European faunas.

The only infallible criterion for correlation with European or other distant sections is the recognition of a world wide crustal movement or change of sea level. If the elevation of the South Atlantic-Antillean region at the close of the Bowden-Alum Bluff time can be definitely correlated with movement in other parts of the world, a definite and logical division line can be drawn between the Oligocene and the Miocene. In the American-Antillean Province this line of division is distinct, as Dall (1898, p. 329) long ago pointed out. The evidence obtained in studying the sections in the Lares District supports the early conclusions of Dall rather than the recent conclusions of Vaughan.

Tertiary History

The entire group of Tertiary formations of Porto Rico were deposited during a continuous period of gradual submergence, which began in Middle Oligocene time. The formations are therefore all conformable with one another, and show a progressive overlap over the Older Series rocks. The relationship is brought out in the ideal section (Fig. 23). With the initiation of submergence, the sea encroached in the valleys of the old land surface, forming embayments, as for example at San Sebas-

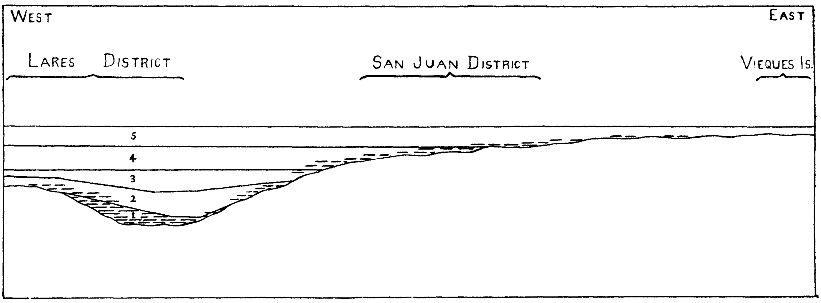

Fig. 23.—*Ideal section along the north coast at the time of maximum submergence (late Oligocene)*

Showing transgressive overlap of the Tertiary formations on the old land surface. The San Sebastian shale is confined to the Lares-San Sebastian embayment. The San Sebastian shale and basal shale facies of the higher horizons are shown by the broken lines. The formations are numbered consecutively: (1) San Sebastian shale, (2) Lares formation, (3) Cibao limestone, (4) Los Puertos limestone, (5) Quebradillas limestone.

tian and Juana Diaz, in which the chief deposits of basal shales accumulated, under an alternation of brackish, freshwater and marine conditions. At San Sebastian coral reefs formed across the mouth of the embayment. The large "heads" or colonies of corals, broken from this reef by the surf, are found imbedded in the marls of the San Sebastian formation, exposed along the Lares Road. In connection with the theories of origin of coral reefs, it is interesting to note that several hundred feet of shale, in part marine, were deposited before the actual reef itself was formed. Comparison of sections at Collazo and Lares would seem to show that the Upper shales and coral marls of Collazo grade into coral-reef limestone when traced toward Lares. This would indicate that the green coral-bearing marls at Collazo were formed behind an off-shore or fringing reef.

With continued submergence corals ceased to be the dominant reef-building organisms, molluscs and foraminifera taking their place. Throughout the entire series, the deposition kept pace with subsidence, as shown by the fact that shallow water organisms predominate in all the formations. In the eastern part of the Lares District, there was apparently frequent emergence, with oxidation of the newly deposited strata. The frequent occurrence of red limestone at various horizons in the eastern part of the district may be evidence of this. The chief evidence, however, is to be found in the thinning of the Cibao limestone and Lares formation toward the west, indicating near shore deposition, with a peninsula in the longitude of Moca. The submergence was probably accompanied by a seaward down-warping movement illustrated by the fact that the Quebradillas limestone dips at lower angles than the lower formations. This statement is true even where the Quebradillas limestone is the basal formation, as in the San Juan District.

MAGNITUDE OF THE SUBMERGENCE

One of the unsettled problems has been the extent to which the island was sugmerged in Upper Oligocene time. Lobeck concludes (1922) that the island was not entirely submerged, as shown by:

1. Presence of gravel and clay at various horizons in the Tertiary beds.
2. Abrupt termination of Tertiary beds against the upland slopes of the old land surface.

The evidence found in the Lares District may be summarized as follows:

1. The faunal difference between the lower formations in the Lares District and the lower formations of the south coast is considerable, and indicates a land mass quite extensive in an east-west direction, with no connecting passages close at hand.

2. The Bowden faunas of the Quebradillas and Upper Ponce show much greater similarity than do the older faunas, but still show greater difference than the present beach faunas of the north and south coasts. The extreme abundance of certain shells (like *Metis trinitaria*) in the Quebradillas limestone, and their rare occurrence in the Ponce limestone is very significant.

3. The great thickness of the Tertiary series (nearly 4000 feet) would seem to show that the island was completely submerged. It has been shown, however, that the formations near the old (Oligocene) shore line are only a fraction of their maximum or off-shore thickness. The beds were undoubtedly deposited with a slight initial dip to seaward, and

hence are of the nature of fore-set beds. The maximum accumulation of limestone was in an outward direction, rather than upward. This may be one reason why the enormous thicknesses recorded for Oligocene reef limestones like those of Haiti and Porto Rico are not comparable with measurements of beds the same age deposited in Florida and elsewhere on the continental shelf.

4. A carful search was made for outliers of Tertiary rock in the higher portions of interior mountains. The only evidence found was a single boulder of Tertiary limestone (probably Lares) in the channel of the Rio Guayaba, two miles southeast of Aguada. However, this does not show that the Tertiary beds covered the Cordillera Central to the south.

From the above evidence, it may be stated that Porto Rico was not completely submerged in Upper Oligocene time.

THE UPLIFT

The uplift was differential. It amounted to at least 1300 feet in the vicinity of Lares, and less than 100 feet in the extreme eastern part of the island. This differential uplift resulted in the truncation of the west end of the island, chiefly by warping. The northwest dip of the Tertiary strata along the west coast has already been referred to in discussing the structure. It is probable that there was some faulting in connection with this truncation of the island, and that the zone of faulting lies somewhere to the west of the island, where faulting is now taking place. This was shown by the 1918 earthquake.

PHYSIOGRAPHY

There are three major physiographic provinces represented in the Lares District:

1. The Complex Mountainous Oldland.
2. The Elevated Coastal Plain.
3. The Playa Plains.

These are the most important physiographic units of the island, and have been described by Hill, Berkey, Lobeck, and the authors of the geological reports on the different districts. The geologic map brings out the contrasts of relief and topographic characteristics of the three provinces as they occur in the Lares District.

The Complex Mountainous Oldland comprises the central mountain chain; the core or backbone of the island. In the Lares District it is the mountainous area south of the Lares Road; that is, the area making up the southern half of the district. The maximum elevation (2000 feet) is in the southeast corner of this area, and the relief here is 500 to 700 feet.

The Coastal Plain comprises the area north of the Lares Road. It is a plateau in a youthful or submature stage of dissection. From a maximum elevation of about 1500 feet (east of Lares), the plateau surface slopes very gradually to the north coast, terminating there in sea cliffs 50 to 100 feet high. The rocks are Oligocene limestones with some basal shale beds, the entire series lying nearly horizontal, or with a slight dip to the north and northwest. These Oligocene formations overlap the mountainous oldland as far as the Lares Road, where they culminate in a more or less distinct cuesta, in places more than 300 feet high. This cuesta marks the boundary between the Coastal Plain and Mountainous Oldland provinces, and its position can readily be seen on the geologic map.

The Playa Plains are the nearly flat alluvial plains at or near sea level, occurring along the coast at the mouths of the rivers. They are especially large on the west coast of the Lares District, as for example, the Culebrinas and Añasco Playas. Smaller ones occur on the north coast of the district, as for example, the Guajataca and Camuy Playas. The Playa Plains (locally known as Playas) are of comparatively recent origin, and are found only along the coast. Some occur adjacent to the mountainous oldland; others adjacent to the coastal plain.

The Complex Mountainous Oldland

This province in the Lares District, includes practically all the area south of the Lares Road (see map). The relief is very considerable throughout the greater part, especially in the southeast corner of the district. The central mountain range of Porto Rico, known as the Cordillera Central, can be traced westward across the island to the vicinity of Adjuntas. West of Adjuntas it divides into a southern range and a northern range. The southern range extends along the southern border of the Lares District, through Maricao and Consumo, to Mayaguez. The northern range passes south of Lares, where it is indistinct, to Atalaya Peak, north of Añasco. Northwest of Point Jiguero, it continues as a distinct submerged range, of which the highest summit forms Desecheo Island, 15 miles from the west coast at Rincon.

The Mountainous Oldland in the Lares District is drained by two master streams, the Rio Añasco-Rio Blanco, and the Rio Culebrinas. These two rivers flow west and northwest through the area to the west coast, following in a general way, the rock structure. The Rio Añasco-Rio Blanco system forms the parting valley between the north and south branches of the Cordillera Central. The Rio Culebrinas forms the parting valley (or inner lowland) between the oldland on the south, and the overlapping Tertiary formations of the coastal plain on the north.

The Mountainous Oldland is maturely dissected. All of the streams are in the stage of youth, and are characterized by narrow, steep-sided valleys, and numerous falls and rapids. As compared with the playas, or lowlands of the coast, the climate of these interior mountains is cool and humid. Rains are of almost daily occurrence, but are typically of short duration. The mountain slopes, almost everywhere developed on clay or laterite, are exceedingly steep, and as a rule, are covered with forest trees. All of the trees are second growth, utilized as shade for coffee. Thus what appears as wild forest land, is in reality highly cultivated coffee land.

Travel in this mountainous area is very difficult. Automobile roads are rare, and the native cart roads (*caminos*) are often impassable after showers. Grades of 30° or more are commonly met with in travelling these roads, and in the areas of greatest relief, coffee, bananas, and all other products must be transported by pack animals. Some of the richest coffee districts of Porto Rico are in the most inaccessible parts of the mountains.

THE PENEPLANE SURFACE

The summits of the Cordillera Central mark the remnants of a formerly continuous surface of moderate relief (Fig. 24). This old surface is the upper peneplane described by Lobeck. Above the peneplane surface rise a few scattered monadnocks of quartz diorite, or other relatively resistant rock (Fig. 1). The peneplane has been maturely dissected in the Lares District, and is not a striking feature except where viewed from certain points of advantage. In the southeast corner of the district, where it has an elevation of 1700 to 1900 feet, it slopes gradually to the west. Near the west coast it is preserved only on portions of the Atalaya Range north of Añasco, and possibly on the Mesa at Mayaguez. In central and eastern Porto Rico, Lobeck has distinguished a lower peneplane, marking a second erosion cycle. No traces of this lower peneplane are found in the Lares District, probably because it is buried here by the overlapping Tertiary formations.

The upper peneplane was formed some time after the close of the Cretaceous Period and before the beginning of the Oligocene Period. This is proven by the fact that late Cretaceous formations make up a portion of the folded Older Series rocks on which the peneplane is developed, and are the youngest formations known to exist in the Older Series. That the peneplanation took place before the Oligocene Period is shown by the fact that the earliest marine formations deposited on the peneplaned area are of middle Oligocene age. As previously noted, Lobeck has shown the existence of two peneplanes in Porto Rico. Both of these must have been made during the interval between the close of the Cretaceous Period and the beginning of middle Oligocene time. The most probable date for the upper peneplane is the Paleocene Period; for the lower peneplane, the Eocene Period. The formation of the

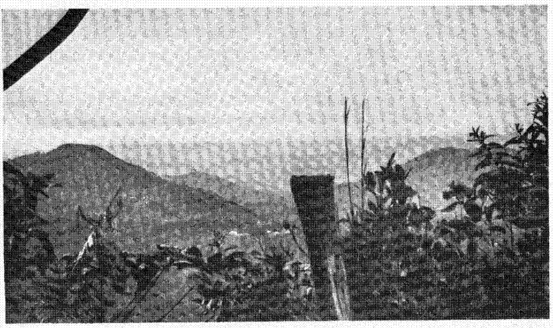

FIG. 24.—*Accordance in level of the summits marking the old land surface peneplane, now maturely dissected*

View looking N. 64° E. from K. 6.9, Consumo-Maricao Road.

lower peneplane seems to have been interrupted by an uplift, initiating a third cycle of erosion, and resulting in the dissection of both peneplanes. This is shown by the fact that the basal formations of the Tertiary Series lie upon an extremely irregular surface, in some places filling old valleys in the oldland surface. From their location, these buried valleys seem to have been cut in the lower peneplane. Coarse gravels occupying one of these buried valleys near Moca, and immediately underlying the basal marine Oligocene formations in this locality, point to the existence of youthful streams in this region just preceding the invasion of the sea in middle Oligocene time. Thus the third erosion cycle belongs to the late Eocene or early Oligocene Periods, or possibly both. This cycle had apparently reached a stage of late youth or early maturity before it was interrupted by the middle Oligocene submergence.

The following are the important physiographic events which took place during the time interval between the folding of the Cretaceous formations of Porto Rico and the deposition of the Tertiary coastal plain strata:

1. First erosion cycle, ending in the formation of the upper peneplane. (Late Cretaceous to end of the Paleocene.)
2. Uplift, with dissection of the upper peneplane, and the formation of a second or lower peneplane. (Eocene.)
3. Uplift, with dissection of the lower peneplane and further dissection of the upper peneplane. (Late Eocene to early Oligocene.)
4. Subsidence, resulting in partial submergence of the island, and interruption of the third erosion cycle. (Middle Oligocene to early Miocene.)

The geological dates given in this outline are to be considered as the probable approximate dates of these events. The date of the close of the third erosion cycle, however, is based on good stratigraphic evidence. At the close of the Oligocene Period, the entire island was uplifted, the amount of vertical movement being differential, but reaching a maximum of 1500 feet in the eastern part of the Lares District. Thus erosion of the present cycle was initiated in early Miocene time, and has continued to the present. Those portions of the interior mountains which were not submerged in Oligocene time have been subjected to erosion since the close of the Cretaceous Period. Other portions nearer the coast have been stripped of some of their mantle of Oligocene strata during the present cycle. This is true of most of the area drained by the Rio Culebrinas and its tributaries.

Drainage Features

All the streams of the mountainous oldland are in the stage of youth. Falls and rapids occur in abundance in streams of all sizes. The only outcrops of fresh, unweathered rock in the oldland area are found in the stream channels. This, in a region where rock decay is extremely rapid, is a good indication that the rivers are still actively deepening their valleys.

River terraces occur in many places along the Rio Añasco, Rio Blanco, and Rio Culebrinas valleys. None of theme are continuous, and they occur at all elevations above river level, from 10 to 100 feet. Most of them are built of river gravel; some are rock cut. In most places they are obscured by forest trees which cover the valley walls, and their true nature is therefore not evident.

A special feature of the drainage of the oldland area is the presence of hanging valleys where small tributaries enter the valleys of trunk streams, such as the Rio Blanco. In the upper Rio Blanco valley in the southeast part of the Lares District, hanging valleys are very numerous. The small streams enter the deep, narrow valley of the main stream with rapids and in many cases falls of considerable height. The same feature may be seen in the upper Rio Culebrinas valley, and, in fact, seems to be the rule wherever small tributaries enter a trunk stream of large volume.

Any attempt at interpretation of the origin of the streams of the mountainous oldland is made difficult because the relationship of stream to rock structure is in most places not apparent, and the structure, where not obscured by soil and vegetation, is as a rule so complex that a long and careful study would be required to unravel it. This statement applies especially to the southeastern part of the Lares District. A glance at the map will show that in the western part of the oldland area, the main streams follow the strike of the Cretaceous formations more or less closely. Such streams are developed in belts of the less resistant rocks, especially tuffs and shales, and should be classified as subsequent streams. Examples of these are the Rio Casey, Rio Cañas, Rio Santiago, Rio Grande, Rio Culebrinas (in part), and Rio Blanco (in part).

The Rio Añasco-Rio Blanco is a stream of complex origin, and being the largest stream in the district, deserves further description. The upper portion, known as the Rio Blanco, follows the structure where it leaves the areas of massive igneous rock and enters belts of stratified rock. In these portions, it may be regarded as subsequent. The lower portion, known as the Rio Añasco, cuts across the strike of the formations without regard to the relative resistance of the different types of rock. That part of the mountainous oldland drained by the Rio Añasco was probably submerged during the Oligocene Period. If so, the deposits formed at that time have been removed by post-Oligocene erosion, and the area is to be classed as a pseudo-oldland. This theory is supported by the fact the nearest outliers of Tertiary strata (at Pt. Jiguero) are of middle Oligocene age, indicating that some 2000 feet of upper Oligocene strata have been removed by erosion. If this portion of the area is indeed a pseudo-oldland, then the Rio Añasco is probably a superimposed stream. Additional evidence favoring this view may be obtained from a study of two other streams flowing to the west coast. These are Calvache Creek and Pueblo Creek, both southeast of Rincon. The map shows that the upper portions of these streams follow the belts of weak rock, and are thus adjusted to the structure. In each case, the stream disregards the rock structure in the lower part of its course, exactly as the Rio Añasco does.

As a whole, the mountainous oldland area in the Lares District presents two contrasting types of drainage pattern (see map). In the eastern part, the pattern is dendritic; in the western part, trellis. The explanation of this is apparent. In the eastern half, the country rock is largely igneous intrusive bodies and massive tuffs and agglomerates. In the western half, stratified rocks and interbedded lava flows and sills predominate, and the beds are nearly everywhere folded and tilted at high angles. The influence of hard and soft beds on the drainage lines is very marked.

The Elevated Coastal Plain

This province includes the area between the Lares Road and the north coast, and a narrow strip along the west coast from Aguadilla to Point Jiguero. The Coastal Plain is developed on a belt of nearly horizontal Oligocene strata, mostly limestone, which overlap the oldland. It has a topography wholly distinct from the topography of the complex mountainous oldland on the south. Because of its elevated position and nearly horizontal strata, the coastal plain belt may be classed as a plateau. It is marked off from the oldland by a more or less distinct cuesta, which faces south and overlooks an inner-lowland. The inner-lowland is developed on the Older Series rocks, and in the Lares District, owes its existence to the erosive action of the Rio Culebrinas and its tributaries.

From the summit of the cuesta, which marks the highest elevation of the Tertiary coastal plain strata, the plateau surface slopes seaward (north and northwest) at an average angle of less than 1°. This plateau surface is in a youthful or submature stage of dissection. Only two master consequent streams cross the belt, from the oldland area to the north coast. These are the Rio Guajataca and the Rio Camuy. They have cut narrow canyons in the limestone to a maximum depth of more than 300 feet. River erosion, however, has not been the only destructive agency at work in this limestone area. Surface solution and underground solution have been exceedingly active, and have produced a peculiar type of Karst topography, characterized by sink holes and conical mounds or hills of limestone known as *pepinos* (Spanish for cucumbers), or haystack hills. This sink-hole—*pepino* hill topography is so rugged that travel across it is possible only by a few favorable routes. Thus, while the plateau is in a youthful stage of dissection, as far as stream erosion goes, the topography in certain belts is as rough as that of a maturely dissected country, because of the activity of underground solution.

The *pepino* hills are the most interesting and unique feature of the coastal plain. Illustrations of them are shown in figures 28 and 29, and their distribution in east-west belts across the plateau surface is brought out on the geologic map. They have been shown on this map

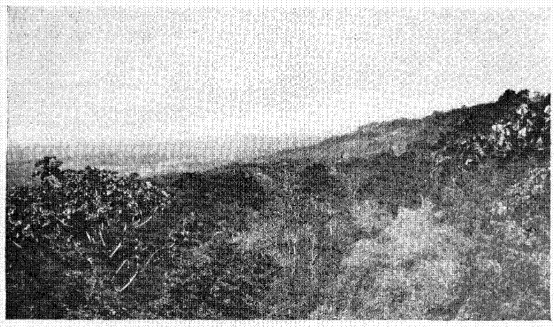

FIG. 25.—*The Tertiary cuesta on the right, with inner lowland (valley of the Rio Culebrinas) on the left*

Town of San Sebastian in the distance. View looking west from the Lares Road at Collazo. The cuesta is developed on Tertiary formations; the Lares limestone at the top, and the San Sebastian shale underlying the talus slope below. The inner lowland is developed on the Rio Culebrinas shales and tuffs of the Older Series (Cretaceous).

by hachures, because to contour them would be an endless task, and a contour interval of 100 feet would fail to bring out the extremely rugged topography of these belts of hills.

As may be seen from the illustrations, these hills are roughly conical or mound-shaped. In size, they range from small mounds less than 20 feet high, to hills at least 300 feet high. They are, where best developed, closely crowded, the intervening spaces being occupied by sink-holes of elongate or irregular pattern. In these belts of *pepino* hills, one can often not find level spaces large enough to pitch a tent on. All trails and cart roads meander around the steep sides of the hills, avoiding the sink-holes. The trails are dangerous to travel after showers, when the residual clay soil is made extremely slippery. Soil, however, is not thick or widespread in these areas, the outcrops and talus of white limestone covering much of the surface.

In viewing these hills from a distance, or from the summit of one of them, it is noticeable that the summits of all the higher hills have a fair accordance in level, presumably marking the plateau surface as it was before being cut up into this rough topography by underground solution.

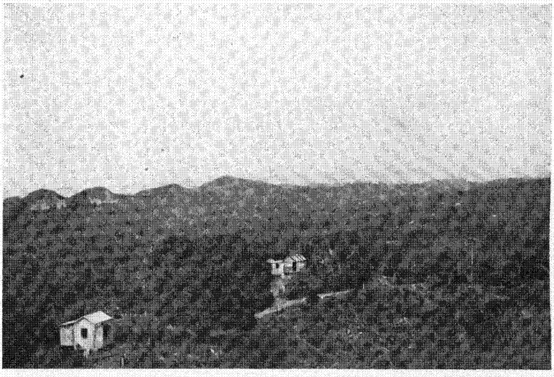

FIG. 26.—*Tertiary cuesta east of Lares*

View looking north from Rio Blanco Road south of Lares. On the left are seen the white cliffs of the Lares limestone. On the right a spur of the old land surface is overlapped by the Tertiary limestone, and the cuesta at that point is not a distinct physiographic feature.

On the plateau surface, adjacent to the belts of *pepino* hills there are belts of relatively smooth, undissected country. Typical views of this type of topography are shown in figure 27. The prairie belts are covered with black or red residual clay soils, excellent for growing sugar cane and tobacco. Where not cultivated, they make good grazing land. They are naturally grass-covered, and the trees are widely scattered, and consist chiefly of the Royal Palm. The smooth or rolling country is broken here and there by canyons, sink-holes, and low cuestas which mark the outcrop of relatively resistant limestone beds dipping 3° or 4° to the north.

The principal cuesta occurs along the Lares Road, overlooking the inner-lowland, as already noted. It marks the southern limit of the Tertiary coastal plain strata which overlap the complex mountainous oldland. Figures 25 and 26 show the variations in the topography of this cuesta. Where the basal shale beds of the Tertiary Series are capped by resistant limestone, the cuesta is prominent and not maturely dissected. Where only Tertiary shale is present, however, the cuesta is so thoroughly dissected by the tributaries of the Rio Culebrinas that it is not a prominent topographic feature. The inner-lowland is developed throughout on shales, tuffs, and other rocks of the Older Series, which in general, are more easily eroded than the Tertiary limestone forming the summit of most of the cuesta. At some points along the cuesta, the basal shale of the Tertiary Series is absent, and the higher horizons of limestone lie directly on half buried spurs of the rugged oldland surface. At such places, there is no inner-lowland, and the cuesta is low and indistinct. Other cuestas, of minor size and importance, occur in various parts of the plateau surface north of the main cuesta. They occur where resistant reef limestones alternate with soft, chalky or argillaceous beds. The regional dip is north or northwest at low angles; thus all of these cuestas face south or southeast.

THE COASTAL PLAIN BELTS

The belted character of the coastal plain has been referred to in describing the belts of *pepino* hills, and it is brought out on the geologic map. Each belt owes its topographic characteristics to the rock formation on which it is developed, hence the boundaries of the different belts are almost the same as the boundaries of the different Tertiary formations. A description of the Tertiary formations has already been given and the topographic expression of each was summarized in Table 4.

The belts, named in stratigraphic order, from the lowest to the highest, are:

1. The Lares Pepino Belt. The belt of *pepino* hills developed in the Lares limestone, on the plateau surface north of the cuesta in the eastern half of the Lares District.

2. The Cibao Prairie Belt. Adjacent to, and north of the Lares Pepino Belt. Developed on the Cibao limestone.

3. The Los Puertos Pepino Belt. North of the Cibao Belt, and developed on the Los Puertos limestone.

4. The Quebradillas Plateau Belt. Developed on the Quebradillas limestone. Extends from the Los Puertos Pepino Belt to the north coast.

To obtain a clear conception of the relationship of these belts, and the obvious reason for the belted character of the coastal plain, the reader is referred to the geologic cross-sections (Plate I), showing the north-south profiles across these topographic belts.

The Lares Pepino Belt. The best development of this belt is the area north of the town of Lares. From the Guajataca River eastward beyond the east border of the Lares District, the plateau surface just back of the cuesta is characterized by high and densely crowded *pepino* hills. These hills are formed in the pure white and pink Lares limestone, both

FIG. 27.—*Typical sink hole in the Cibao limestone prairie*
View looking E. N. E. from field station 156, Bario of Cibao.

of the massive and thin-bedded types. West of the Guajataca River, the Lares formation grades from pure limestone into soft, chalky and argillaceous limestones, and finally into shales and gravel beds. It is therefore significant to note that the *pepino* hills do not extend very far west of the Guajataca River in the Lares Belt.

The Cibao Prairie Belt. This belt is a relatively flat, rolling, grass-covered prairie, situated between the two belts of *pepino* hills (see map), and at a slightly lower elevation than the adjacent *pepino* hill country on either side. The Cibao limestone is chiefly a soft, chalky rock, with intercalated beds of hard limestone, which form low cuestas. Figure 27 shows typical views of the topography of this belt.

The Los Puertos Pepino Belt. This belt is essentially like the Lares Belt, but the *pepino* hills are larger, and the topography correspondingly more rugged and difficult to traverse. The Los Puertos Belt is much more continuous east and west than is the Lares Belt. The striking contrast between this *pepino* hill topography and the Cibao prairie topography is shown in figures 28 and 29.

The Quebradillas Plateau Belt. This belt is for the most part a plateau in a youthful stage of dissection, sloping gradually seaward, and terminated by sea cliffs along most of the coast line. The surface

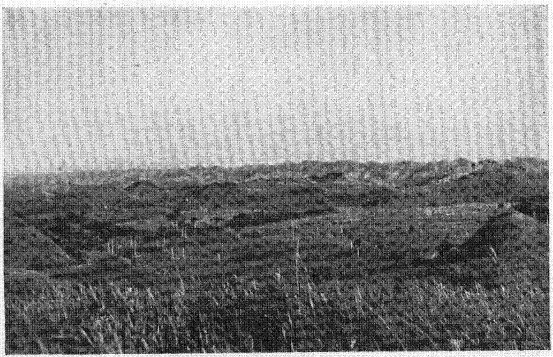

FIG. 28.—*View looking N. N. W. from field station 25, barrio of Cibao*

Showing Cibao limestone prairie in the foreground and *pepino* hills of the Los Puertos limestone in the background.

is remarkably flat, especially in the northwest corner of the district. Above this surface rise a few hills of the *pepino* type, grouped irregularly, or in long, ridge-like chains some of which are quite continuous east and west. Sink holes are common, but not as large or numerous as those of the Cibao prairie.

DRAINAGE

The coastal plain is traversed by two master consequent streams, the Rio Guajataca and Rio Camuy, each of which has its headwaters in the oldland area to the south. With the exception of these two streams, which cut deep canyons (Fig. 30) through the limestone belt, about nine-tenths of all the drainage is subterranean. Even the Camuy takes to a subterranean course in crossing the Cibao belt (Fig. 31). In many places, particularly in the Cibao prairie, the low rumble of underground rivers can be heard; in other places they are seen in the bottoms of the large sink-holes, where the water comes briefly to view, boiling as though in some giant cauldron. After a continuous 24 hours of rain, it was noted that there was practically no surface run-off on the Cibao prairie, not even the smallest rivulet being in evidence. The rain water had escaped almost immediately into the underground channels.

FIG. 29.—*View looking south from field station 153, barrio of Cibao*

Showing Cibao limestone in the foreground, *pepino* hills of the Lares formation in the background.

It is possible that the Rio Guajataca and Rio Camuy were at one time largely subterranean in their courses through the limestones, and that the present canyons have been produced in many places by caving of the surface. The following considerations support this theory:

1. Most of the present drainage lines are subterranean.

2. Sink-holes are evidently forming at the present time above these subterranean channels, and given time enough, should result in the complete caving in of the rock overlying such channels.

3. Large masses of limestone, many of them more than 100 feet in diameter, occur in the Rio Camuy canyon, more or less obstructing the stream. They are especially numerous in that part of the canyon adjacent to the subterranean route of the river. They indicate that at

one time, a larger portion of the Rio Camuy was subterranean, and that the present subterranean course is in process of being destroyed.

The future drainage history of the coastal plain will very probably be an opening up of underground water courses by caving, until surface drainage of the area is eventually established.

ORIGIN OF THE PEPINO HILLS

The topography of these hills has been described, but a discussion of their origin has been left for the last, because it is a subject closely con-

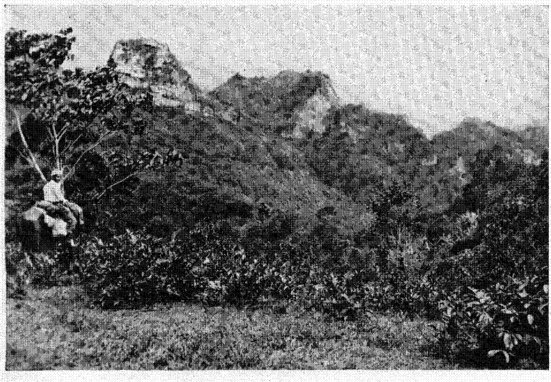

FIG. 30.—*View looking N. W. from field station 181*
Showing canyon wall of Rio Camuy in the Los Puertos limestone belt.

nected with the draining of the coastal plain. It is believed that the following observations are of critical importance in formulating any theory of the origin of this type of topography:

1. The Cibao and Quebradillas limestone belts do not have a typical development of *pepino* hills. Likewise, these hills do not occur in the Lares formation in the western part of the Lares District. In analyzing these associations, it is evident that certain types of formations are not favorable to their development. These types are (*a*) shales, marls, argillaceous or impure limestones, (*b*) continuous limestone strata of the hard, fine-grained, flinty type, characteristic of the Quebradillas formation.

2. In the most arid portion of the coastal plain, the northwest corner, there are no *pepino* hills. This is illustrated by the even plateaus back of Point Borinquen. The more arid the climate, the less the amount of surface solution which has taken place.

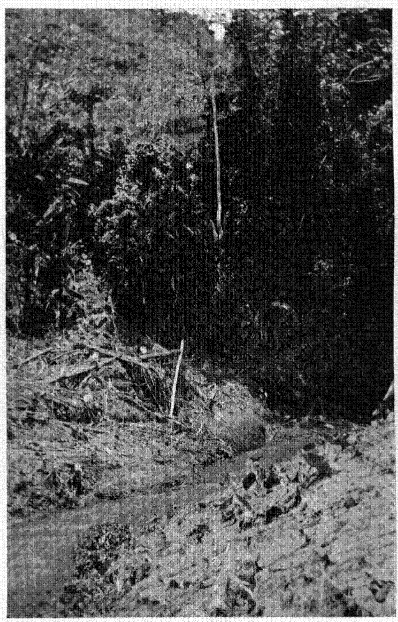

FIG. 31.—*"Blue Hole" of the Rio Camuy*

The river flows through a deep canyon terminated abruptly by an almost vertical wall, and there takes to a subterranean channel in passing through the Cibao limestone belt. The "blue hole" is seen at the extreme right, nearly blocked by the timber jam in the foreground.

3. The *pepino* hills are not individual reefs, since they are not limited to the massive reef type of limestone. Some of them are developed in

well stratified limestone, and in such cases, the same strata can be traced in detail from one hill to another (Fig. 32).

4. *Pepino* hills topography is best developed where the limestone is the most cavernous; that is, in those limestones which have suffered the maximum amount of solution by ground water. The hills are not invariably found, however, in this type of limestone formation.

5. In many localities the hills show a north-south linear grouping, with intervening lanes of sink holes (Fig. 33). This arrangement of

FIG. 32.—*View looking east from field station 6, Lares limestone, north of Lares*
Showing adjacent *pepino* hills developed on soft thin-bedded limestone, with the same strata traceable from one hill to the other.

sink holes can be produced in no other way than by caving along subterranean drainage lines.

6. Careful observation shows that the hills have a tendency to be steepest on the side toward the west. This feature is so noticeable in places as to give a saw-tooth effect to the sky line (Fig. 34). Further observation shows that this asymmetry has no relation to slumping or tilting, no relation to difference in structure or composition of the rock, and no relation to vegetation covering the hills. The only apparent explanation left is that of differential weathering and solution. The daily showers occur usually in the afternoon, when the sun has been shining on the hills from the west, and hence while the rock on the west is at a higher

temperature than that on the east or shaded sides. This increases the rate of solution, and results in a more cavernous structure being developed on the west sides. Such differential surface solution would be noticeable only where the process is extremely rapid.

From the above observations, it is believed that the *pepino* hills are the byproduct of extensive underground solution and extremely rapid surface solution, combined with the other necessary factors, lithologic and climatic, above described. Under these conditions, *pepino* hills might be developed anywhere in the tropical zone.

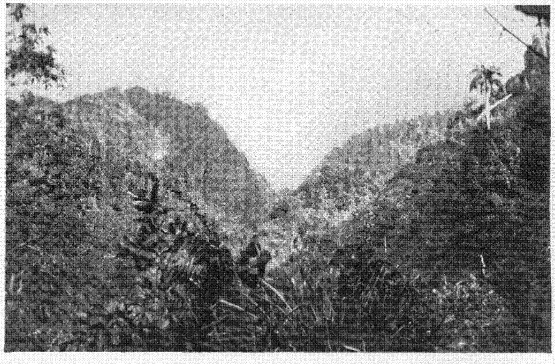

FIG. 33.—*View looking north from field station 151, in Los Puertos limestone belt*

Showing one of the north-south lanes of sink holes passing through the *pepinos*, and through which the Atlantic Ocean is visible on clear days.

THE PLAYA PLAINS

The term Playa is used in the West Indies to denote the flat or gently sloping alluvial plains which occur along the coasts of nearly all the large islands at the mouths of rivers. Such playas are in many cases several miles wide, but none is elevated more than a few feet above sea level.

In the Lares District, large playas occur at the mouth of the Rio Añasco and at the mouth of the Rio Culebrinas. There are many smaller ones on the north and west coasts. The playas, or playa plains differ chiefly in size and outline, and a description of the largest (the Añasco Playa) will include all the features to be found in any of the others.

The Añasco Playa occupies the mouth of a drowned valley, and is bounded on its inland sides by the mountains or hills of the oldland. In ground plan, the playa is fan-shaped, which is the form of a typical delta or alluvial fan. The surface in most places is smooth and apparently level, but hand-level measurements show a gradual slope to seaward from the interior portion, where the elevation is 20 to 30 feet above high tide level. The coastal margin is marked by a broad sandy beach, sand dunes back of the beach, and a zone of cocoanut palms back of the ridge of dune sand. There is a narrow zone back of the zone of palms where the

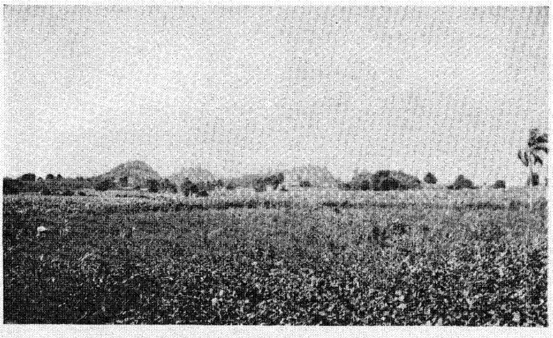

FIG. 34.—*View looking south from near K. 4, Aguadilla-Isabela Road*

Quebradillas limestone plateau in foreground, *pepino* hills of the Los Puertos limestone in the background. The view illustrates the "saw-tooth" skyline, the steeper sides of the hills being on the west.

land stands at or slightly below sea level, with small patches of salt marsh, but no large or continuous lagoon. The remainder of the playa is planted in sugar cane. The town of Añasco is located in the interior part of the playa, at an elevation of about 20 feet above sea level.

The Rio Añasco, leaving the narrow flood plain between the mountains, east of Añasco, takes a meandering course across the playa to the sea. In the interior part of the playa, the river is intrenched 10 to 15 feet below the playa surface, exposing and actively eroding the layers of unconsolidated material of which the playa is built. Numerous gullies have been eroded into adjacent parts of the playa surface by small intermittent tributaries of the main stream.

The lower (seaward) portions of Añasco Playa are said to be flooded by the river during periods of very high water, but this is of rare occurrence. On the north coast, however, small playas of intermittent streams, as, for example, the playa of Los Cedros, are flooded more frequently and more completely. This is because the river water is ponded behind an unbroken ridge of dune sand at the outer margin of the playa. The playas, while making up but a small part of Porto Rico, are very important economically, since they are the best sugar cane districts of the island, and the sites of nearly all the large sea-port towns.

FEATURES OF THE COAST LINE

Terraces

Terraces were first noted by Berkey (1915) and classed as coastal (marine) and river. The marine terraces are prominent features in many places along the coast line of the Lares District and on Desecheo Island. They are more or less local in extent and occur at elevations ranging from 2 or 3 feet above high tide to about 200 feet. Most of the lower terraces carry "fossil" beaches or sands and gravels of undoubted marine origin. The higher terraces, however, rarely show exposures of gravels, and where such gravels occur, they are not always recognizable as marine deposits. Along the automobile road west of Camuy are extensive exposures of conglomerate, composed entirely of fragments of Oligocene limestones, highly weathered and disintegrated. Similar deposits occur elsewhere along the north coast on the higher terraces. No marine Pleistocene or Recent fossils are found in these conglomerates, but their marine origin is suggested by the fact that they are never found except near the coast at altitudes up to about 200 feet. On the coast of the Ponce District, Mitchell (1922) has found coastal terraces carrying undoubted marine deposits, Pleistocene to Recent in age, and ranging in altitude from 10 to 200 feet. In comparing the terrace elevations listed by Mitchell with those recorded in the Lares District, it was found that the elevations covering the stretch of coast from Camuy to Juana Diaz fall into four rather distinct groups, indicating as many stages in the Pleistocene-Recent uplift of this portion of the island. These stages may be described as follows:

1. The Isabela Stage. Named from the well-preserved terrace (175 feet) at Isabela on the north coast. Other well marked terraces of this stage were found near Camuy (125 feet), Quebradillas (160 feet), Pt. Jiguero (165 feet), and by Mitchell near Guanica (150 feet), Yauco

(200 feet), south of Yauco (150 feet), southwest of Guayanilla Harbor (160 feet), and west of Ponce (160 to 180 feet). These are the highest terraces on which deposits of undoubted marine origin have been found. The average elevation of the group is probably close to 150 feet.[9] The fossils recorded by Mitchell show that the age is not older than Pleistocene.

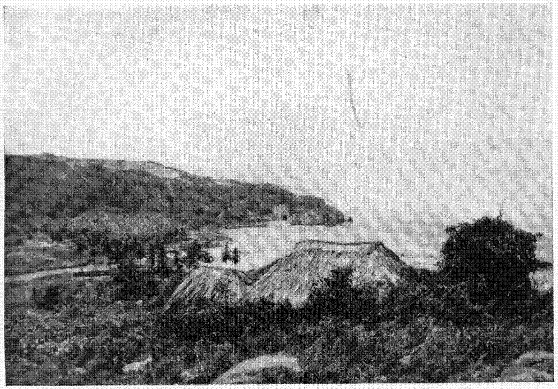

FIG. 35.—*Mouth of the Rio Guajataca*

View looking west, showing entrance to the American railroad tunnel in the distance. Above the tunnel is shown a terrace of the Cabo Rojo Stage (elevation, about one hundred feet). Above this, and to the left, is seen a portion of the highest terrace (Isabela Stage).

2. The Cabo Rojo Stage. Named from the well marked terrace found by Mitchell on Cabo Rojo (75 feet). Other terraces of this group were

[9] The discrepancy in elevation of terraces grouped together as belonging to the same stage, may be explained in one or more of the following ways:

1. Errors in aneroid readings, by which the elevations were determined.
2. Errors of judgment in selecting the top of the terrace for measurement. Many of these terraces are not level, but slope to seaward. Furthermore, they have been extensively eroded by wave and river action. Thus the eroded remnant of the outer margin might give a much lower aneroid reading than would a remnant of the inland border of the same terrace.
3. Local warping, affecting the terraces along the coast.
4. The terraces grouped under any single stage, as under the Isabela Stage of uplift, may not necessarily have been exactly contemporaneous in origin. Thus during the time interval in which all the terraces of the Isabela Stage were formed, there may have been a series of minor uplifts, totaling 50 feet.

found near Quebradillas (50 to 100 feet), Pt. Jiguero (45 to 70 feet), and by Mitchell southwest of Mayaguez, at the Reform School (50 feet), Ensenada (75 feet), Guanica (50 feet), Guanica Light House (50 feet), Pt. Brea (65 to 100 feet), and southwest of Guayanilla Harbor (60 feet). These are the highest terraces carrying the typical indurated dune sands and beach conglomerates known as the San Juan formation (Fig. 35).

3. The Upper Desecheo Stage. Named from the excellent rock terrace with consolidated beach gravel (elevation, 20 to 25 feet) preserved in many places on Desecheo Island (Fig. 36). Terraces of this stage on Porto Rico were found at the old Port of Quebradillas between Camuy

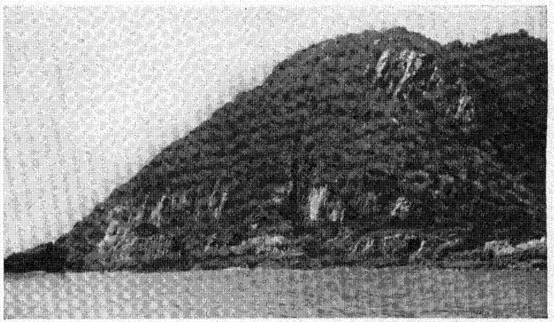

FIG. 36.—*View of southeast side of Desecheo Island*

Showing rock terrace of the Upper Desecheo Stage (elevation, twenty-five feet) and remnants of the terrace of the Lower Desecheo Stage (elevation, two to three feet above the high tide) on the right.

and Quebradillas (10 to 15 feet), near Isabela (20 feet), Pt. Jiguero (10 to 30 feet), and by Mitchell at Pt. Aguila (25 feet), and Guanica Light House (10 feet). Many of these terraces, as on Desecheo Island and at Pt. Jiguero Light House, are carved in highly tilted Older Series rocks, and their marine origin is indisputable.

4. The Lower Desecheo Stage. Named from the well defined lower rock terraces (elevation, 2 to 5 feet) on Desecheo Island (Fig. 37). Evidence on the Porto Rico coast consists chiefly in the exposures of consolidated beach sand and gravel a few feet above high tide level at various points along the north and west coasts of the Lares District. On the beach at Camuy, these consolidated beach deposits are made up in part

of calcareous algæ, marine worms, and corals, apparently still *in situ,* but slightly above high tide level. On the lower portions of the terrace at the old Port of Quebradillas, many corals were found in position of growth at elevations of from 3 to 6 feet above high tide level. Similar occurrences were found at higher elevations in other localities, but nowhere offering such unmistakable evidence of recent uplift as here.

The San Juan Formation

The name San Juan Formation was first applied by Berkey to the consolidated dune sands of Pleistocene or Recent age found at many localities along the north coast, notably at San Juan. The term has since been extended to include the firmly consolidated elevated beach gravels, such as those on Desecheo Island. Both types are found along the coast in the Lares District. As these deposits have an important bearing upon the question of Pleistocene and Recent changes in the coast line, a somewhat detailed description of them will be required.

THE CONSOLIDATED DUNE SANDS

These deposits occur in three different forms:

1. As a solid core, anchoring the modern unconsolidated dune ridges. This can be seen at a number of places, notably at Camuy, and at the mouth of Los Cedras canyon. Consolidation of the grains seems to commence around the roots of palm trees (Fig. 38). These dune ridges are so thoroughly anchored by the solid core and fixed along the rear slope by cocoanut palms that migration is apparently impossible.

2. As promontories, reefs, or small islands a short distance from the shore. Most of these have the form of spits. A glance at any map of Porto Rico will show the great number of these spits along the north coast, all solidified, all elevated well above sea level, and all pointing toward the west in the direction the littoral currents move. Excellent illustrations in the Lares District are Peñon Pt. near Camuy, Sardina Pt. near Isabela, and Jacinto Pt. near Los Cedras canyon. Fossil palm roots (molds) are found in the upper portions of these outcrops, but never occur below 4 or 5 feet above sea level.

3. Capping the elevated beach gravels. The best illustration of this type is found at Pt. Jiguero Light House. In this occurrence, molds of cocoanut palms are well preserved (Fig. 39).

In general, consolidated dune sands may be distinguished from consolidated beach sand by the following criteria:

1. The dune sands have cross-bedding dipping characteristically as high as 30°, while the dips of the beach sand bedding are very much less.

2. The consolidated dune sands never contain large pebbles. The only fossils are small shells which could be easily moved by wind.

3. The consolidated dune sands contain calcareous molds of palm roots (Fig. 38).

4. The consolidated dune sands contain relatively few fossils; the consolidated beach sands have occasional strata made up of little else but fossil shells.

It is very important to distinguish between dune and beach sand in the consolidated state, because elevated rock of dune origin does not

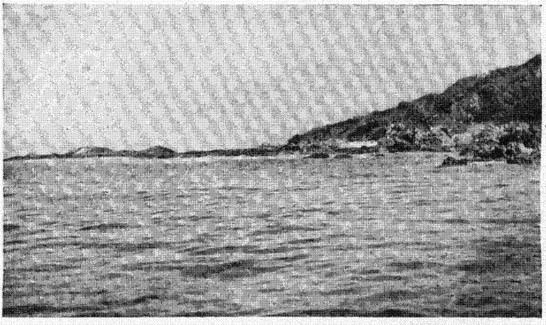

FIG. 37.—*West end, Desecheo Island*

Terrace of the Lower Desecheo Stage on the left; remnant of the Upper Desecheo terrace on the extreme right.

necessarily show evidence of uplift, since the process of solidification (cementing with $CaCO_3$) takes place above and below sea level.

THE CONSOLIDATED BEACH DEPOSITS

These consist of both sands and gravels, in all stages of cementation occurring from below sea level to elevations far above the reach of the waves. The elevated gravels are generally stratified and very fossiliferous. They differ in no respect from the gravels on the present beaches. The same is true of the elevated and present day beach sands. Both sands and gravels are made up in part of material derived from the

Cretaceous rocks, mixed with material from the Oligocene limestones and Pleistocene or Recent shell fragments. The rock is in some localities so firmly cemented that it might readily be mistaken for basal sandstone or conglomerate of the Tertiary series. On Desecheo Island, guano is the chief cementing material, but in other localities it is calcium carbonate.

EVIDENCE OF UPLIFT

Lobeck (1922) has advanced the theory that many of these elevated gravels may have been deposited by storm waves, and hence are not evidence of uplift of the coast. There are two considerations which make this theory doubtful:

1. At the old Port of Quebradillas, on the marine bench previously described, there stands an old stone structure (Fig. 40) in which the roof, cross-beams, and other wooden parts have long since turned to dust and disappeared. This old building is at least 100 years old.[10] It stands upon the high inward portion of the elevated marine bench, at an elevation of about 12 feet above the sea level. Firmly cemented to the floor of the surrounding rock terrace are gravels, fossiliferous sandstone, and large coral heads (mæandra) above the reach of the average waves. Within the old stone building, however, none of these materials are found. Although the open doorway faces the sea, only wind blown sand has found entrance. Furthermore, the building fails to show any injuries which might have been caused by hurricane waves.

2. The beach gravels and fossiliferous beach sands are in many places too well stratified and too well assorted to be the work of hurricane waves. They show no differences from the present beach deposits at sea level and below sea level.

THE AGE OF THE SAN JUAN FORMATION

It has been pointed out that there are very few exposures of San Juan formations in the Lares District on terraces higher than the Upper Desecheo Stage. Mitchell (1922) has shown that the highest fossiliferous gravels and the highest outcrops of typical San Juan formation (Cabo Rojo Stage) contain fossils of Pleistocene or Recent age, in any case not older than Pleistocene. In the Lares District, the writer made a collection of more than 1500 specimens from the modern beach, the San Juan formation of the Lower Desecheo Stage, and of the Upper Desecheo Stage, representing a total of 25 localities on the coast of the Lares Dis-

[10] Personal communication from Señor Ramon Cordova, Sub Commissioner of Agriculture and Labor, Porto Rico.

trict and Desecheo Island. Of this material, 103 species and varieties were identified, comprising molluscs, corals, echinoderms, and crustacea. The data thus gathered may be summarized as follows:

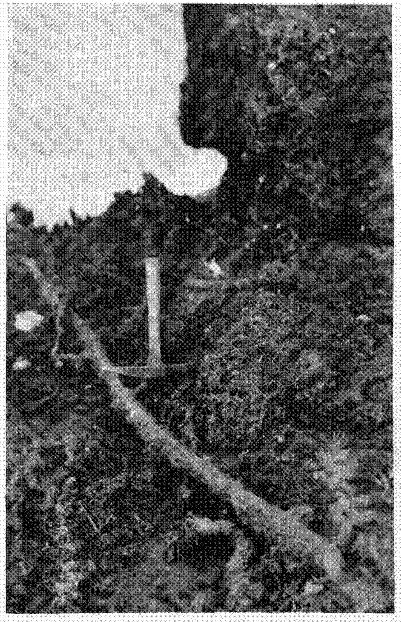

FIG. 38.—*San Juan formation at Pt. Sardinera, Isabela*

Showing solidified dune sand with calcified root of cocoanut palm imbedded in the rock.

1. Number of genera identified in modern beaches was 53, and 47 in San Juan formation.
2. Number of species and varieties identified in modern beaches was 92, and 50 in San Juan formation.
3. Number of molluscan species not recorded by Dall (1901) is 6 in San Juan formation and 2 in modern beaches.

4. Number of species or varieties in San Juan formation of the Upper Desecheo Stage which were not found on the modern beaches was 11.

5. Numbers of species or varieties in San Juan formation of the Lower Desecheo Stage which were not found on the modern beaches was 4.

6. Number of molluscan species in the modern beaches which seem to show slight mutational changes when compared with specimens of the same species from the San Juan formation is 6.

7. Other faunal differences which cannot be recorded quantitatively, but which are evident from casual observations are:

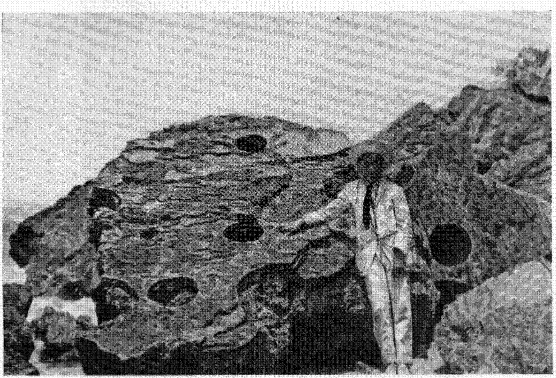

FIG. 39.—*San Juan formation at Pt. Jiguero light house*

Indurated dune sands, showing external molds of the trunks of cocoanut palms.

(*a*) The marked difference in faunal content of certain elevated beach gravels and the modern or present beach gravels immediately adjacent.

(*b*) Some of the most abundant molluscan species found on the modern beaches are rare in the San Juan formation, and *vice versa*. This difference is more pronounced for the Upper Desecheo Stage than for the Lower.

(*c*) Certain corals, particularly *Mæandra clivosa* (Ell. and Sol.) and *Mæandra labyrinthiformis* (Linn)[11] are extremely abundant in the San Juan formation and *in situ* on the elevated benches; but on the adjacent subsea flats, where *Porites* sp., *Siderastræa radians* (Pallas), and

[11] Determinations of corals were made by Dr. T. W. Vaughan.

Agaricia sp. grow in great abundance, *Mœandra* is conspicuous by its absence.

CONCLUSIONS

The faunal differences above noted are too numerous and persistent to be accidental. From a careful study of the fossils and from the various data described above, the following statements seem highly probable:

1. The deposits of the Upper Desecheo Stage are distinctly older than those of the Lower Desecheo Stage, and both are older than the present beach deposits. The higher gravels, therefore, cannot be attributed to hurricane waves, without ignoring certain facts of critical importance.

2. The following ages may be assigned to the elevated beach deposits of the different stages of the uplift:

(*a*) Isabela Stage—Early Pleistocene.
(*b*) Cabo Rojo Stage—Late Pleistocene.
(*c*) Upper Desecheo Stage—Post Pleistocene.
(*d*) Lower Desecheo Stage—Recent (Historic?).

The Playa Deposits

The Playa Plains have already been described. The material underlying these plains is for the most part fine-grained alluvium, deposited in horizontal and very regular, extensive strata. Typical exposures are to be seen in many places along the lower courses of the Rio Culebrinas and Rio Añasco, where these streams have intrenched their channels, exposing in some places (as due south of Añasco) at least 15 feet of strata. Except for a few pebble beds here and there, the material is very fine grained, consisting of carbonaceous clay, silt, and sandy loam. The fossils are chiefly fresh water or land molluscs and plant remains, but occasionally one may find beds carrying marine shells (*Strombus, Arca, Mytilus,* and others) and brackish water forms (chiefly *Neritina*). Near the coastal margins, the number of intercalated marine beds is greater. Marine and land molluscs are found mixed in the same strata. Old fossil beaches (San Juan formation) are found almost buried by Playa deposits near Camuy, at Columbus Monument, and at other places, demonstrating that the Playas have been extended within recent time. This feature might conceivably be the result of recent uplift, but it cannot be used as one of the criteria. No marine terraces or deposits were found around the interior borders of the larger Playas of the west coast in the Lares District. The smaller Playas (Los Cedras and Guajataca in particular) show evidences of marine action (caves) in the limestone cliffs which form their inland boundaries (Fig. 41).

A. Plistocene. Formation of the highest terraces during the interglacial epochs, and the submarine benches during the glacial epochs.

B. Post-Pleistocene.

1. Rise of sea level and formation of the present playas.

2. A series of uplifts, affecting the western part of Porto Rico, initiated possibly in early Pleistocene time, totaling at least 200 feet, and possibly continuing at the present time.

In the earthquake of 1918, which wrecked so many towns on the west coast of Porto Rico, the tremors travelled from west to east (Cordova, 1918). The probable source was somewhere in the submarine banks not far from the west coast. This earthquake is of special significance because it may indicate that the movements which elevated the western end of the island in Recent time, are still going on. However, further evidence is needed to settle this question.

MINERAL RESOURCES

Iron

No iron ore in commercial quantity occurs in the Lares District. Several small patches of limonite soil with limoite concretions, derived from serpentine, are found south of Aguada. The locations are shown on the geologic map. This ore is like that of the Mesa at Mayaguez and is of the same origin. From samples obtained in the area south of Aguada, Fettke (1918, p. 673) determines the content of iron as 13.76 percent, which shows that the ore is too low grade to be used, even if it occurred in large enough quantity.

Copper

Copper is found at a locality 2½ miles south of Aguada in the area of volcanic flows. The southern portion of this volcanic area, shown on the geologic map, is largely made up of a dark scoriaceous, vesicular, or amygdaloidal augite andesite. It doubtless represents a succession of surface flows, but these are too irregular to distinguish in the exposures. Locally the amygdaloidal cavities are filled with calcite, amorphous silica, and zeolites, but throughout the greater portion, the cavities, where present, are empty.

In a small portion of this volcanic area near its southern limit, and covering only a few acres, is the mineralized zone in which the copper occurs. The approximate location of the test pits and adit where it is mined is shown on the map. The rock at this particular location is considerably faulted, and the amygdaloidal cavities are entirely filled, principally with calcite, and some zeolites. The copper occurs in and adjacent to the crush zones, which are never much more than 1 foot wide, and average only 2 or 3 inches. The richest vein, which has been followed for a short distance in the adit, averages 2½ inches thick, strikes north 25° west, and dips 58° to the northeast. Other veins encountered in the excavation range from ½ to 2 inches thick, strike east and west, and dip at angles of from 70° to 90°. The adit has penetrated the side of the small hill for a distance of only 27 feet and

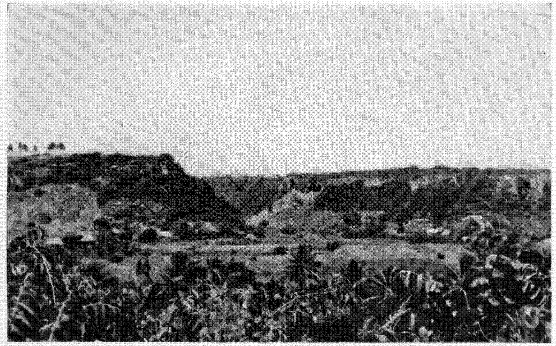

FIG. 41.—*Playa of Los Cedras, north coast*

View looking south from the dune ridge, showing the mouth of the canyon, the old sea caverns in the cliffs, and the plateau surface of the Quebradillas limestone. The Cedras is an intermittent stream, and during rainy periods the Playa is sometimes flooded to a depth of two or three feet. The dunes form an unbroken barrier around the outer edge of the Playa and are the cause of this ponding of the water.

has a cross-section of 9 by 6 feet. Besides the copper-bearing veins, many minor veinlets were encountered, carrying calcite and stilbite. The ore consists of native copper, chalcocite, malachite, tetrahedrite, and azurite, of which the first is by far the most abundant. It occurs in small irregular masses in the veins, and with the malachite and chalcocite, forms a matrix for the crushed fragments of wall rock. Azurite is frequently found encrusting the other copper minerals, but never in any great quantity. Occasional amygdaloidal cavities and blow holes adjacent to the mineralized crush zones are filled with native copper, usually intermixed with minor amounts of the other copper minerals. One of these large nuggets, almost entirely of native copper, is shown in Fig. 42.

This property, covering 160 acres, is owned by Señor Antonio Sanchez and Judge Luis Vadis of Aguada, Señor Poali of Cataño and Dr. Jimenez of Aguadilla. These gentlemen have rented adjoining land for exploration. In addition to the small adit, which represents the chief excavation on the property, several test pits have been sunk at various points nearby, and in some of them small amounts of copper have been

FIG. 42.—*Nugget of native copper taken from adit in the location south of Aguada*

found. Altogether, about five tons of ore have been shipped to Aguada. All work has been done by hand labor, no machinery of any kind having been used.

In the opinion of the writer, this prospect will not warrant the installation of elaborate machinery or expenditure of large sums of money for developing and exploitation. While this ore is rich and the veins numerous, the area involved seems to be very limited in extent. However, the property will doubtless yield considerable profit if worked on a small scale with simple methods, using hand labor and transportation by oxcarts. The topography between this property and the town of Aguada on the American railroad, is not excessively hilly, and the distance not great. Improvements in the present cart road could be made at small expense. It is to be further recommended that more test pits be dug in this area, most of which is covered by clay soil.

Kaolin

Kaolin of high grade of purity occurs at many places in the Older Series, but especially along the road south of Lares, near the Rio Blanco (Fig. 2). For the present, however, with the scarcity of fuel, distance from railroad, and lack of any nearby market, the material will remain of potential value only.

Brick Clay

Clay is the most common type soil in the district, especially in the mountainous portions developed on the Older Series rocks. Most of these clays would require mixing with sand before using for brick manufacture. Considerable red clay and black clay loam is developed in the Tertiary limestone area north of Lares, particularly along the belt of Cibao limestone. Generally this material is too high in organic matter to be of any value, and otherwise it is altogether inaccessible. Along the belt of Quebradillas limestone, particularly over the plateau west and southwest of Isabela are many areas of red sandy clay which may some time prove valuable for brick. Some brick has been made at Lares, and doubtless at other localities from time to time, chiefly for local use. The only place where brick is now being made is in and around Mayaguez, where, according to the reports, there are three plants, all of small size. One of these was visited by the writer and the following notes regarding it may be of interest: The material used is taken from the small flood plain of the Yaguez River, close to the plant. The section exposed in the excavations shows a dark red clay overlain by 6 feet of lighter colored reddish brown clay with a capping of 1 to 4 feet of river gravel. The plant contains three compound ovens, a mixing pit, and drying racks with wooden molds. The mixer consists of a circular pit in which is set a center-post. On this post as pivot is mounted an horizontal shaft, counterweighted at one end and at the other hitched to a pair of oxen, who operate on a circular path surrounding the pit. A large cart wheel, mounted on the horizontal shaft ploughs through the clay and water in the pit and serves as the mixing device. This wheel revolves on the beam, and is regulated in position from center to periphery of the pit by a system of ratchet and worm gears operated from the end of the shaft. In the pit, with the clay and water, is mixed sand from the river channel to the extent of one cartload per 1000 bricks produced, or for a single filling of the pit, 12 cartloads of red clay (known locally as the "black clay" because of its relatively dark color), 12 cartloads of the reddish brown clay, and 6 loads of sand, with water to give proper consistency. It takes 1 day to fill the pit, 2 days for the mixing, and then the material is dumped by hand into the molds (wooden frames laid on planks), and left to dry. This takes 8 days in dry weather. Frames are then removed, and the bricks loaded into the ovens, requiring two days to fill. Fires are built during the third day, starting with wood charcoal, and then adding coke (one-inch size). Two cartloads of coke are said to be required for every 15,000 bricks. The bricks are baked for 24 hours.

The shrinkage of the sun-dried brick was found to be high, between 20 and 30 per cent by volume, with further very slight shrinkage after firing. The price obtained (in 1916) in the local market was $10 per thousand. The quality of the brick is very poor, owing to the poor material used and lack of proper mixing. The apparent success of this enterprise, with its more or less primitive methods, would seem to warrant further development of the brick industry, using more up-to-date methods, and taking a full advantage of the more valuable clays and other materials occurring abundantly in this portion of the island.

Lime

Pure limestone for burning purposes may be obtained at so many easily accessible points on the American Railroad along the north and west coasts from Camuy to Aguadilla that no specific localities need be mentioned. The material as a whole, however, will not be found as good for this purpose as the limestone farther east from Camuy to San Juan, and on the south coast near Ponce.

Building Stone

No first-class building stone is to be found among the Cretaceous rocks of the Lares District. The lime-shales are too thin-bedded and fractured to obtain slabs of proper size. The igneous rocks are of little value owing to the weathered condition, difficulties in quarrying, and high content of ferro-magnesian minerals and oxides of iron. The best building stones are to be found in the Tertiary limestones. At various places along the north coast in the Quebradillas limestone, hard, flinty beds alternate with chalky layers. These hard strata can be easily quarried into large blocks. In many places, however, the rock will be found too massive and riddled with solution cavities to be of much value.

Road Metal

Road metal of first-class type is being quarried in many parts of the Lares District, chiefly along the automobile roads where they traverse rocks of the proper type. On the Lares Road, andesite porphyries are used in the neighborhood of Lares. Near San Sebastian, the large coral heads, imbedded in the soft marl of the San Sebastian shale horizon are accessible in cliffs along the road; they are easily quarried, and make an excellent and durable material. Farther west, around Aguadilla, the massive Los Puertos, and underlying limestones are quarried extensively. Northwest from Añasco, the lime shales are quarried along the road at several places. These hard beds are easily broken to proper size and the material is of lasting quality. On the Mayaguez-Las Marias Road the various andesitic rocks are employed, and at a few places the black pyritic shale, which is quarried near Consumo. This shale is hard and fresh, and apparently a good material, but the high content of pyrite, and the depth to which this shale is characteristically weathered, makes it doubtful if it will last any length of time as road ballast. In general, the Tertiary limestones produce the smoothest and best road beds of any rock to be found in the district. Where igneous rocks are used, a covering of this limestone would produce ideal conditions.

Lignite

At Lares, San Sebastian, west of Moca, and many other points along the Lares Road, the basal shales (San Sebastian) carry lenses of lignite of no great extent or thickness. They are seldom over six inches thick at a maximum, and average much less. They are extremely high in marcasite, and hence more or less completely oxidized where exposed at the surface. These coal lenses are valueless except occasionally for local use. An enterprising Lares blacksmith has dug out considerable quantities for use in his forge. The frequency with which these lignite lenses are exposed in the San Sebastian shale along the Lares Road has led many of the local residents to believe that coal must occur in commercial quantity. This false impression has spread to other parts of the island, where people will often refer to the coal of the Lares-San Sebastian locality. Such lenses of this material as occur would not repay exploitation unless they were continuous over considerable distance. That they are not continuous can be seen from observation, and from a consideration of the conditions of origin of the San Sebastian shale in which they occur.

Guano

Bat guano, taken from caves in the Tertiary limestone area, is used to some extent for fertilizer by local farmers. Bird guano is found on the Desecheo Island, chiefly as a cement matrix in the elevated beach gravels (San Juan formation). However, it has not accumulated as abundantly as on Mona Island, where it is now being quarried and shipped to Porto Rico.

Oil

No oil shales or surface indications of oil were found in the Lares District. The San Sebastian shale is the only formation observed in which hydrocarbons might originate, but lignite seems to be the only carbonaceous material present. In view of this, there is very little to warrant an exploration for oil in this part of the island. Nevertheless, the San Sebastian formation is not essentially different from formations in Trinidad which carry bituminous material, and therefore the possibility of oil in the Tertiary series of the Lares District must not be overlooked. The most promising location for test drilling is the area north of the Tertiary cuesta between the meridians of Collazo and San Sebastian, since it is in this area that the San Sebastian shale attains its maximum thickness, and greatest development of carbonaceous clays.

Summary

The chief assets of the Lares District are the varied soils, and the agricultural products. Important studies in this field are being made at the Agricultural Experiment Station at Mayaguez. Of mineral resources, clays, road metal, and natural fertilizers will prove to be the most important. Copper is the only metallic mineral which shows possibility of commercial importance. The reported presence of coal beds proved to be thin seams of lignite in the San Sebastian shale, and are of no value. No oil shales were found, and there is no good evidence that oil exists in any of the rocks of the district.

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ERRATUM

Corrected Legend for Map of Lares District Porto Rico—Hubbard.

Scientific Survey of Porto Rico and the Virgin Islands, Vol. 2, pt. 1.

LEGEND

PLEISTOCENE TO RECENT
- PLAYA DEPOSITS UNCONSOLIDATED
- SAN JUAN FORMATION

UPPER OLIGOCENE
- QUEBRADILLAS LIMESTONE
- LOS PUERTOS LIMESTONE

MIDDLE OLIGOCENE
- CIBAO LIMESTONE
- LARES FORMATION
- SAN SEBASTIAN SHALE

UPPER CRETACEOUS
- SHALES
- LIMESTONE
- CHERT
- ASH, TUFF AND AGGLOMERATE

LATE CRETACEOUS
- ANDESITE FLOWS
- ANDESITE PORPHYRY
- AUGITE ANDESITE PORPHYRY
- GABBRO PORPHYRY
- QUARTZ DIORITE PORPHYRY
- SERPENTINE

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